Advanced Planning & Integration Office

National Research Council
Dialogue to Assess Progress on Development of NASA's

High Energy Power and Propulsion Capability Roadmap

General Background and Introduction

Perry Bankston

April 7, 2005

Agenda

- General Background and Introduction of High Energy Power and Propulsion Capability Roadmap
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

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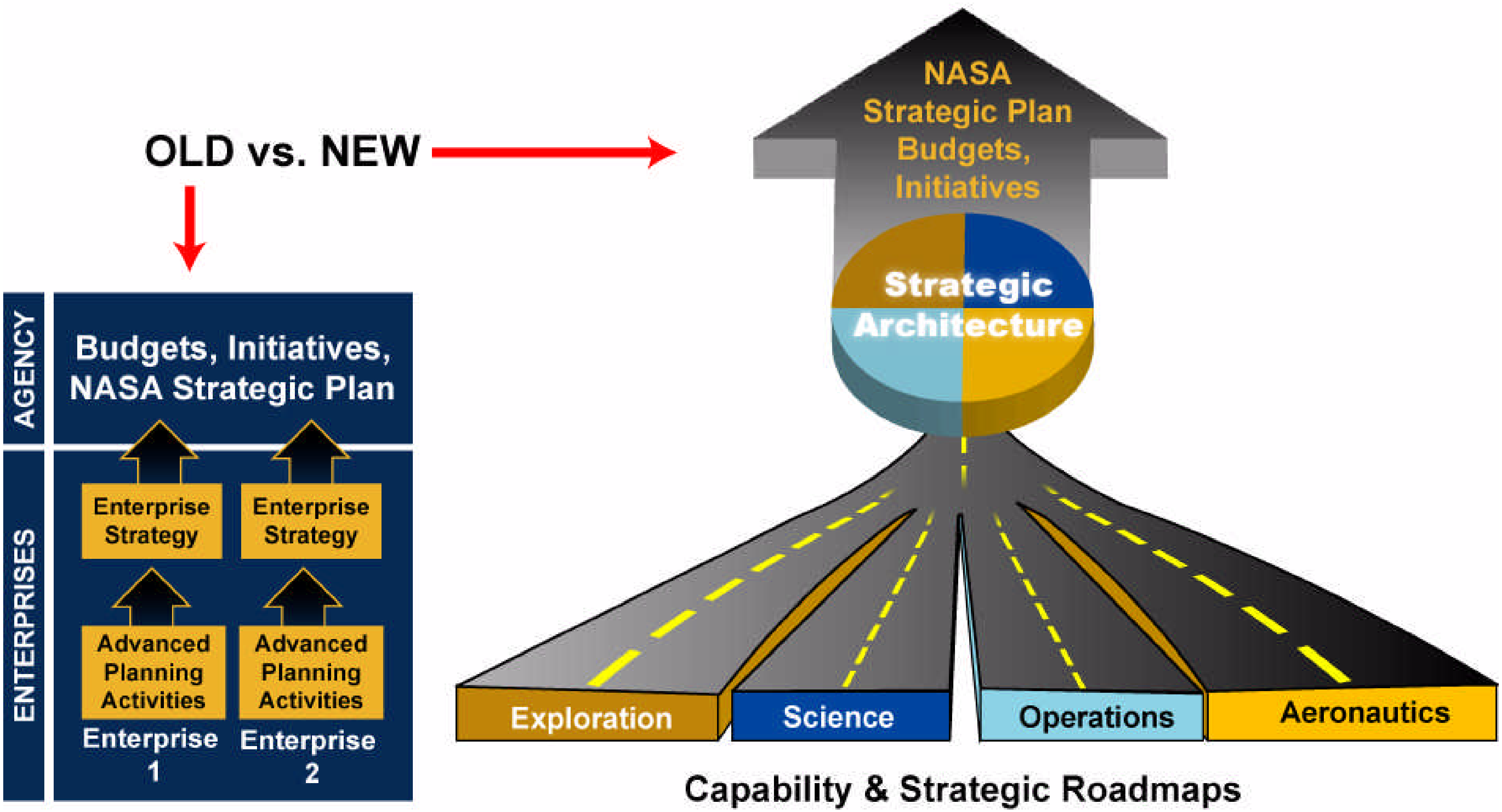
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	1. Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	6. Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	7. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	8. Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	4. Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	9. Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	5. Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	10. Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

Agency Goals and Objectives

National Goal0	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	3. Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration.	4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	5. Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	11. Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	14. Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems. (SRM 9)	17. Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)
	12. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	15. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)	18. Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)
	13. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	16. Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	

Strategic Planning Transformation

ACHIEVING THE VISION



Strategic Planning Transformation - continued

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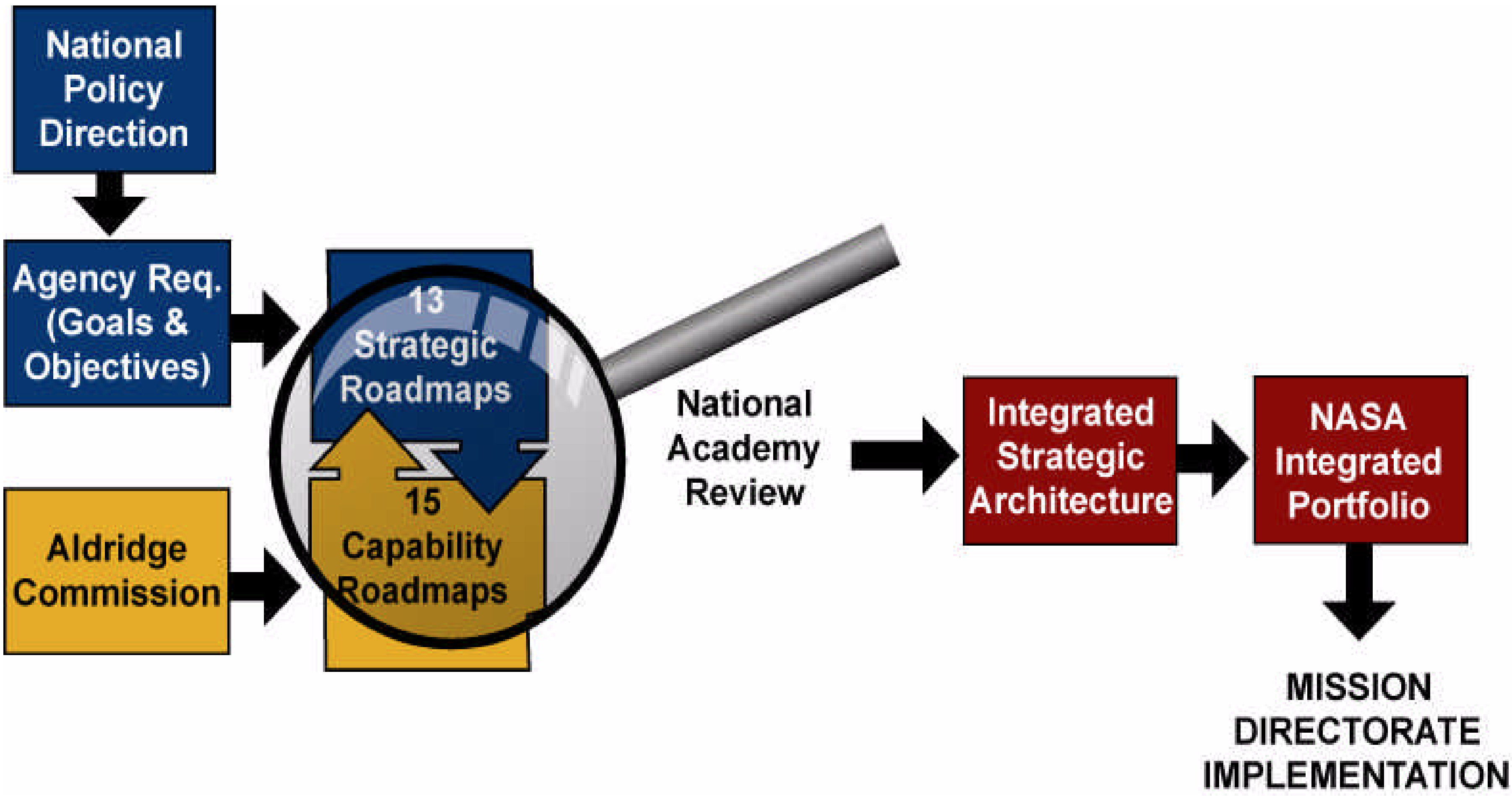

Advanced Planning Organizational Roles

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Director for Advanced Planning (Charles Elachi through 24 Mar 05)
  - Develops input, options, & assessments for Strategic Planning Council
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

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- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

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- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.
- Roadmaps will include:
  - Broad human and robotic science and exploration goals, priorities, anticipated discoveries
  - High-level milestones, options, and decision
  - points
  - Implementation approaches, suggested
  - missions

Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

Strategic Roadmaps - continued

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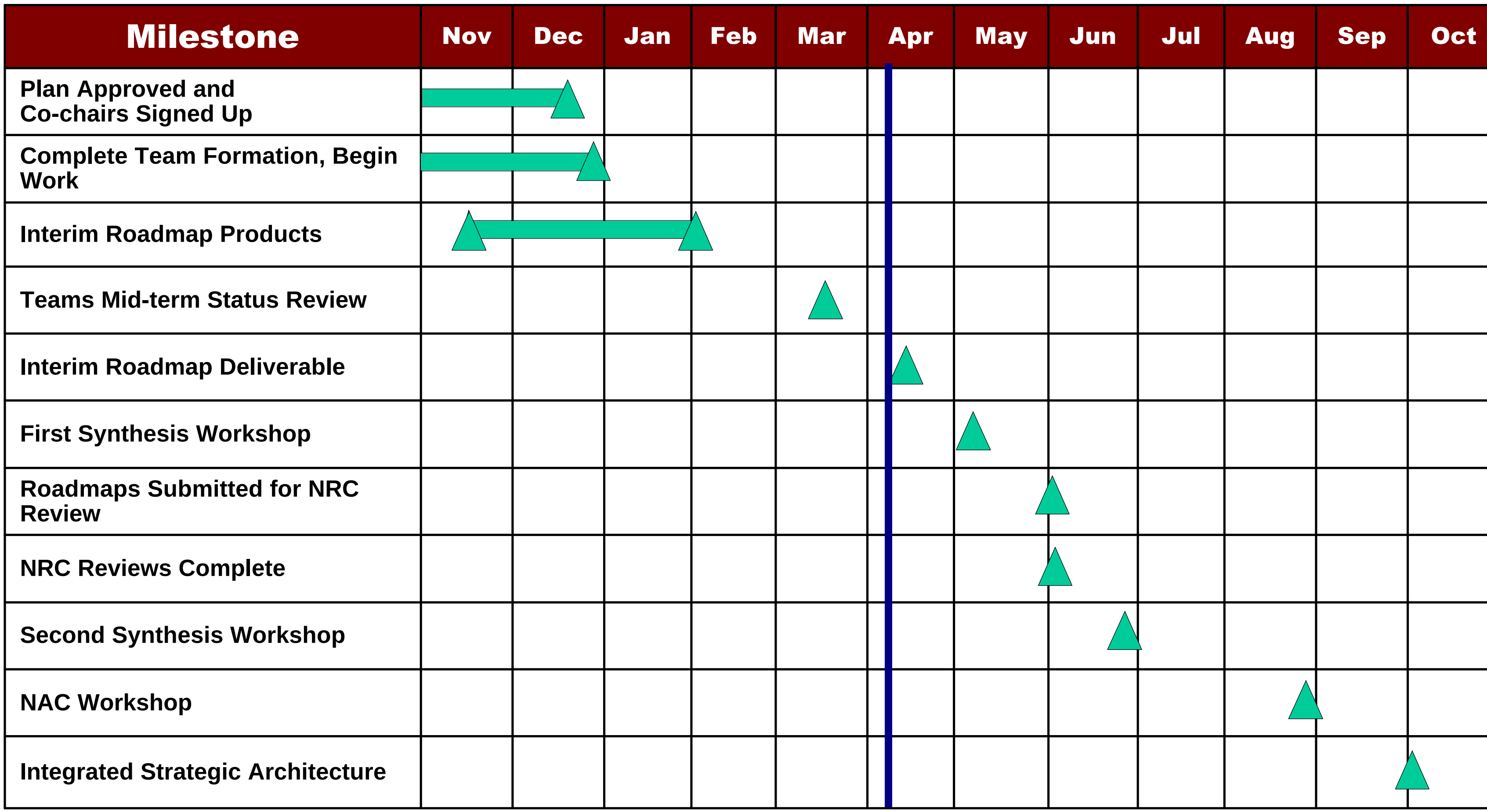
Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

Strategic Roadmaps Schedule



Capability Roadmaps

- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

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- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

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- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**
    - **1/3 Industry**
    - **1/3 NASA & other Government Agencies**
    - **1/3 Academia**
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

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Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

Capability Roadmaps - continued

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Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

Capability Roadmap Development Schedule Overview

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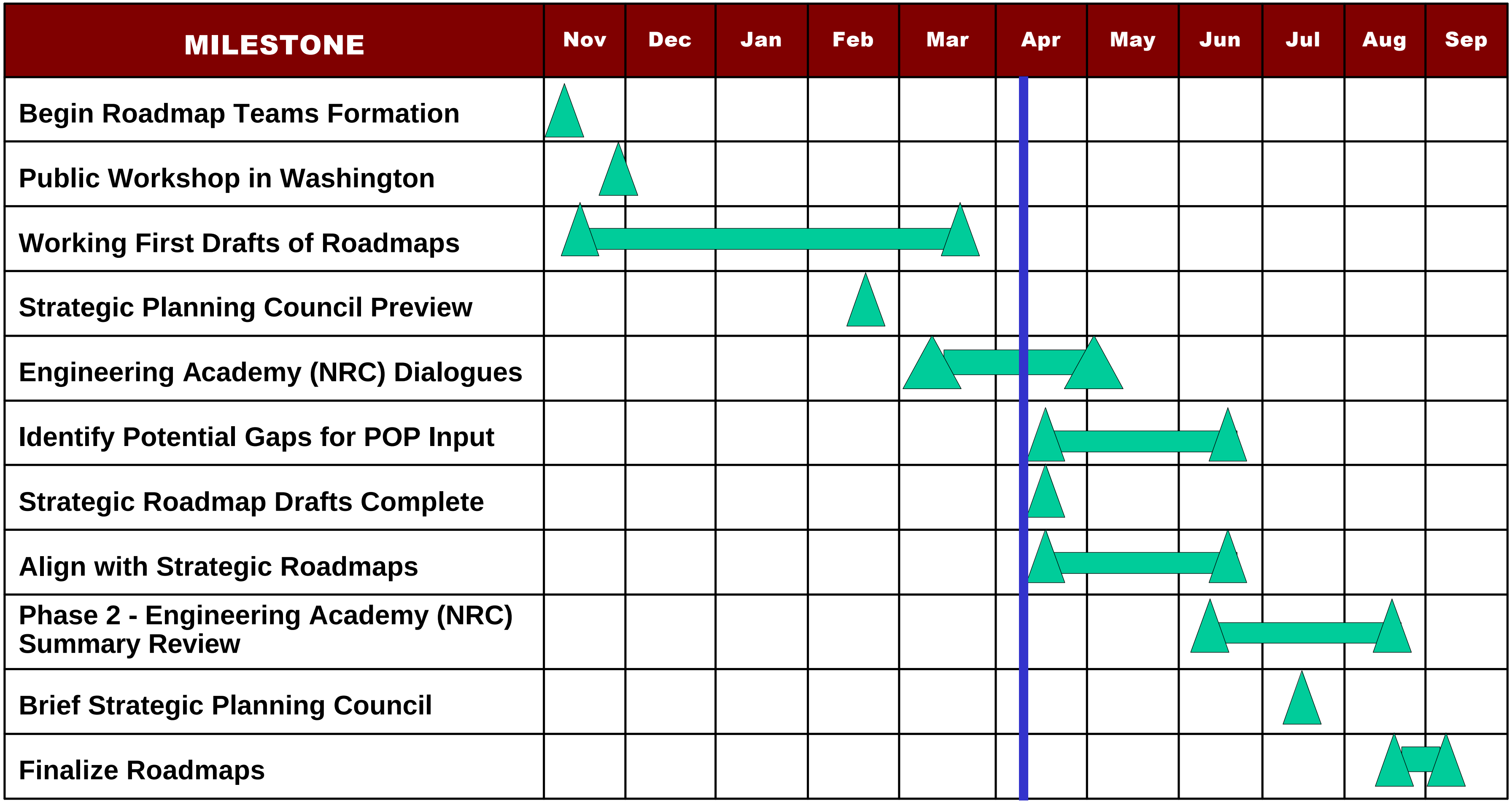
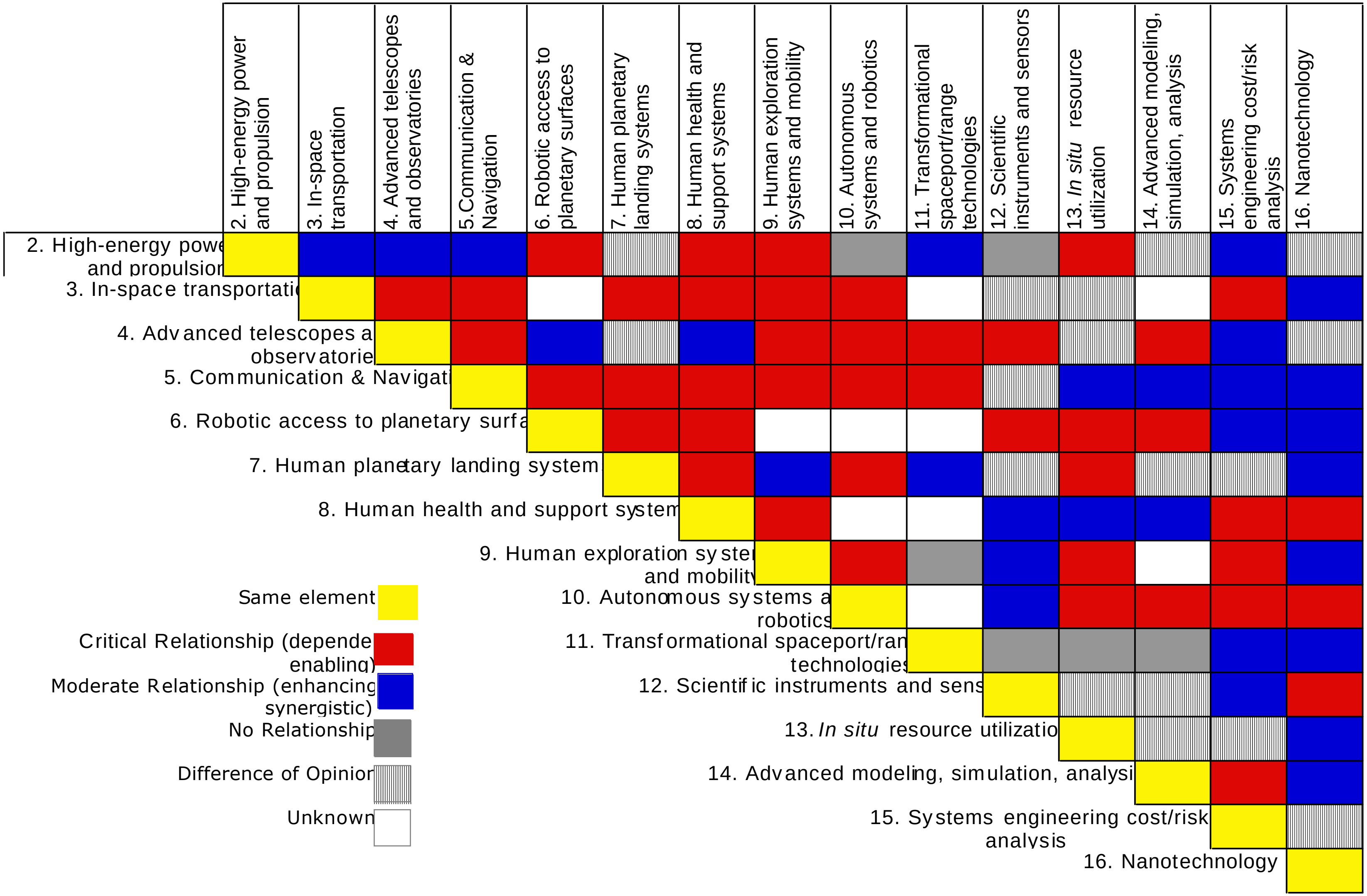


Integrated Capability Crosswalk



HEP&P Capability Crosswalk

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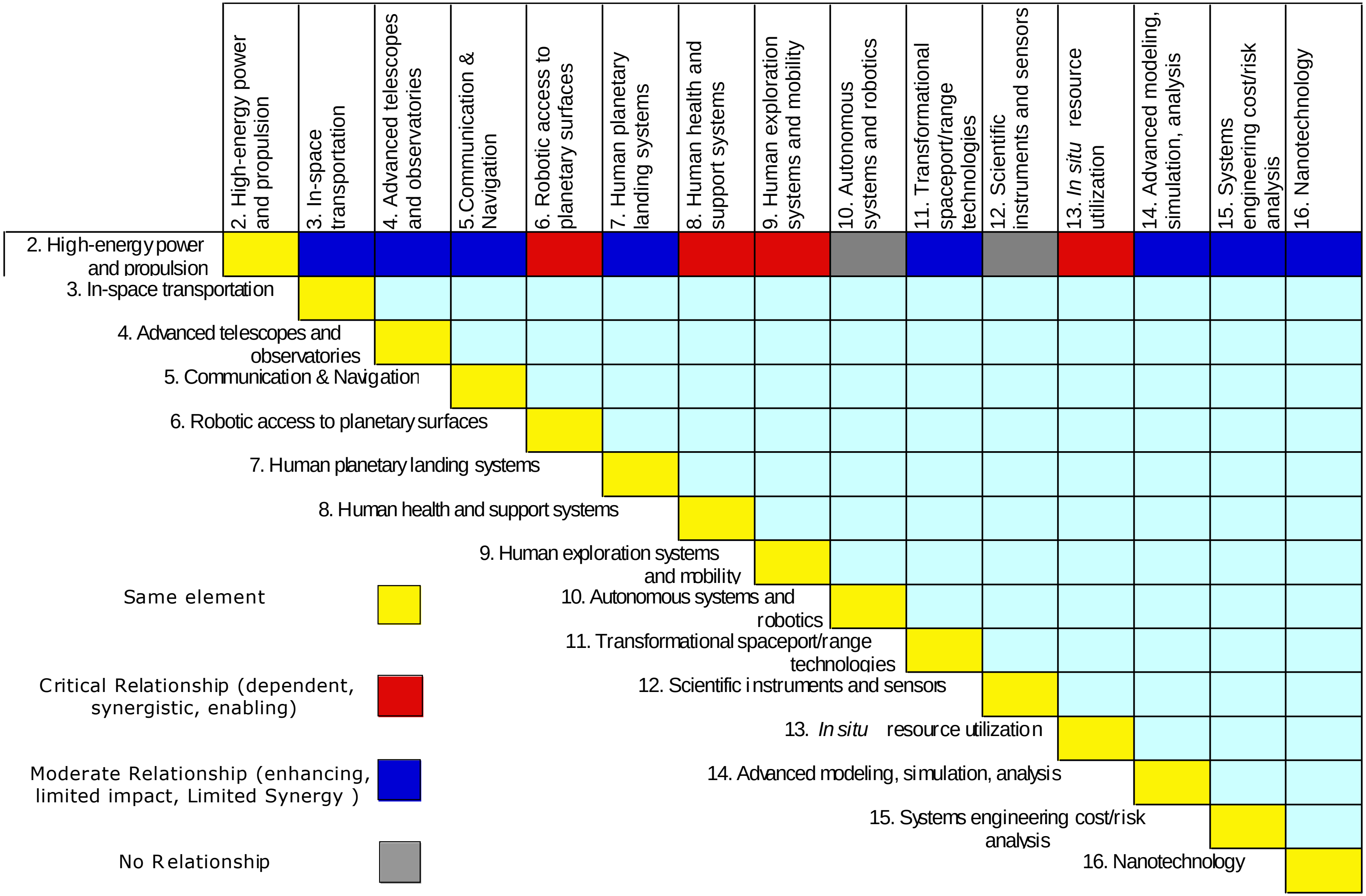

Capability Crosswalk Details(Ex)

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High Energy Power and Propulsion	Capability Flow and Criticaltiy	Related Roadmap	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
		Human Exploration Systems & Mobility	
Surface Power (PV/Radioisotope)	→	Crew Mobility/Surface rovers	Power sources required for crev surface rovers
Surface Power (PV/nuclear fission)	→	In-Space Assembly Large & Intermediate Scale Assy Syst	High Power needed for cranes, tools, etc.
		In Situ Resource Utilization	
Surface Power (PV/nuclear fission)	→	Resource Extraction; excavation, drilling, Resource Processing; consumable(O2), f feedstock, etc. production In situ manufacturing	All of these ISRU processes wi depend upon high power/enegry sources
		Human Health & Support Systems	
Component Technologies; Batteries, PMAD	→	Life Support & Habitation; EVA(Portable I Support Systems)	Advanced batteries; efficient power supplies
Surface Power(PV/nuclear fission)	→	Life Support & Habitation; Advanced life support, habitats	High power systems will be needed to support human activities
		Nanotechnology	
Component Technologies	←	Advanced Nano-Scale Materials & Concep for Nano-Scale Devices; Nano-to-Micro Systems Integration	Battery electrode materials, quantum dot PV, thermoelectric materials, thermal control materials, etc.

Purpose of NRC Review

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metrics for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate?

Technology Readiness Levels

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Level	Description
9	Actual System Proven in Operation
8	Actual System Qualified by Demonstration
7	System Prototype Demonstration in an Operational Environment
6	System/Subsystem Model or Prototype Demonstration in a Relevant Environment
5	Component and/or Breadboard Validation in a Relevant Environment
4	Component and/or Breadboard Validation in a Laboratory Environment
3	Analytical and Experimental Critical Functions Characteristic Proof-of-Concept
2	Technology Concept and/or Application Formulated
1	Basic Principles Observed and Reported

Capability Readiness Levels

Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

Back-up charts

Capability Readiness Levels Defined

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- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  – The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  – A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modelling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  – A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  – An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  – The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).
  -full scale flight articles
  -demonstration in appropriate operational 'envelope'
- **CRL 7: Capability Operational Readiness**
  – The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

High Energy Power and Propulsion (HEP & P) Capability Roadmap

Joseph J. Nainiger, NASA Glenn Research Center, Chair
Tom Hughes, Penn State, Applied Research Lab, Co-Chair
Jack Wheeler, DOE Headquarters, Co-Chair

April 7, 2005

Disclaimer:
This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 HEP & P Team members, and is not the official view of NASA or DOE.

Agenda

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- Introduction – Tom Hughes
- Capability Roadmaps
  – Solar Systems – Rao Surampudi (for Henry Brandhorst)
  – Energy Storage Systems – Rao Surampudi
  – Radioisotope Systems – Bob Wiley
  – Nuclear Fission Systems – Sherrell Greene
- Conclusion/Summary – Joe Nainiger

HEP & P Capability Roadmap Team

Advanced Planning & Integration Office

Co-Chairs

- NASA: Joseph J. Nainiger, Glenn Research Center
- External: Tom Hughes, Penn State, Applied Research Lab
- DOE: John (Jack) P. Wheeler, DOE HDQs

Team Members

- Government
  - Elaine Kobalka, NASA Glenn Research Center
  - Stan Borowski, NASA Glenn Research Center
  - Jose Davis, NASA Glenn Research Center
  - Jeff George, NASA Johnson Space Center
  - Rao Surampudi, Jet Propulsion Laboratory
  - Sherrell Greene, Oak Ridge National Laboratory
  - George Schmidt, NASA Marshall Space Flight Center
  - Bob Wiley, DOE HDQs
  - Wayne Bordelon, NASA Marshall Space Flight Center

Team Members (continued)

- Industry
  - Samit K. Bhattacharyya, President, RENMAR Enterprises
  - Gary L. Bennett, Consultant
  - Dave Byers, Consultant
- Academia
  - James Gilland, Ohio Aerospace Institute
  - Henry W. Brandhorst, Jr., Director, Space Research Institute, Auburn University

Coordinators

- Directorate: Overall: Doug Craig, ESMD, Technical: Raynor Taylor, ESMD, (Day-to Day, Jay Jenkins, ESMD)
- APIO: Perry Bankston, Jet Propulsion Laboratory

Red = Sub-team lead

Capability Description

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- **The High Energy Power and Propulsion (HEP & P) capability roadmap addresses the systems, infrastructure and associated technologies necessary to provide power and propulsion for human and robotic exploration of space and to provide power for human and robotic exploration of planetary surfaces.**

Capability Breakdown Structure – HEP&P

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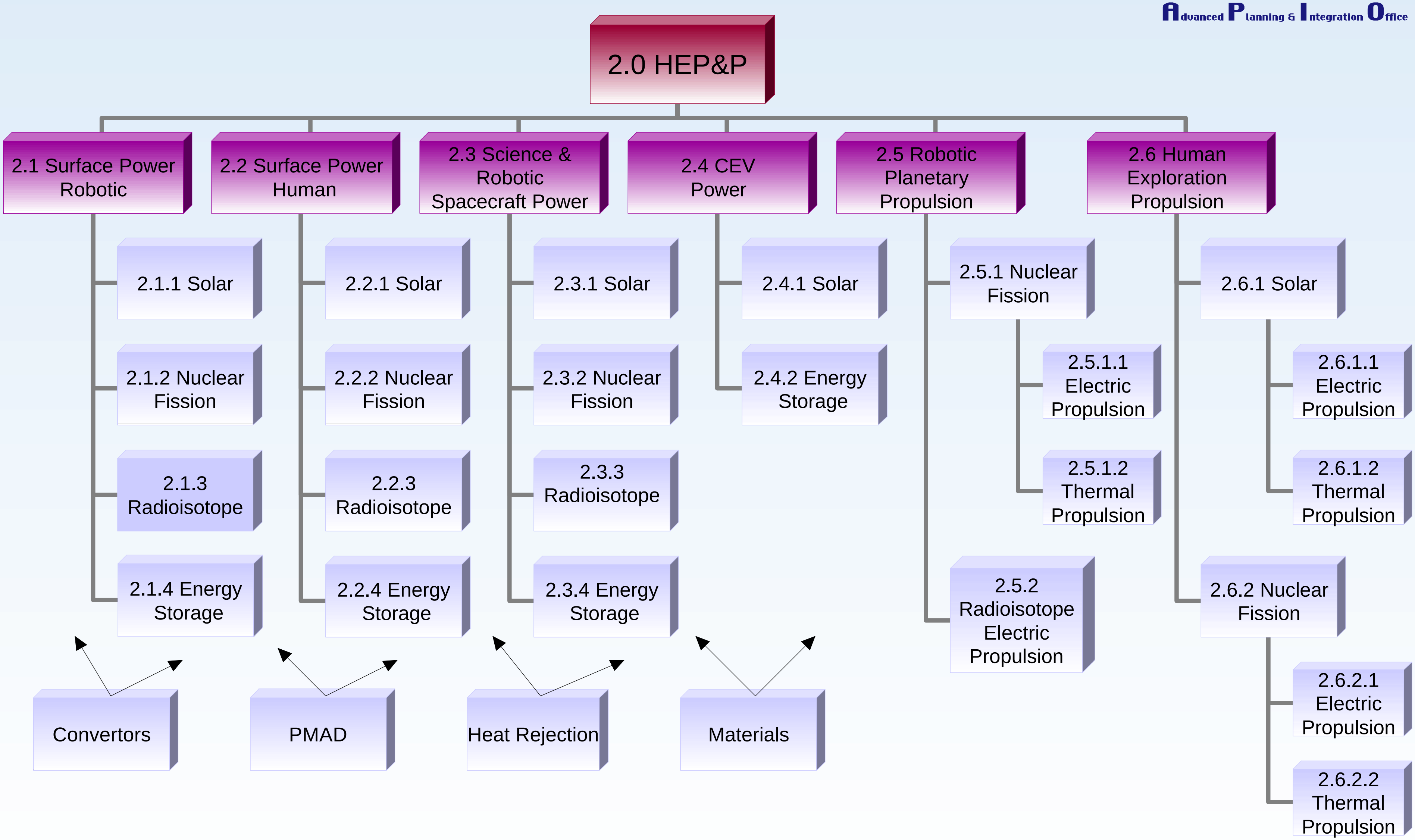

Benefits of High Energy Power & Propulsion

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High Energy Power and Propulsion Systems could:

- Enable extended human missions and presence
- Enable advanced propulsion (NEP, SEP, NTP,REP)
- Allow longer missions
- Allow reduced transit times
- Allow more extensive and powerful science mission instruments
- Reduce required spacecraft mass or increases available payload mass
- Enable exploration where solar energy is limited or absent
- Enable In Situ Resource Utilization (ISRU)

HEP & P Relevance to Exploration – Aldridge Commission Recommendation

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Aldridge Commission Report: " Finding 4: The Commission finds that successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedules and affordable costs. There was significant agreement that helped the Commission identify 17 areas for initial focus….we identify the following enabling technologies…

- ***Advanced power and propulsion* – primarily nuclear thermal and nuclear electric, to enable spacecraft and instrument operation and communications, particularly in the outer solar system, where sunlight can no longer be exploited by solar panels….**

Recommendation 4-1:

The commission recommends that NASA immediately form special project teams for each enabling technology to:

- **Conduct initial assessments of these technologies**
- **Develop a roadmap that leads to mature technologies**
- **Integrate these technologies into the exploration architecture; and**
- **Develop a plan for transition of appropriate technologies to the private sector"**

Roadmap Process and Approach

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- Created 4 sub-teams; Solar, Storage, Radioisotope and Fission
- Developed strawman requirements and assumptions in consultation with SRC-13 and other capability teams
- Sub-teams developed initial “independent” Capability Roadmaps based on strawman requirements and assumptions, current state-of-technologies and projected trajectories of advancing technologies
- Sub-team roadmaps “rolled up” into overall roadmaps in an iterative process that continues
- Process of highlighting decision points (choices) and technology gaps is current focus

Current State-of-the-Art for Capabilities

Top Level Summary

- Fission Systems
  - Power (US Only)
    - SNAP-10A (1965)
    - SP-100 (1980-1992)
    - Ground tests of power conversion candidates (Brayton, potassium Rankine, etc.) in previous programs
  - Propulsion
    - Ion – Isp 3300 sec, Efficiency 70%, Life 10,000 hrs, Power 2.7 kW, TRL 9 (Deepspace 1)
    - Hall – Isp 1640 sec, Efficiency 67%, Life 4,000 to 8,000 hrs, Power 1.2 kW, TRL 9 (SMART 1)
    - MPD – Isp 1000 to 10,000 sec, Efficiency 45 to 60%, Life 500 hours, Power 1000 to 10,000 kW, TRL 3
    - PIT – Isp 4000 to 6000 sec, Efficiency 50%, Life pulsed, Power MW/pulse, TRL 3
    - Rover/Nerva Program 1959-1972, Highest Power 4100 MWt, Isp 875 sec, Continuous Operation 62 min.
- Radioisotope Systems
  - Power
    - RTG with GPHS – specific power 5.3 We/kg, efficiency = 6.6%
  - Propulsion
    - Same as ion above
- Solar Systems
  - Power
    - Solar array specific power – 40-60 We/kg, Solar cell efficiency – 26 to 28%
  - Propulsion
    - Same as above
- Energy Storage Systems
  - Primary Batteries – Specific Energy 90-250 Wh/kg, Mission Life 1-9 years
  - Rechargeable Batteries – Specific Energy 24-35 Wh/kg, Cycle Life > 50,000 @ 25% DOD, Mission Life > 10 years
  - Adv. Rech. Batteries – Specific Energy 90 Wh/kg, Cycle Life > 400 @ 50% DOD, Mission Life > 2 years
  - Fuel Cells – Specific Power 90 We/kg, Maintenance Frequency 2600 hours (Shuttle)

ASSUMPTIONS

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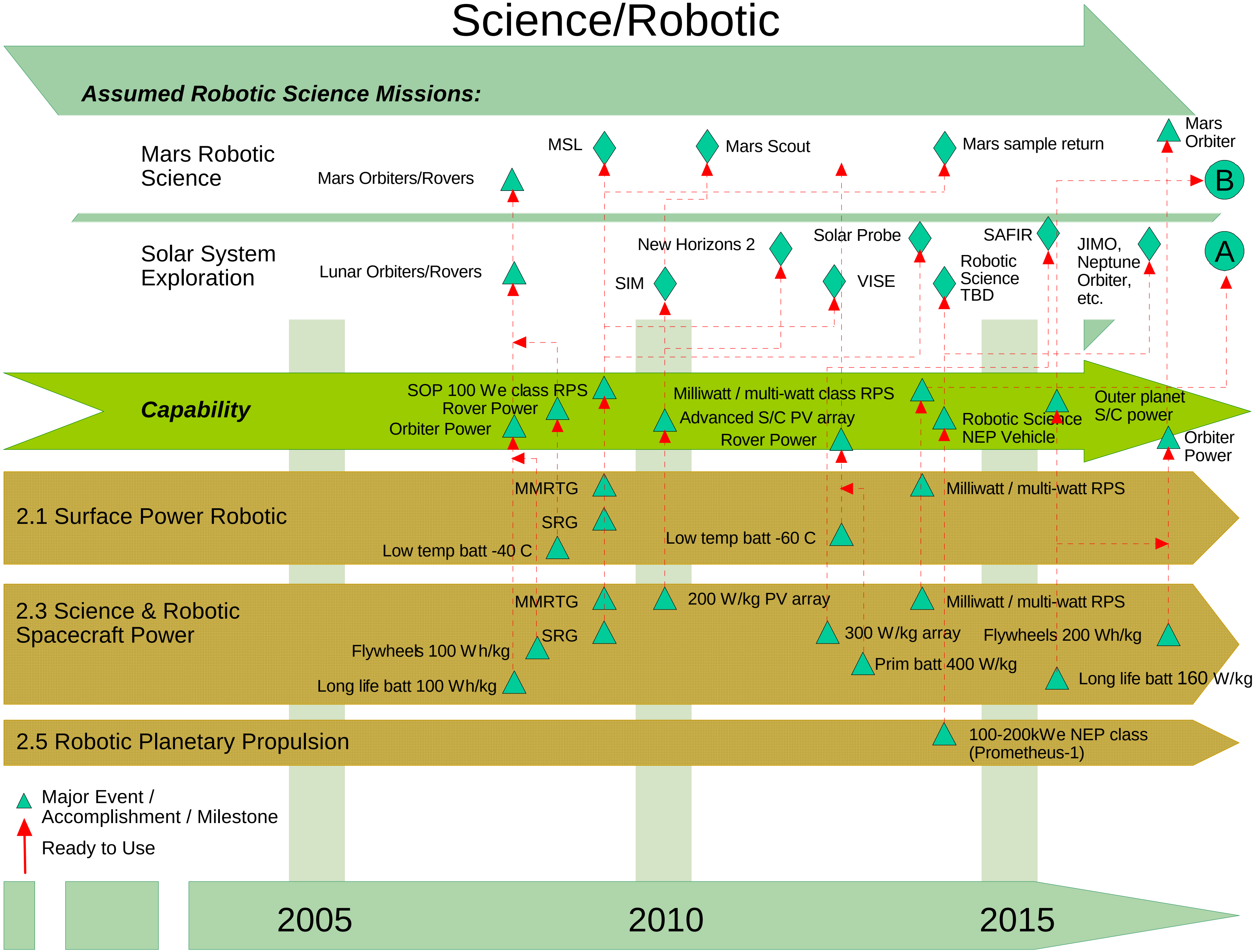
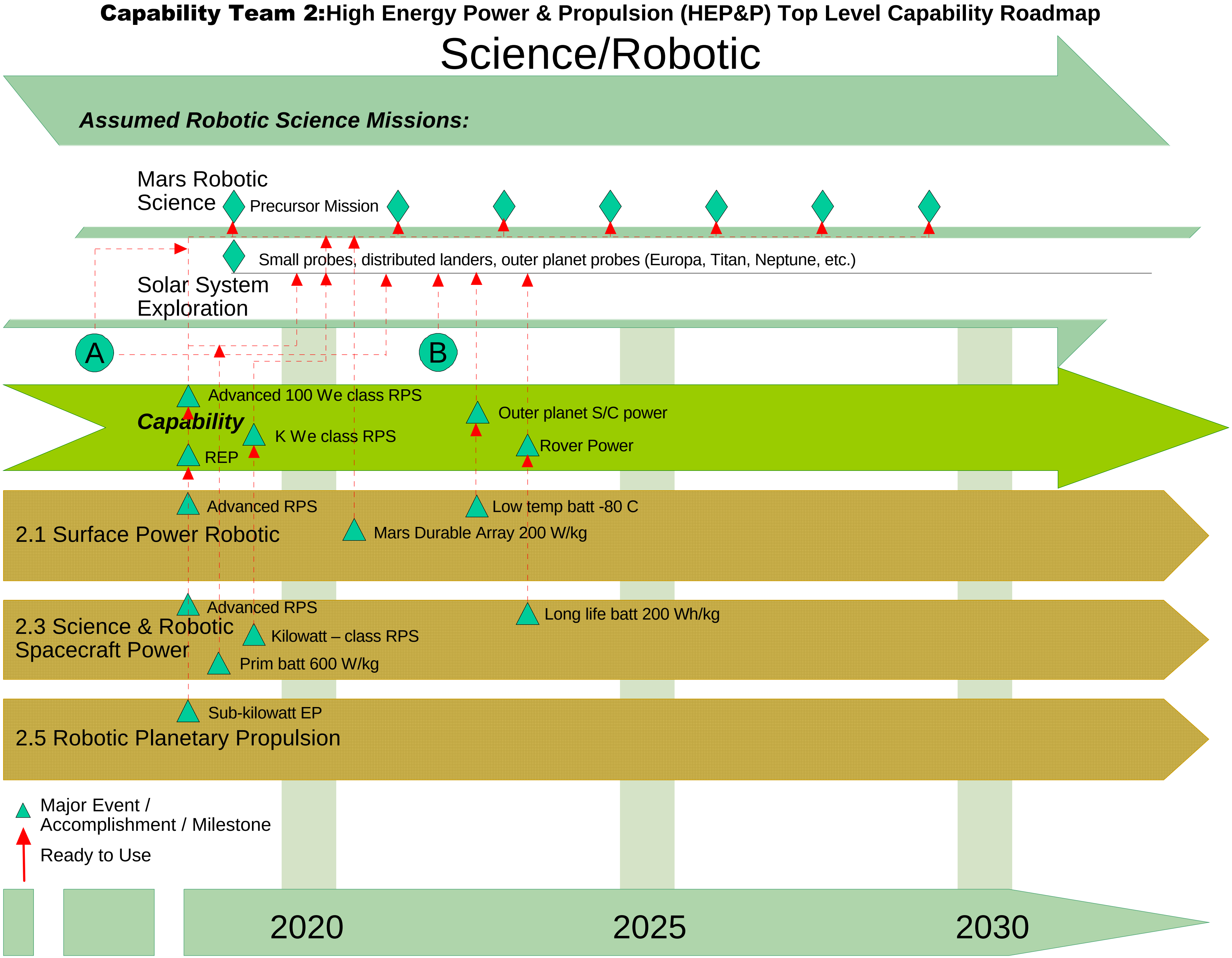
- Nuclear power will be required to fulfill the VSE
- Advanced propulsion will be required to fulfill the VSE
- Solar power systems are effective in many applications
- Sub-capabilities such as PMAD, power conversion, heat rejection and materials technology are cross-cutting and apply to all roadmap capabilities
- Each roadmap path is intended to be technically achievable in a focused effort
- Roadmap paths will continue to be developed during the ongoing dialog with other capability and strategic roadmap teams
- New and emerging technologies must be pursued and integrated into the roadmaps in an organized fashion
- Power roadmap developed for CEV, but not shown due to current CEV acquisition
- Power and propulsion advanced concepts recognized as part of roadmap, but not yet included

Driving Missions for HEP & P

- Scientific
  - Lunar and Mars Orbiters
  - Planetary Landers
  - Outer Planetary Probes
  - Jupiter Icy Moons Orbiter(JIMO) and other outer planetary missions requiring high power and/or high degree of maneuverability/multiple destinations, Interstellar Probe
- Human Exploration
  - Crew Exploration Vehicle
  - Lunar and Mars Surface Power
  - Piloted and cargo propulsion systems

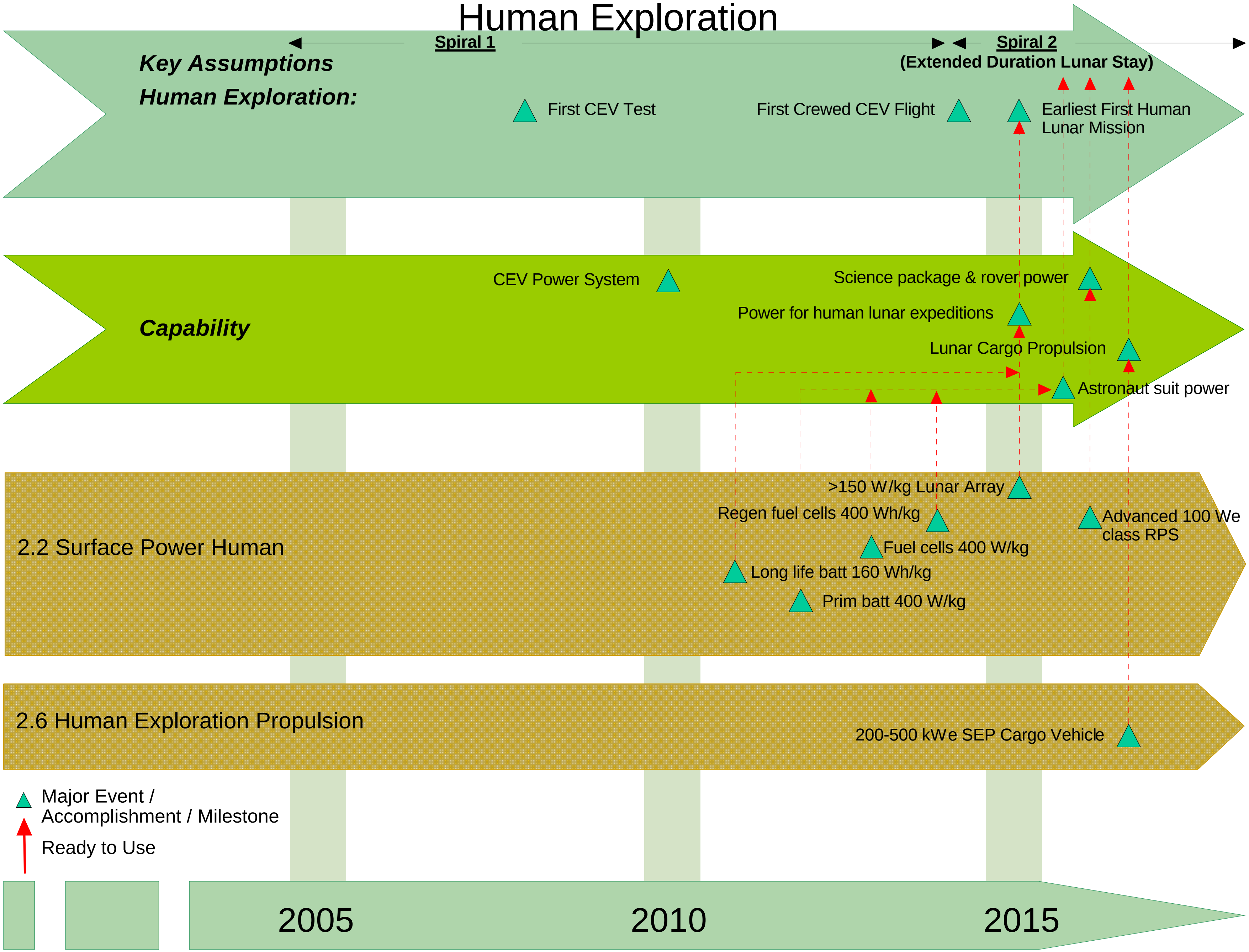
Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap



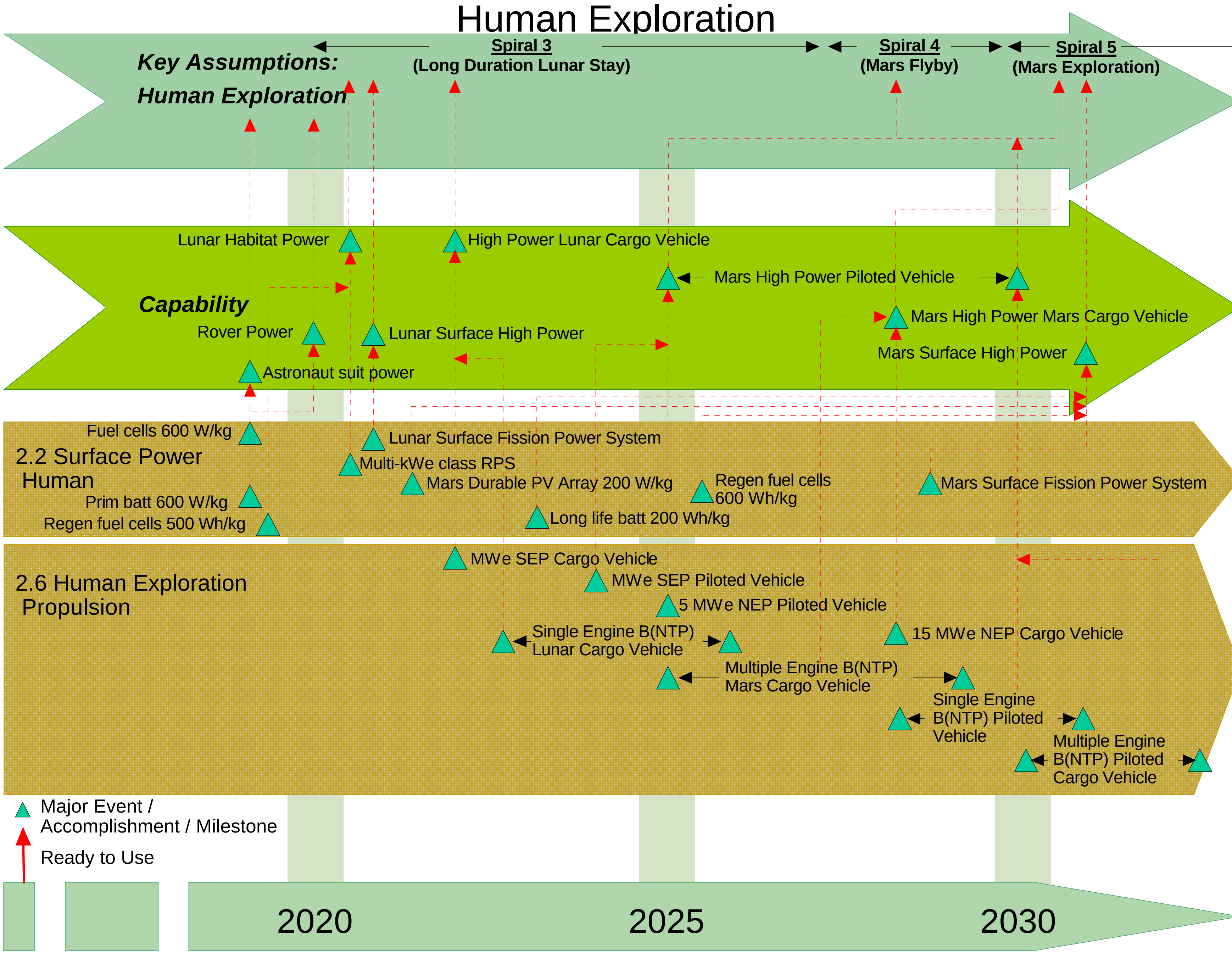


Capability Team 2:High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap
Science/Robotic
Assumed Robotic Science Missions:
Mars Robotic Science
Precursor Mission
Small probes, distributed landers, outer planet probes (Europa, Titan, Neptune, etc.)
Solar System Exploration
A
B
Capability
Advanced 100 We class RPS
K We class RPS
REP
Outer planet S/C power
Rover Power
2.1 Surface Power Robotic
Advanced RPS
Low temp batt -80 C
Mars Durable Array 200 W/kg
2.3 Science & Robotic Spacecraft Power
Advanced RPS
Kilowatt – class RPS
Prim batt 600 W/kg
Long life batt 200 Wh/kg
2.5 Robotic Planetary Propulsion
Sub-kilowatt EP
Major Event / Accomplishment / Milestone
Ready to Use
2020
2025
2030

Capability Team 2:High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap



Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap



Capability 2.1.1, 2.2.1, 2.3.1 2.4.1 2.6.1: Solar Power

Presenter: Rao Surampudi, JPL

Henry W. Brandhorst, Jr., Auburn University

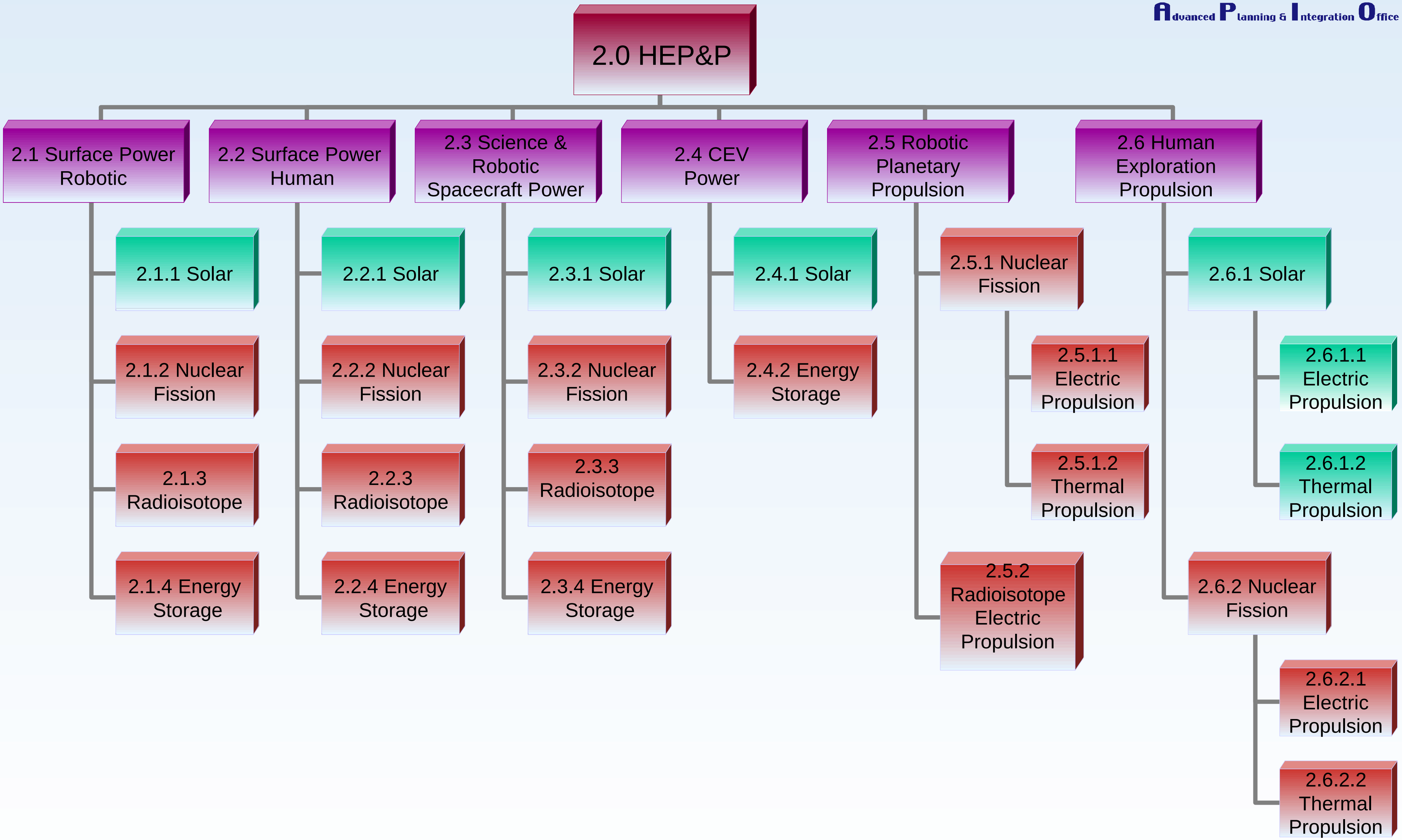
Chair, Solar Sub-Team

April 7, 2005

Disclaimer:

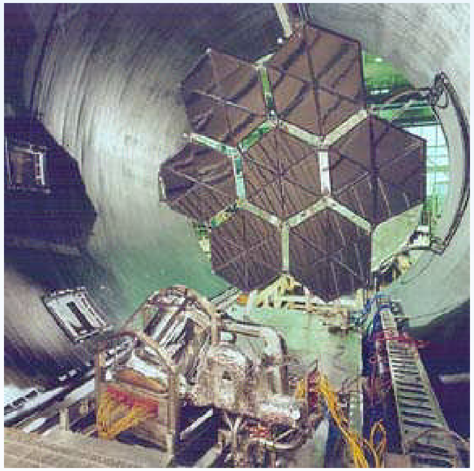
This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 Solar Power Sub-Team members, and is not the official view of NASA or DOE.

Capability Breakdown Structure – HEP&P



Solar Capability Description

- Solar power system provides electrical power to space missions by converting solar energy into electrical energy either by direct or indirect conversion.
- Two types of solar power systems
  – Photovoltaic Power System/Solar Cell and Arrays
  – Solar Thermal Power System
- A photovoltaic power system converts converts solar illumination to electricity directly through the photovoltaic effect.
  – The key components: solar cells , substrate / panel, array structure and deployment mechanisms (and energy storage)
  – Photovoltaic power systems have been widely used in robotic science and human exploration missions
- A solar thermal power system converts input solar illumination to heat. The heat is then used to power either a thermal-to-electric power conversion subsystem for the spacecraft or surface application.
  – Static (Direct Current): (thermoelectric, TPV, TI)
  – Dynamic (Alternating Current): (Brayton, Rankine or Stirling)
  – Note: PMAD, Thermal, structures are not included



2 kW Solar Thermal System

Applications of Photovoltaic Power Systems

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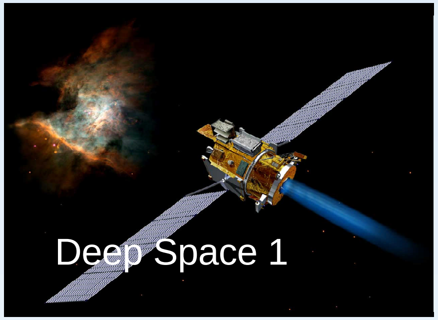
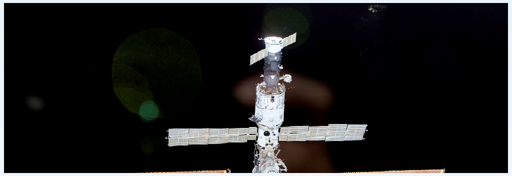
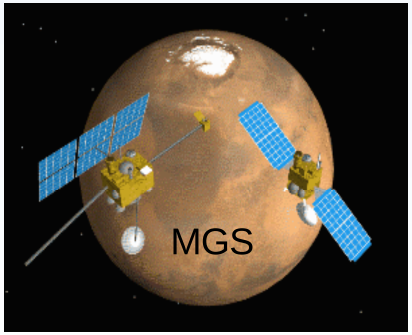
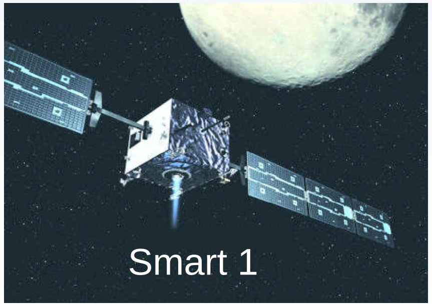
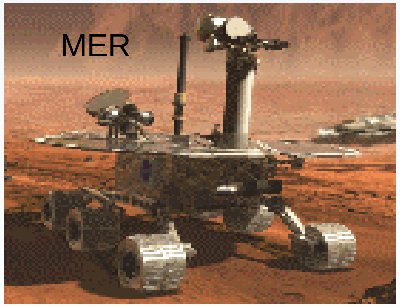
- Used on >99%* of the space missions launched to date:
  - Near sun – Venus, Mercury…
  - Outbound – Mars, Asteroids…
  - Earth: – Comsats, earth observing, weather, ISS, DoD…
  - SEP: Smart 1, Deep Space 1…
  - Surface: MERs, Pathfinder, ALSEP
- Other benefits
  - Modular, reliable
  - Established manufacturing base
  - Cost effective











Potential Future Missions for Solar

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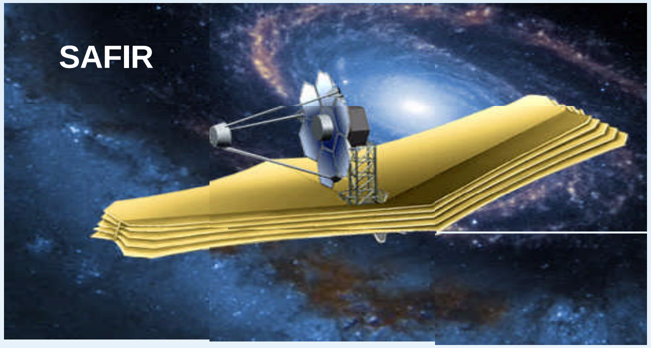
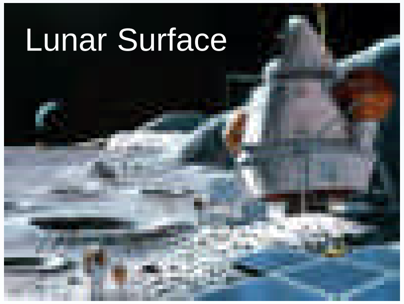
- Mission Types Considered
- Orbital Missions
  - Earth & Mars
  - Outer planets
  - Inner planets
- Surface Missions
  - Moon
  - Mars
- SEP Missions
  - Robotic science: asteroids…
  - Lunar cargo
  - Mars cargo & Human transp
    (considered for the purposes
    this study)



Space Interferometry Mission



What is / Why Solar Spacecraft Power?

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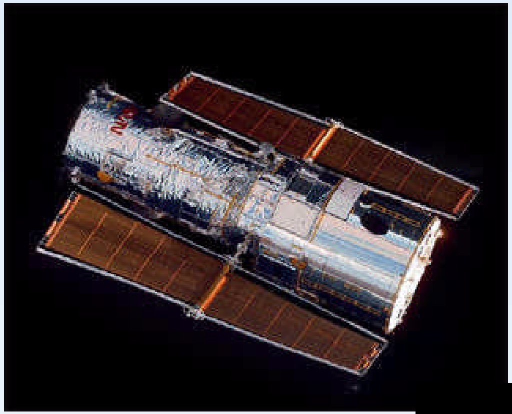
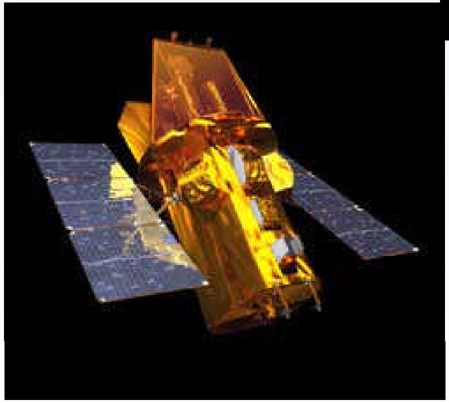
- Solar spacecraft power converts sunlight into electricity for robotic and human uses
  - Key Subsystems
    - Photovoltaic arrays provide electric power
    - Power management distributes and conditions power
    - Energy storage
    - Thermal management for PMAD
- Used on ~99% of space missions
  - Crewed and robotic systems
  - Modular, evolvable, early availability at high power levels
  - Major leverages from prior/on-going developments
    - DoD, Industry, DoE
  - Supports other exploration sectors

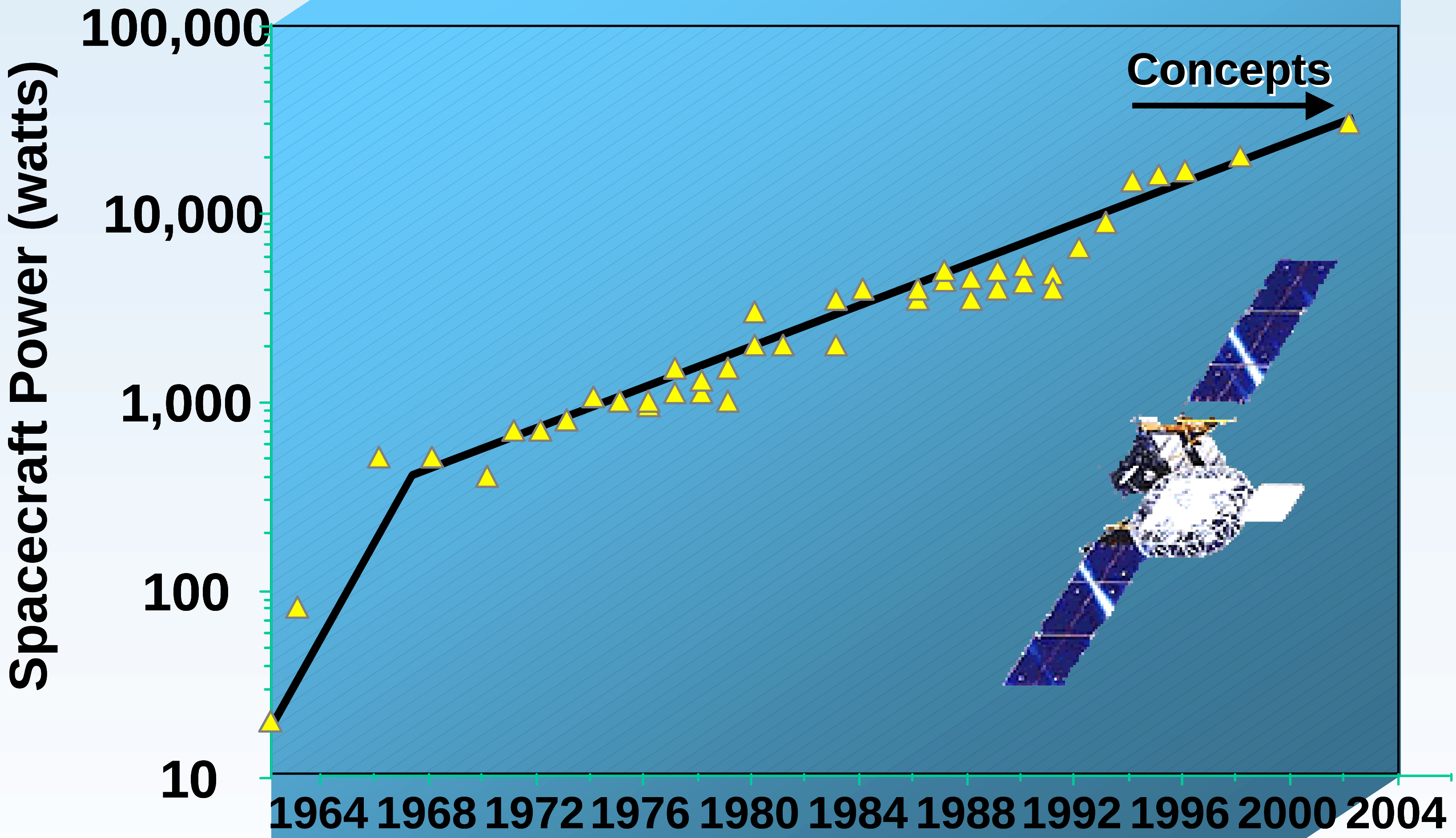


Hubble Space Telescope



Swift Gamma Ray Telescope

Commercial and D… Increasing



Courtesy: Hughes et.al.,
Includes DoD & Commercial

Spacecraft power levels have **doubled** every 5.5 years

Spacecraft Power

- History/State of Practice

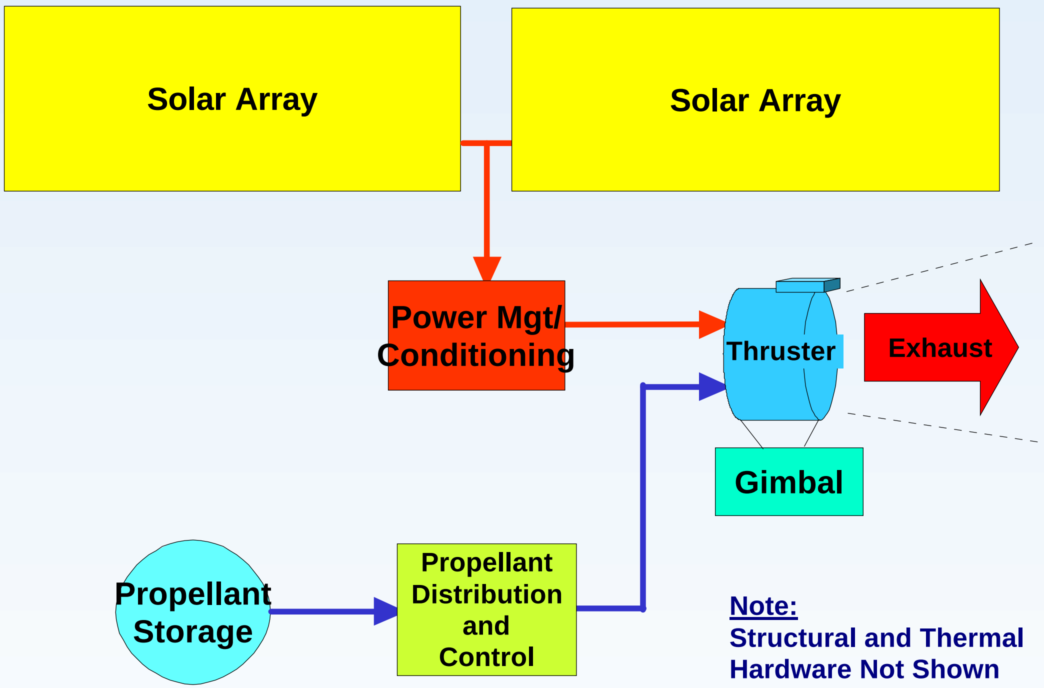
- Capabilities Identified

Candidate Advanced Technologies
- Solar cell technologies

- Missions/Strategic Drivers Identified
  - Earth/Moon/Mars

What is Solar Electric Propulsion (SEP)?

- **Photovoltaic arrays** convert solar energy into electricity to accelerate a propellant in a **thruster**
  - SOA (less than about 7 kW)
  - Exploration capabilities need 0.2 to10 MW
- Key Subsystems
  - Solar arrays provide electric power
  - Power management & conditioning distributes and conditions thruster input power
  - Electric thrusters convert power/propellant to thrust
  - Thermal Management For Power Management
  - Structure



Status of Solar Electric Propulsion

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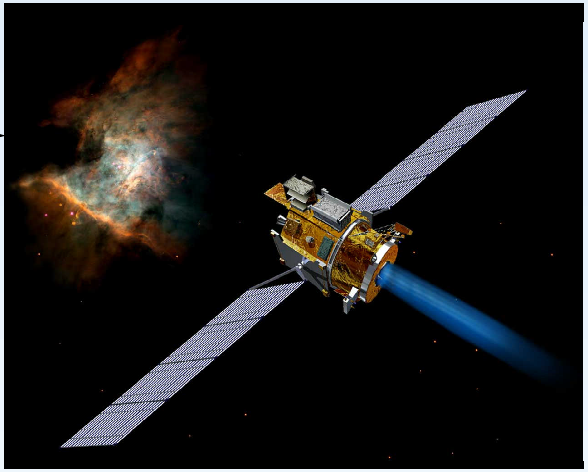
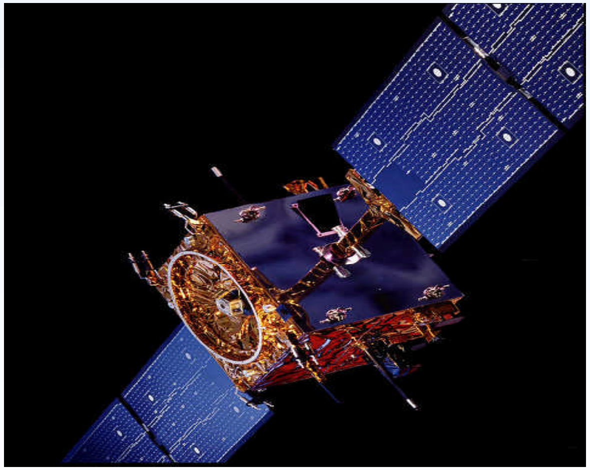
- Planetary Missions
  - Deep Space 1 (US)
    - 2.7 kW, asteroid/comet rendezvous
    - Concentrator array
    - Ion propulsion
  - HAYABUSA (Japan)
- Lunar and Earth OTV
  - Smart 1 (ESA)
    - Planar array
    - Ion propulsion
- High Power Earth Orbital
  - ComSats (6 kW)
  - Elite (USAF – 27 kW)

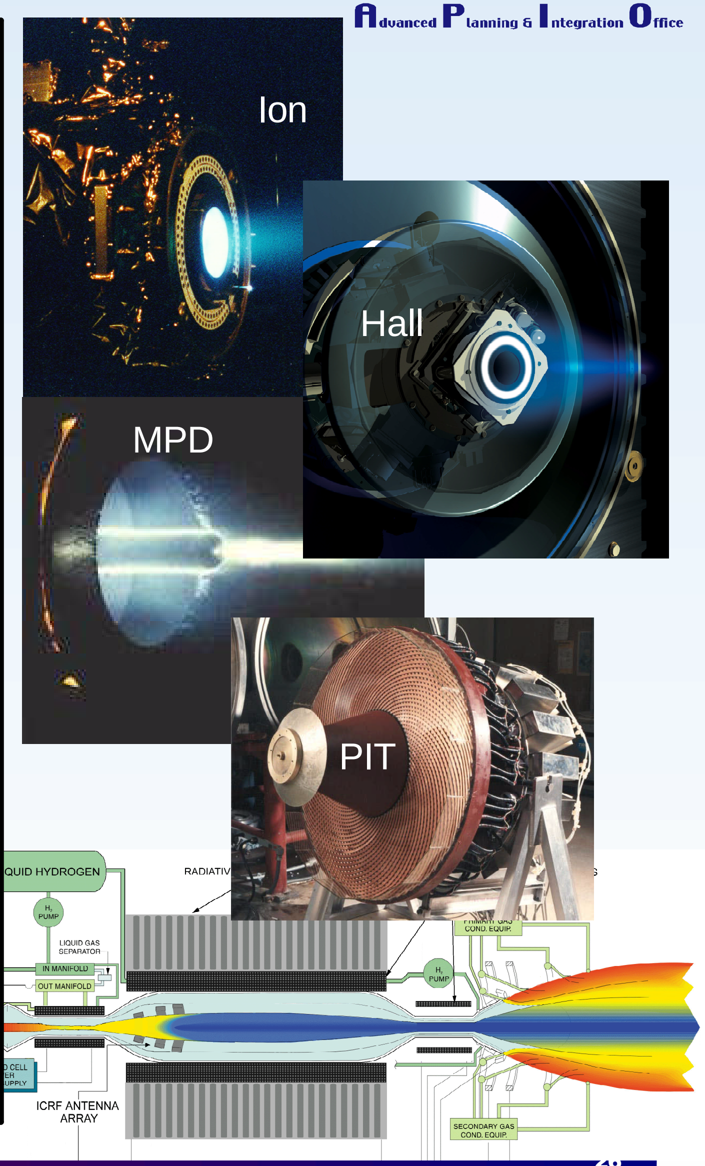




Electric Propulsion SOA/SOP

Thruster Concept	SOA/SOP		Capability Goal	
Ion	**Isp (s):**	**3300**	**Isp (s):**	**2000 - 8000**
	h[3] **:**	**0.7**	h **:**	**0.7**
	Life (kh):	**10**	**Life (kh):**	**30-100**
	Power (kW):	**2.7**	**Power (kW):**	**200 - 500**
	TRL:	**9(Deepspace-1)**		
Hall	**Isp (s):**	**1640**	**Isp (s):**	**2000 - 3500**
	h **:**	**0.67**	h **:**	**0.7**
	Life (kh):	**4-8**	**Life (kh):**	**8-30**
	Power (kW):	**1.2**	**Power (kW):**	**200 - 500**
	TRL:	**9 (SMART-1)**		
MPD[1]	**Isp (s):**	**1000 - 10000**	**Isp (s):**	**4000 - 8000**
	h **:**	**0.45 - 0.6**	h **:**	**0.65**
	Life (kh):	**0.5**	**Life (kh):**	**5 - 10**
	Power (kW):	**1000 - 10000**	**Power (kW):**	**250 - 2500**
	TRL:	**3**		
PIT[2]	**Isp (s):**	**4000 - 6000**	**Isp (s):**	**4000 - 8000**
	h **:**	**0.5**	h **:**	**0.65**
	Life (kh):	**Pulsed**	**Life (kh):**	**>10**
	Power:	**MW/pulse**	**Power (kW):**	**50 - 1000**
	TRL:	**3**		
Advanced Concepts	**Isp (s):**	**Not measured**	**Isp (s):**	**2000 - 10000**
	h **:**	**"**	h **:**	**0.55 - 0.65**
	Life (kh):	**"**	**Life (kh):**	**>10**
	Power (kW):	**300 - 3000**	**Power (kW):**	**200 - 5000**
	TRL:	**2**		

[1]Magnetoplasmadynamic [2]Pulsed Inductive Thruster [3]Thrust Efficiency



SEP Can Reduce IMLEO for Lunar Exploration

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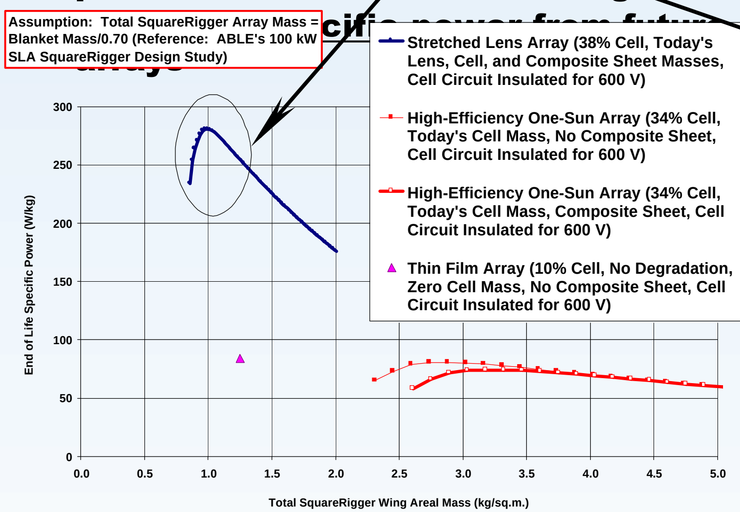
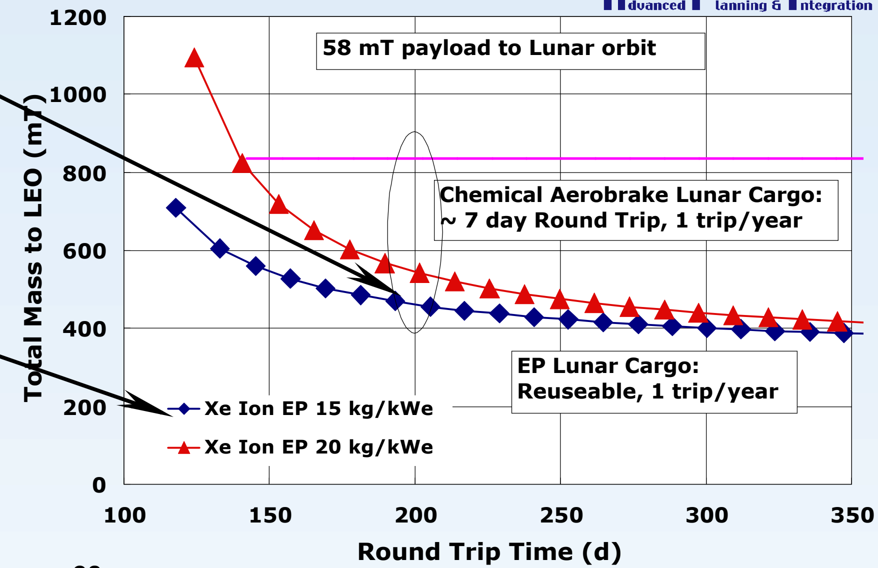
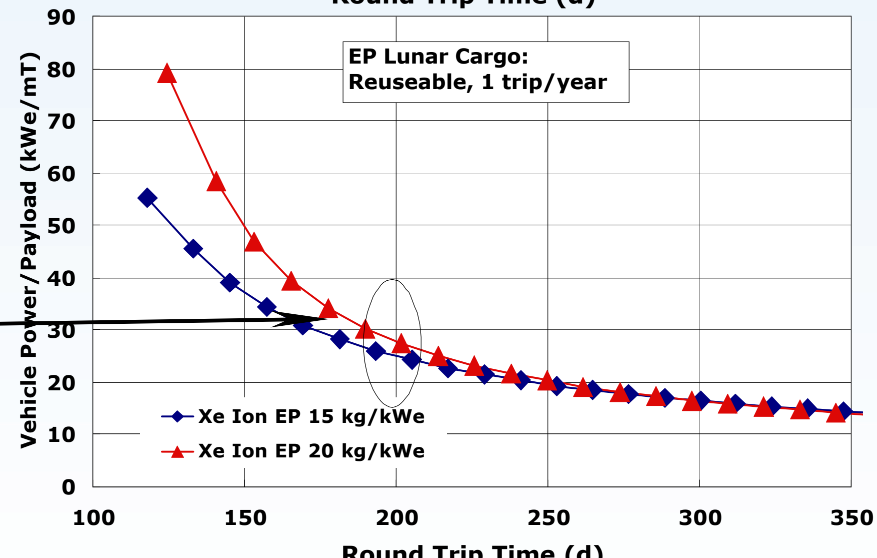
- **~ 50% mass reduction with SEP lunar cargo**
  - IMLEO for 5 years of lunar cargo, 1/year
  - Based on previous SEI studies - 58 mT/yr payload
  - Near term array and thruster performance assumed: 15-20 kg/kWe
  - [illegible]cific power from futur[illegible] arrays



7 round trips through the radiation belts





- **Early, small payloads require modest power levels**
  - <1 year round trip, 50 kW for 2 MT payload
  - Reusable, capability useful for other areas

Exploration Electric Propulsion (EP)

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- **History/State of Practice**
  - Power (• 7 kW) (3 kW single string)

- **Capabilities Identified**

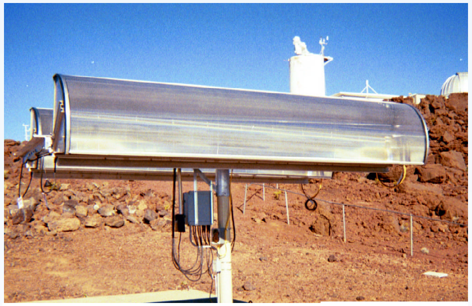
- **Candidate Advanced Technologies**
  - Solar cell technologies

- **Missions/Strategic Drivers Identified**
  - Lunar Cargo Missions

What is Solar Surface Power?

- Solar surface power converts sunlight into electricity for robotic and human uses
  - Solar Photovoltaic
  - Solar Thermal
    - Moon only
- Key Subsystems
  - Photovoltaic arrays provide electric power
  - Solar collectors collect sunlight and provide heat to a conversion unit that produces electricity
  - Power management distributes and conditions power
  - Energy storage
  - Thermal management
  - Structures
- Megawatt-class terrestrial photovoltaic and thermal power systems are operating around the world

100 kW Terrestrial Array with Si Cells (TX)



1.3 kW Array with MJ Solar Cells HI)

25 kW Solar Stirling (CA)

Solar Surface Power

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- story/State of Practice
  - Lunar

- Capabilities Identified

- Candidate Advanced Technologies
  - Robust power systems for lunar and Mars surface operation

- Missions/Strategic Drivers Identified

Potential Photovoltaic Array Advances

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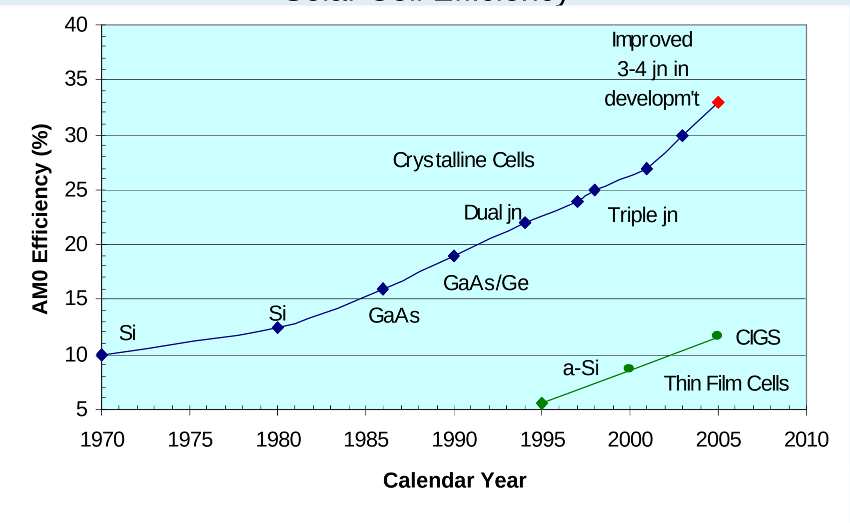
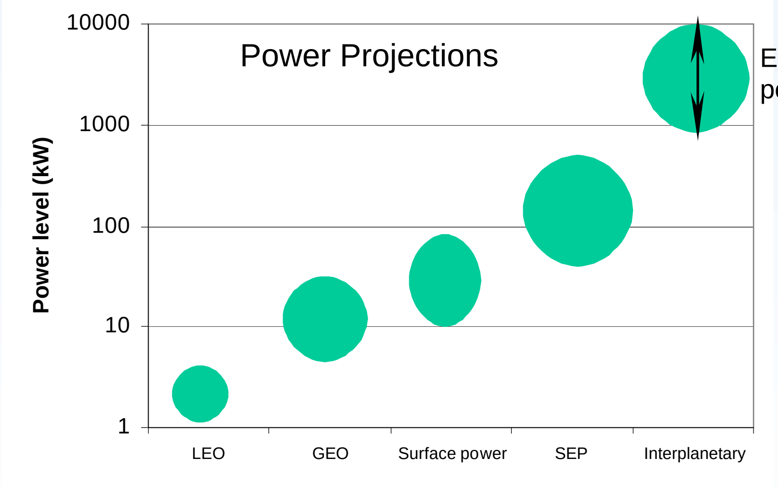
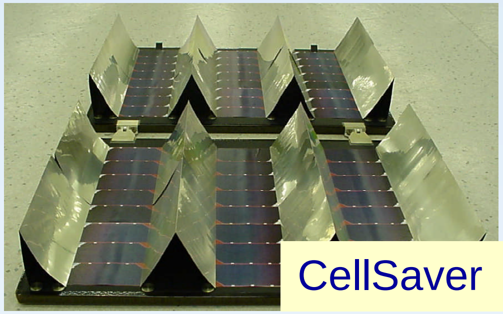
Solar Cell Efficiency





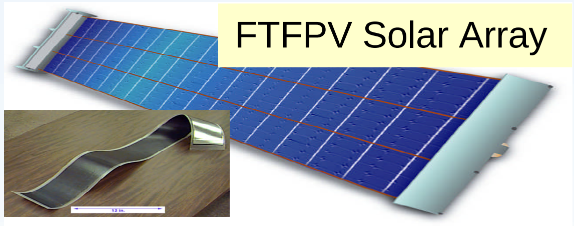
Estimated power range

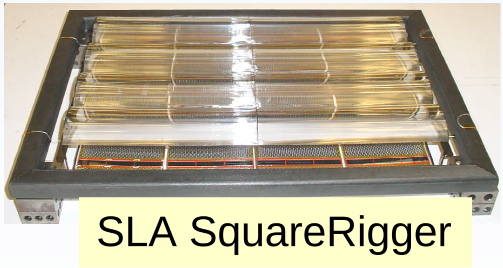
Commercial



NASA ST-8

USAF





NASA HR&T BAA

2.1.1, 2.2.1, 2.3.1, 2.4.1: Spacecraft & Surface Power Roadmap

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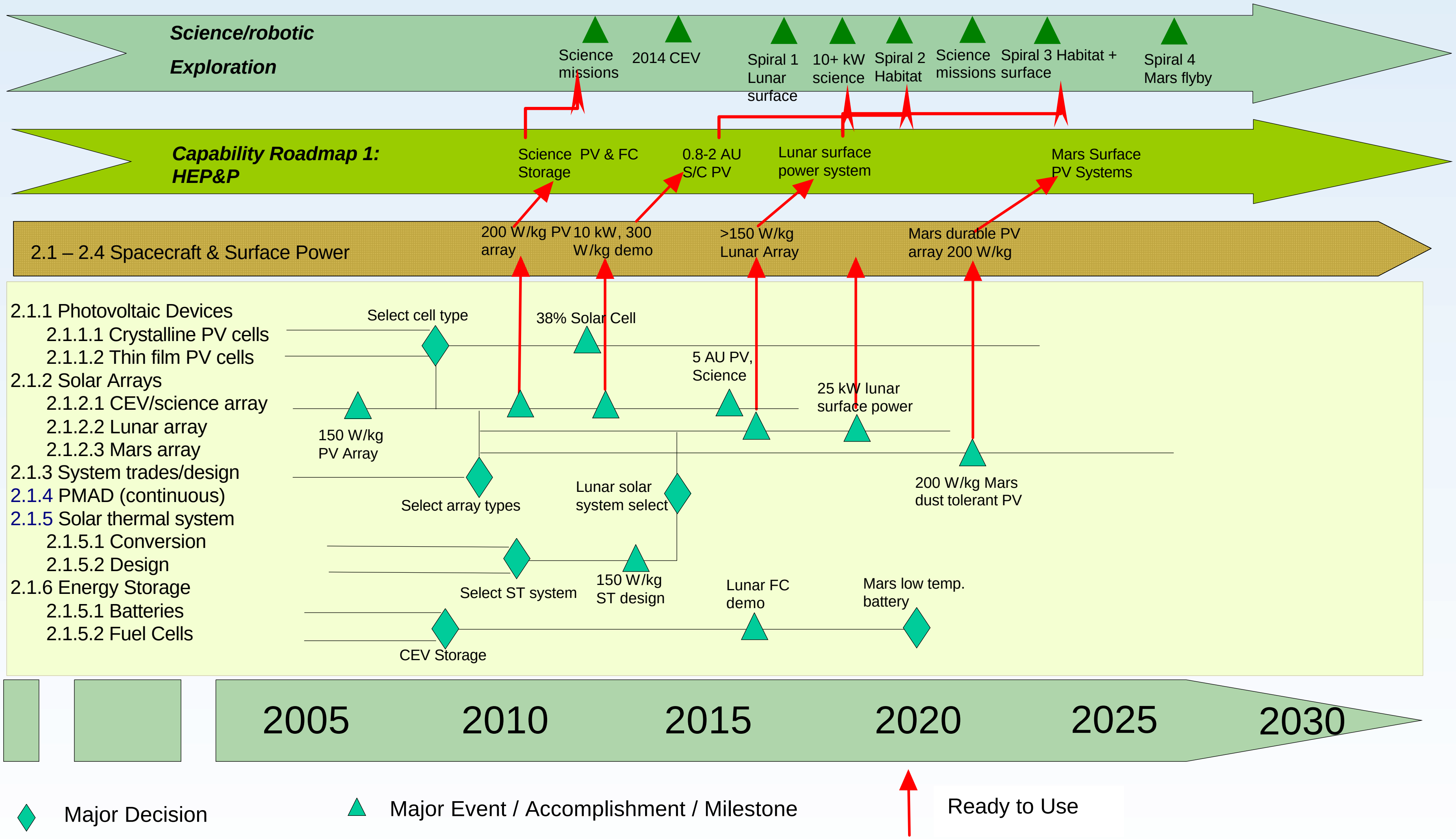

2.6.1 Solar Electric Propulsion Roadmap

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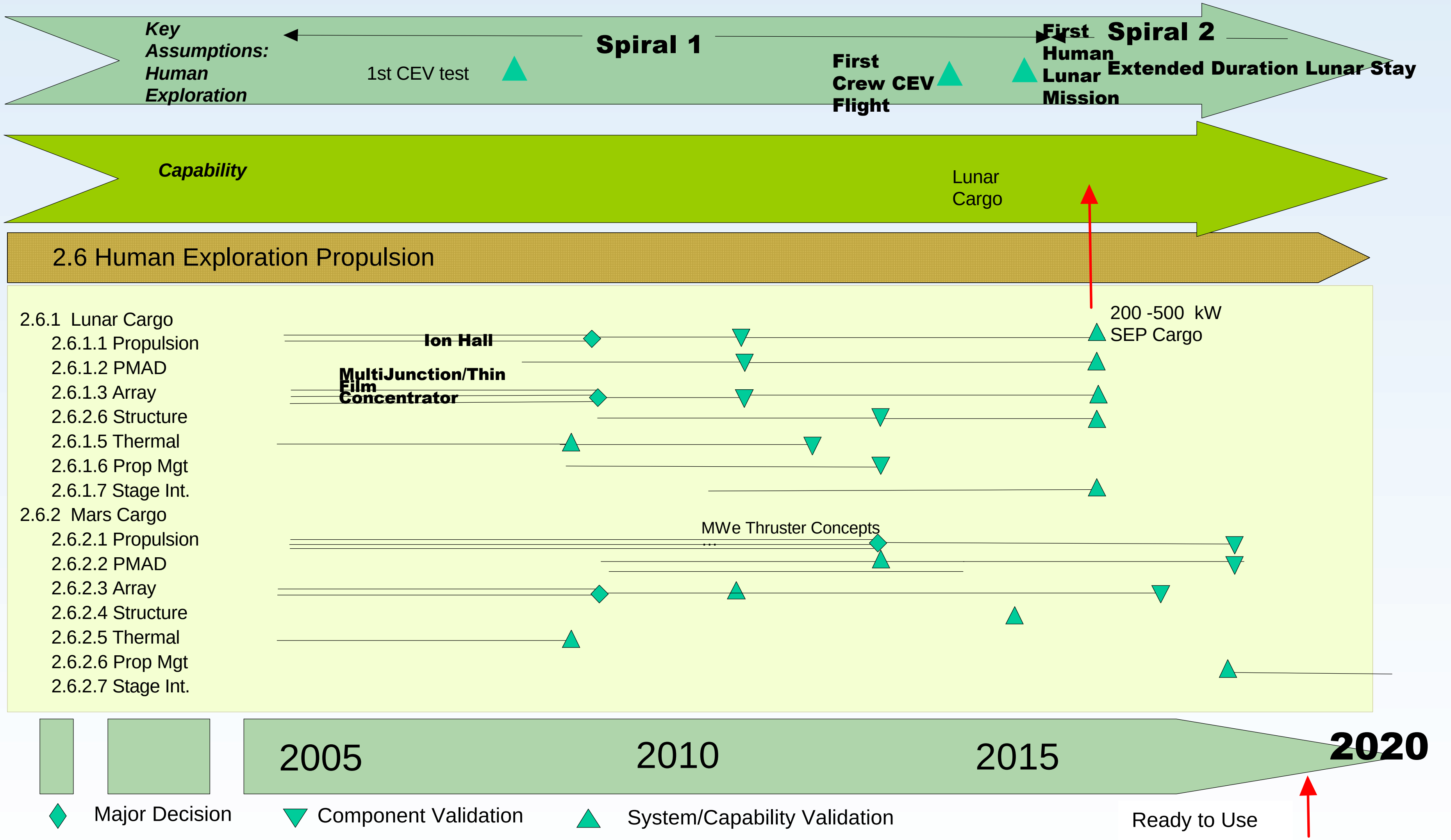
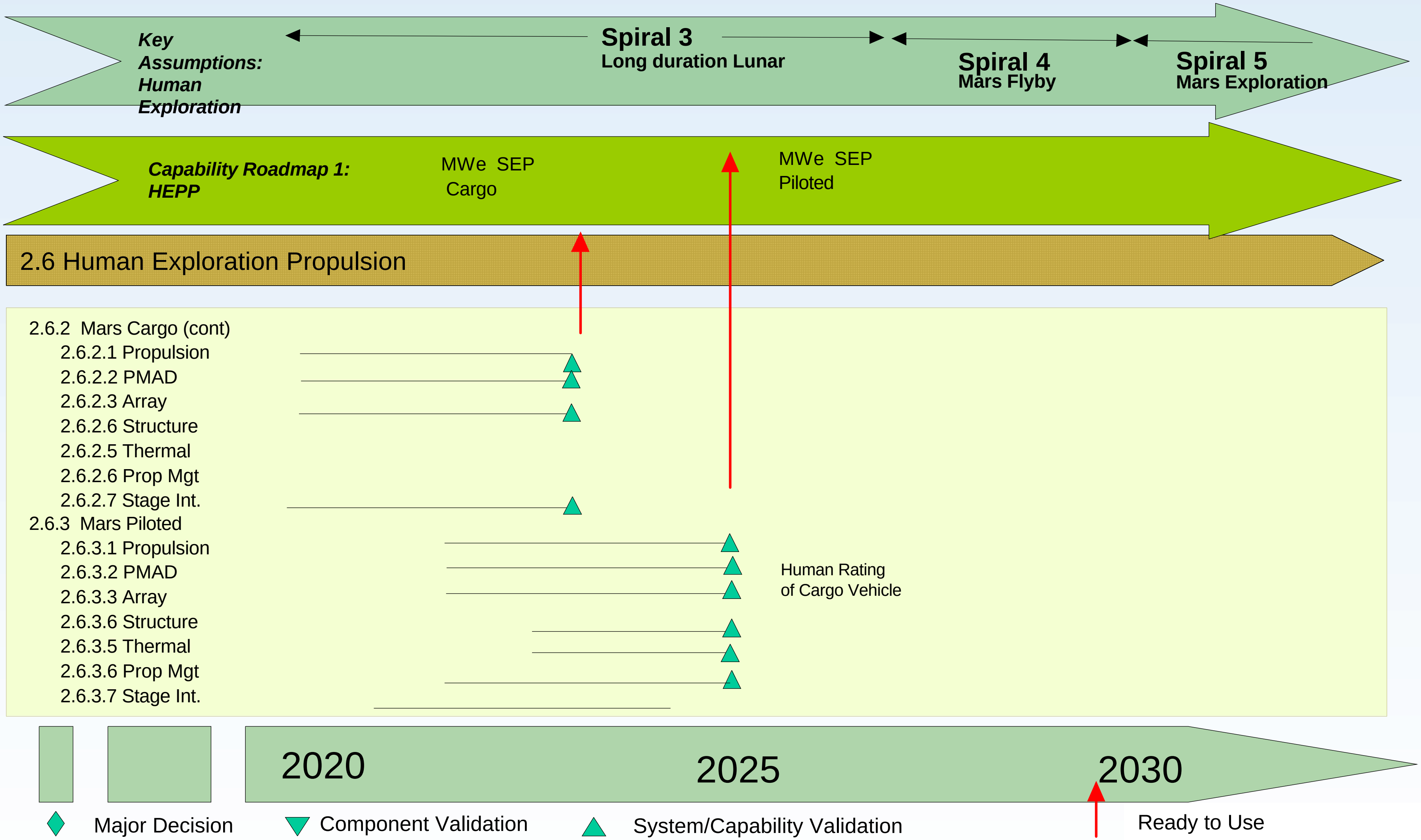


2.6.1 Solar Electric Propulsion Roadmap



Summary

- Solar power/propulsion is routinely used for all space sectors
  - Power levels and electric propulsion applications increasing
  - Established for use from LEO to Mars surface, a robust supporting base exists
- Major improvements are being realized in cell, array and propulsion technologies that can translate into:
  - Significant mission performance increases
  - Realizable new missions for NASA, commercial, DOD and others (spin offs)
  - Can provide early availability for robotic science and lunar SEP
  - Supports later lunar and Mars missions as well
- High power systems (MW class) will require focused solar and other technology thrusts:
  - Large, high power, radiation robust, low cost solar arrays
  - High power electric propulsion systems
    - Ground test facilities
  - In-space operations (e.g. assembly, refueling, refurbishment…)
  - GN&C, advanced structure and thermal management concepts
  - Surface power adaptations for the moon and Mars
- Reusable SEP could have a major impact on the exploration infrastructure
- Advanced concepts were not included in this briefing
  - Several may well have substantial impact over the next decade

Energy Storage System Capability Roadmap

Rao Surampudi, JPL

Energy Storage System Sub-Team Chair

Henry Brandhorst, Auburn University

Energy Storage System Sub-Team Co-Chair

April 7, 2005

Capability Breakdown Structure – HEP&P

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- 2.0 HEP&P
  - 2.1 Surface Power Robotic
    - 2.1.1 Solar
    - 2.1.2 Nuclear Fission
    - 2.1.3 Radioisotope
    - 2.1.4 Energy Storage
  - 2.2 Surface Power Human
    - 2.2.1 Solar
    - 2.2.2 Nuclear Fission
    - 2.2.3 Radioisotope
    - 2.2.4 Energy Storage
  - 2.3 Science & Robotic Spacecraft Power
    - 2.3.1 Solar
    - 2.3.2 Nuclear Fission
    - 2.3.3 Radioisotope
    - 2.3.4 Energy Storage
  - 2.4 CEV Power
    - 2.4.1 Solar
    - 2.4.2 Energy Storage
  - 2.5 Robotic Planetary Propulsion
    - 2.5.1 Nuclear Fission
      - 2.5.1.1 Electric Propulsion
      - 2.5.1.2 Thermal Propulsion
    - 2.5.2 Radioisotope Electric Propulsion
  - 2.6 Human Exploration Propulsion
    - 2.6.1 Solar
      - 2.6.1.1 Electric Propulsion
      - 2.6.1.2 Thermal Propulsion
    - 2.6.2 Nuclear Fission
      - 2.6.2.1 Electric Propulsion
      - 2.6.2.2 Thermal Propulsion

Types of Energy Storage Systems

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Electrochemical Energy Storage Systems

- **Capacitors**
- **Primary Batteries**
- **Rechargeable Batteries (Secondary)**
- **Fuel Cells (Primary)**
- **Regenerative Fuel Cells**

Mechanical Energy Storage Systems

- **Energy Flywheels**
- **Energy / Momentum Flywheels**

Energy Storage Systems: Capabilities and Applications

System	Capability	Application
Capacitors – **Double-layer, ultra super**	**Stores very low amounts of energy. Provides high power for short duration (seconds). Can be recharged electrically several times.**	**RPS Powered Missions.**
Primary Batteries – **Ag-Zn, Li-SO_2, Li-$SOCl_2$**	**Provides up to several watts to hundreds of watts of power for several minutes/ hours to days. Can not be recharged. One time use only.**	**Launch vehicles, probes, and astronaut equipment.**
Rechargeable Batteries – **Ni-Cd, Ni-H_2, Li-Lion**	**Can store up to tens of kWh of energy. Can be recharged electrically several times.**	**Earth / Mars Orbital Missions; Outer / Inner Planetary Orbiters; Surface Missions; Astronaut Equipment**

Energy Storage Systems: Capabilities and Applications

System	Function	Application
Fuel Cells – **Alkaline, PEM**	**Provide medium – high power (hundreds of W to several kW) for several days. Can be recharged with chemicals.**	**Surface Missions; Shuttle / CEV**
Regenerative Fuel Cells – **Alkaline, PEM**	**Can store up to several MWh of energy. Can be recharged electrically several times**	**Lunar Habitat; Mars Habitat**
Flywheels – **Energy only; Energy and momentum**	**Can store up to tens kWh of energy. Provide power during eclipse periods and peak power demands. Can be recharged electrically several times.**	**Earth Orbital Missions (GEO & LEO);**

Energy Storage Systems: Metrics/Requirements for Space Applications

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General Requirements

Mass and Volume Efficiency

- High Specific Energy (Wh/kg)
- High Energy Density (Wh/l)

High Power Capability (Peak/continuous)

- High Specific Power (W/kg)
- High Power Density (W/l)

High Charge/Discharge Efficiency

- Charge/discharge Efficiency (%)

Charge Retention

- Minimal Capacity Loss on

Mission Dependent Requirements

Long Operational and Storage Life

- Cycle Life (cycles@ % DOD):
- Calendar Life (Years)

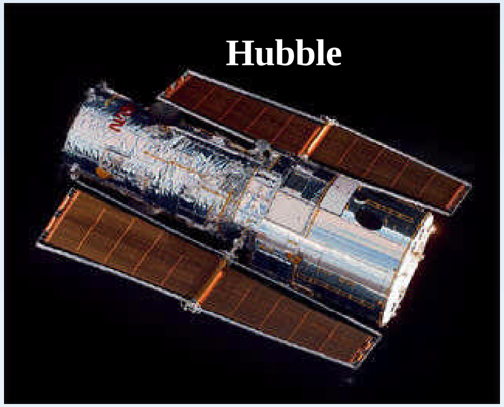
Operation at low and high temperatures

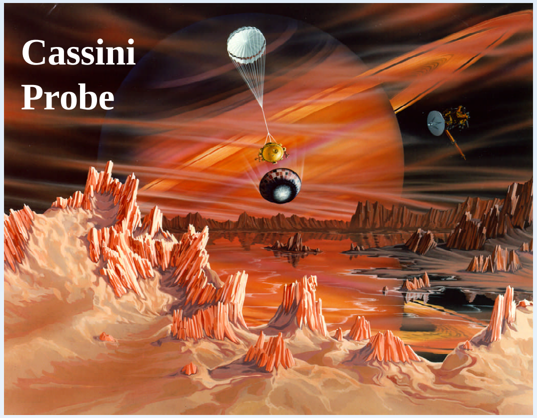
- Operational capability (with minimal performance losses) at low temperatures
- Operational capability with minimal performance losses) at high temperatures.

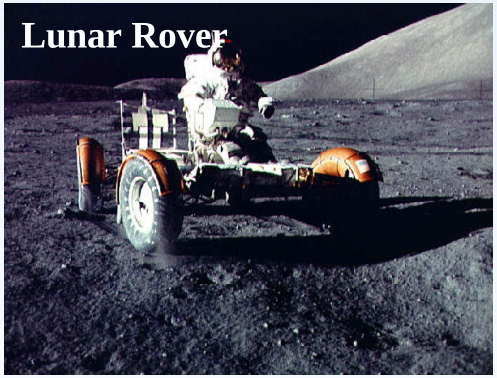
Energy Storage Systems: Current State-of-Practice

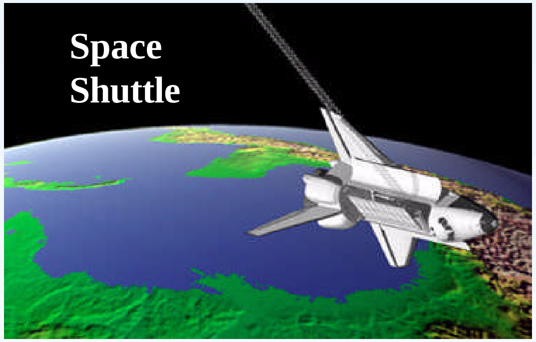
System	Technology	Mission	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Cycle Life	Mission Life (yrs)	Issues
Primary Batteries	Ag-Zn Li-SO2, Li-SOCl2	Delta Launch Vehicles Cassini Probe MER Lander Sojourner Rover	90-250	130-500	-20 to 60	1	1-9	• Limited operating temp range • Voltage delay
Rechargeable Batteries	Ni-Cd, Ni-H2	TOPEX HST Space Station	24-35	10-80	-5 to 30	> 50,000 @25%DOD	>10	•Heavy and bulky • Limited operating temp range
Adv. Rech. Batteries	Li-Ion	Spirit & Opportunity Rovers	90	250	-20-30	> 400 @ 50% DOD	>2	Cycle Life
			Power Rating (kW)	**Specific Power (W/kg)**	**Power Density (W/l)**	**Efficiency %**	**Maintenance Frequency (hrs)**	
Fuel Cells	Alkaline H2-O2	Apollo, Shuttle	10	90	155	70%	2600	Heavy and Bulky Limited to short missions

Energy Storage Systems: Past Applications



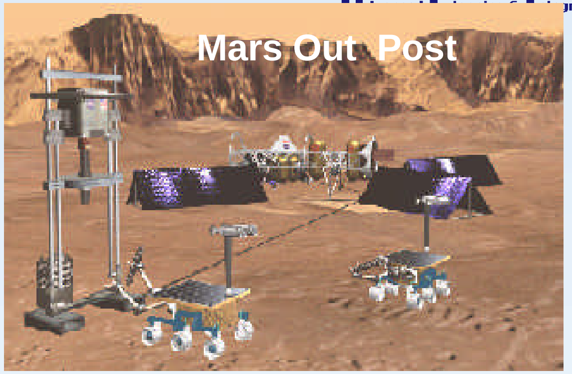


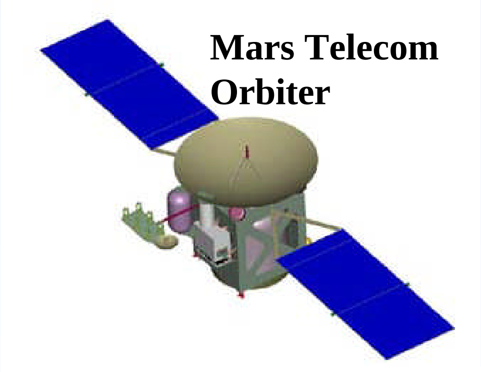


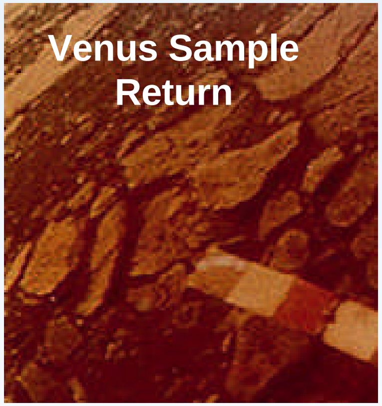


Energy storage systems have been used in 99% of the robotic and human space missions launched since 1960

Energy Storage Systems: Future Space Applications







Future human and robotic exploration missions require advanced energy storage systems.

- **Critical capability requirements include: mass and volume efficiency (2-10 X Vs SOP), long life and the ability to operate in extreme environments.**

Crew Exploration Vehicles

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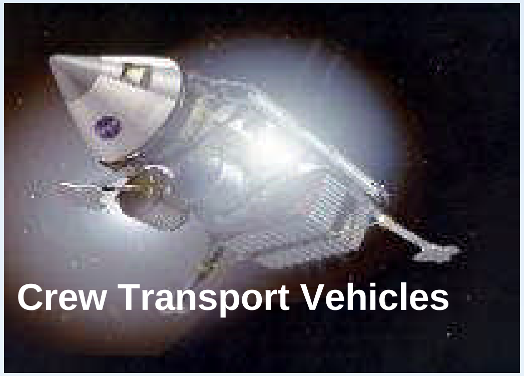
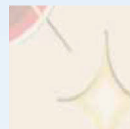




CEV-LEO, CEV –Lunar, CEV-Mars

Capabilities Needed

- **TBD**

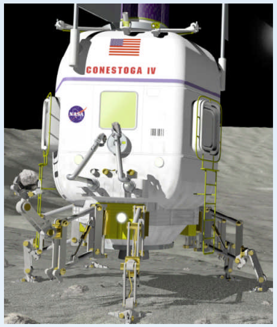
Capability of State of Practice Systems

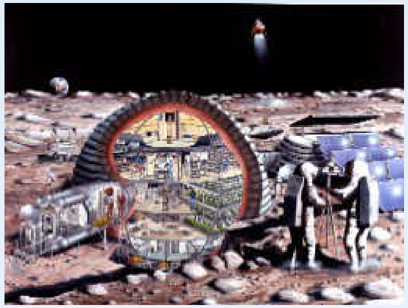
- **System: Alkaline Fuel Cells**

Status of Advanced Energy Storage Systems

- **TBD**

Human Lunar/Mars Surface Habitat





Long Duration Lunar/Mars Surface Habitat,

Capabilities Needed

- **Power 20-40 kW,**

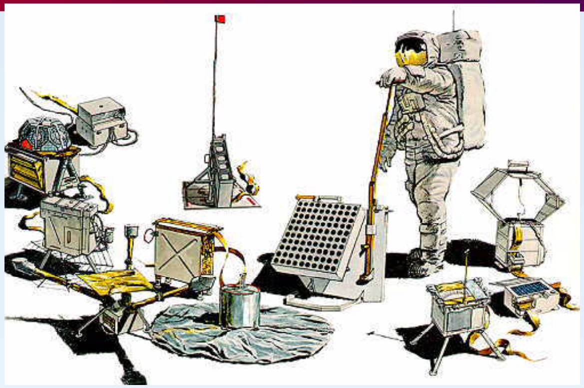
pabilities of State of Practice Systems

- **System: Ni-Hydrogen Batteries**

v. Status of Adv. Energy Storage Systems

- **Potential Systems: Regenerative H_2-O_2 Fuel Cells, Adv. Rechargeable Li-Ion Batteries,**

Astronaut In space and Surface Mobility/EVA



Astronaut Suit, EVA Tools & Instruments

Capabilities Needed

age Systems
bilities of State of Practice Systems (EVA)
ial Systems: Small Fuel Cells, Li-Ion / Polymer Batteries

Robotic/Human Landers / Rovers

Robotic & Human Rovers

Landing Systems /

Capabilities Needed

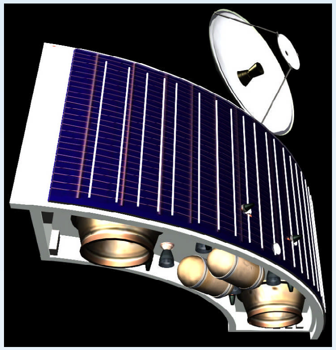
- **Power : 0.1 to 5.0 kW**

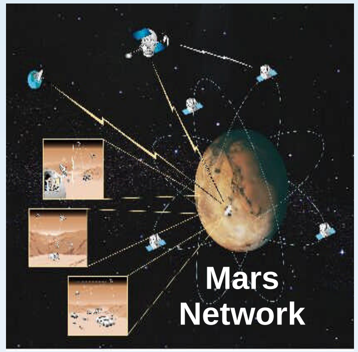
bilities of State of Practice Systems

Ion batteries, Polymer Batteries/Fuel Cells

Solar Powered Earth/Mars Orbiters

Advanced Planning & Integration Office





Lunar/ Mars Telecom Orbiters

Capabilities Needed

Energy Storage: 1-5 kWh

abilities of State of Practice Systems

- **System: Ni-H_2 Batteries**

Radioisotope Powered Robotic Orbital /Surface Missions

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Europa Orbiter

Capabilities Needed

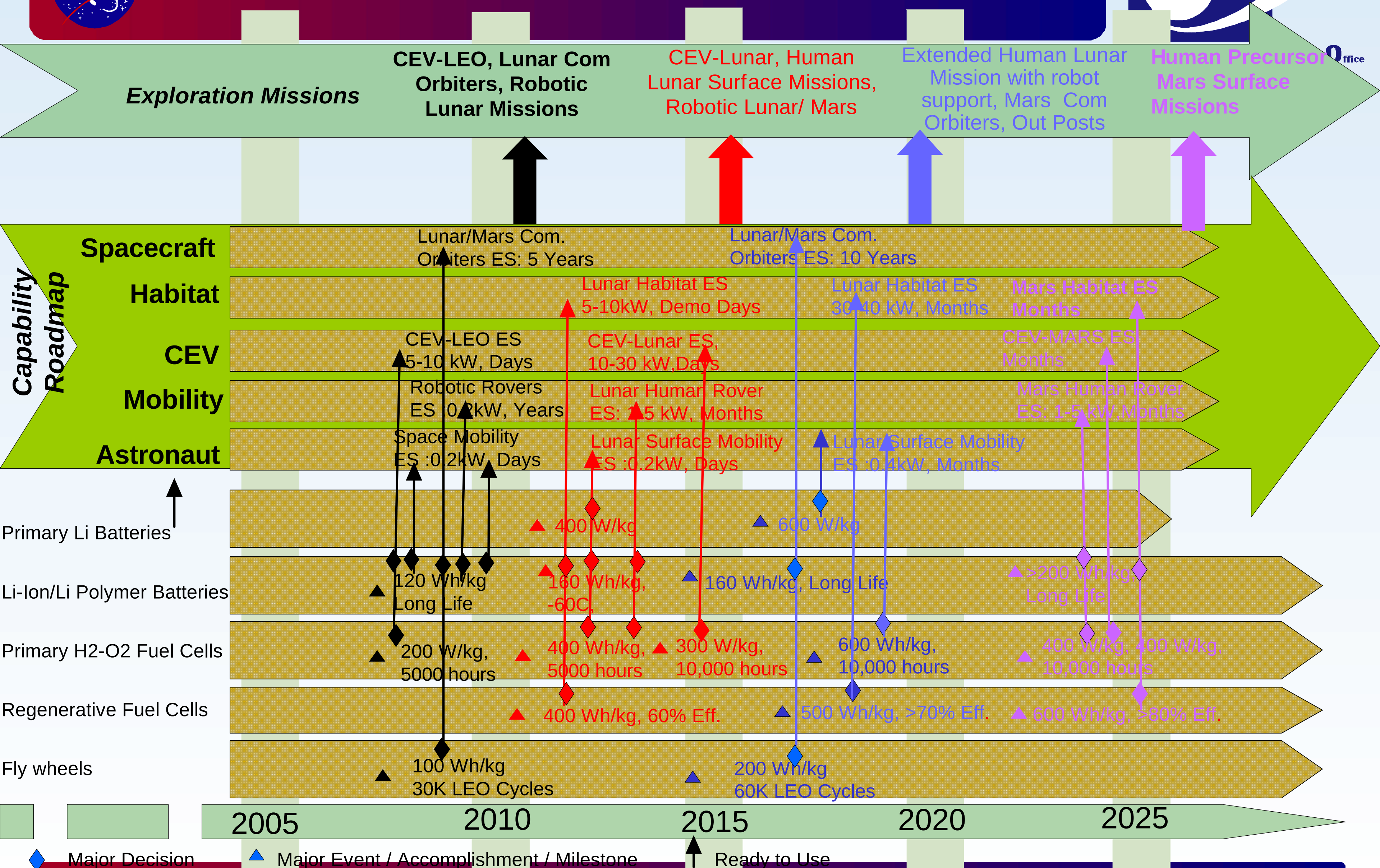
- Power : 100-200 W

y, Energy Storage Systems

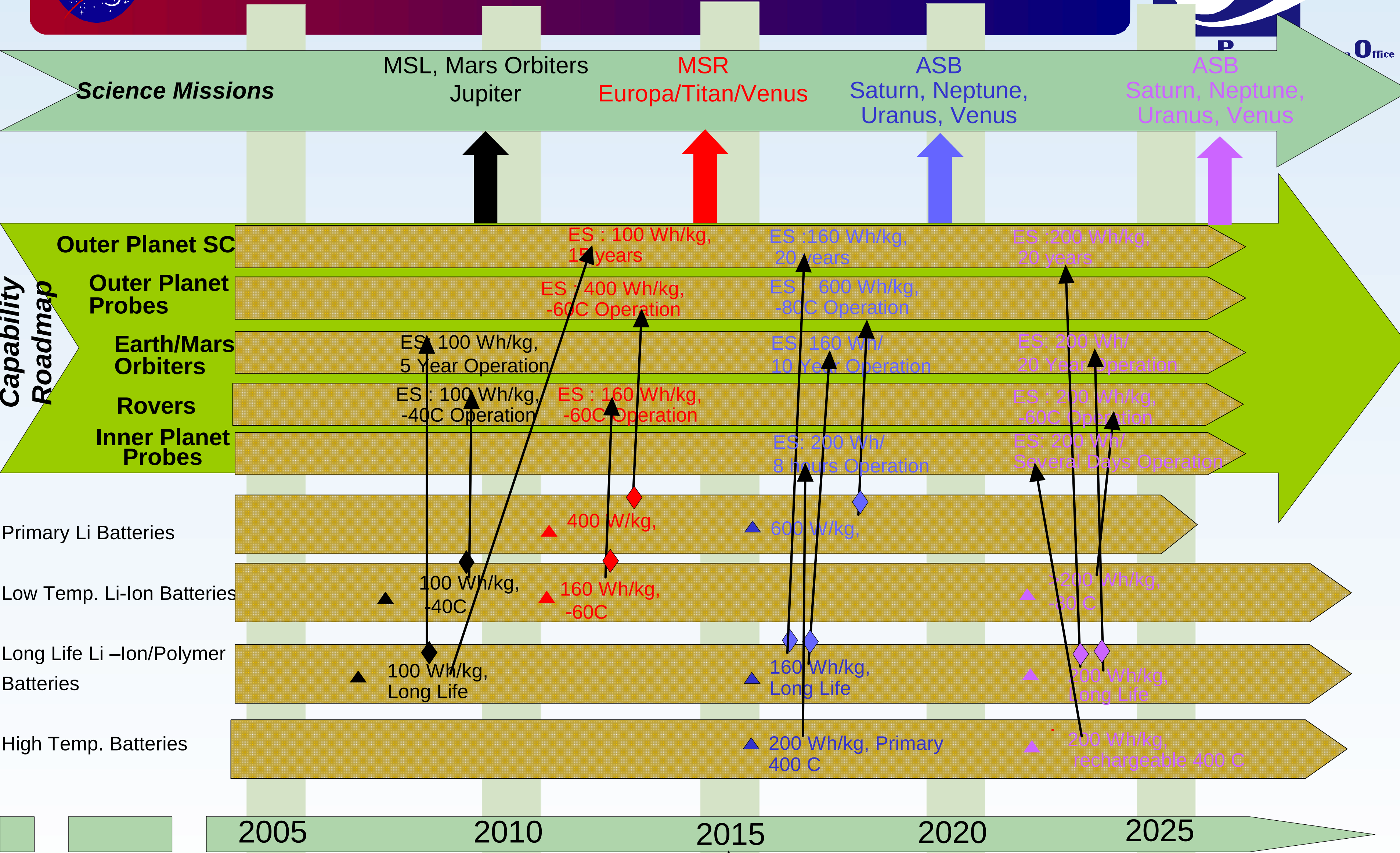
apabilities of State of Practice Systems

- **Potential Systems: Li-Ion/Li-Polymer**
- **System: Li-ion Batteries**

Energy Storage System Capability Roadmap-1



Energy Storage System Capability Roadmap-2



Major Decision Major Event / Accomplishment / Milestone Ready to Use

Summary

- Critical capability requirements for future space missions include:
  - Mass and volume efficiency (2-10 X Vs SOP)
  - Long life (> 15 years)
  - Ability to operate in extreme environments
- NASA has modest energy storage technology development programs. These programs are insufficient to meet future missions needs
  - ESMD program is reasonably strong, but requires modest augmentation
  - SMD has no technology development program
- DOD/DOE/Commercial industry are developing advanced energy storage systems specific to their needs.
  - NASA has unique requirements that are different from DOD/DOE
  - NASA may benefit significantly by working with AFRL/DOD, wherever synergism exists
- Building a strong robust energy storage technology program at NASA will have a significant impact on future missions

Radioisotope Power System (RPS) Capability Roadmap Status

Bob Wiley, DOE HQ

RPS Sub-Team Chair

April 7, 2005

Disclaimer: This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 RPS Sub-Team members, and is not the official view of NASA or DOE.

Capability Breakdown Structure – HEP&P

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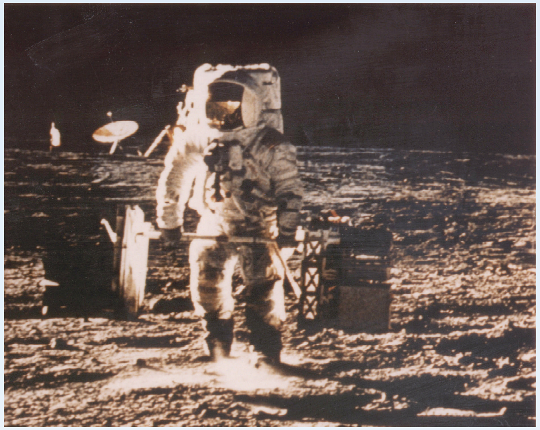
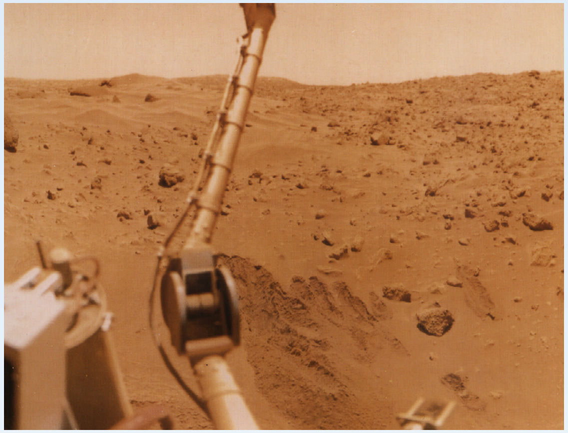
- 2.0 HEP&P
  - 2.1 Surface Power Robotic
    - 2.1.1 Solar
    - 2.1.2 Nuclear Fission
    - 2.1.3 Radioisotope
    - 2.1.4 Energy Storage
  - 2.2 Surface Power Human
    - 2.2.1 Solar
    - 2.2.2 Nuclear Fission
    - 2.2.3 Radioisotope
    - 2.2.4 Energy Storage
  - 2.3 Science & Robotic Spacecraft Power
    - 2.3.1 Solar
    - 2.3.2 Nuclear Fission
    - 2.3.3 Radioisotope
    - 2.3.4 Energy Storage
  - 2.4 CEV Power
    - 2.4.1 Solar
    - 2.4.2 Energy Storage
  - 2.5 Robotic Planetary Propulsion
    - 2.5.1 Nuclear Fission
      - 2.5.1.1 Electric Propulsion
      - 2.5.1.2 Thermal Propulsion
    - 2.5.2 Radioisotope Electric Propulsion
  - 2.6 Human Exploration Propulsion
    - 2.6.1 Solar
      - 2.6.1.1 Electric Propulsion
      - 2.6.1.2 Thermal Propulsion
    - 2.6.2 Nuclear Fission
      - 2.6.2.1 Electric Propulsion
      - 2.6.2.2 Thermal Propulsion

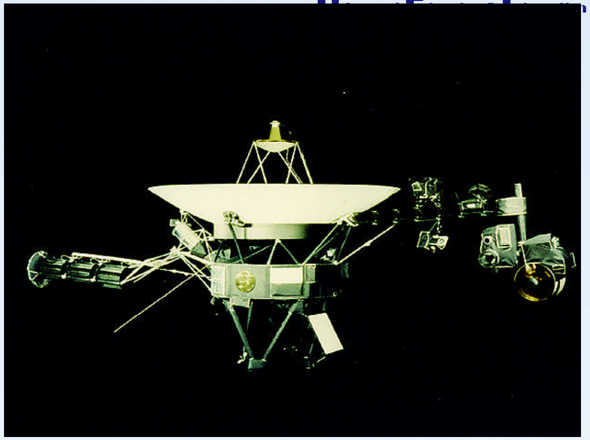
Past NASA Missions Using RPS – Including Moon and Mars



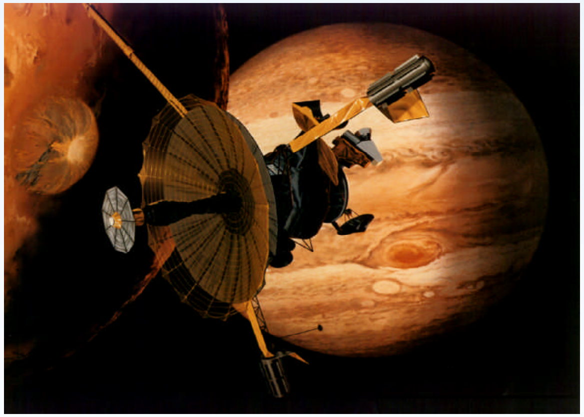
Apollo



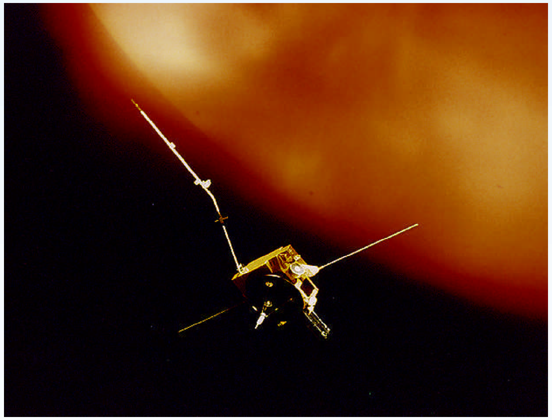
Viking



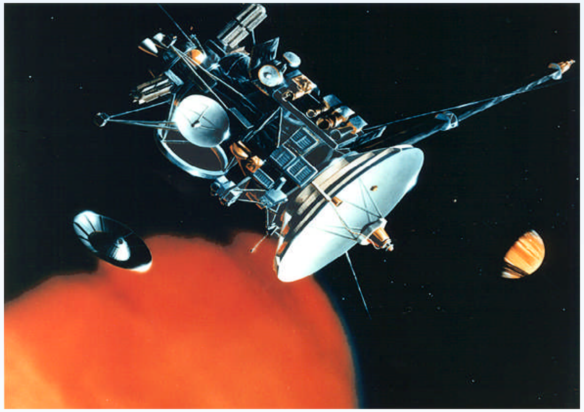
Voyager



Galileo



Ulysses



Cassini

Since 1961, 40 RTGs have been used on 22 US space systems.

Many Potential Future Science Missions Require RPS

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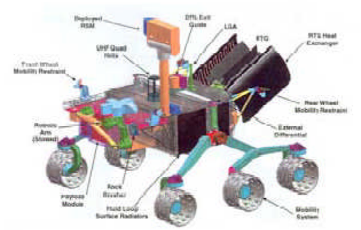
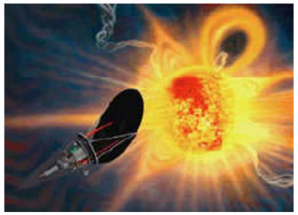


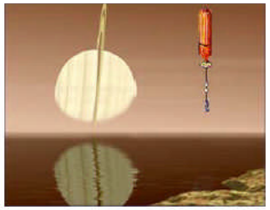
Near-term (2006 to 2015)

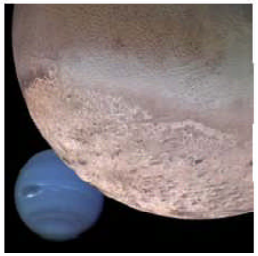
- New Horizons Pluto-Kuiper Belt Explorer (launch ~2006)
- Mars Science Laboratory (launch by 2009)
- Mars Scout Missions (launches 2011 & 2015)
- Solar Probe (launch ≥2012)

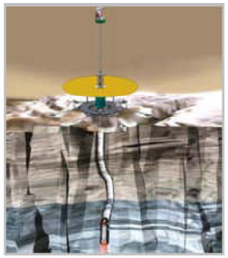


Vision Missions (≥2015)

- Medium Size (New Frontiers)
  - *Trojan/Centaur Recon Flyby*
  - *Asteroid Rover/Sample Return*
  - *Io Observer*
  - *Ganymede Observer*
- Flagship Class
  - *Europa Lander*
  - *Titan Explorer*
  - *Neptune-Triton Explorer*
  - *Uranus Orbiter with Probes*
  - *Saturn Ring Observer*
  - *Mercury Sample Return*
  - *Comet Cryogenic Sample Return*
  - *Interstellar Probe*
  - *Venus Sample Return*

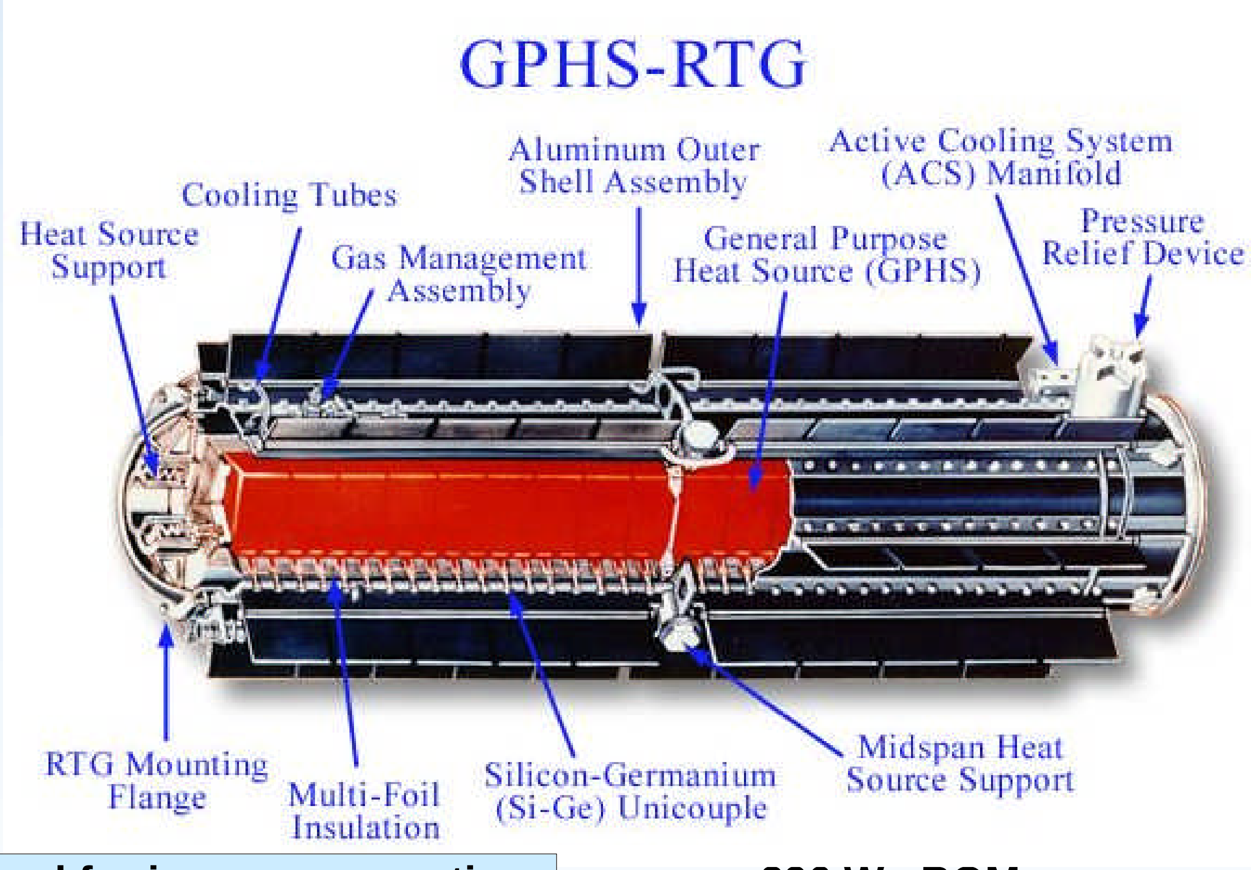






* *From NRC Space Science Decadel Surveys: "New Frontiers in the Solar System (2003)," and "The Sun to the Earth and Beyond (2003)."*

State-of-the-Practice Radioisotope Thermoelectric Generator

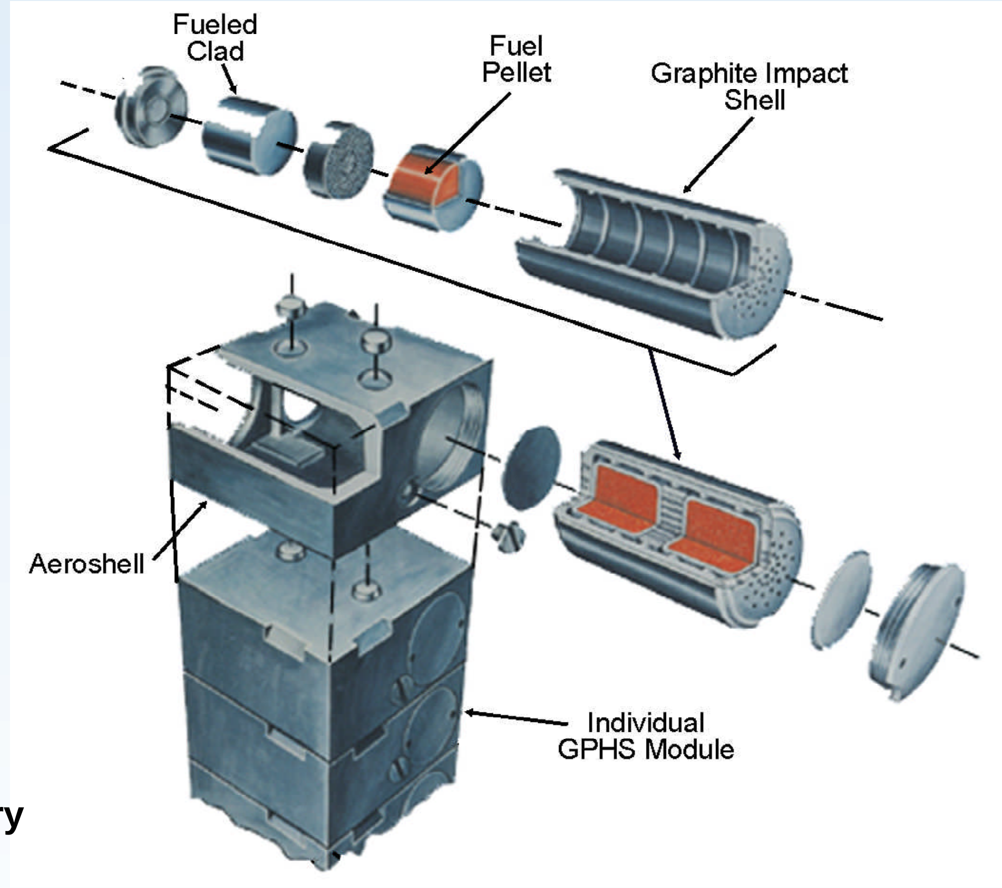


- Designed for in-space operation
- 18 GPHS modules
- SiGe thermoelectrics
- No longer in production

- 296 We BOM
- 56 kg (5.3 We/kg)
- 112 cm L x 40.6 cm D
- 6.6% system efficiency
- 30 year lifetime technology (Voyager)

State-of-the-Practice General Purpose Heat Source (GPHS)

- Pu-238 dioxide fuel
  - Nominal 250 Wt from 4 fuel pellets
  - Alpha-emitter, 87-year half life
  - Nonweapons material
  - Highly insoluble
- Ir Cladding (encases the fuel)
  - Fuel containment (normal operations or accidents)
  - High melting point -- thermal protection
  - Ductile -- impact protection
- Graphite aeroshell (protects fuel & cladding)
  - Impact shell -- impact protection
  - Insulator -- protect clad during re-entry
  - Aeroshell -- prevent burnup during re-entry
- Mass 1.6 kg (0.6 kg Pu-238)
- Dimensions 10 cm x 9.3 cm x 5.8 cm



Mass, Efficiency and Life are the Key RPS Metrics

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	BOM Power	BOM Specific power	System efficiency	Lifetime
State of Practice (GPHS-RTG)	296 We	5.3 We/kg	6.6%	30 years (Voyager)
Milliwatt/ multi-watt class	10-100 mWe 1-20 We	Low - TBD	5-20%	5-14 years
SOA 100 We class	110+ We	3-4 We/kg	6-20%	14+ years
Advanced 100 We class	110+ We	8-10 We/kg	8-40%	14+ years
Kilowatt class	1-2 kWe	8-10 We/kg	8-40%	5-14 years
Multi-kilowatt class	5 kWe	10-12 We/kg	30-40%	5+ years

Milliwatt and Multiwatt RPS

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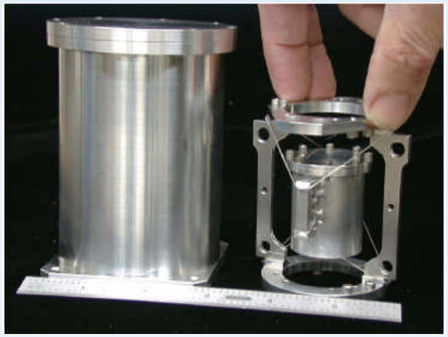
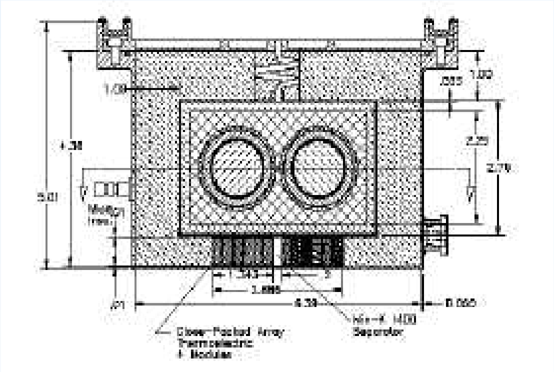


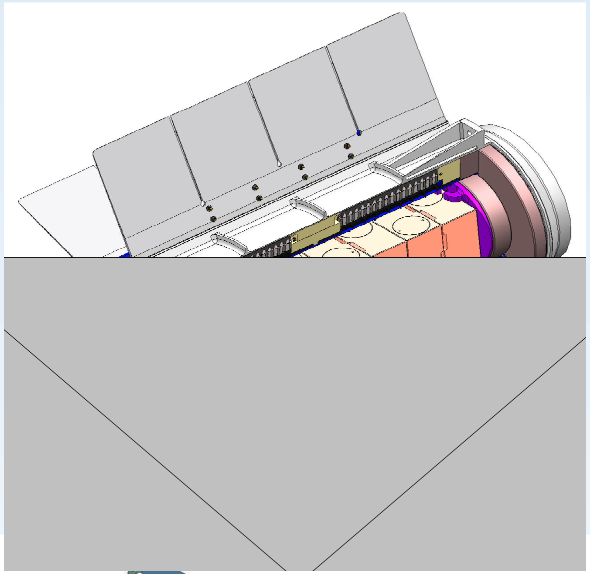
- **Milliwatt-class RPS**
  - 10-100 mWe of interest
  - RHU-based heat source

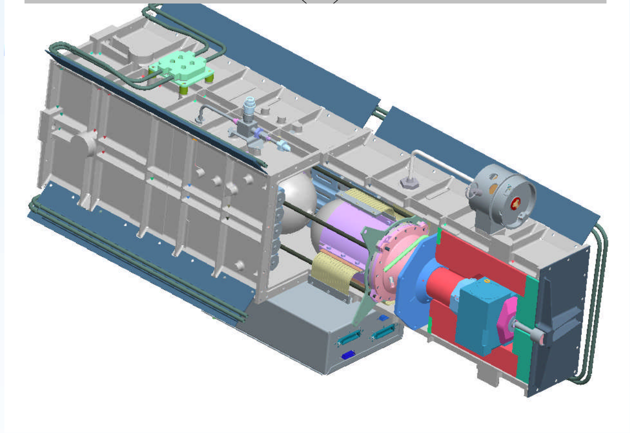


- **Multiwatt-class RPS**
  - 1-20 We of interest
  - GPHS-based heat source

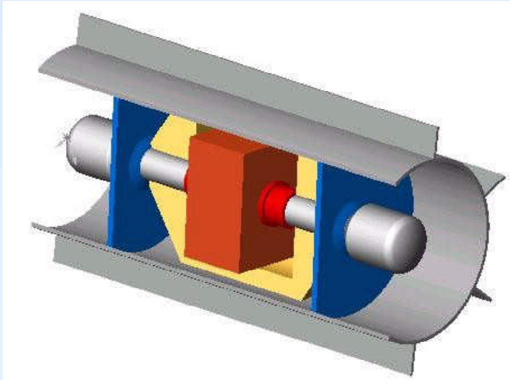
- DOE to issue solicitation in 2005 for system design and non-nuclear testing of engineering-type units
- Funded by NASA Science Mission Directorate

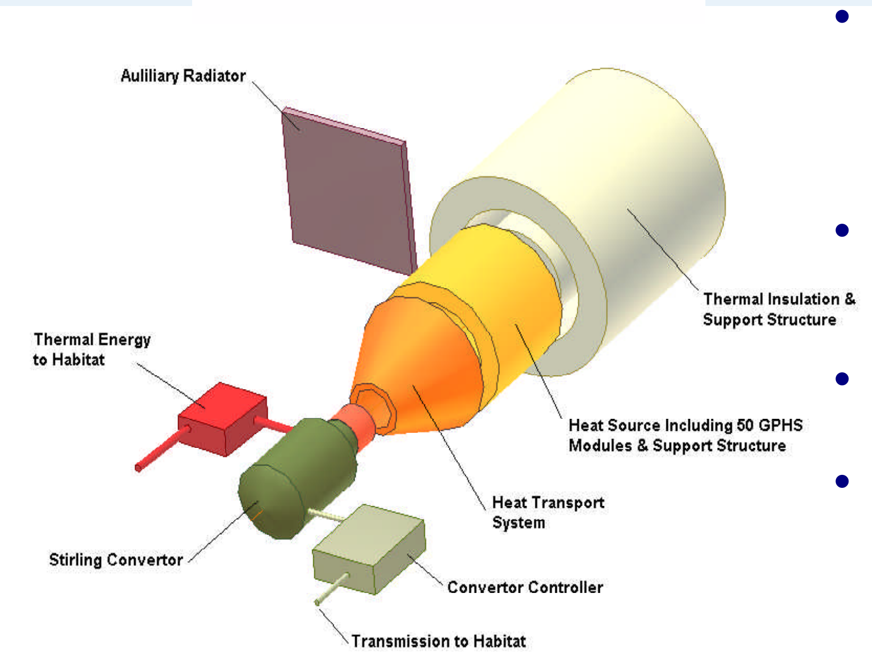
State-of-the-Art 100 We Class RPS





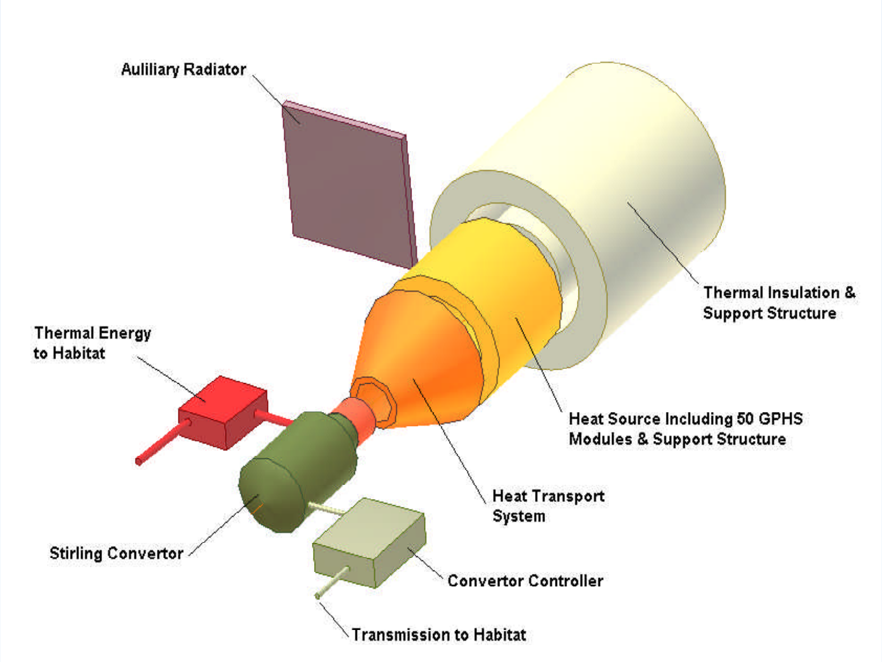
Advanced RPS Options

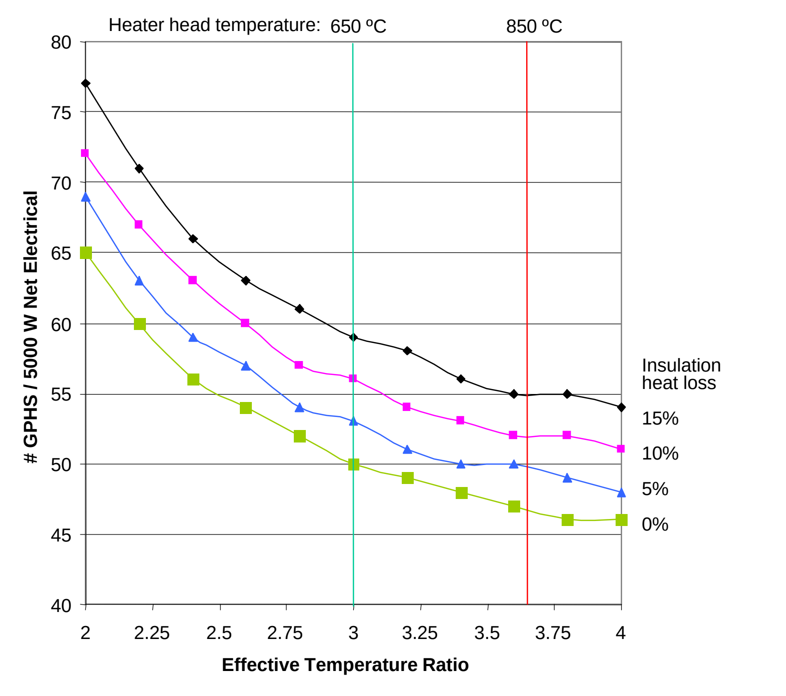




- Capability option for Spiral 2 robotic missions (landers/rovers), Spiral 3-5 human missions, and radioisotope electric propulsion (REP)
- Based on GPHS heat source
- Development candidates
  - Advanced 100-We class @ 8-10 We/kg
  - Kilowatt-class (1-2 kWe) @ 8-10 We/kg
  - Multikilowatt-class (5 kWe) @ 10-12 We/kg
- Technology gaps exist for such lightweight systems – need improved conversion systems, heat rejection and PMAD
- Lightweight RPS enhances mission payload fraction and REP performance
- Application of kilowatt and multikilowatt-class capability may be limited by GPHS processing throughput

Multi-kilowatt RPS Option for Spiral 3-5 Missions





- 5 kWe module; ~ 400 kg
- Provides both power and heat
- Only modest shielding or separation distance needed to limit radiation dose
- Relatively low-risk development needs
  - High efficiency energy conversion
  - Light-weight thermal management and PMAD

- Pu-238 Required Per Module Is Comparable to Total Flown on Cassini
  - Cassini: 3 x 18 = 54 GPHS modules

RPS Research and Technology Development

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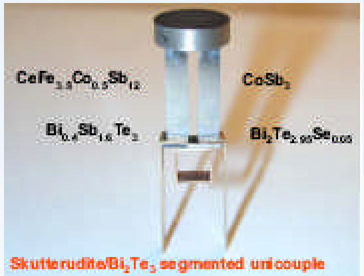
RPS Power Conversion Technology (RPCT) Project

- **Ten competitively awarded NRA contracts aimed at improving efficiency, specific power and reliability of future RPS**
  - **Five research (TRL• 3) and five development-focused (TRL• 5) for milliwatt (~40 mW) and nominal (~100 W) systems (scalable to 1-10 W)**
  - **Contracts initiated in 2003. Each consists of three 1-year phases**
- **Selections covered Stirling, thermoelectric, thermophotovoltaic (TPV), and Brayton power conversion technologies**
- **Of development contracts, only Stirling continuing**

Segmented Thermoelectric Research @ JPL

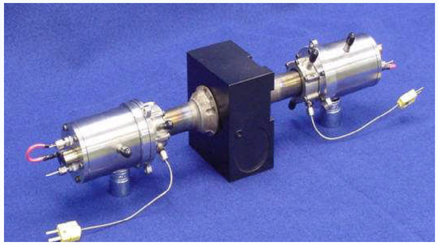
- **Direct-funded research on higher efficiency thermoelectric technology**
- **Demonstrated 12.5% efficiency with single unicouple: skutterdite/Bi2Te3 at 700-87** °C • T
- Developing sublimation-inhibiting coatings and insulation



Skutterudite/Bi_2Te_3 segmented unicouple

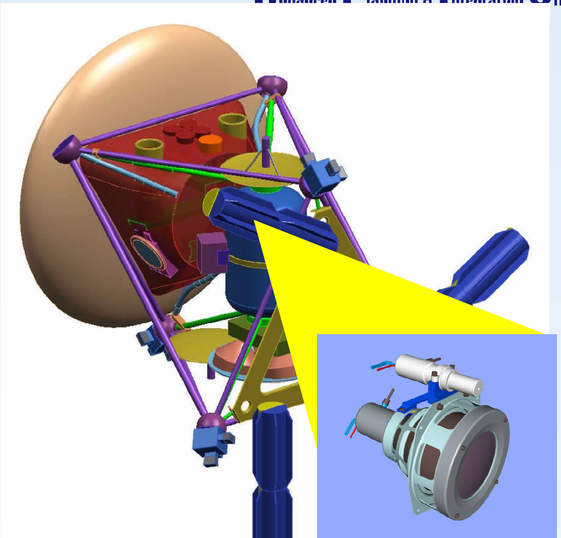
Advanced Stirling Research @ NASA GRC

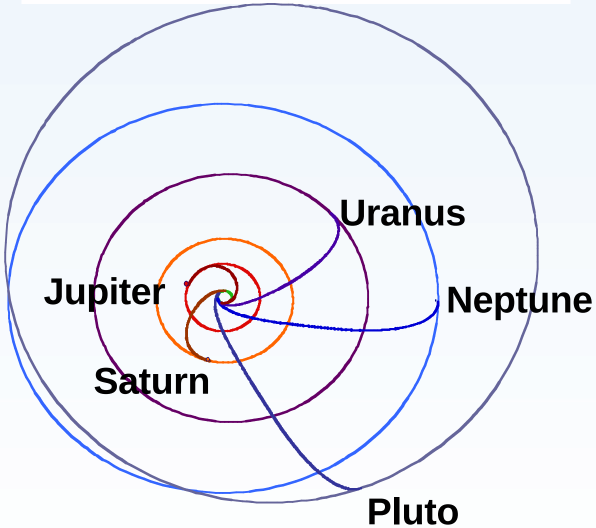
- Direct-funded research on technologies for 2nd Generation SRG
- Achieved 36% engine efficiency (AC out) on 85-watt testbed at 650-30 °C • **T**
- **Focus on potential use of higher temperature materials, mass reduction, and improvement in controller reliability/operation**
- **Identified and evaluated candidate materials**
- **Developed simulation of new controller operation**



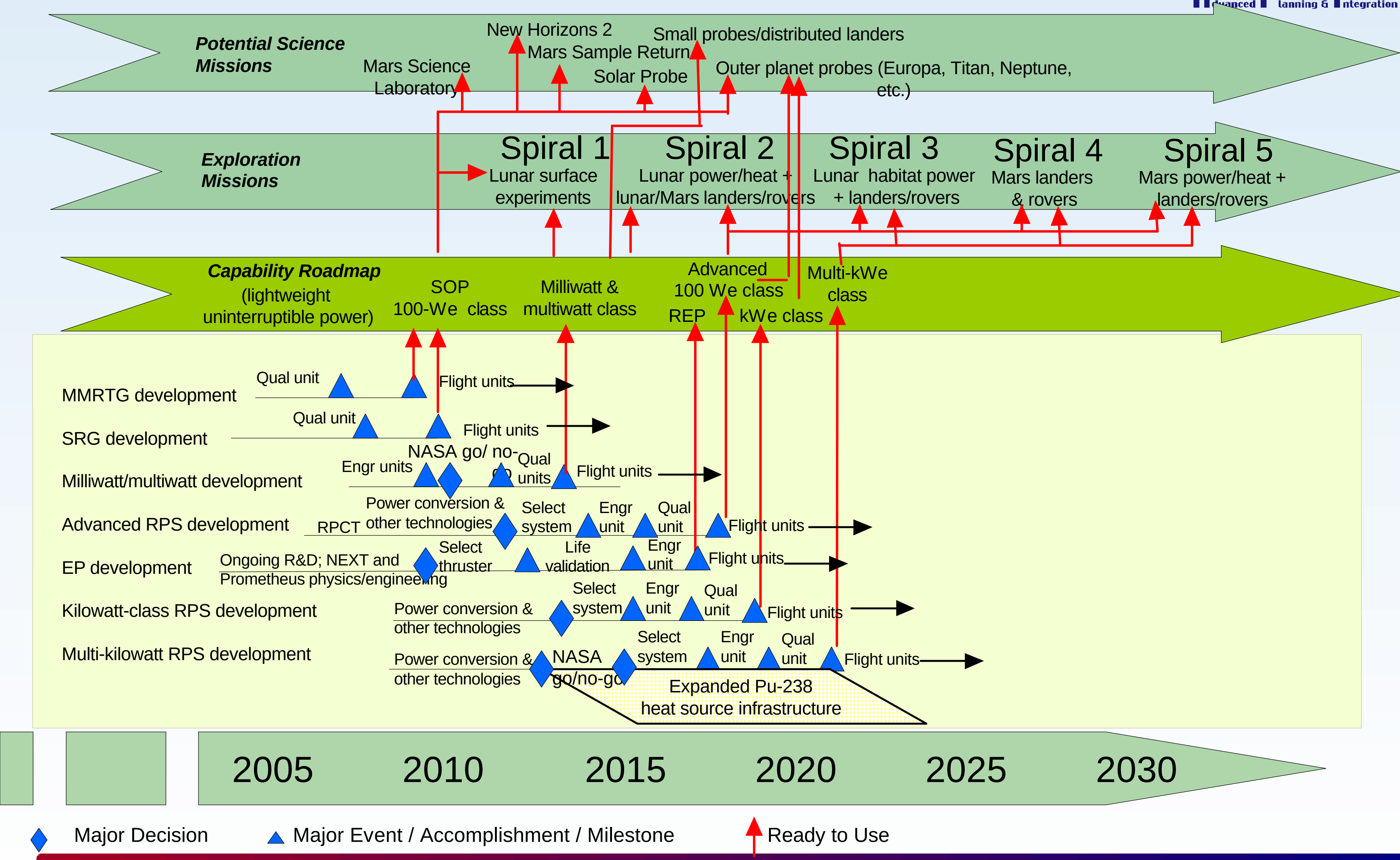
Capabilities Provided by REP

- REP best suited for science missions employing robotic spacecraft
- With existing medium launchers, could enable rendezvous with small planetary bodies and deep space objects
  - Launch system boosts spacecraft to velocities above earth escape (positive C3)
  - REP provides portion of in-space acceleration, deceleration and maneuvers about target
  - Small spacecraft with up to several 100's kg payloads
- With existing heavy launchers, could provide propulsive augmentation for orbital missions to outer planets
  - Chemical and/or solar electric propulsion serves as main propulsion up to distance of Mars/asteroid belt
  - REP used for "end game" propulsion maneuvers for deceleration and orbital changes about planetary body
- Implementation requires modest investment in technologies that could be fielded by end of this decade
  - High-specific power radioisotope generators based on advanced Stirling engine or segmented thermoelectric technology currently under development
  - Long-lived 100 We to ~1 kWe-class electric thrusters capable of 5-10 year lifetimes
  - Lightweight bus and payload technologies


Ion or Hall Thrusters



RPS Capability Roadmap



RPS Plays a Vital Role in NASA's Future

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- For many Science missions, the RPS (power and heat) is enabling.
  - Most outer planet and beyond spacecraft
  - Certain solar and inner planet missions
  - Certain Mars and other surface applications
- For Exploration:
  - RPS can be fielded to support early lander/rover missions.
  - RPS is an option for entry-level power and heat for Spiral 3-5 human missions and surface operations.
- Multimission RPS (MMRTG and SRG) are being developed with SMD funds, but no RPS is currently in production.
- Improved RPSs can be developed to provide full range of capabilities.
  - Robotic spacecraft and surface missions
  - Radioisotope Electric Propulsion (REP)
  - Spiral 3-5 human surface missions
- Lightweight components are needed to fill technology gaps for RPS system development.
  - High-efficiency energy conversion (reduced Pu-238 cost)
  - Heat rejection
  - PMAD

High Energy Power and Propulsion Fission Sub-Capability Roadmap Status

Sherrell Greene
CR-2 Fission Sub-Team Chair
Oak Ridge National Laboratory

Presented to
National Research Council

April 7, 2005

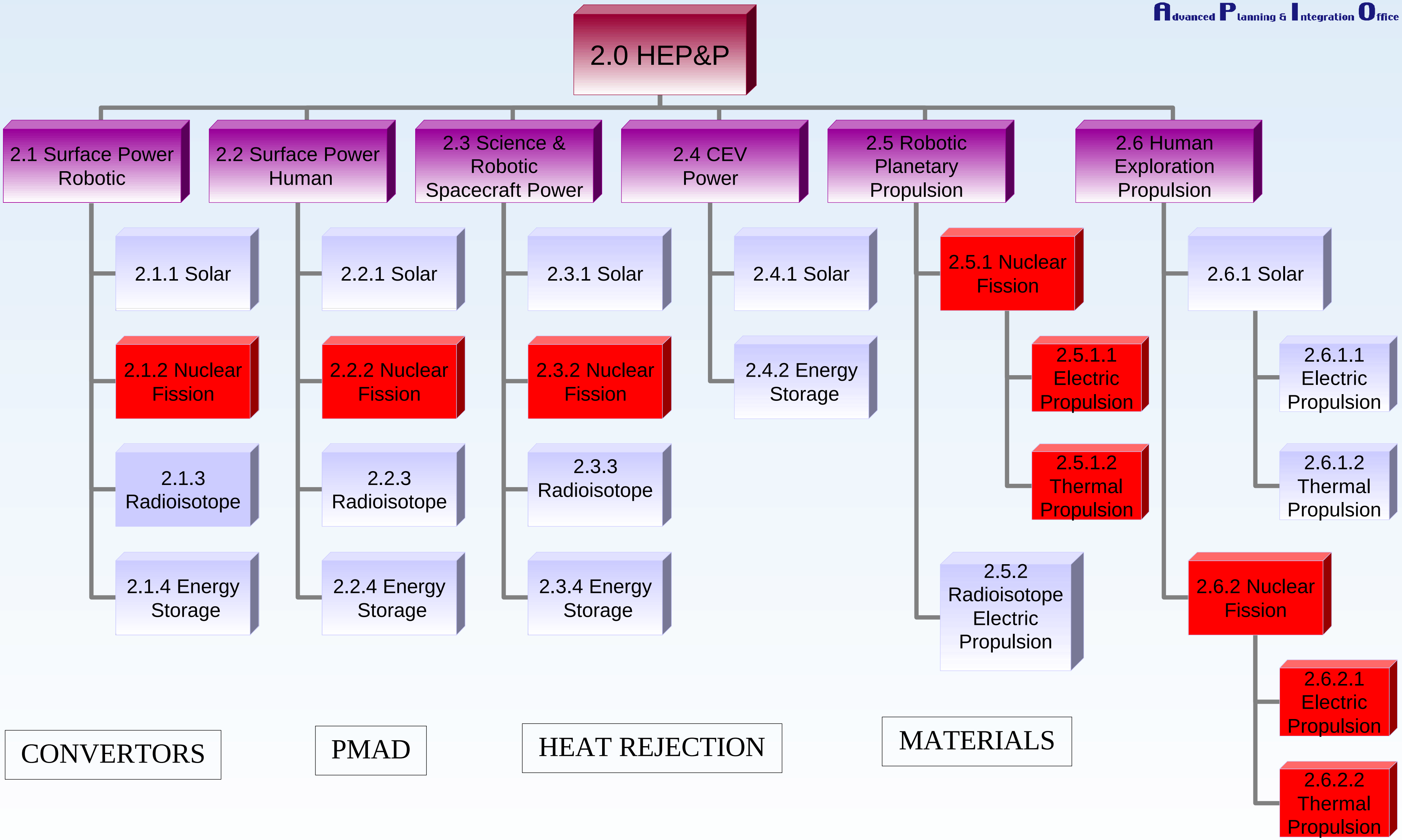
Disclaimer:
This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 Fission Sub-Team members, and is not the official view of NASA or DOE.

Presentation Outline

Advanced Planning & Integration Office

- Space Fission Propulsion and Power Introduction
- Nuclear Electric Propulsion (NEP)
- Surface Power (SP)
- Nuclear Thermal Propulsion (NTP)
- Bi-Modal Nuclear Thermal Propulsion (BNTP)
- Summary

This Presentation Addresses All Space Fission Power and Propulsion Capabilities Within CRC-2 Scope



Fission Technology Enables Or Enhances…

- Fuel energy densities ~ 10^7 that of chemical systems
- In-space Power and Propulsion
  - Power and propulsion independent of proximity to sun or solar illumination
    - Constant power level available for thrusting and braking
  - Go where you want, when you want
    - Expanded launch windows
    - Enhanced maneuverability
    - Faster trip times / reduced human radiation dose
- Surface Power
  - Provides power-rich environments
    - Telecom
    - Habitat
    - Insitu Resource Utilization / Propellant Production (ISRU / ISPP)
  - Enables planetary global access
  - Enables Lunar overnight stays

Space Fission Power and Propulsion Are Characterized By Key Parameters

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- **Power:** Thermal and/or electric power generated by system
- **Mass:** Total power or propulsion system mass
- **Lifetime:** Length of time of operation at full power (or equivalent)
- **Specific Mass (a):** Ratio of total power and/or propulsion system mass to electric power distributed to spacecraft
- **Engine Thrust-to-Weight:** Thrust produced per unit engine mass
- **Initial Mass In Low Earth Orbit (IMLEO):** Total spacecraft mass launched and assembled in low earth orbit (LEO) prior to mission start
- **Specific Impulse (Isp):** Thrust per unit mass flow of propellant
- **Efficiency (h):** Ratio of electric or jet power input to thermal power

Space-Based Fission Systems Differ From Earth-based Commercial Power Systems

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- Highly-Enriched-Uranium (HEU) fuel
- Mass
- Power densities and temperatures
- Fuels / coolants / materials systems
- Power conversion and heat rejection technologies
- Shielding technologies
- Automated or autonomous operation and control
- Limited or no maintenance & refueling
- Space or planetary operational environments

ORNL 2001-1605C EFG

U.S. Has Pursued Several Aerospace Nuclear Development Programs Since 1945

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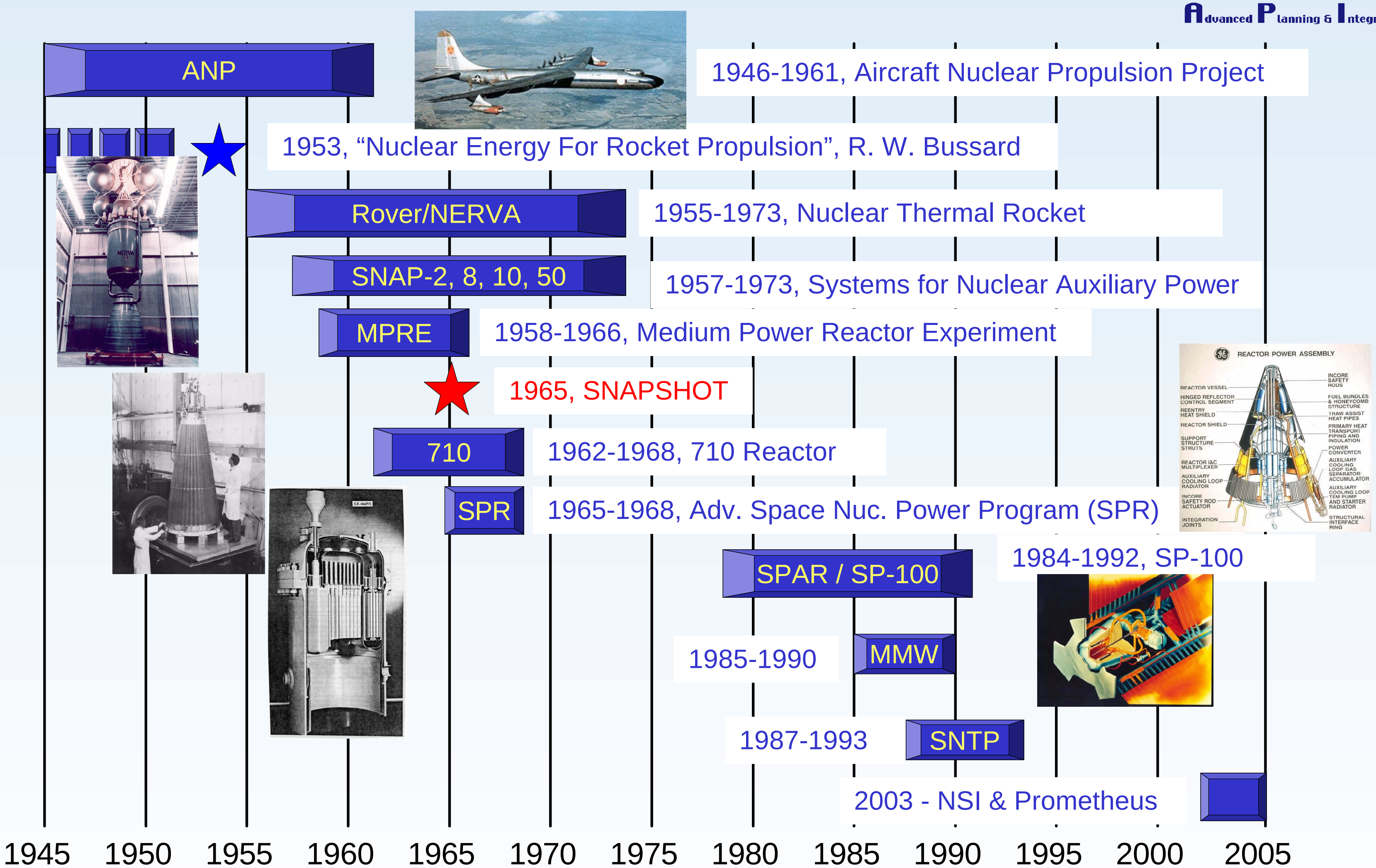

Significant Space Fission Technology Development Has Been Conducted

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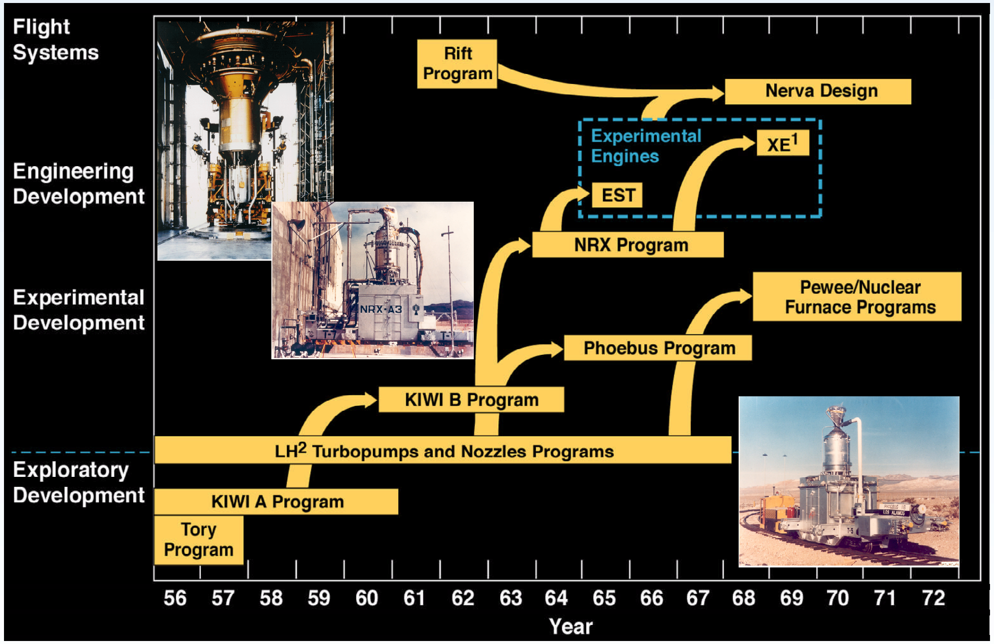
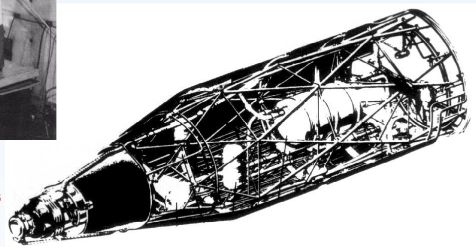
No U.S. Flight and Ground Test Experience Since 1972

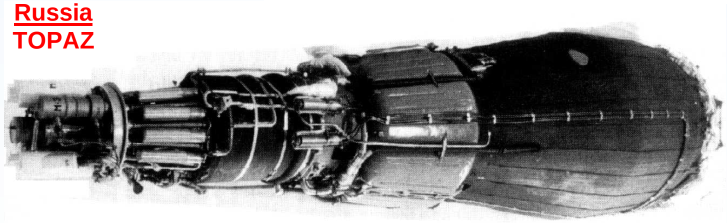
- **Nuclear Thermal Propulsion**
  - **20 Ground Test Reactors Operated**
- **Space Power**
  - **36 Systems Flown (1 U.S., 35 Russian)**
  - **5 U.S. ground test reactors operated**



Russia
BUK



Russia
TOPAZ



Nuclear Fission Flight System Development Programs Require Sustained Effort

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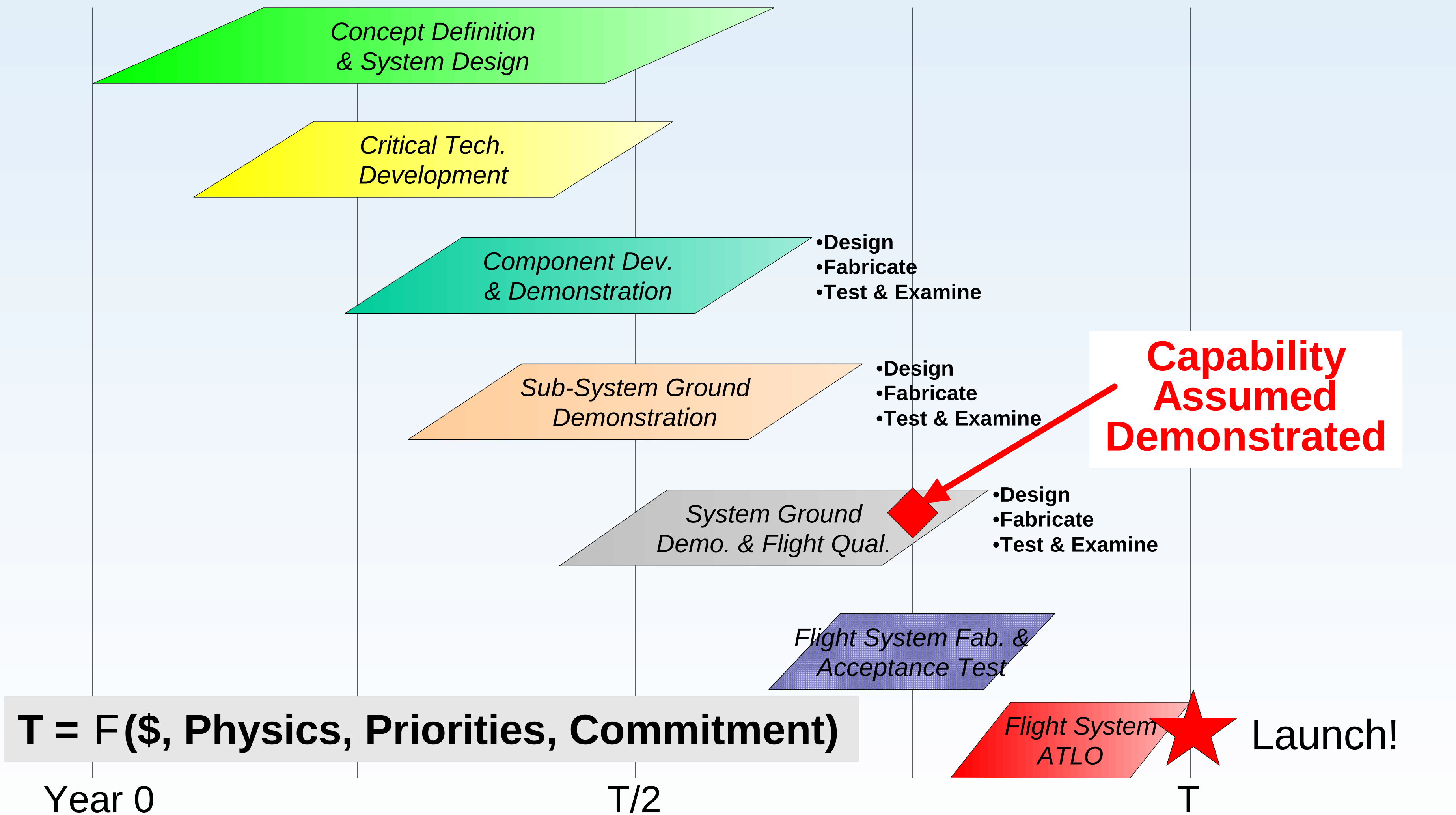

CRC-2 (HPE&P) Is Developing Fission Sub-Capability Roadmap

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- **Philosophy**
  - Address scope of VSE
  - Update prior major studies (SEI, CRAI, etc.) strategies and recommendations to accommodate
    - Current technology status
    - Current infrastructure status
    - Current thinking with respect to likely missions and mission architectures
- **Process**
  - Develop initial “independent” MMW-NEP, Surface Power, and NTP and BNTP Capability Roadmaps
    - Assume no resource constraints
    - Only technology and knowledge constraints
  - Integrate four roadmaps to leverage synergisms, identify intersections and off-ramps, and eliminate gaps
  - Integrate Prometheus-I/II plan as available
  - Overlay strategic objectives, mission bogies, funding profiles as information becomes available

Nuclear Electric Propulsion

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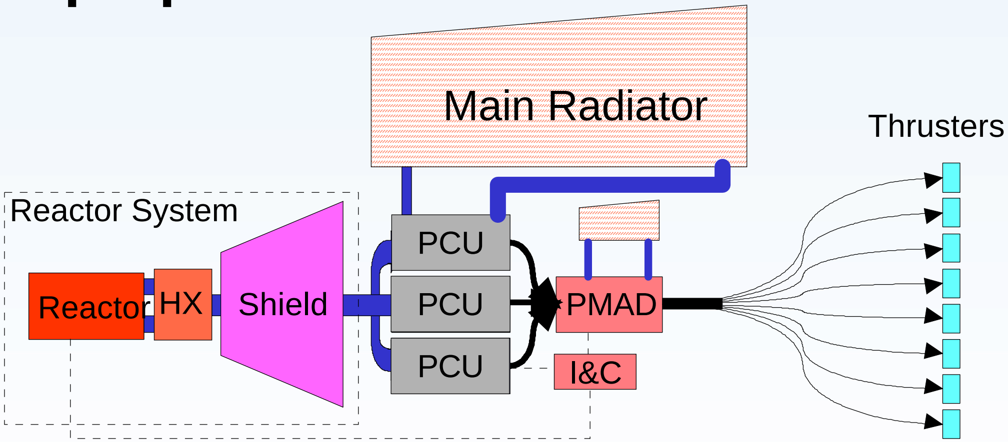
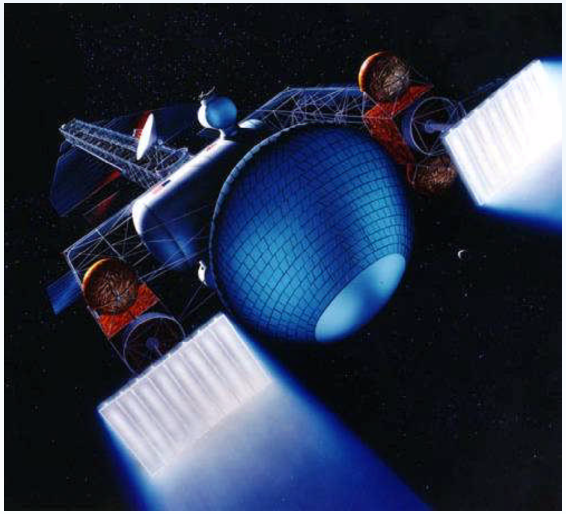
- Compact system capable of providing spacecraft propulsion and electrical power for deep space robotic missions or near-Earth cargo and piloted Mars missions.
- Primary subsystems include: reactor system, power conversion unit(s), power management and distribution unit, heat rejection system, and electric thrusters.
- Characterized by extended operation and minimum propellant mass.





Benefits of Nuclear Electric Propulsion

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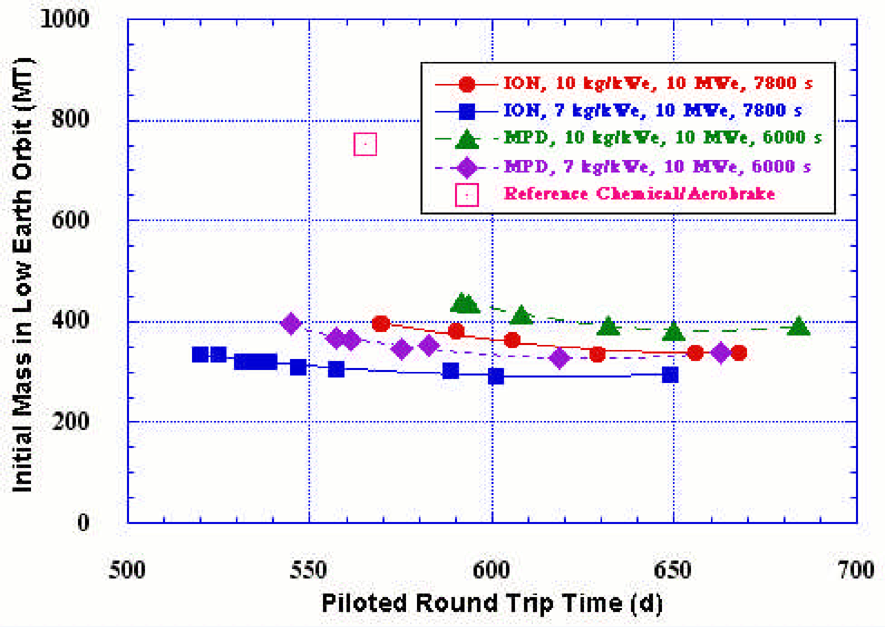
- Propulsion and electrical power from single system
- Constant power source for on-board life support and science instruments
- High specific impulse enables low initial propellant mass and re-supply mass
- High power system (1-10 MWe) supports large cargo, deep-space science, and short trip times for piloted missions to Mars.
- Provides increased flexibility for launch opportunities compared to chemical rockets



Desirable Nuclear Electric Propulsion Performance Characteristics*

Mission	Specific Mass (kg/kWe)	Power (MWe)	Specific Impulse (ks)	Lifetime (yr)
Orbital transfer	10 – 30	0.1 – 1.0	2 – 8	3 – 10
Robotic interplanetary	30 – 50	0.1 – 1.0	5 – 10	10 – 12
Lunar cargo	10 – 20	0.5 – 5.0	3 – 10	3 – 10
Mars cargo	10 – 20	2 – 10	5 – 10	2 – 10
Mars piloted	< 10	5 – 40	5 – 10	2 – 10

*NASA TM 105707, "Summary and Recommendations on Nuclear Electric Propulsion Technology for the Space Exploration Initiative," April 1993

Preliminary Planning Assumptions: NEP Mission & Performance Evolution

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Science/Human/Cargo NEP Mission Studies

- 2002 JIMT
- 2002 DRM
- 2002 DRM
- 1994 Clark
- 1993 George
- 1992 George
- 1992 McDonald Douglas
- 1991 Boeing

Science/Human/Cargo NEP Missions

- Lunar Orbiter
- Jupiter Moon Tour
- Outer Planets
- Kuiper Belt

- Lunar Cargo
- Mars Cargo
- Mars Piloted

Entry-Level Science NEP Performance

- 200 kWe
- 3-yr life
- 70 kg/kWe
- Robotic
- Isp = 5000 s

High-End Human/Cargo NEP Performance

- 5 MWe
- 5-yr life
- 10 kg/kWe
- Human
- Isp = 10000 s

Current State-of-the-Art for Nuclear Electric Propulsion

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- Reactor subsystem (U.S. only)
  - 44 kW(t)/530 W(e) – SNAP-10A (1965)
  - 2400 kW(t)/100 kW(e) – SP-100 (1984-1992)
- Power conversion subsystem
  - Stirling: 12.5/25 kWe NASA MTI, Commercial SOA 10s-100s We
  - Brayton: 10 kWe, 1144 K PCS tested for 38,000 hr
  - LM-Rankine: 200 kWe K-Rankine turbine tested ~ 4000 hrs in MPRE (1962-67), ~ 160,000 hrs component tests
- Power management and distribution subsystem
  - 160 V; 57+ kWe; 400 K – ISS
- Heat rejection subsystem

Current NEP Sub-system Maturity Levels and MMW NEP Development Needs

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Subsystem	Current CRL	Development Needs for MMW NEP
Reactor	6 @ 43 kWt* 2 @ 2 MWt 1 @ 25 MWt	• High temperature fuel (1500-2000 K) • High burnup fuel (>10%) • High temperature structural materials (1500 K) • Rad-hard I&C (10^{23} n/cm^2 and 100 Mrad) • Robust shield material
Power Conversion	5-6 For static* 3-4 For dynamic	• Refractory metal components (1500 K) • High temperature bearings and seals • Rad-hard alternator insulation • Two-phase flow management (LM-Rankine)
PMAD	5-6 @ < 10 kWe 2 @ > 100 kWe	• High temperature semiconductors (600-700 K) • High power • Rad-hard electronics
Heat Rejection	6 @ ~ 100 kWt**	• High temperature, low mass materials • High temperature heat pipes
Electric Thrusters	6 @ < 10 kWe 2 @ > 100 kWe	• Scaling to high power • Or development of high power concepts

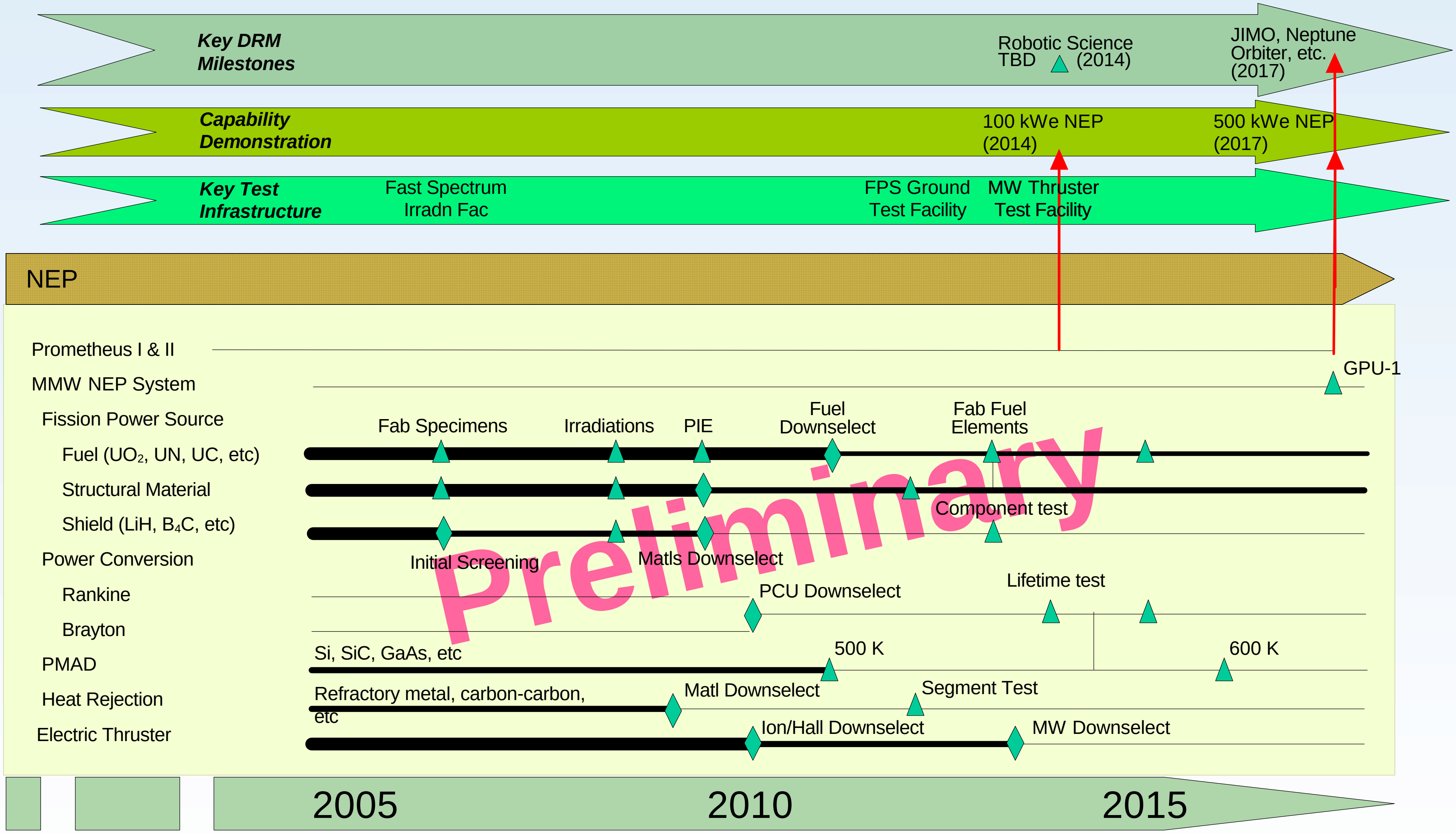
* SNAP-10A **TOPAZ

Metrics for Nuclear Electric Propulsion

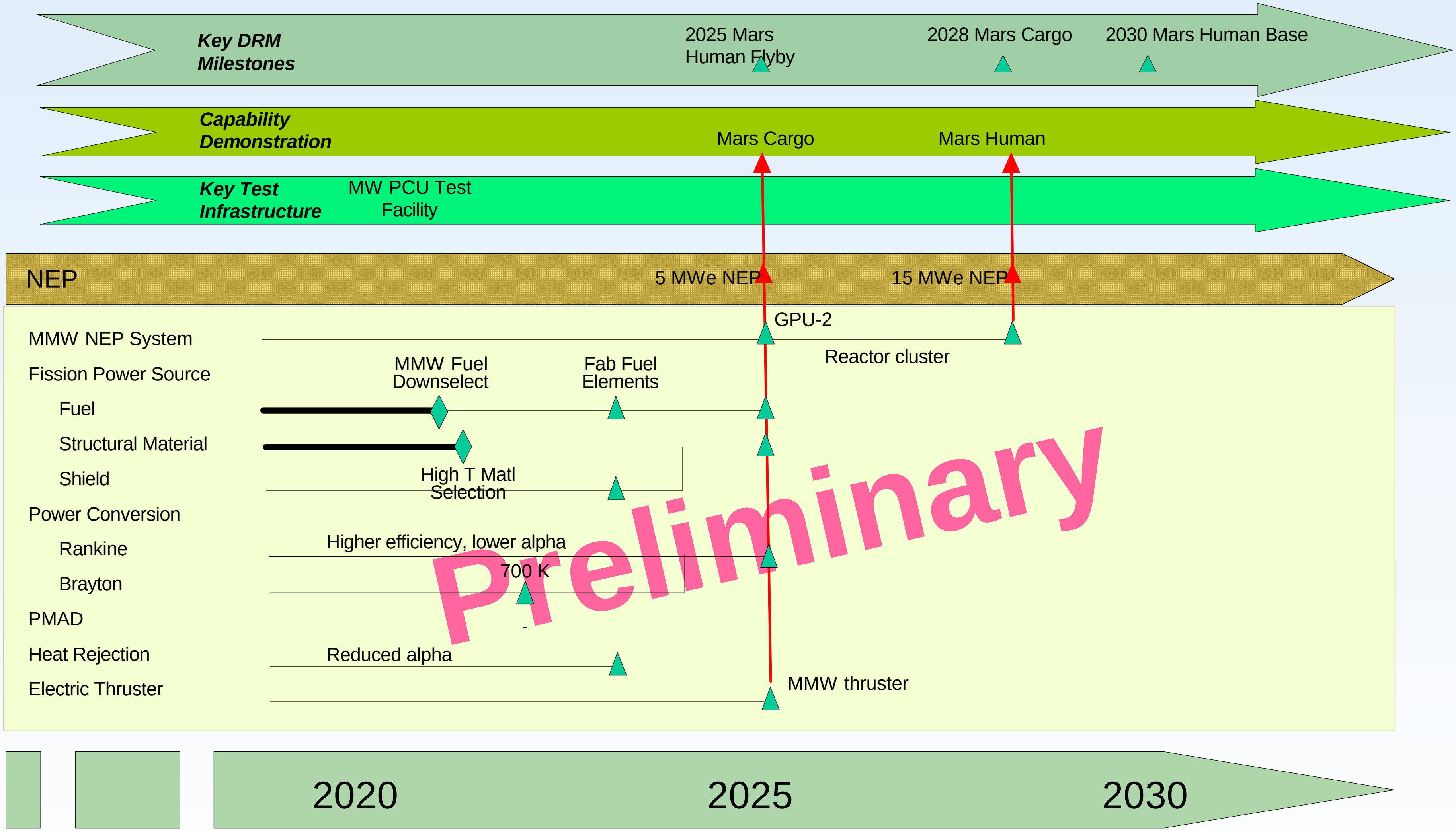
Subsystem	Figure of Merit	Development Targets	
		Entry-Level (Science)	Long-term (Human Exploration)
Fission Power Source	Power Specific Mass Lifetime*	1 MWt 50-70 kg/kWe 3 yr	25 MWt 5-10 kg/kWe 5 yr
Power Conversion	Efficiency Lifetime*	20% 3 yr	35% 5 yr
PMAD	Temperature Specific Mass Power	500 K 30 kg/kWe 100 kWe	700 K 3 kg/kWe 1 MWe
Heat Rejection	Areal Density Temperature	10 kg/m^2 500 K	2 kg/m^2 900 K
Electric Thrusters	Power Specific Impulse Efficiency	100 kW 2 – 8 ks 70%	1 MW 2 – 10 ks >60%

Lifetimes exceeding 10 yr are required for many NEP science missions.

NEP Capability Roadmap (2005–2020)

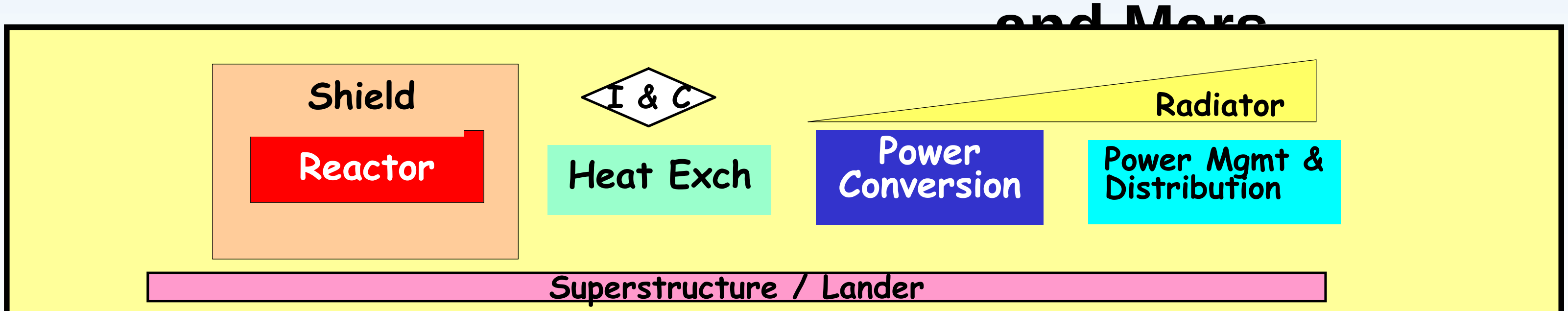


NEP Capability Roadmap (2020–2030)



Surface Fission Power Capability Description

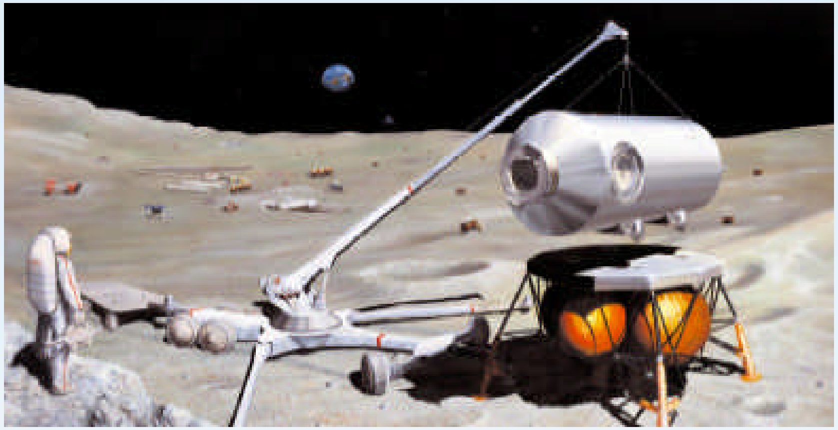
Surface fission power **provides the primary power generation and distribution for both robotic pathfinder and human exploration missions to the surface of the moon and Mars**

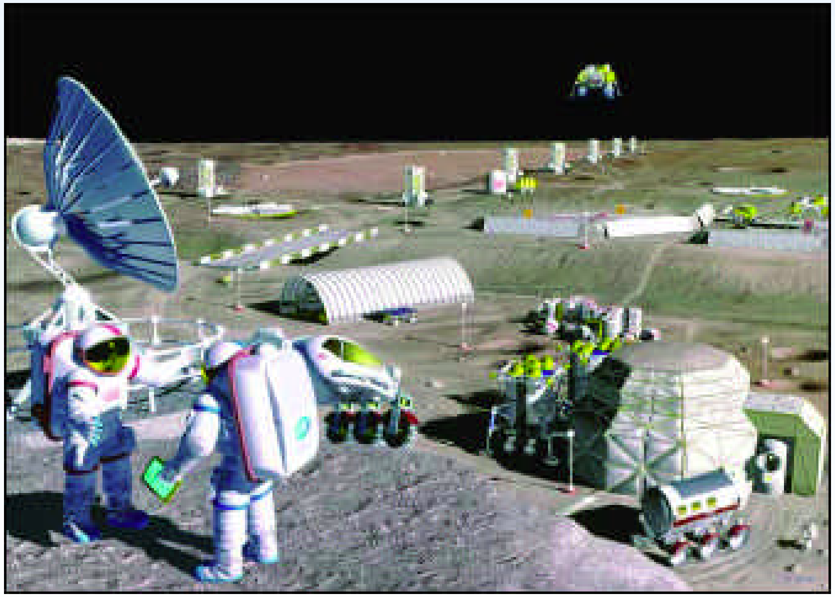


Principal Subsystems for Space Reactor Power System

Surface Fission Systems Provide Power-Rich Environment

- Significant power (10s - 100s kWe)
  - Life support
  - Telecom
  - ISRU/ISPP
- Power independent of the sun
  - AU
  - Latitude
  - Diurnal cycle
  - Topography
- Enables repeat or extended mission durations with continuous source of power
- Compact, flexible, high-energy density power source





Key Mission Architecture Assumptions and Strategies

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Assumptions

- Robotic system operation should not preclude later human presence

- All systems must incorporate robust autonomous control
  - Must demonstrate operability prior to crew arrival
  - Must be capable of ISRU/ISPP and providing continual power for life support system (habitat) in absence of crew
  - Should not require astronaut's attention
- Safety & Reliability are technical focus
  - To ensure power is available for human life support

Strategies

- Gain early success on the moon
- Minimize technical development risk
- Provide high reliability and minimize mass (max performance)
- Assure extensibility to human Mars applications

Desirable SP Capability Performance Levels*

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Mission	Power (kWe)	Lifetime (yr)	Landed Mass (kg)
Robotic Lunar Outpost	10 – 30	3 – 10	5000
Human Lunar Base	30 – 100	5 – 10	5000
Robotic Mars Outpost	10 – 30	3 – 10	2000
Human Mars Base	30 – 100	5 – 10	2000

*NASA Exploration Team (NEXT) Human Exploration Requirements For Future Nuclear Systems, Version 1.0, 12/19/02

Current Roadmap Planning Assumptions: Mission Evolution and Performance Levels

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Surface Power Mission Studies

- 2002 NEXT Study
- 1992 FLO
- 1989 "90-Day Study"
- 1971 Lunar Base Synthesis Study
- 1959 Project Horizon

Surface Power Mission Evolution

- Lunar Human Base
- Mars Human Base

Surface Power Performance

Entry Level

- 30 kWe
- 3 yr life
- 10000 kg
- Human-rated
- Stationary
- Lunar

"Beta" Level

- 50 kWe
- 7 yr life
- 12000 kg
- Human-rated
- Stationary
- Mars

Differences Between Moon and Mars Must Be Considered in Design of Surface Fission Power System

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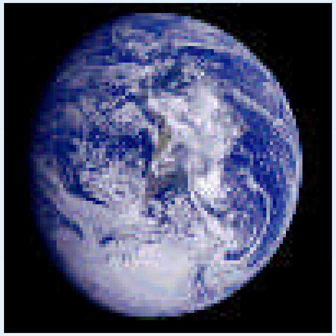
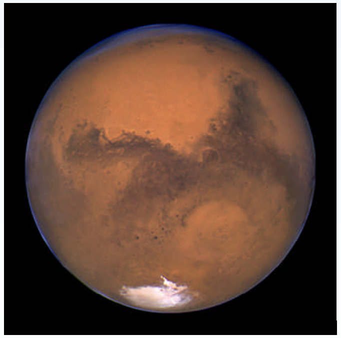
Parameter	Earth	Moon	Mars
Surface gravity, m/s^2	9.78	1.62	3.69
Mean atmospheric pressure, millibars	1013	None[a]	1Š10
Average atmospheric density, kg/m^3	1.2	None[a]	0.02
Average atmospheric temperature, K	288	None[a]	210
Diurnal atmospheric temperature range, K	184Š242	None[a]	140Š270
Day length	24 h	27.3 d	24 h 37 min
Minimum atmospheric temperature, K	183	None[a]	140
Maximum atmospheric temperature, K	329	None[a]	340
Atmospheric composition (by volume)	79% N_2 20% O_2 0.93% Ar 0.03% CO_2	Hydrogen[a] Helium[a] Neon[a] Argon[a]	95.32% CO_2 2.7% N_2 1.6% Ar 0.13% O_2 0.08% CO 210 ppm H_2O
Trace	Neon Methane Helium Krypton Hydrogen Xenon	Trace	Neon Krypton Zenon
Atmospheric optical depth	0.01Š3	None	0.1Š10
Wind speed, m/s	>90	None	2Š30
Atmospheric mean molecular weight, g/mole	29		43.34

[a]Lunar atmospheric density is 1×10^4 to 2×10^5 molecular/cm^3• 14 orders of magnitude less than that of Earth.

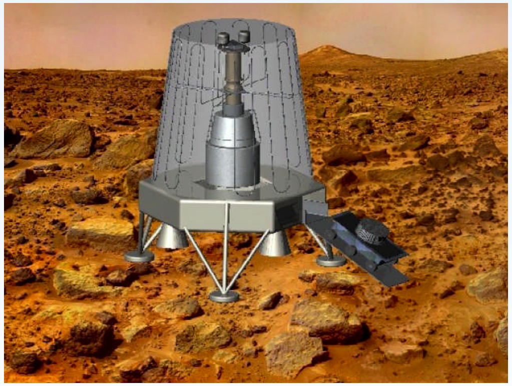




Note: Regolith chemical and isotopic compositions not shown.

Current Capability Readiness for Surface Fission Power

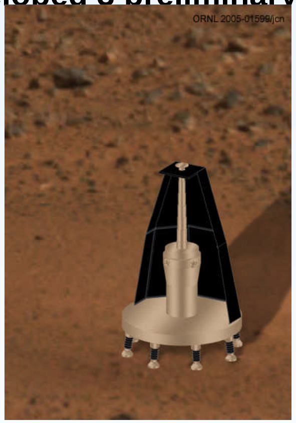
- Current CRL for Integrated SRPS for surface power - 2
- Comparable to in-space flight fission systems?
  - Fuels - UO_2 and UN near-term options
  - Materials
    - Viable concepts with SS/superalloys for low temp designs
    - Refractory systems for high temp operation requires development
  - Infrastructure
    - No fast-flux fuel and materials irradiation facilities in U.S.
    - Available system test facilities limited – no new facilities for space power since early 1970's
  - Lander / deployment issues TBD
- Technology based on SNAP, SP-100, and terrestrial reactor (LMFBR & GCR) programs
- Limited design/assessment for surface fission power applications
  - Most previous mission studies "assumed" use of SP-100 reactor
  - Recent efforts by DOE-NE developed 3 preliminary conceptual designs



Robotic – 3 kW(e) – Homer

Heat Pipe Rx w/Stirling

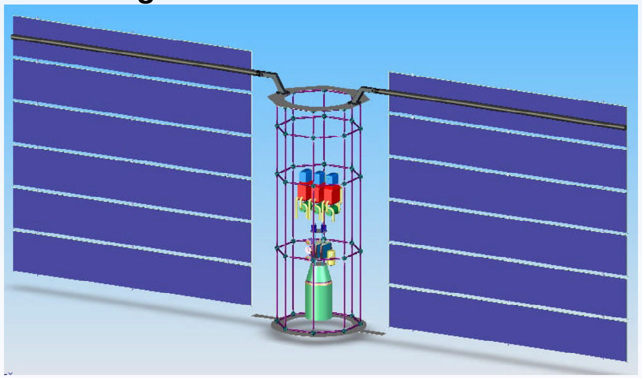
381 kg/kW(e)



Robotic – 12.5 kW(e) – PRESTO

Boiling Liquid Metal Rx w/Stirling

160 kg/kW(e)



Human – 50 kW(e) – LMR

Pumped Liquid Metal Rx w/Brayton

289 kg/kW(e) – not optimized

Maturity Level – Technologies for Surface Fission Power

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Mission Architecture (power requirements as function of mission phase and duration) influence reactor and PCS options

Preliminary

Reactor Candidate Technologies

- **Liquid-metal – TRL 3 (TRL 9 in 60's-70's for Russia and U.S.)**
  - Technology pedigree established (SNAP, SP-100, MPRE, LMFBR) and scalable
  - Flexible with Stirling, Brayton, Rankine, TE
  - Freeze/thaw and system complexity issues
  - Flown but not landed
- **Gas-cooled – TRL 3**
  - Technology pedigree from terrestrial program/scalable
  - Naturally couples only with closed-cycle Brayton PCS
  - Larger mass than LMR
- **Heat-pipe – TRL 2**
  - Passive cooling system/fewer dynamic components than LMR and GCG
  - Scalability questions above 100 kWe

Power Conversion Technologies

- **Thermoelectric – TRL 9 (flying today)**
  - Most mature – RTG pedigree, static system
  - Highest mass/lowest efficiency (5-8%)
  - Used on SNAP 10A
- **Stirling – TRL 4**
  - Free piston configuration operating with helium as working fluid/high efficiency
  - Maintain uniform hot head temperature
  - Efficiency: 20-25%
  - Rad-tolerance: TBD
- **Brayton – TRL 3-5**
  - Substantial experience with open-cycle systems
  - Space system employs closed cycle
  - 38,000 hr ground test by NASA
  - Efficiency: 15-20%
  - Large radiators
  - Rad-tolerance: TBD
- **Rankine – TRL 3-4**
  - Water Rankine systems used in most of world's 440 operating power reactors
  - Liquid-metal Rankine turbine ground demos in SNAP and and MPRE (4000 hr turbine test)
  - Efficiency: 15-25%
  - Smallest radiators
  - Rad-tolerance: TBD
  - 2-Phase fluid mechanics

Surface Power Capability Roadmap (2005–2015)

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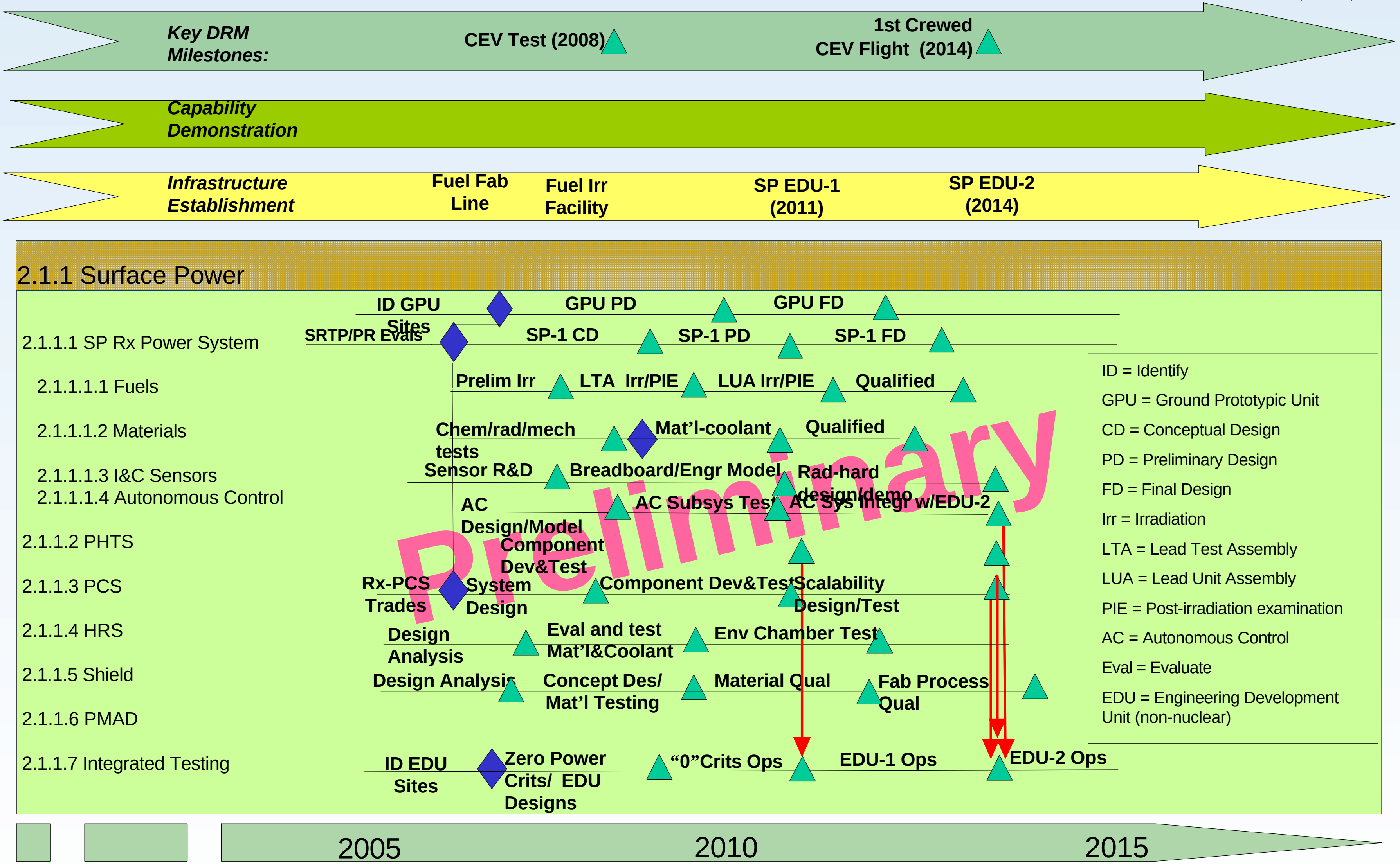

Surface Power Capability Roadmap (2015–2030)

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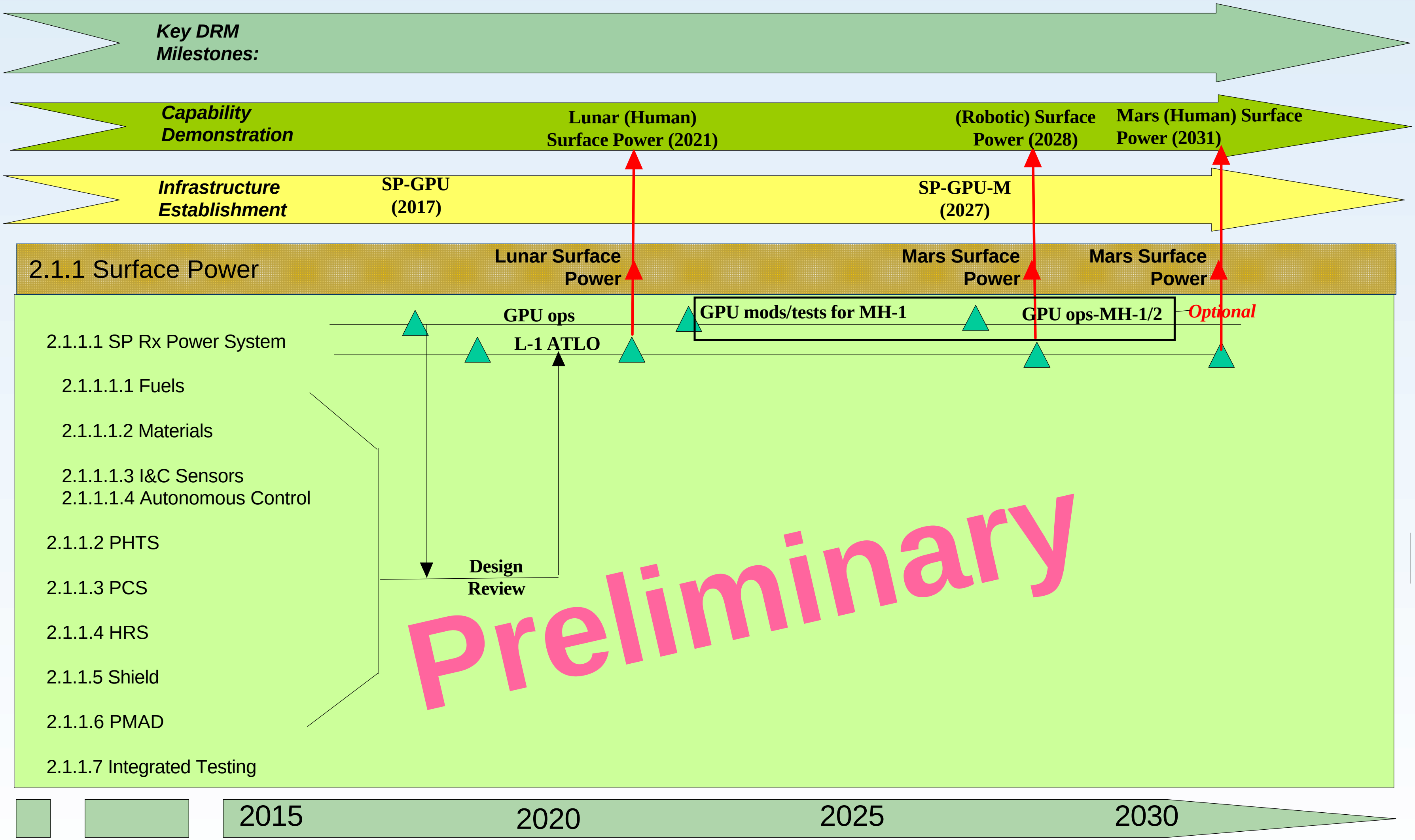
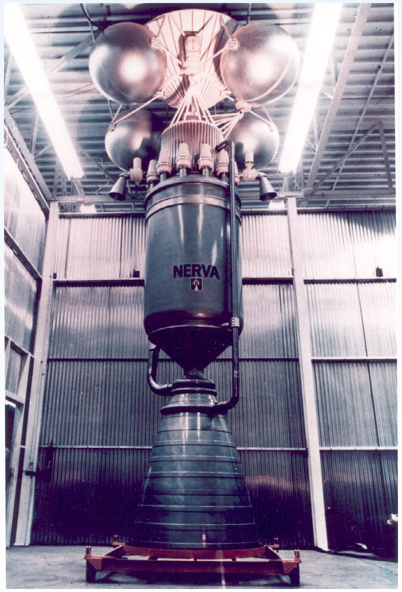


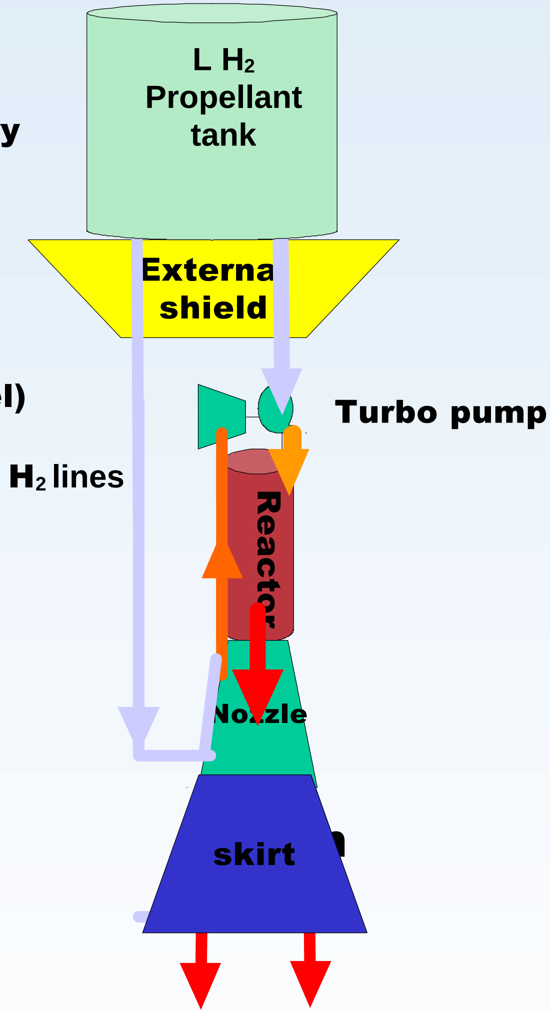
NTP Stage Integrates Nuclear and Non-Nuclear Subsystems

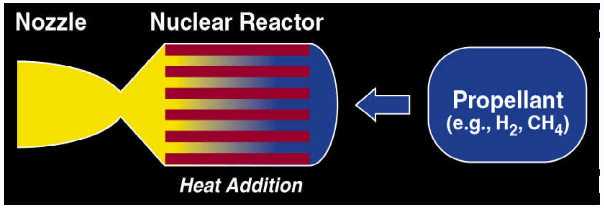
Expendable TLI Stage for First Lunar Outpost Mission using Clustered 25 klb$_f$ Engines -- “Fast Track Study” (1992)



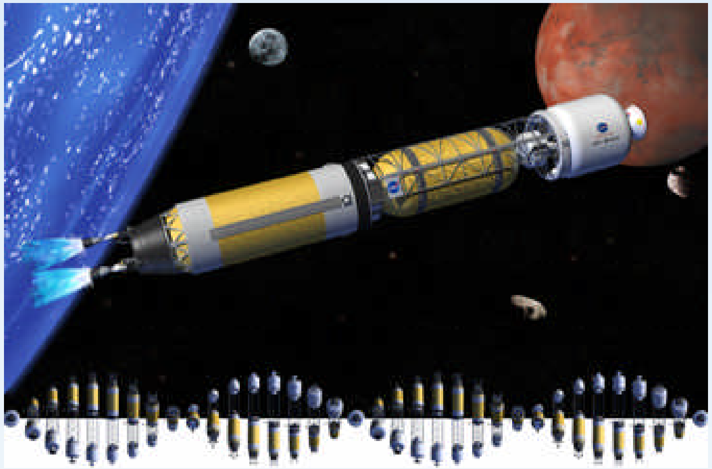
Full Scale Mockup a NERVA Engine

- Stage
  - Propellant storage and delivery
  - I&C
  - Engine
    - Reactor
      - Nuclear Reactor fuel
      - Structural materials/moderator/shield
    - Thrust Chamber (outer vessel)
    - Propellant feed system
      - Turbine
      - Pump
      - Plumbing/valves
    - Nozzle
      - Regen section
      - Skirt
    - I&C
  - External Nuclear Shield
  - Thrust Vector Control
  - Structure





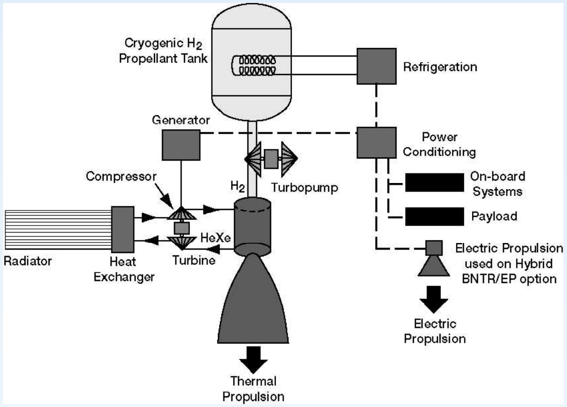
Bimodal Nuclear Thermal Propulsion (BNTP) Adds Electrical Power Capability

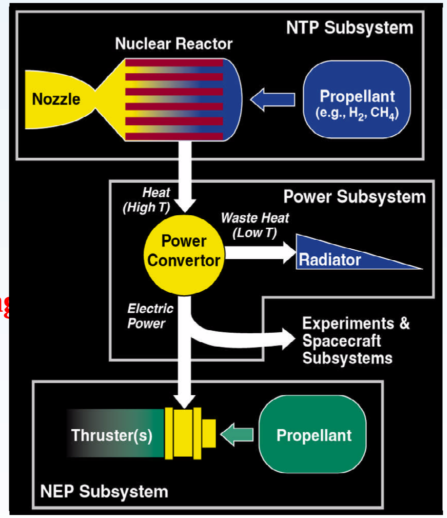


NASA 50 kW$_e$ BNTP Mars Crew Transfer Vehicle Designs. A 5 kW$_e$ Photovoltaic Array is shown above for Size Comparison

- Stage
  - Propellant storage and delivery
  - I&C
  - Engine
    - Nuclear Reactor
      - Fuel
      - Structural materials/moderator/shield
    - Thrust Chamber (outer vessel)
    - Propellant feed system
      - Turbine
      - Pump
      - Plumbing/valves
    - Nozzle
      - Regen section
      - Skirt
    - I&C
  - External Nuclear Shield
  - Thrust Vector Control/Structure
  - Power Conversion System

  - Pumps/valves/turbine/compressor/plumbing
    - Heat Exchanger
    - Radiator
  - PMADS





NTP & BNTP Provide Many Benefits

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NTP
- Capable of high thrust, high thrust/mass ratio, and high specific impulse (2 times the best chemical rocket systems)
- Reduced transit times (reduced exposure for manned missions)
- Reduced IMLEO requirements
- Greater mission flexibility for VSE Mars (cargo and especially piloted) missions with respect to departure windows
- Potential for single small engine design to satisfy a broad variety of exploration missions
- Operated for only short duration (hours/mission) vs months for other systems

BNTP
- Provides continuous onboard power for spacecraft/crew
- Provides power for refrigeration of coolant to reduce boiloff
- Facilitates artificial gravity during transit flights
- One propulsion system capable of meeting ***"broad range" of robotic and piloted exploration missions***
- Allows hybrid mission - combining rapid transit times with NEP maneuverability

Candidate Missions for NTP and BNTP

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Requirements / Missions	Engine thrust (klb_f)	T/W_{eng}	T_{ex} (ºK)	I_{sp} (s)	No. engines	P_{elec} [kW(e)]	Tin* (K)	Power mode duration (days)	Total burn duration (hr)	No. burns
Robotic science	15	3	2550	875	1	$\lesssim 10$	1150	~28–12.6 years	<0.5	1
Lunar cargo	15	3	2550	875	1–2	$\lesssim 10$	1150	7–14	0.5–1.0	2–3
Lunar piloted	15–25	3–4	2550–2700	875–900	1–2	25	1150	45–90	~1.0	3
Mars cargo	15	3	2700	900	2–3	10–25	1150	270–300	0.5–1.0	2–3
Near Earth asteroid (NEA) piloted	15	3	2700	900–915	3	50	1150–1300	365	<1.5	3–4
Mars piloted	15–25	3–4	2700	900–925	3	50	1150–1300	545–900	<2.0	4–5

***Tin: Turbine Inlet Temperature.**

Assumed NTP & BNTP Mission Evolution and Target Performance

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NTP Mission Studies

- 2004 RASC (Mars Orbital)
- 1999 DRM 4.0
- 1998 DRM 3.0
- 1995 Fast Outer Planets
- 1993 DRM 1.0
- 1992 First Lunar Outpost
- 1990-91 SEI
- 1989 "90-day Study"

NTP Mission Evolution

- NTP Lunar Cargo
- NTP Mars Cargo
- NTP Piloted Mars

NTP / BNTP Mission Evolution

- BNTP Lunar Cargo
- BNTP Piloted Mars

Entry Level NTP & BNTP

- 15 klb_f (single engine)
- 1-hr Burn-time
- 0.5-hr max. single burn
- 3 restarts/mission
- T/W (klb_f/klb_m) = 3
- Isp = 875 s
- 15 kWe (BNTP only)

"Beta" Level NTP & BNTP

- 25 klb_f (single engine)
- 1.5-hr Burn-time
- 0.5-hr max. single burn
- 8 restarts/mission
- T/W (klb_f/klb_m) = 3+
- Isp = 925 s
- 25 kWe (BNTP only)

Basic Engineering Feasibility of NTP Has Been Demonstrated

- Estimated current NTP CRL (stage) is 3-4 (?)
- NTP Pedigree
  - From 1959- 1972, 20 Nuclear Thermal Reactors were built and tested (17 test reactors, 1 safety test, 2 ground test engines) as part of the Rover/NERVA Program
    - Best Parameters Achieved:
      - Highest Power 4100 MWt
      - Peak Fuel Temperature 2750 K
      - Max. Hydrogen Exhaust Temperature 2550 K
      - Specific Impulse 875 s
      - Maximum Restarts 28
      - Accumulated Time at Full Power 109 minutes
      - Continuous Operation 62 minutes
  - Rover/NERVA program reached a technical maturity level sufficient to begin planning for a Reactor In-Flight Test (RIFT)
  - Additional fuel and materials tests conducted in Space Nuclear Thermal Propulsion Program (SNTP), GE 710 Program, and ANL Cermet Nuclear Rocket Program
  - High Temperature and pressure non-nuclear rocket components developed for the Space Shuttle and LOX/LH_2 Centaur in-space stage may have applicability to NTP
  - Demonstration of conformance with extant safety requirements (e.g. fuel fission product release, water/sand immersion criticality, etc.) will be required

- BNTP introduces additional issues
  - Short duration high power operation + long-duration low power operation
  - Clustering (if small engine)

- BNTP designs have been proposed but no technology development or demonstration
  - Estimated BNTP CRL (stage) is 2-3 (?)

NTP Technology Readiness

TRL levels assessed relative to first mission (single-engine lunar cargo).

WBS	TRL rating	Basis for rating	Comment
Stage			
Propellant Storage and Delivery System	7-8	- Centaur - S IV-B	Relevant cryogenic stages have flown
I&C	7-8	- Centaur	Reactor radiation environment minimal
Engine			
Reactor			
Fuel	3	Fuel fission product release Infrastructure & fabrication status	Recapture improve fabrication and infrastructure
Moderator/Structural Materials	3		
Propellant Feed System	7	J-2, RL-10	Radiation assessment on components needed.
Nozzle			
Regen	7-8	SSME	Radiation assessment
Rad. cooled extension	5-6	RL-10 B-2	~300:1 deployed nozzle ratio
I&C	4-5	Rover/NERVA	Radiation environment assessments
External Nuclear Shield	4-5	SP-100 XE	- Design, but no fab
Thrust Vector Control/Structure	7-8?	Centaur S IV-B	Reactor radiation environment

NTP & BNTP Technology Needs (Gaps)

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Hardware Tree Element	Need	Why
Stage Propellant Storage and Delivery System I&C	- Clustering - Radiation environment testing - Radiation environment testing	- Small engine - Reactor - Reactor
Engine Reactor Fuel Moderator/Structural Materials	- Water/sand immersion subcriticality - Fuel fission product retention - Recapture/improve fabrication	- Nerva-derived design - Clustering (Coupled physics & I&C) - Bimodal operation - Degraded infrastructure
Propellant Feed System Nozzle Regen. Cooled Rad. Cooled extension	- Radiation environment testing - Radiation environment testing - Radiation environment testing - Radiation environment testing	- Reactor
I&C	- Rad-hard I&C - Bimodal and Clustering Control	- Reactor - Bimodal operation
External Nuclear Shield	- Design and materials fabrication	- Capability and infrastructure not currently present at DOE
Thrust Vector Control/Structure	- Radiation environment testing	- Reactor
Power Conversion	- 10s kWe Power Capability - Transition/Control demonstration - Radiation env. & life testing	- Bimodal operation - Reactor
Heat Rejection	- Radiation env. & life testing	- Reactor
PMAD	- 10s kWe Power Capability - Radiation env. & life testing	- Reactor

NTP Small-Engine Development Approach Maximizes Leverage of Legacy Technology

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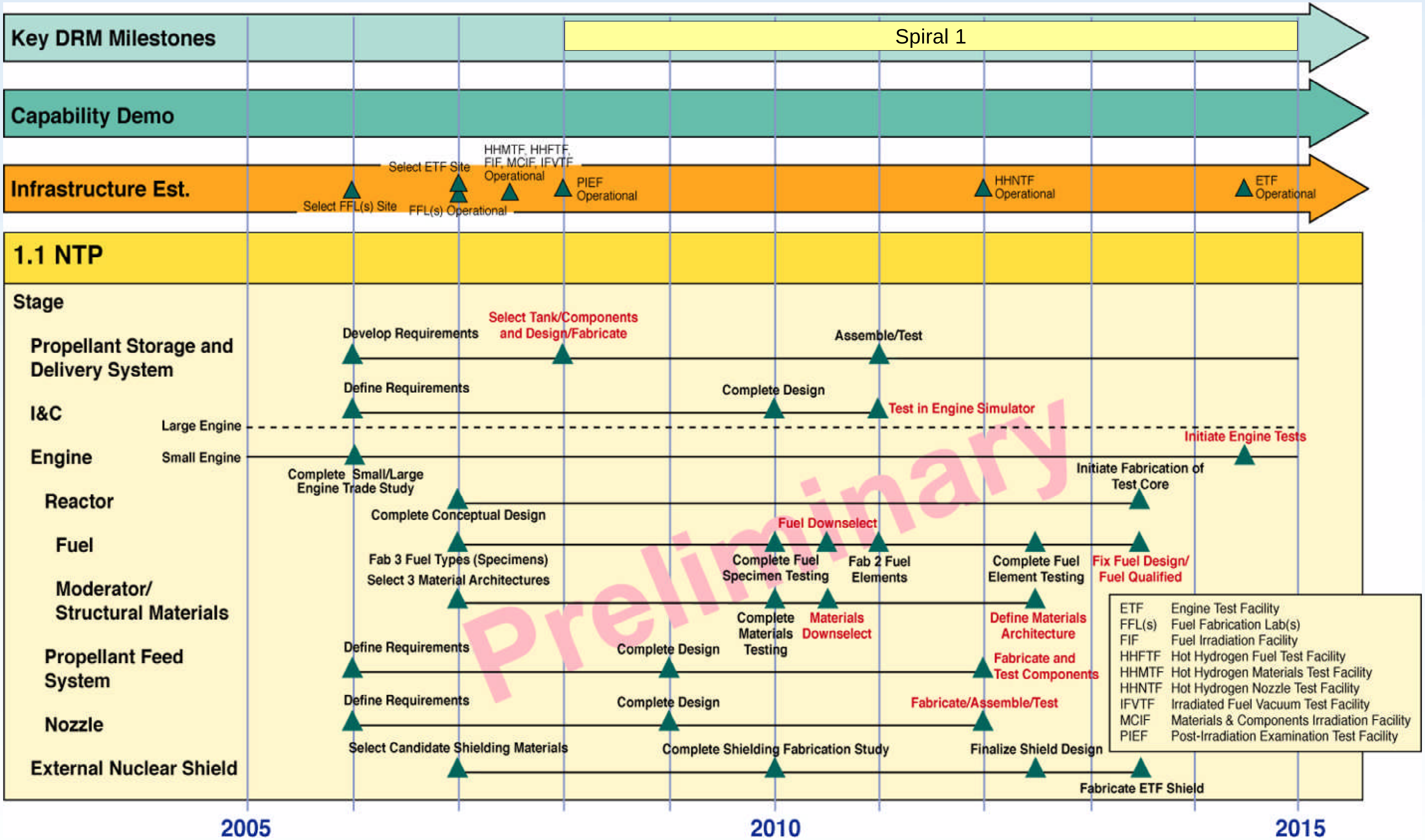
- Assumed Development Approach
  - Adapt Pewee engine design
    - Lower thrust
    - Adapt for water immersion sub-criticality
  - Utilize composite fuel
    - Adapt for acceptable fission product retention
    - Develop required coatings
    - Carry cermet fuel as backup
  - Nuclear furnace (NF) is not a precursor to first engine
    - Effort to qualify NF fuel refocused on qualification of engine fuel
    - Rely on expanded suite of separate-effects testing
    - Bypasses schedule and budget impacts of NF for initial mission
  - Ground test engines (developmental and flight)
    - Small engine may be testable in existing facilities
  - First flight
  - Post-flight Option: Build NF and expand fuels R&D as desired to enhance capability
    - Use fuel developed for first engine as NF driver fuel
- Use Strategy
  - Single non-human-rated engine for science and lunar cargo
  - Cluster non-human-rated engines for lunar or Mars cargo
  - Cluster human-rated engines for human Mars or asteroid exploration

NTP Capability Roadmap (2005–2015)



ETF	Engine Test Facility
FFL(s)	Fuel Fabrication Lab(s)
FIF	Fuel Irradiation Facility
HHFTF	Hot Hydrogen Fuel Test Facility
HHMTF	Hot Hydrogen Materials Test Facility
HHNTF	Hot Hydrogen Nozzle Test Facility
IFVTF	Irradiated Fuel Vacuum Test Facility
MCIF	Materials & Components Irradiation Facility
PIEF	Post-Irradiation Examination Test Facility

NTP Capability Roadmap (2015–2030)

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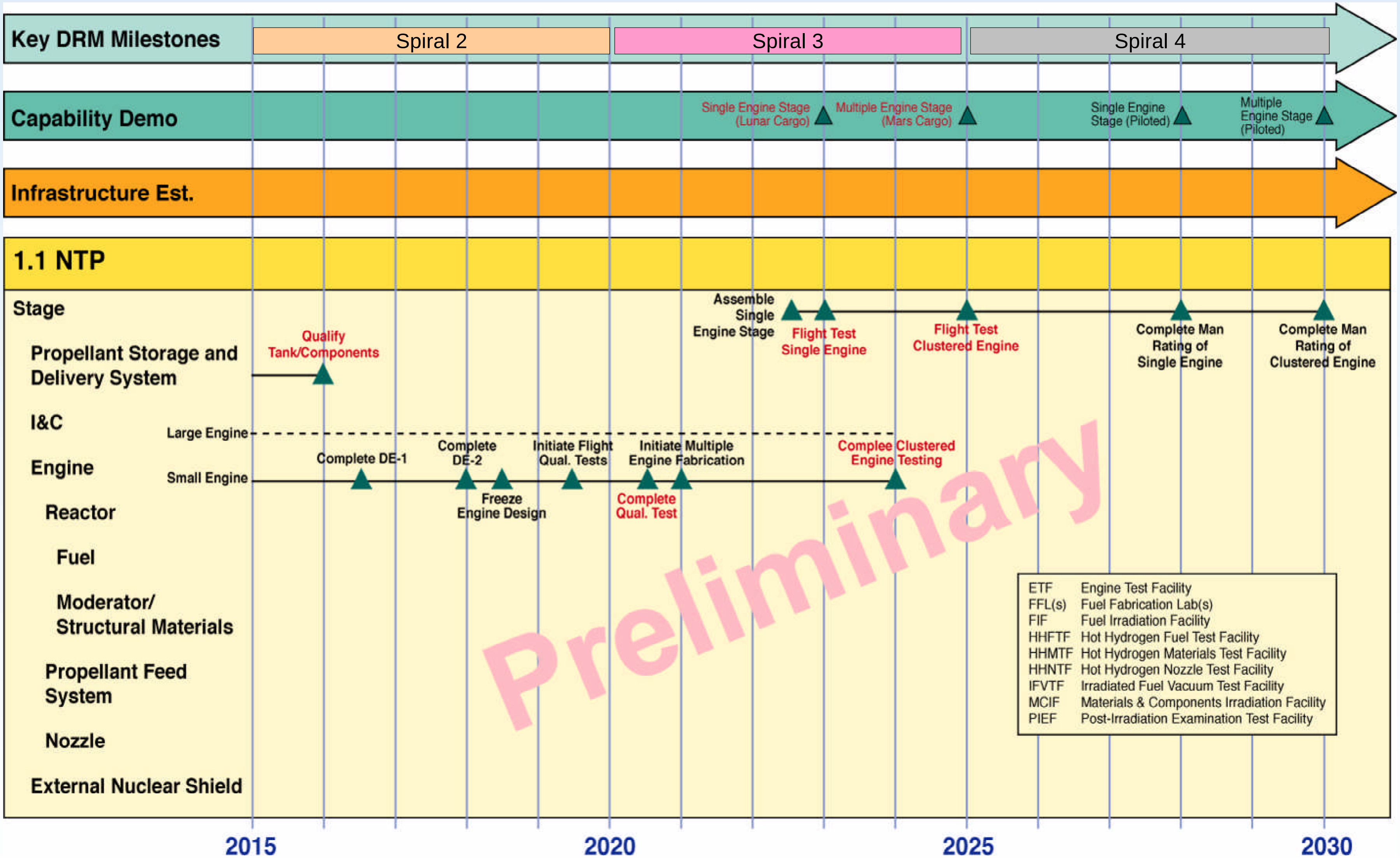

BNTP Capability Roadmap (2005–2015)

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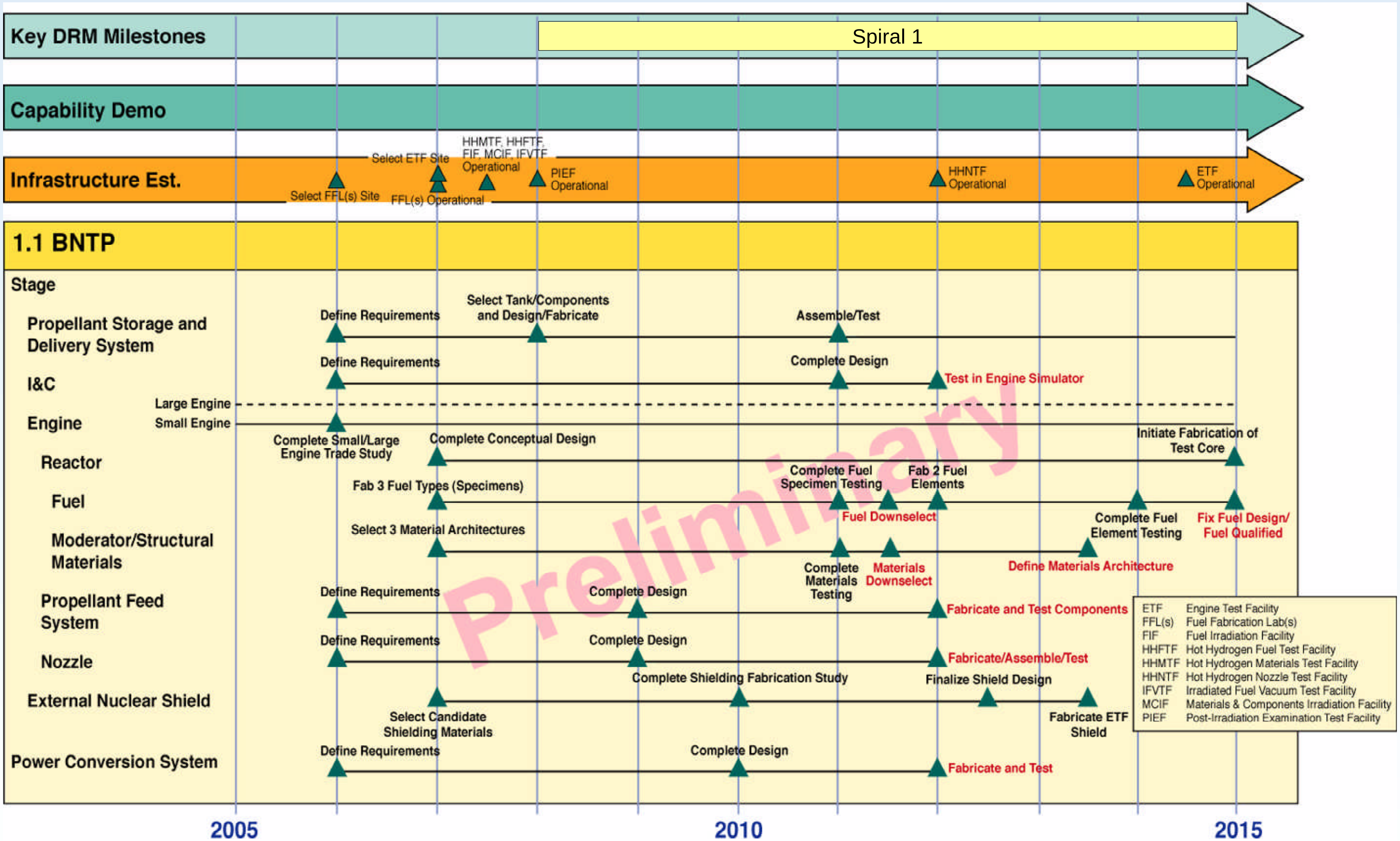
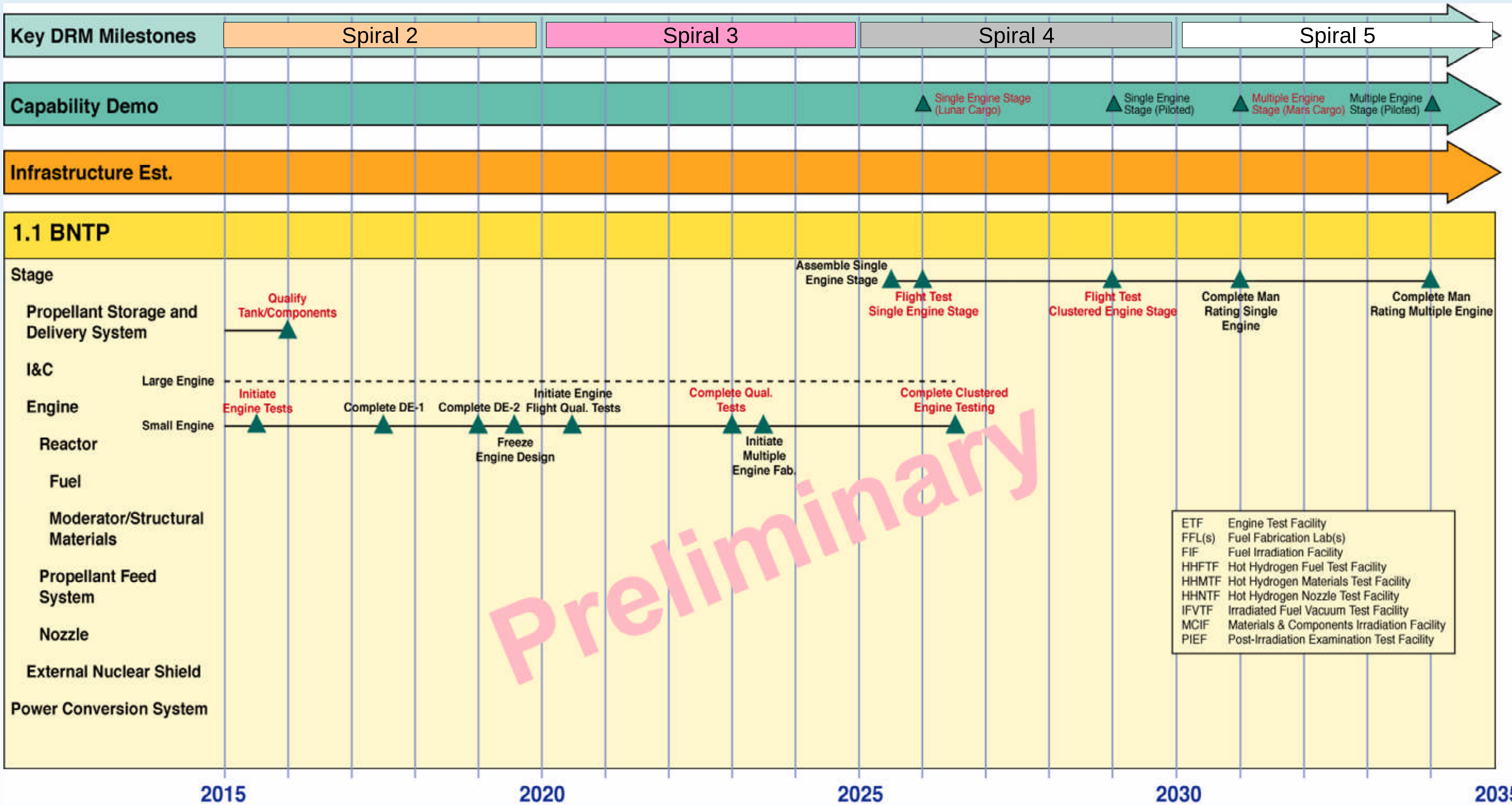


BNTP Capability Roadmap (2015–2030)



Summary

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- Fission power and propulsion enable/enhance key elements of VSE
- Fission surface power and propulsion systems can be available to support human exploration and science missions within timeframes envisioned by the VSE…
  - Spiral 3 (2020+) – Surface power & NTP cargo for long-duration human lunar missions
  - Spiral 4 (2025+) – NTP, BNTP, & NEP for cargo & piloted missions to Moon and Mars
  - Spiral 5 (2030+) – Surface power & NTP/BNTP/NEP for human Mars surface missions
- *IF* aggressive and sustained technology development efforts are initiated immediately…
  - Fuels
  - Materials
  - Shielding
  - Power Conversion
  - Power Management & Distribution (includes NEP Power Processing)
  - Heat Rejection
  - Propulsion
- Significant, but dated technology base exists
- Technology (knowledge and art) recapture will be a key
- Infrastructure development can pace technology development
- Opportunities exist to leverage technology investments

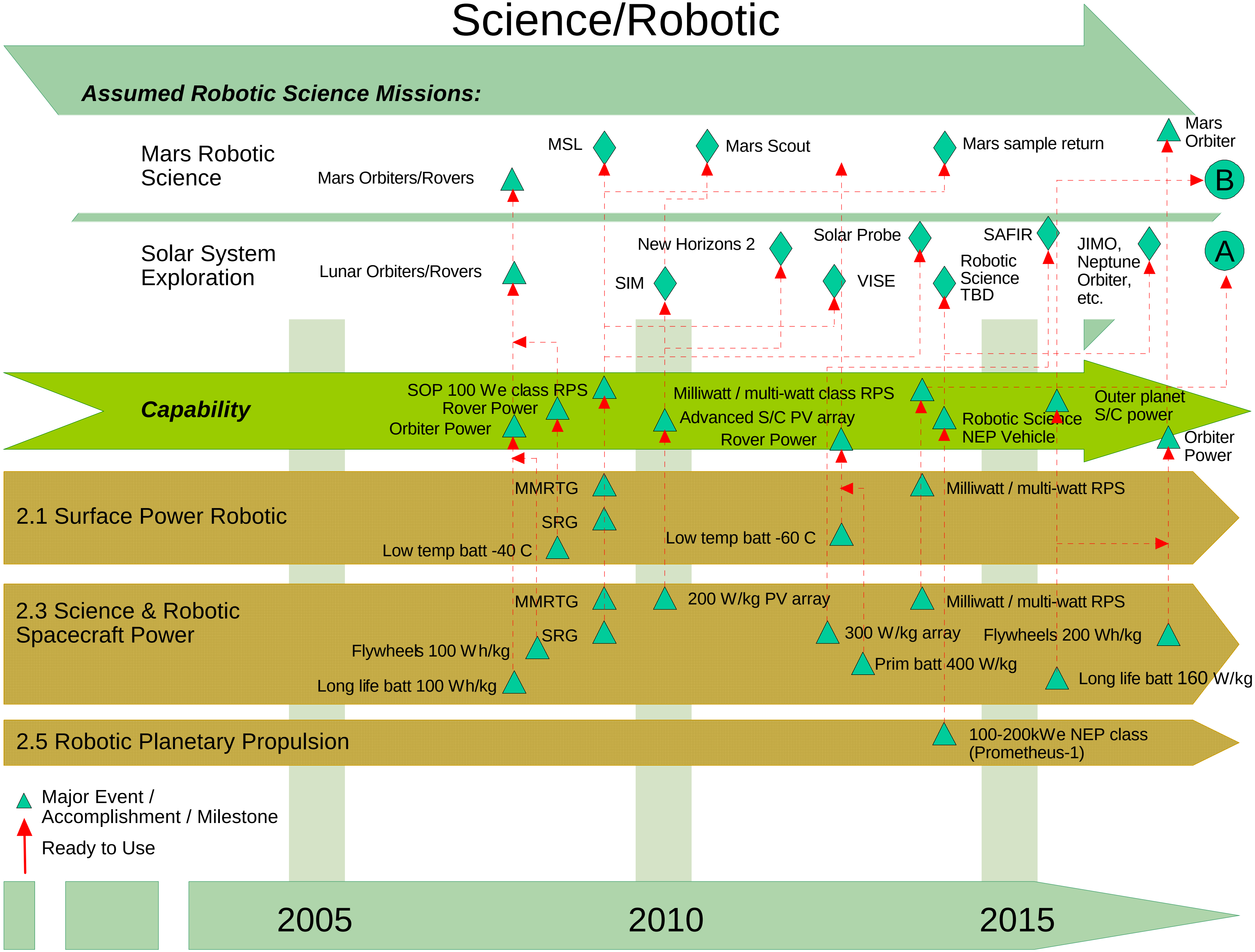
Concluding Charts

Joseph J. Nainiger, NASA Glenn Research Center, Chair

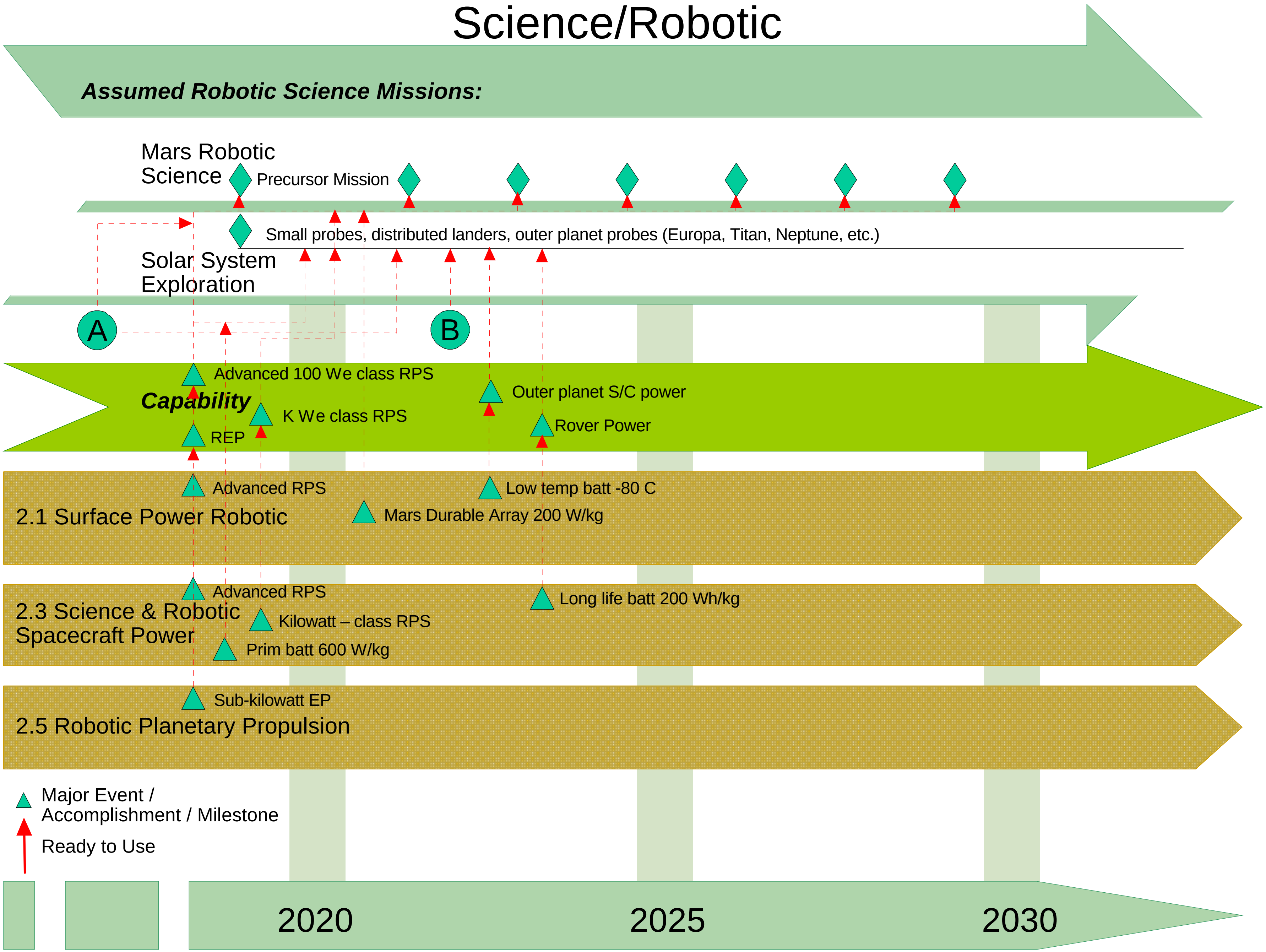
Disclaimer:
This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 Team members, and is not the official view of NASA or DOE.

Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap

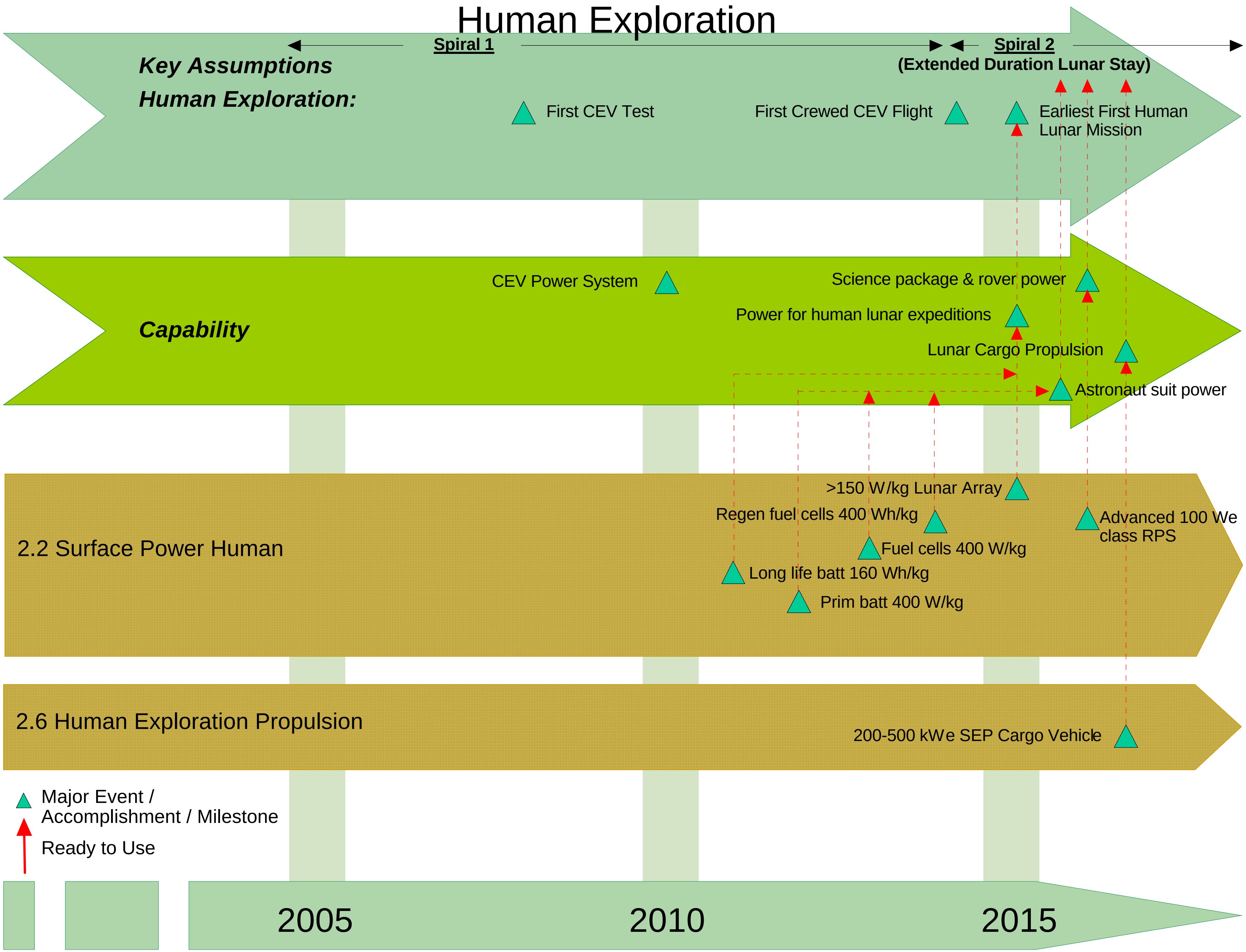
Science/Robotic



Capability Team 2: **High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap**

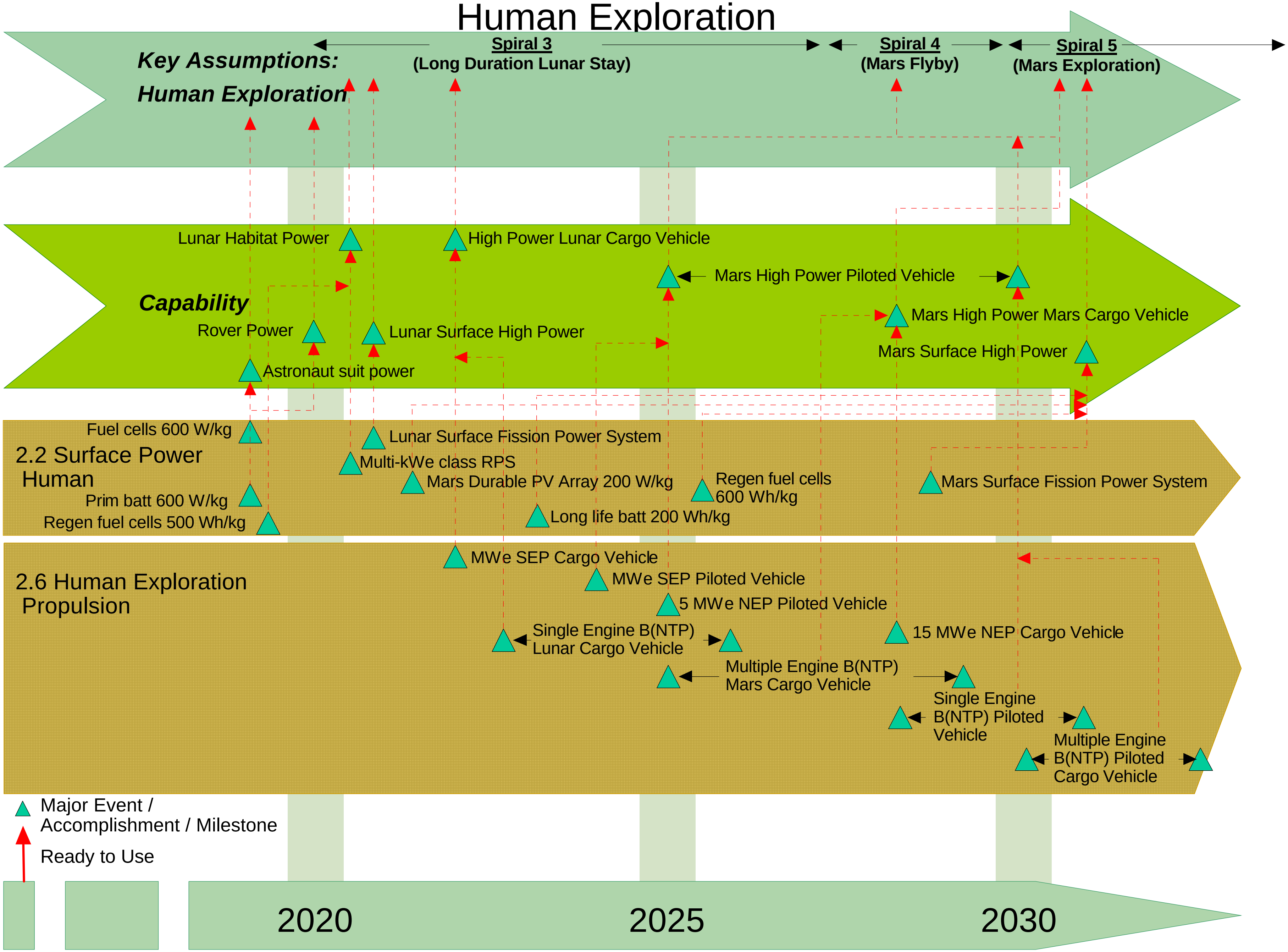


Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap



Capability Team 2: High Energy Power & Propulsion (HEP&P) Top Level Capability Roadmap

Human Exploration



HEP & P Capability Technical Challenges

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- Fission Systems
  - Infrastructure reestablishment (separate chart)
  - Technology capture (i.e., Rover, Nerva, SP-100…)
  - High temperature fuels and materials
  - Shielding
  - Autonomous control
  - Lifetime
  - Dynamic power conversion
  - Heat rejection
  - PMAD
  - High power thruster technology
  - Ground Testing (subsystems and systems)
- Radioisotope systems
  - Lightweight components (power conversion, heat rejection, PMAD)
  - High efficiency power conversion (reduce PU-238 cost)
  - Sub-kW electric propulsion sub-system
  - Infrastructure (separate chart)
- Solar Systems
  - Very large (100s of kWe to MWe), high specific power (300 to 500 W/Kg) solar arrays
  - Ground testing of very large, deployable arrays
  - Radiation resistant solar cells
  - High power thruster technology
- Energy Storage
  - Fuel Cells: Medium power PEM Fuel Cells, Regenerative fuel cells, Small fuel cells
  - Primary Batteries: High specfic energy, RAD hard Low temperature batteries
  - Secondary Batteries: High Specfic energy, Long Life, RAD Hard, Low Temp. Batteries
  - Fly wheels:

Infrastructure/Facility Needs

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- Fission Systems
  - Fuels and materials fabrication
  - Fuels & materials irradiation facilities
  - Physics criticals facilities
  - Ground test facilities
  - Fast-spectrum Test Reactors
  - Large EP thruster test facilities
  - Vehicle integration facilities
  - Launch site facilities
  - Fuel & reactor shipping & transportation facilities
  - Hot hydrogen test facilities
- Radioisotope Systems
  - Domestic production of Pu-238 (5 kg/year)
  - Increase purchase quantity of Russian PU-238 to supplement
  - Increase capabilities to assemble larger RPSs
- Solar Systems
  - Testing of large photovoltaic arrays
  - Large EP thruster test facilities
- Energy Storage Systems

HEP & P Capability Crosswalk

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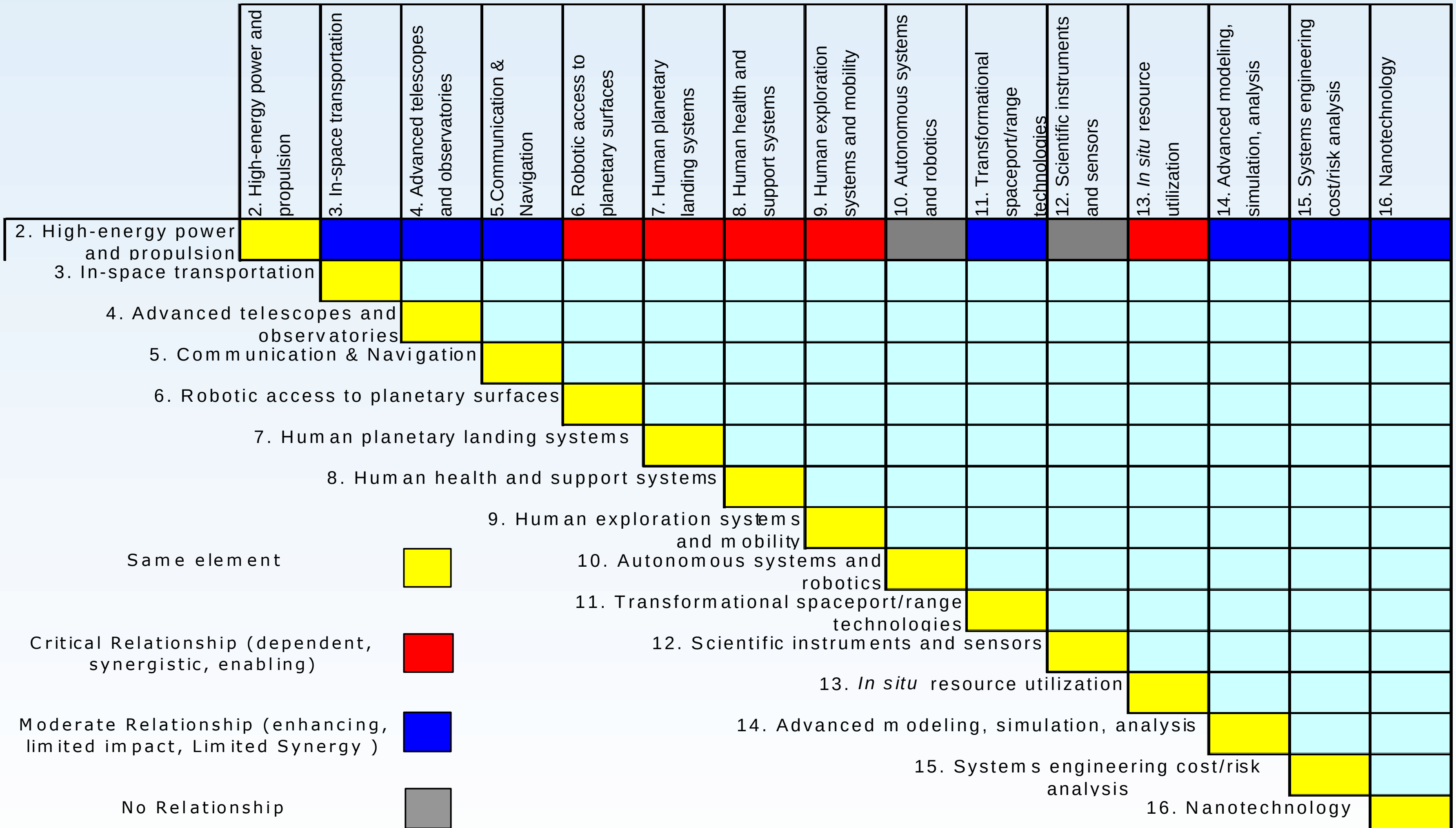

Concluding Remarks

- The High Energy Power and Propulsion (HEP & P) Roadmap Team has been pleased to present to the NRC panel our interim roadmap results to date
- We have addressed the four questions given to this panel for evaluation, i.e.,
  - Do the capability roadmaps provide a clear pathway to (or process for) technology and capability development?
  - Do the capability roadmaps have connection points to each other when appropriate?
  - Are technology maturity levels accurately conveyed and used?
  - Are proper metrics for measuring the

Summary/ Forward Work

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- Adjust roadmaps as appropriate based on verbal feedback from NRC review
- Initiate more interaction with other Capability Roadmap Teams to exchange capability requirements and data
- Receive the draft Strategic Roadmaps
- Review and assess all applicable Strategic Roadmaps and their requirements for HEP & P capability
- Adjust HEP & P roadmaps as appropriate to ensure consistency with Strategic Roadmaps requirements
- Develop rough order of magnitude cost estimates for the HEP & P Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Backup Slides for Introduction and Conclusion For CR-2

Click to add subtitle

HEP & P Capability Roadmap Process and Approach – Initial Requirements

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- Each sub-team has been given the same set of initial requirements from which more detailed requirements will be determined
    - Lunar Roadmap Framework: Short Stay
    - Lunar Roadmap Framework: Long Stay
    - Lunar DRM TP2001
    - Lunar Robotic Science DRM
    - Mars Roadmap Framework
    - Mars FY03 NEP Architecture
    - Mars NASA SP2
    - Mars NASA SP-6107
    - Mars TP 2002
    - Mars Robotic Science DRM
    - Outer Solar System Science DRM

HEP & P Relevance

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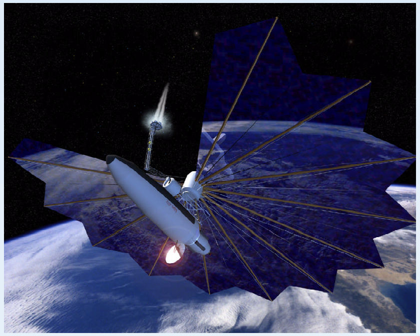
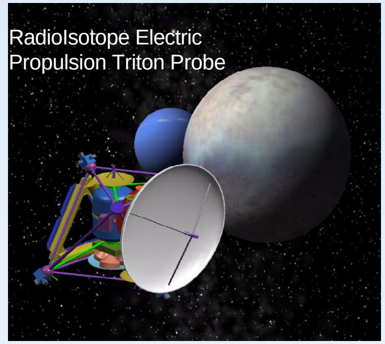
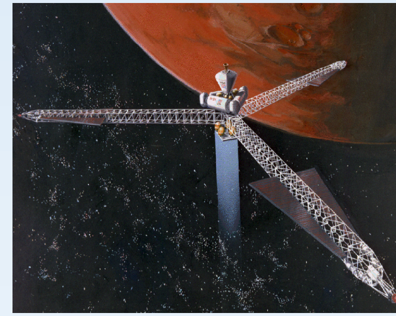
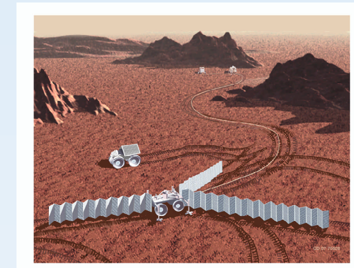


SEP/Chemical Mars Transport Stage



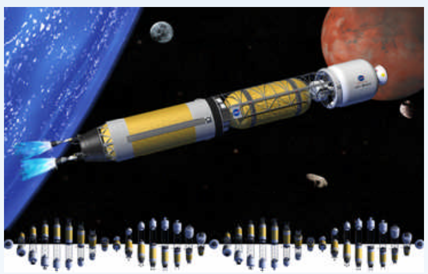


15 MWe NEP Mars Piloted Vehicle

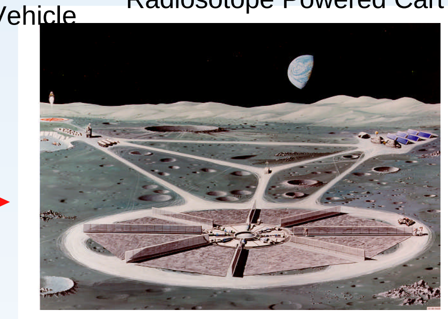


Nuclear Fission Mars Power System
Radiosotope Powered Cart

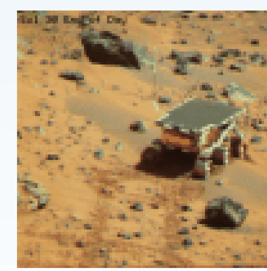
High Energy Power
& Propulsion



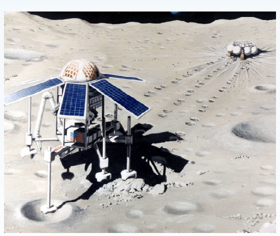
Nuclear Thermal Propulsion
Piloted Vehicle



Nuclear Fission Lunar Power System

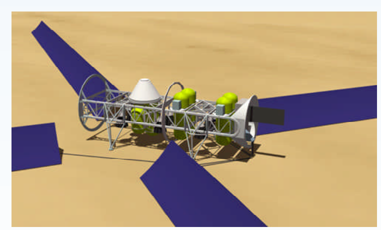


Photovoltaic Powered Mars Rove



Photovoltaic Powered Robotic
Lunar Lander

Radioisotope Powered
Deep Space Probe



Photovoltaic Mars Power System

Additional Assumptions

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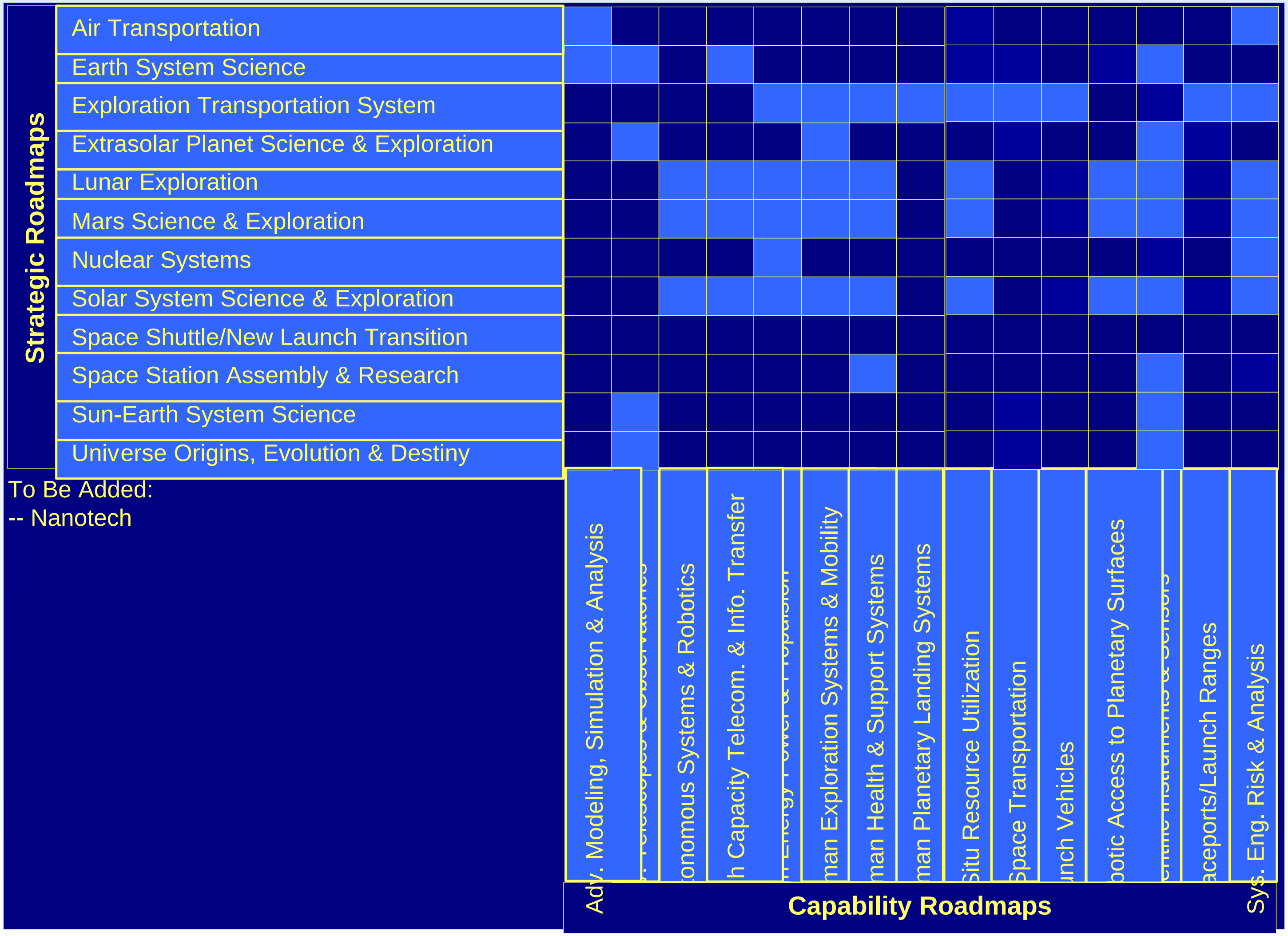
- The Spiral definitions given by ESMD were used as a basis for implied power and propulsion requirements/needs for human exploration
- Develop a human-rated lunar fission power system that is extensible to Mars for long-duration missions
- The current NASA Prometheus Nuclear Program has initiated preliminary technology development in advanced power conversion and electric propulsion
- Roadmap activity will highlight the need for capability choices/decisions without actually making those decisions
- Although cognizant of cost/budget issues, the team has not yet prioritized developments based on budget
- Multi-hundred kW to MW size space solar arrays are achievable

Strategic/Capability Relationship Example



HEP & P Connection Points with Other Capability Roadmaps

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High Energy Power and Propulsion	Capability Flow and Criticaltiy	Related Roadmap	Nature of Relat
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
		Human Exploration Systems &	
Surface Power (PV/Radioisotope)	→ (red)	Crew Mobility/Surface rovers	Power sources requ crew surface rovers
Surface Power (PV/nuclear fission)	→ (red)	In-Space Assembly Large & Intermediate Scale Assy	High Power needec cranes, tools, etc.
Component Technologies/PMAD	→ (blue)	In-Space System Deployment Electrical & Data Interconnects	Power managemer distribution equipm
		In Situ Resource Utilization	
Surface Power (PV/nuclear fission)	→ (red)	Resource Extraction; excavation, drilling, etc. Resource Processing; consumable(O2), fuel, feedstock, etc. production In situ manufacturing	All of these ISRU pr will depend upon hi power/enegry sourc
		Human Health & Support Systems	
Component Technologies; Batteries, PMAD	→ (blue)	Life Support & Habitation; EVA(Portable Life Support Systems)	Advanced batteries power supplies
Surface Power(PV/nuclear fission)	→ (red)	Life Support & Habitation; Advanced life support, habitats	High power system needed to support h activities
		In-Space Transportation	
Component Technologies: Fuel tanks & ancillary components, guidance & nav, avionics, vehicle health management	→ (blue)	All Human & Robotic Earth, lunar, and planetary ascent and descent stages	Advanced technolo components will enh may enable In-Spac Transportation capa
		Nanotechnology	
Component Technologies	← (blue)	Advanced Nano-Scale Materials & Concepts for Nano-Scale Devices; Nano-to-Micro Systems Integration	Battery electrode m quantum dot PV, etc

HEP & P Connection Points with Other Capability Roadmaps (continued)

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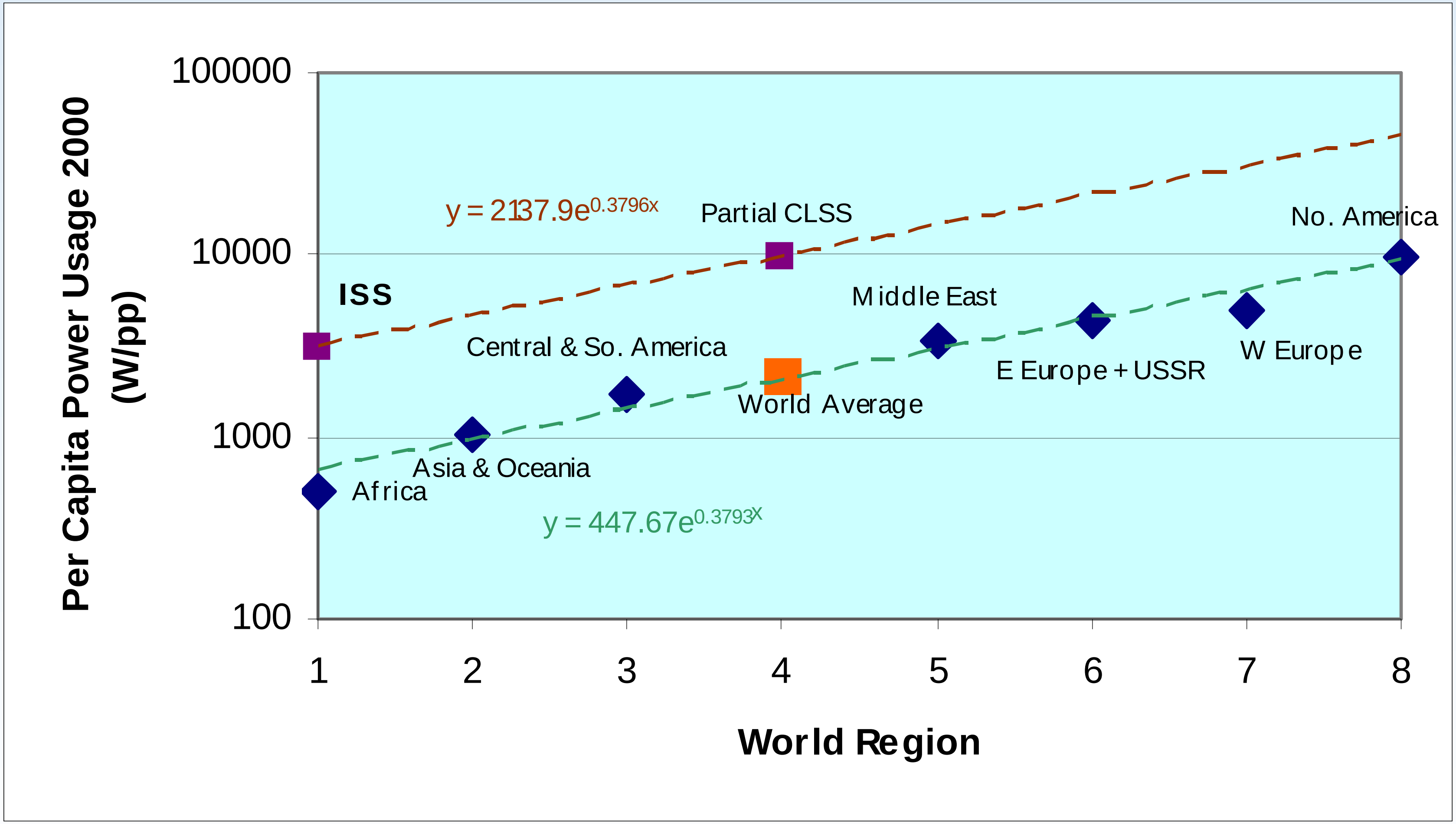
		Robotic Access to Planetary	
Surface Power (PV/Radioisotope)	→ (red)	Surface Access: Mobility	Power sources requ surface rovers, clim
Surface Power (PV/Radioisotope)	→ (red)	Surface Material Access and Processing	Power for drilling, c sample acquisition, transfer.
Component Technologies (PV, GPHS, batteries, PMAD)	→ (red)	Aerial Systems	Power for planes, g balloons, etc.
		System Engineering Cost/Risk	
All Sub-topics in High Energy Power & Propulsion	← (blue)	All system engineering sub-topics.	All elements of syst engineering can be to conceptual decis design, developme cost & risk analyses
		Communications & Navigation	
Component Technologies/PMAD	→ (blue)	All communications systems types; power supplies	High efficiency pow are often needed fo performance comm
High Eneryg Propulsion Systems/Guidance & Nav	← (red)	Comm/navigation	Comm system play in nav.
		Advanced Telescopes &	
Component Technologies (solar cells, photovoltaic arrays, energy storage,thermal heat rejection, power management and distribution, material and structures, guidance and Nav, avionics...)	→ (blue)	Filled aperture systems, interferometers, formation flying, microwave systems, gravity wave observatories	All advanced telesc observatories requi component technolo described. Future v systems will require power capabilities. technologies in thes would be enhancing
		Transformaitonal Spaceport/Range Technologies	
Surface Nuclear Fission Power Systems High Energy Nuclear Electric & Nuclear Thermal Propulsion Systems	↔ (blue)	Vehicle-Independent Spaceport System Capabilities; Advanced Servicing Systems, Rapid Transportation, Handling & Assembly, Inspection & System Verification Integrated Space- & Ground-based Range System Capabilities; Decision	New/large nuclear s may require new sp capabilities.
Red – Critical Blue – Moderate			

Backup Charts For Solar Systems

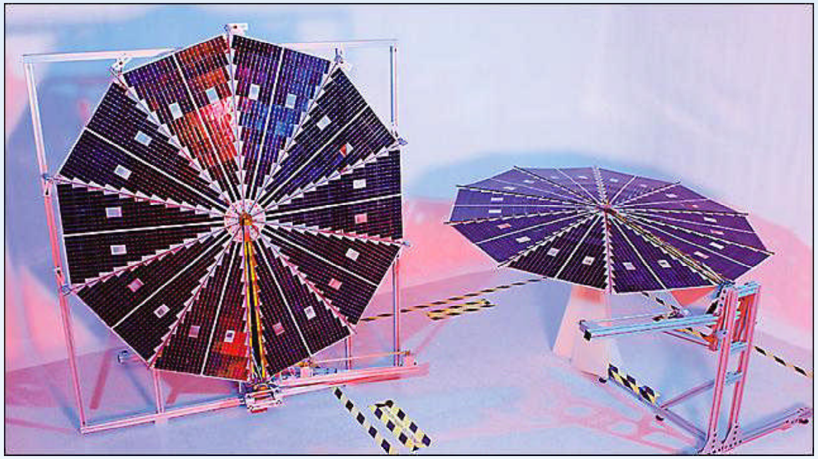
Power Needs for Humans in Space

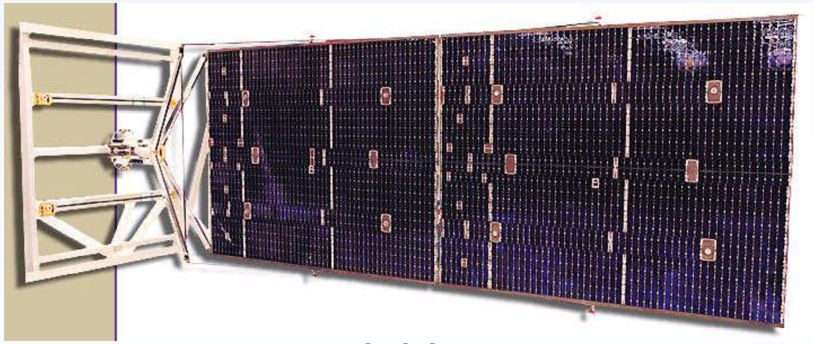


Solar arrays

Teledesic Solar Array

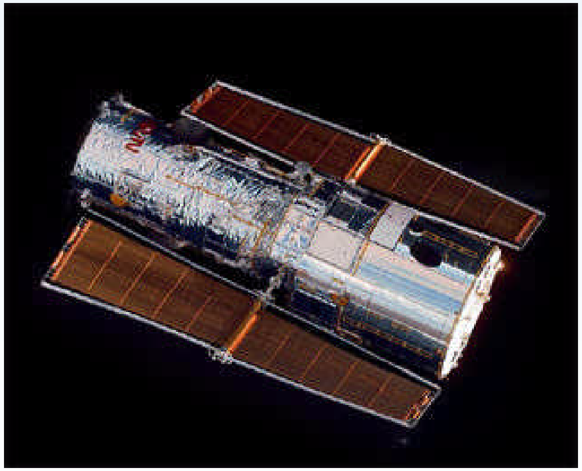
Ultraflex Array





PUMA rigid array

Hubble Space Telescope



Capability for Exploration Propulsion

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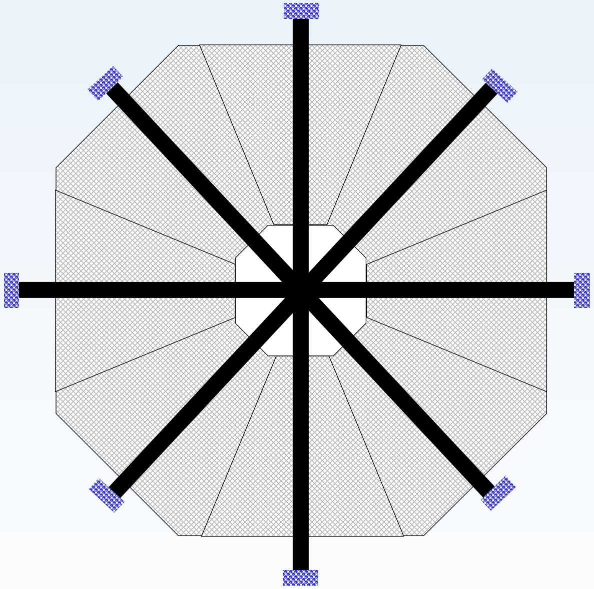
- **SEP Lunar Cargo Vehicles**
  - 0.1 - 1 MWe Spacecraft power (dependent on payload mass)
  - 50 - 100 kW versions of SOA thruster concepts (Hall/Ion)
  - Near term solar arrays (500 W/kg)
  - 200 kW advanced array comparable in size to ISS arrays
  - • 1 year round trip, reusable
- **SEP Mars Transportation Vehicles**
  - 2 - 10 MWe envisioned for Lunar/Mars Applications
  - 500 kW - MW thrusters (Hall/Ion/Advanced)
  - Advanced solar arrays (1000 W/kg)
  - Large, lightweight deployable structures
  - ~ 2 year trip time, possible reuse

0.5 MWe SEP Mars Cargo (1999)*



5 MWe SEP concept (1990) 30,000 m^2*

**** Not to Scale***

Backup Charts for Energy Storage Systems

Future Mission Requirements for Capability Area: Energy storage

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Category	Mission Type	Driving Requirements	SOP Capability	Challenge
Human Exploration Missions	Lunar/Mars Surface Mission: Habitat/Outposts	Very High (MWh) energy Storage Capability & High Specific Energy (>500 Wh/kG)	Hundreds of Kwh 30-90 Wh/kg	10X Energy storage capability 5-10 X Higher Specific Energy
Human Exploration Missions	EVA: Suit, Astronaut Equipment	Very High Specific Energy Rechargeable Battery/Fuel Cell (> 300 Wh/kg) with Long Life	100 Wh/kg with six month operational life	3x Higher specific energy Longer life
Human Exploration Missions	Crew Transportation Vehicle: CEV	High power (5-30 kW), Low Mass (> 200 W/kg) and Low Maintenance Fuel Cells, 5000 hours Operating life	10 kW, 90 W/kg alkaline fuel cells that require periodic maintenance(2600 hours)	2-3 X Hgher specific power Long Life
Robotic and Human Exploration Missions	Solar powered surface missions: Rovers, Landers	High Specific Energy (>200 Wh/kg) rechargeable batteries with low temperature operational capability (<-80 C)	-20 C rechargeable batteries (70 Wh/kg)	2X Higher specific energy Very low temperature operation
Robotic Exploration Missions	Outer Planetary Probes and sensor networks	Low mass and compact primary batteries(500 Wh/kg) with low temperature operational capability (<-80 C)	-20 C primary batteries (150 Wh/kg)	2-3 X Higher specific energy Long life, Very low temperature operation
Robotic Exploration Missions	Orbital Spacecraft: Earth Orbiters. Planetary Orbiters	Low mass (> 100 Wh/kg) rechargeable batteries with Long Life Capability (>20 years), •Radiation resistance (5-20 M Rads)	30 Wh/kg with > 15 year life	2-3 X Higher specific energy Long life Rad hard
Robotic Exploration Missions	Inner Planetary Probes	High Temperature Primary and Rechargeable Batteries (400 C)	0-60 C	High Temperature operation

Candidate Advanced Storage Systems and Capability Readiness Levels of SOA Systems

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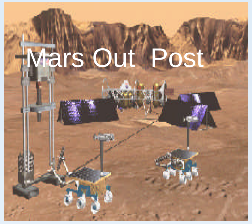
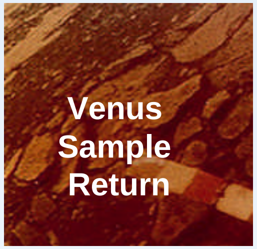
Mission Type	Driving Capability Requirements	Candidate Adv. Technology	Current CRL	Required Date for CRL3
Lunar/Mars Surface Missions: Habitat /Out Posts	MWh energy Storage Capability	Regenerative Fuel Cells Fly Wheels	2	2015
EVA: Suit, Astronaut Equipment	Low mass and compact rechargeable energy storage system (> 300 Wh/kg)	Adv Rechargeable Batteries Small Fuel cells	2	2015
Crew Transportation Vehicle: CEV	High power (20-40 kW) Low Mass (> 200 W/kg) Low Maintenance Fuel Cells	PEM Fuel Cells and Advanced Hydrogen and Oxygen Storage	2	2010
Solar powered surface missions: Rovers, Landers	Low mass(>150 Wh/kg) rechargeable batteries with low temperature capability (<-80 C)	Adv Li rechargeable Batteries	2	2012, 2015
Outer Planetary Probes and sensors	Low mass (> 500 Wh/kg) and compact primary batteries with low temperature operational capability (<-80 C)	Advanced Li rimary batteries	2	2010, 2015
Orbital spacecraft: Earth orbiters, Lunar Orbiters, Planetary Orbiters	Low mass (> 150 Wh/kg) rechargeable batteries with Long Life Capability (>20 years), •Radiation resistance (5-20 M Rads)	Adv. Li-Ion/Li-Polymer Rechargeable Batteries	2	2010-2015
Inner Planetary Probes	High Temperature Primary and Rechargeable Batteries (400 C)	High Temperature Na/Li Batteries	1	

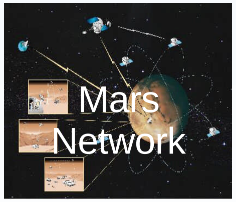
Summary of Energy Storage Technology Needs of Robotic Science Missions

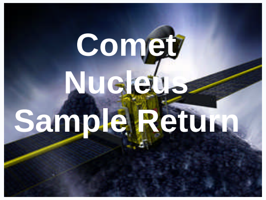
Advanced Planning & Integration Office

- Low temperature primary(<-100°C) and rechargeable (<-60°C) batteries for planetary probes and mars surface missions
- High temperature batteries (> 475 °C) for inner planetary missions
- Long calendar life (>15 years), high specific energy (>120 Wh/kg) & radiation tolerant rechargeable batteries for outer planetary missions
- Long cycle life (>30,000 cycles) and high specific energy (>120 Wh/kg) rechargeable batteries for Mars and earth orbital SEC, SEU & origins missions
- High specific energy primary batteries (>500 Wh/kg) for comet/asteroid probes









Characteristics of SOP Primary Batteries

Type	Application	Mission	Specific Energy, Wh/kg (b)	Energy Density, Wh/l (b)	Operating Temp. Range, °C	Mission Life (yrs)	Issues
$Li\text{-}SO_2$	Cell		238	375	-40 to 70	<10	Voltage Delay
	Battery	Galileo Probe Genesis SRC MER Lander Stardust SRC	90-150	130-180	-20 to 60	9	
$Li\text{-}SOCl_2$	Cell		390	878	-30 to- 60	>5	Severe voltage delay
	Battery	Sojourner Deep Impact DS-2 Centaur Launch batteries	200-250	380-500	-20 to 30	< 5	
$Li\text{-}CF_x$	Cell		614	1051	-20 to 60		Poor power capability

Limitations

- Moderate specific energy (100-250 Wh/kg)
- Limited operating temp range (-40 C to 70°C)
- Radiation tolerance poorly understood
- Voltage delay

Characteristics of SOA Primary Batteries

Advanced Planning & Integration Office

Type	Application	Voltage (a)	Specific Energy, Wh/kg (b)	Energy Density, Wh/l (b)	Specific Power, W/kg (c)	Operating Temp. Range, °C	Capacity Loss % Per Year	Mission Life (yrs)	Manufacturer	Configuration
Ag-Zn	Cell	1.61	200	550	1100	0-55	60	1	Yardney	Prismatic
	Typical Launch Vehicle	28	119	283	118	5 to 40	60	1	Eagle Picher	Manually Activated
Li-SO_2	Cell	2.9	238	375	682	-40 to 70	<2.5			Cylindrical
	Galileo Probe Battery	38	91	147	261	-15 to 60	<2.5	9	Alliant Tech	Three 13 cell batteries
	Genesis Battery	24	142	127	402	-20 to +30	<2.5	6	SAFT	Two 8 cell batteries
	MER	30	136	388	390	0 to 60	<2.5	5	SAFT	Five 12 cell batteries
	Stardust	20	192	182	519	-26 to +50	<2.5	10	SAFT	Two 8 cell batteries
Li-$SOCl_2$	Cell	3.2	390	878	139	-30 to- 60	<1			Cylindrical
	Sojourner	9	245	514	102	-20 to 30	<1	5	SAFT	Three 3 cell batteries
	Deep Impact	33	221	380	106	-20 to +30	<1	4	SAFT	Three 13 cell batteries
	DS-2	14	128	339	64	-80 to +30	<1	4	Yardney	Two 4 cell batteries
	Centaur Launch batteries	30	200	517	83	-20 to +30	<1	6	Yardney	One 9 cell batteries
Li- BCX	Cell	3.4	414	933	148	-40 to 70	<2		Wilson GB	Cylindrical
	Astronaut Equipment	6	185	211	115	-40 to +72	<2	3	Wilson GB	2 cell radio batteries
Li-CF_x	Cell	2.6	614	1051	15	-20 to 60	<1		Eagle Picher	Cylindrical DD
	Range Safety battery	39	167	149	14	-20 to 60	<1		Eagle Picher	15 Cell Battery

Characteristics SOP Rechargeable Batteries

Advanced Planning & Integration Office

Technology	Mission	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Design life, Years	Cycle life	Issues
Ag-Zn	Pathfinder Lander	100	191	-20 t0 25	2	100	Electrolyte Leakage Limited Life
Ni-Cd	Landsat, TOPEX	34	53	-10 to 25	3	25-40K	Heavy Poor Low Temp. Perf.
Super Ni -Cd	Sampex Battery, Image	28-33	70	-10 to 30	5	58K	Heavy Poor Low Temp. Perf
IPV Ni-H_2	Space Station, HST, Landsat 7	8-24	10	-10 to 30	6.5	>60K	Heavy, Bulky Poor Low Temp. Perf
CPV Ni-H_2	Odyssey, Mars 98 MGS, EOS Terra Stardust, MRO	30-35	20-40	-5 to 10	10 to 14	50 K	Heavy, Bulky Poor Low Temp. Perf
SPV Ni-H_2	Clementine, Iridium	53-54	70-78	-10 to 30	10	<30 K	Heavy Poor Low Temp. Perf
Li-Ion	MER-Rover	90	250	-20to 30	1	>500	Limited Life

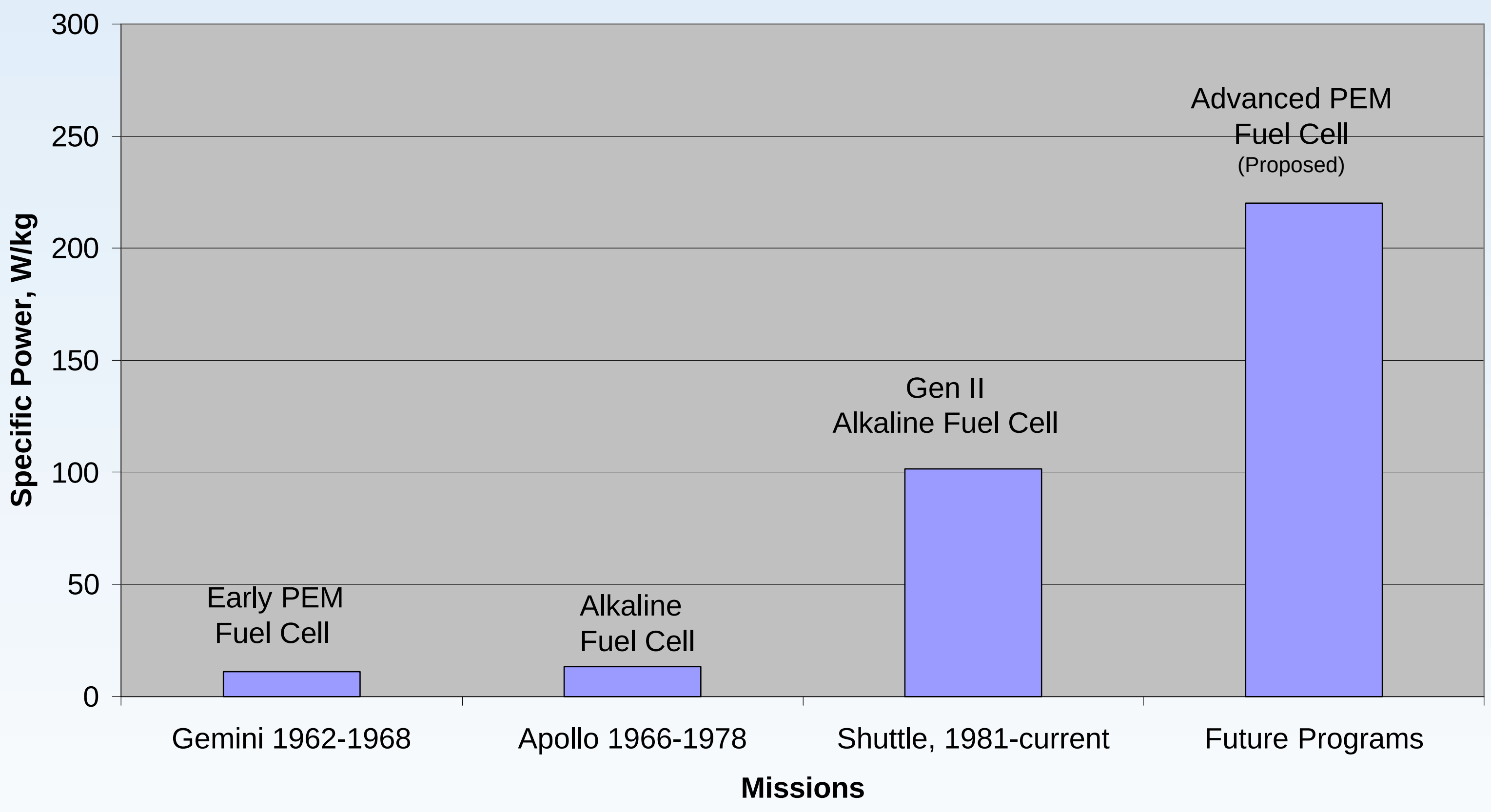
Limitations of Ni-Cd & Ni-H2 batteries:

- Heavy and bulky
- Limited operating temp range (-10°C to 30°C)
- Radiation tolerance poorly understood.

Characteristics of Rechargeable Batteries

Technology	Use	No of Batteries / Cells in Bat	Ah Rated/actual	Operating Voltage	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Design life, Years	Cycle life to Date	Manufacturer
Ag-Zn	Cell	1	40/58	1.5	128	248	-20 to 25			BST
	Pathfinder Lander	1/18	40/58	27	100	191	-20 to 25	2	100	Yardney
Ni-Cd	Standard 50 Ah	1	50/62	1.25	37	111	-20 to 25	3		Gates
	Landsat	3/22	50 /60	22-36	34	53	-20 to 26	3	25K	MDAC
	TOPEX	3/22	50/60	22-36	34	53	-10 to 30	3 to 5	40K	MDAC
Super Ni-Cd	9 Ah Cell	1	9/12	1.25	31	93	-20 to 30	15		EPI
	50 Ah Cell	1	50/63	1.25	32	100	-20 to 30	15		EPI
	Sampex Battery	1 /22	9/12	28	28	72	-20 to 30	5	58K	EPI
	Image	1/ 22	21/24	28	33	71	-20 to 30	5	14K	
IPV $Ni-H_2$	IPV Cell	1	98/83	1.25	48	71	-10 to 30		10	EPI
	Space Station	6/76	81/93	48	24	8.5	-10 to 30	6.5	11K	Boeing
	HST	6/22	80/85	28	8	4	-10 to 30	5	65K	EPI
	Landsat 7	2/17	50 / 61.7	24			-10 to 30	5	>50K	LMAC
CPV $Ni-H_2$	CPV Cell	2	16/17.5	2.50	43.4	77	-10 to 30	10		EPI
	MIDEX MAP	1/11	16/17.5	28	36	21	-10 to 30	5	50K	
	Odyssey	2/11	16/17.5	28	36	21.1	-3 to 8	10 to 14	1K	LMAC
	Mars 98	1/11	16/17.5	29	37	41	5-10	3		LMAC
	MGS	2/16	20/23	20	35	25	5-10	1 Mars Yr	50K	LMAC
	EOS Terra	2/54	50/	67		21	-5 to 10	5		
	Stardust	1/11	16/17.5	28	36	21	-5 to 11	7	1135 days	LMAC
SPV $Ni-H_2$	SAR 10065	1/12	50/60	28	54.6	59.3	-10 o 30	10		JCI/EPI
	Clementine	1/22	15/18	28	54.8	78	-10 to 30	200 cycles	200 cycles	JCI/NRL
	Iridium	1/22	60/70	28	53.4	67.7	-20 to 30	3 - 5	50K	JCI/ EPI
Li-Ion	Cell	1	8.6/10	4.0	133	321	-20 to 30	1		Yardney
	MER-Rover	2/8	16-20	28	90	250	20 to 30	1	n/a	Yardney

Characteristics of Fuel Cells



Fuel Cells In Space

Advanced Planning & Integration Office

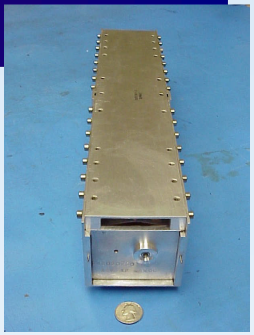
Type	Gemini	Apollo	Shuttle
No. Flights	7 (#5 -12)	All	All
Manufacturer	General Electric	Pratt & Whitney	United Technologies
Type	PEMFC	AFC	AFC
Fuel Cell Modules	3 - 350 W	3	3
Peak Power	1 kW	2.3 kW	36 kW
Power Module (continuous)	500 -620 W	1.5 kW	14 kW
Cell temperature (°C)	40 to 60	200 -250	83 - 105
Voltage	23.3 - 26.5V	26 - 31 V	26.5 - 32.5V
Fuel Cell Stack Mass	31	110	91
H_2 Storage pressure	210 to 250 psi	245 psi	290 -290 psi
O_2 Storage pressure	800 psi	900 psi	850 -950 psi
Electrolyte	Sulfonated polystyrene	85% KOH	30 - 40 % KOH
Efficiency	50 – 60%	60%	61.8% @6 kW
Service life	400 - 800 Hrs @ 0.5kW	400 -1500 Hrs @ 1kW	2000 Hrs @ 4.5 kW
Time in Space	840 Hrs	1995 Hrs	Serviced 2000Hrs

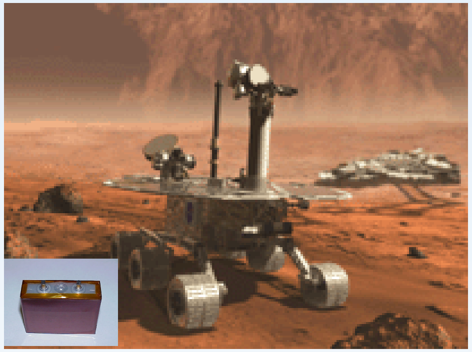
Characteristics of SOA Alkaline Fuel Cells

Advanced Planning & Integration Office

Characteristic	Alkaline Fuel Cell
Specific Power, Watts/kg Power Density, Watts/liter	90 155
Efficiency	70%
Maintenance frequency	Every 2600 h
Differential Pressure Limit	41 kPa
Operating Temperature	90^{o}C
Failure Mechanisms	Attack of epoxy frames and Noryl insulator plates by KOH.

Li-Ion Batteries





Technology Status

- **Small capacity cells & batteries are being used in several commercial applications(> 100 Wh/kg, <500 cycles)**
- **Work in progress to develop cells and batteries for aerospace & DoD applications**
  - **Low temperature (-20 C) & limited cycle life (1000 cycles) batteries developed and qualified for Mars surface missions (TRL 8-9)**
  - **Technology infused to Mars surface missions (Spirit and Opportunity rovers)**
  - **Batteries under qualification for aircraft applications**
- **TRL: Long life batteries (3-4), -60 C batteries (2-3)**

Mission Benefits

- **Enabled MER (3-4 X mass and volume savings, -20 C)**
- **Outer planetary orbiters/fly-by (Mass and volume)**
- **Mars/Earth orbiters (Mass and volume)**
- **Mars surface missions(Low temp.operation)**

Technical Issues

- **Limited Cycle Life**
- **Limited Calendar Life**
- **Safety**

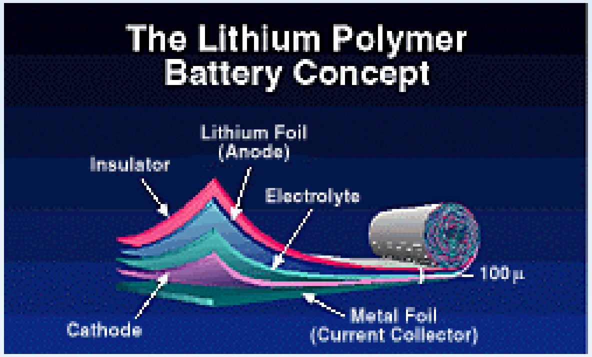
Potential Capabilities

Battery Level:	SOA Li -Ion	Adv. Li-Ion
Specific Energy (wh/kg)	90	200
Energy Density (wh/l)	180	400
Cycle Life (30% DOD)	15 K	> 30 K
Calendar Life (years)	3	> 15
Operating Temperature	-20 to 30	-60 C to 60 C

Li-Polymer Batteries

Technology Status

- Two types: Gel Electrolyte, Solid Polymer
- Gel polymer electrolyte batteries in use in commercial applications(> 120 Wh/kg, <500 cycles). Similar to Li-Ion batteries
- True solid polymer electrolytes under development
  - SOA electrolytes: 10^{-5} S/cm (Goal : 10^{-3} S/cm)
  - TRL: (1-2)



Advantages

- **Mass and volume savings (4-5 X Vs SOP)**
- **Long Life (> 15 years)**

Mission Benefits

- Outer planetary orbiters/fly-by (mass & volume)
- Mars/Earth orbiters (mass & volume)

Technical Issues

- Poor electrolyte conductivity
- Hermetic sealing of cells
- Life

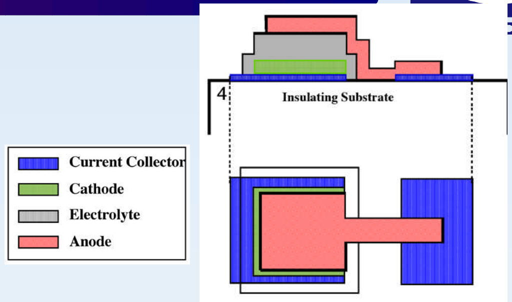
Potential Capabilities

Battery Level:	SOA (Gel)	Adv. Polymer
Specific Energy (wh/kg)	100	150
Energy Density (wh/l)	200	300
Cycle Life (30% DOD)	5k	> 30 K
Calendar Life (years)	2	15

Li-Solid Electrolyte Batteries

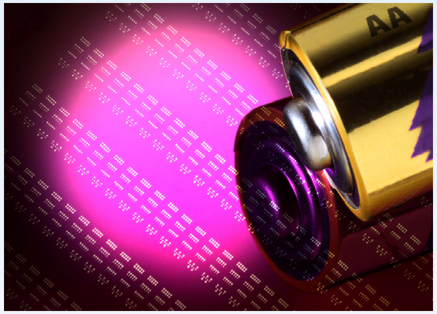
Technology Status

- Micro-batteries, with 70 microAh/cm^2 have been developed for memory back-up and low-power MEMS applications.
- Long cycle life (> 20 K) demonstrated
- TRL: 1-2



Advantages

- Mass and volume savings (4-5 X Vs SOP)
- Long Life (> 20 years



Mission Benefits

- Outer planetary orbiters/fly-by (mass & volume)
- Mars/Earth orbiters (mass & volume)

Technical Issues

- Poor electrolyte conductivity
- Low area-specific capacity
- Scale up to large capacity cells

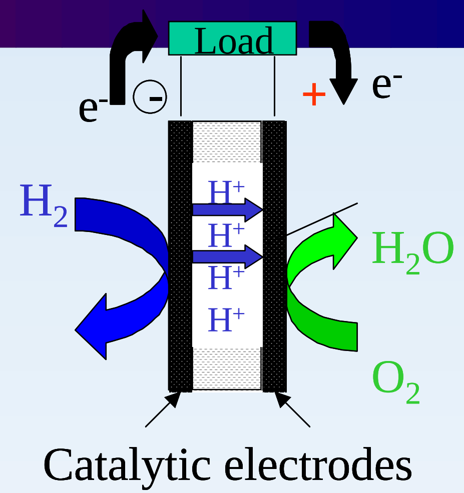
Potential Capabilities

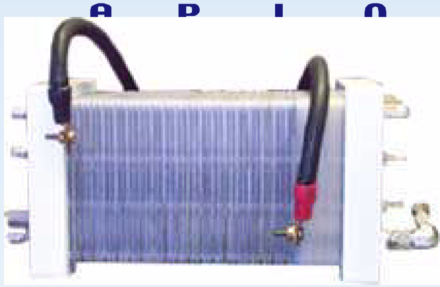
Battery Level:	SOA	Adv. Solid State
Specific Energy (wh/kg)	n/a	>200
Energy Density (wh/l)	n/a	>300
Cycle Life (30% DOD)	20 K	100 K
Calendar Life (years)	> 3Y	20
Operating Temperature	0 to 40^{o}C	0 to 100 ^{o}C

PEM Fuel Cells

Technology Status

- > 30 kW PEM fuel cell systems developed for EV applications
- 50-500 W Hydrogen-air systems are under development for DOD applications
- 5-10 kW PEM fuel system is being developed for RLV applications
- TRL: 4





Technical Issues

- H2 & O2 storage
- System complexity
- Life validation

Advantages

- High specific energy (500 Wh/kg)

- Mission Benefits
  - Crew Exploration Vehicles
  - Human Lunar Exploration Missions
  - Human Mars Exploration Missions

Current programs

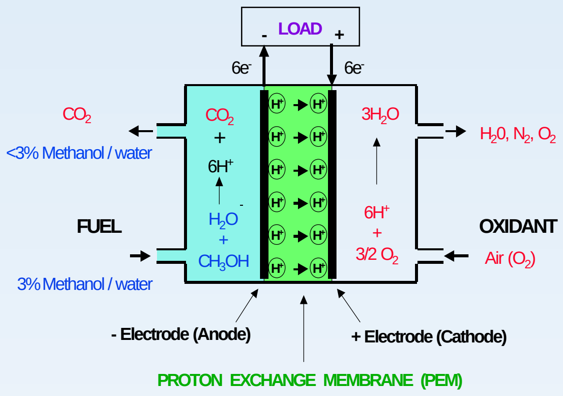
DOE EV program

NASA RLV Program

Potential Capabilities

Advanced Fuel Cell Technology-NASA

Primary Fuel Cells



Description

- Provides high specific energy & energy density compared to SOA primary batteries
- Consists of PEM Fuel Cell, fuel & O2 Storage Tanks
- Suitable for missions requiring >5 kWh
- Provides 2-3 X mass savings compared to primary batteries

Technology Status

- Prototypes fabricated & tested
- 300 Wh/kg
- TRL: 4-6 (01)

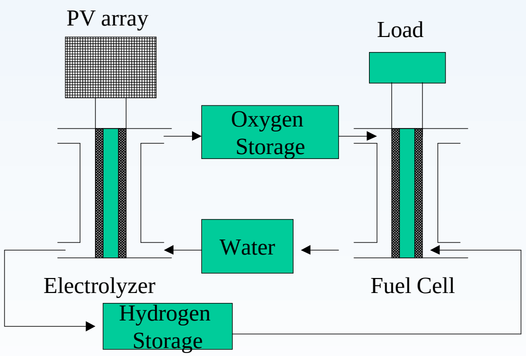
Future Development

- Improve to 500 Wh/kg
- Improve H2 & O2 storage capability
- Optimize system design to reduce mass and volume
- Demo tech readiness for missions

Technical Issues

- H2 & O2 storage
- Safety

Regenerative Fuel Cells



Description

- Provides high specific energy & energy density compared to SOA rechargeable batteries
- Consists of Electrolyzer, Fuel Cell, fuel & O2 Storage Tanks
- Attractive for high energy storage applications (>5 kWh)

Technology Status

- Prototypes fabricated & tested
- 100-200 - Wh/kg
- TRL: 4-6 (01)

Future Development

- Improve Specific Energy to 200-300 Wh/kg
- Improve charge/discharge efficiency to 70%
- Improve H2 and O2 storage capability
- Optimize system design to reduce mass & volume
- Demo tech readiness for surface rovers, orbiters, sample return missions

Technical Issues

- Charge/discharge eff.
- H2 & O2 storage
- Safety

Fly Wheels

Technology Status

- Two Types:
  - Fixed-Axis Energy-Only System
  - Fixed-Axis Energy/Momentum System
- Engineering model units fabricated and tested (25-30 Wh/kg)
- TRL: 3

Advantages

- High usable Specific energy (> 75 Wh/kg)
- Long cycle Life (> 50,K Cycles @ high DoD)
- Wider operating temperature range (-40 C to 100 C)
- Probable radiation tolerance (> 5 Mrads)

Mission Benefits

LEO/GEO missions

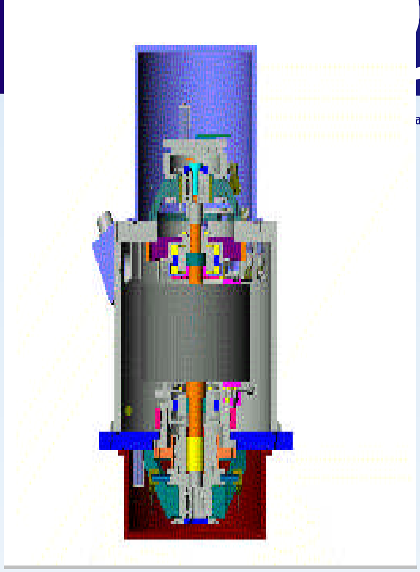
Space Station

Technical Issues:

- Miniaturization
- Safety
- Reliability

Current programs

- NASA Code-R Program
- AFRL FACETS Program



Fixed-Axis Energy-Only System

Potential Capabilities

Characteristics of Advanced Rechargeable Batteries

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Characteristic	SOP Ni-H_2	Li-Ion with liquid electrolyte	Li-Solid Polymer Electrolyte*	Li-Solid Inorganic Electrolyte*
Technology Readiness Level	10	5-9	3	1-2
Specific energy (Wh/kg)	30-40	100-150	>200	> 200
Energy density (Wh/l)	40-50	200-300	300-450	> 300
Cycle life	60, 000 (at 30% DOD)	1500 (at 100% DOD)	1500 (at 100% DOD)	>10,000 at 100% DOD
Operating temperature	-5-30 C	-60 to 80 C	0-80 C	0-80 C
Self discharge rate		1% / month	0.25% / month	0.1% month
Shape factor /packing eff	Poor	Good	Excellent	Excellent

Long Life Rechargeable Battery Performance Targets

	Ni-H2	Lithium Technology		
Characteristics	Present State of Practice	Present State of Practice	Goal 5 years	Goal 10 years
Specific Energy (Wh/kg)	30	100	120	200
Energy Density (Wh/liter)	10	200	200	400
Cycle Life at 30% DOD *	50,000	10-15,000	30,000	50,000
Calendar Life (years)	15	3	10	15

* DOD = Depth-of-discharge

Low Temperature Primary Battery Performance Targets

Primary Energy Storage Characteristics	Present State of Practice	Goal (5 years)	Goal (10 years)
Specific Energy at 0°C (Wh/kg)	250	400	600
Specific Energy at –40°C (Wh/kg)	100	200	300
Specific energy at –80°C (Wh/kg)	50	100	200
Discharge rate (hrs)	> 20	> 20	> 20

Low Temperature Rechargeable Battery Performance Targets

Advanced Planning & Integration Office

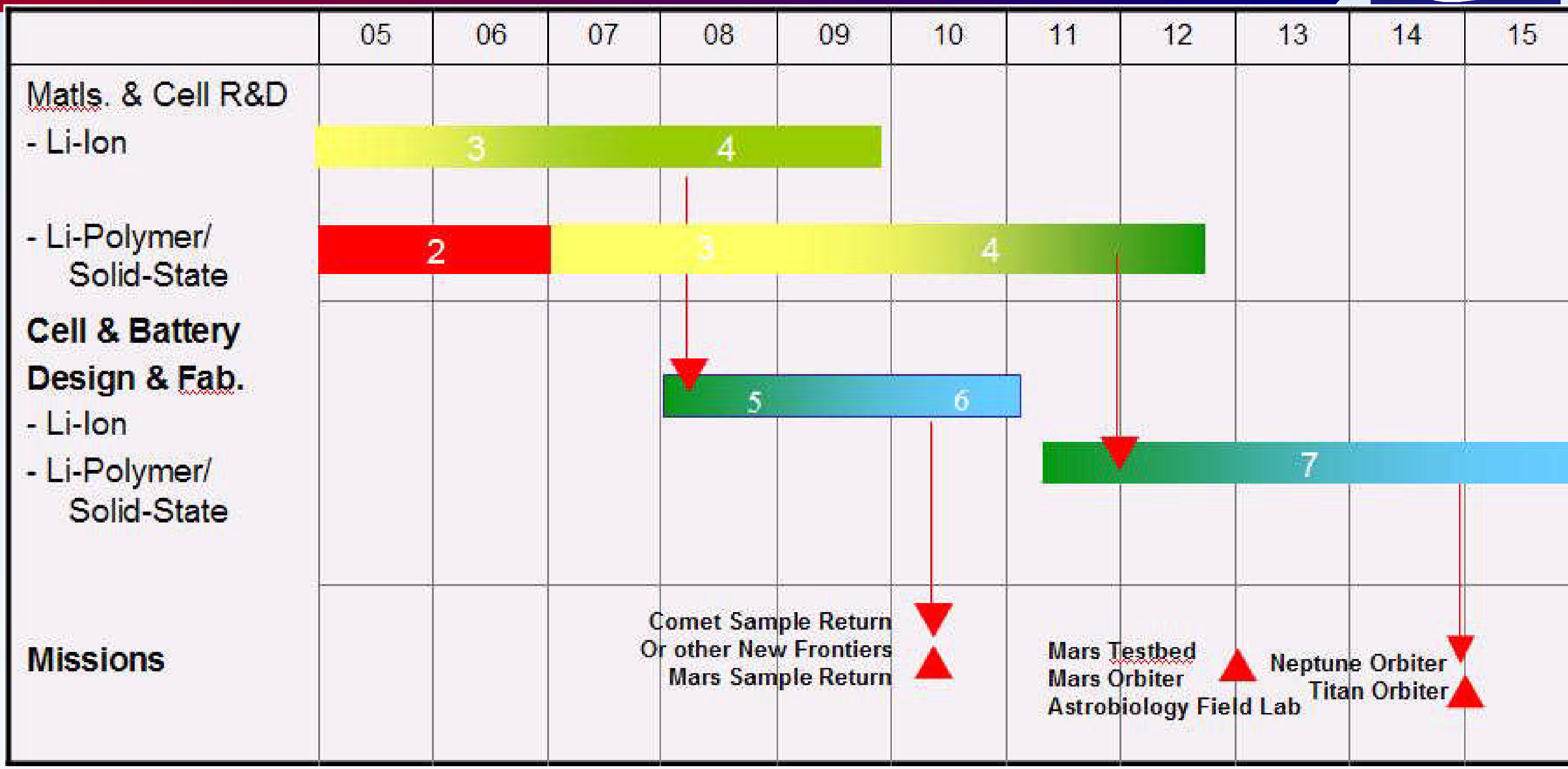
	Lithium Ion Technology		
Characteristics	Present State-of-Practice	5 years	10 years
Specific energy at $0^{o}C$ (Wh/kg)	100	120	200
Life Time (yrs)	5 yrs	10yrs	15 yrs
Cycle Life (# of cycles) (80%DOD)	> 500	> 500	> 500
Low Temperature Performance			
Specific Energy at $-20^{o}C$	70	100	160
Specific Energy at $-40^{o}C$	40	80	140
Specific Energy at $-60^{o}C$	0	65	120
Specific Energy at $-80^{o}C$	0	40	80
Discharge rate (hours)	>10	> 10	> 10

Projected Capabilities of Fly Wheels

Advanced Planning & Integration Office

	Current Values			Post-2013	
Parameter	NiH_2	Li ion	Flywheels (6)	Li-Ion	Flywheels
energy density	35	35	44	150	70
orbit time	100	100	100	100	100
eclipse time	35	35	35	35	35
DOD	0.35	0.35	0.89	0.35	0.89
RT efficiency	0.8	0.8	0.95	0.93	0.95
charge/discharge efficiency	0.9	0.9	0.95	0.9	0.95
delivered energy	2900	2900	2900	2900	2900
stored energy	9206	9206	3430	9206	3430
required energy	4475	4475	3382	3850	3382
spacecraft power	5524	5524	5233	5524	5233
battery replenish	4131	4131	3122	3554	3122
% energy before taper		70	N/A	70	N/A
% insolation time before taper		55	N/A	55	N/A
P1		4674		4523	
P2		223		215	
Total Array Power	9655	9655	8355	10047	8355
storage mass (1)	263.0	263.0	78.0	61.4	49.0
electronics mass (2)	27.6	27.6	included	27.6	included
Subtotal	290.7	119.7	78.0	89.0	49.0
array mass (4)	50.8	50.8	44.0	52.9	44.0
Subtotal	341.5	173.4	122.0	141.9	93.0
attitude control sys mass (3	47.4	47.4	N/A	47.4	N/A
Total System Mass	388.9	388.9	122.0	189.3	93.0
array power density (5)	190				
battery electronics density	200				

Long Life Rechargeable Battery Technology Development Roadmap

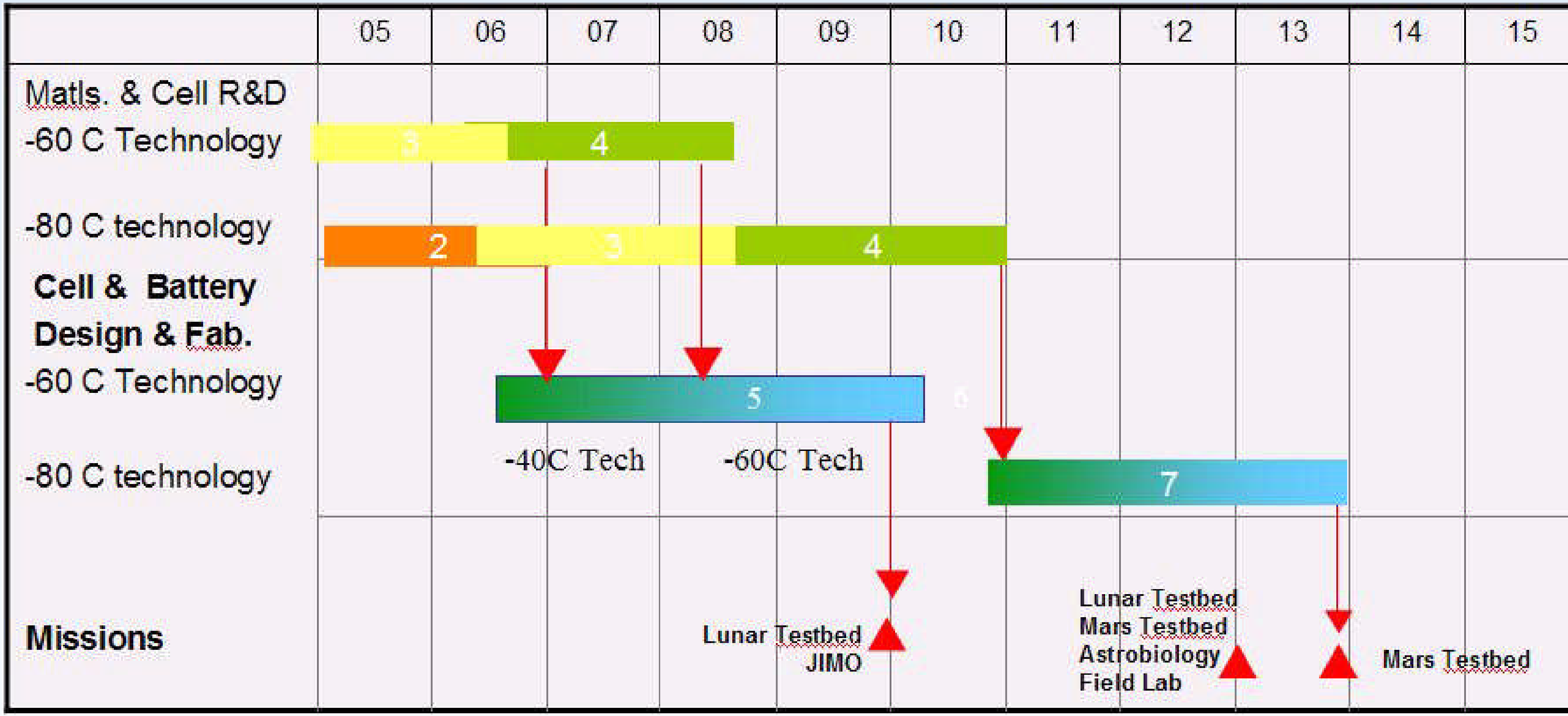


Rough Estimated Cost for the Development Long life Rechargeable Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Materials & Cell R&D (TRL 1-3)												
Li Ion Technology-1	1	1	1	1	1							5
Li Polymer/SolidstateTechnology-2	2	2	2	2	2	2	2	1				15
Tech Maturaration TRL(4 to 6)			2	2	2	2	2	2	2	2	2	18
Total Development Cost	3	3	5	5	5	4	4	3	2	2	2	38
DOD Cost Share for Tech Maturation			1	1	1	1	1	1	1	1	1	9
NASA Cost Share	3	3	4	4	4	3	3	2	1	1	1	29

Low Temperature Rechargeable Battery Technology Development Roadmap

Advanced Planning & Integration Office

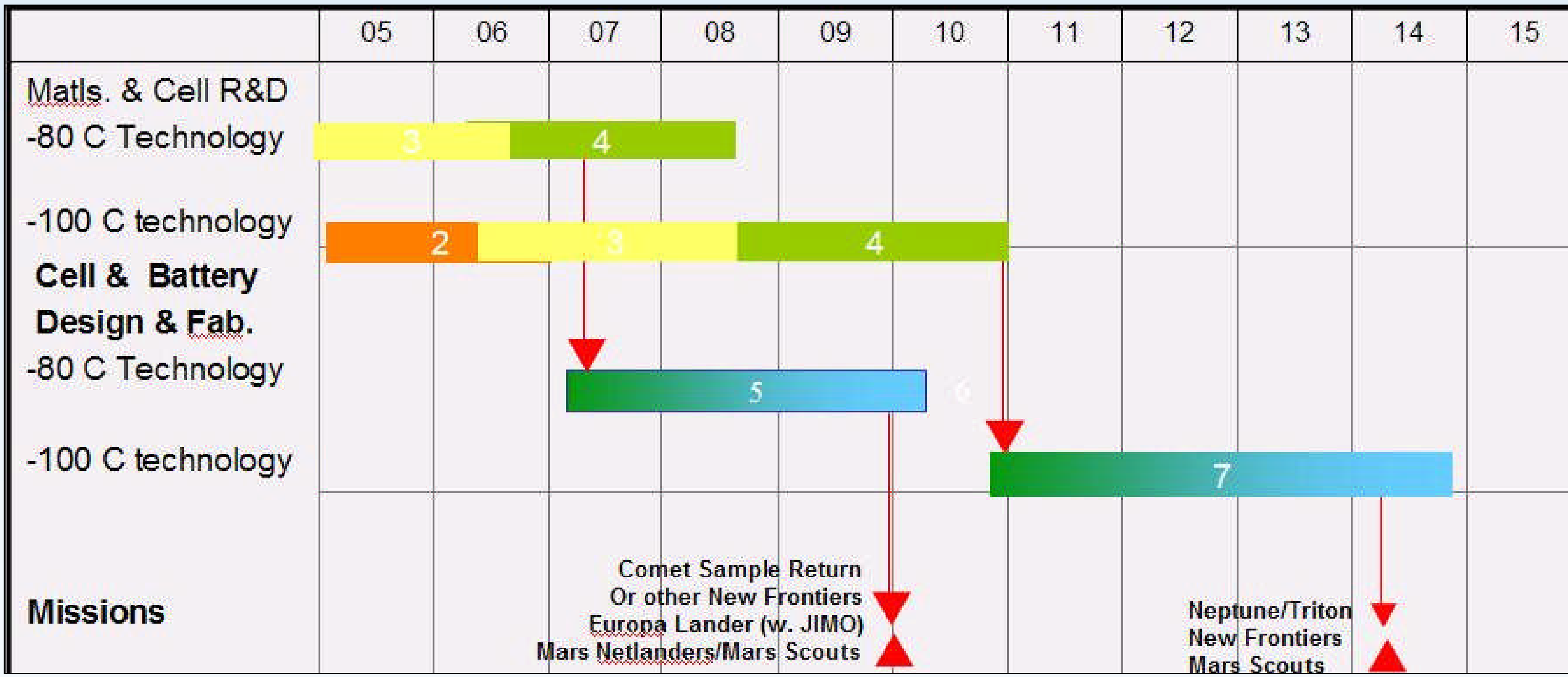


Rough Estimated Cost for the Development Low Temperature Rechargeable Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Materials & Cell R&D (TRL 1-3)										
Li Technology-1	0.6	0.6	0.6	0.6						2.4
Li Technology-2	0.8	0.8	0.8	1.2	1.2	1.2				6
Tech Maturaration TRL(4 to 6)			1	1	1	1.5	1.5	1.5	1.5	9
Total Cost	1.4	1.4	2.4	2.8	2.2	2.7	1.5	1.5	1.5	17.4

Low Temperature Primary Battery Technology Development Roadmap

Advanced Planning & Integration Office



Rough Estimated Cost for the Development Low Temperature Primary Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Materials & Cell R&D (TRL 1-3)											
Li Technology-1	0.6	0.6	0.6								1.8
Li Technology-2	0.6	0.6	0.6	0.6	0.6	0.6					3.6
Tech Maturaration TRL(4 to 6)			1	1	1	1	1	1	1	1	8
Total Cost	1.2	1.2	2.2	1.6	1.6	1.6	1	1	1	1	13.4

Energy Storage Needs of Code S Missions

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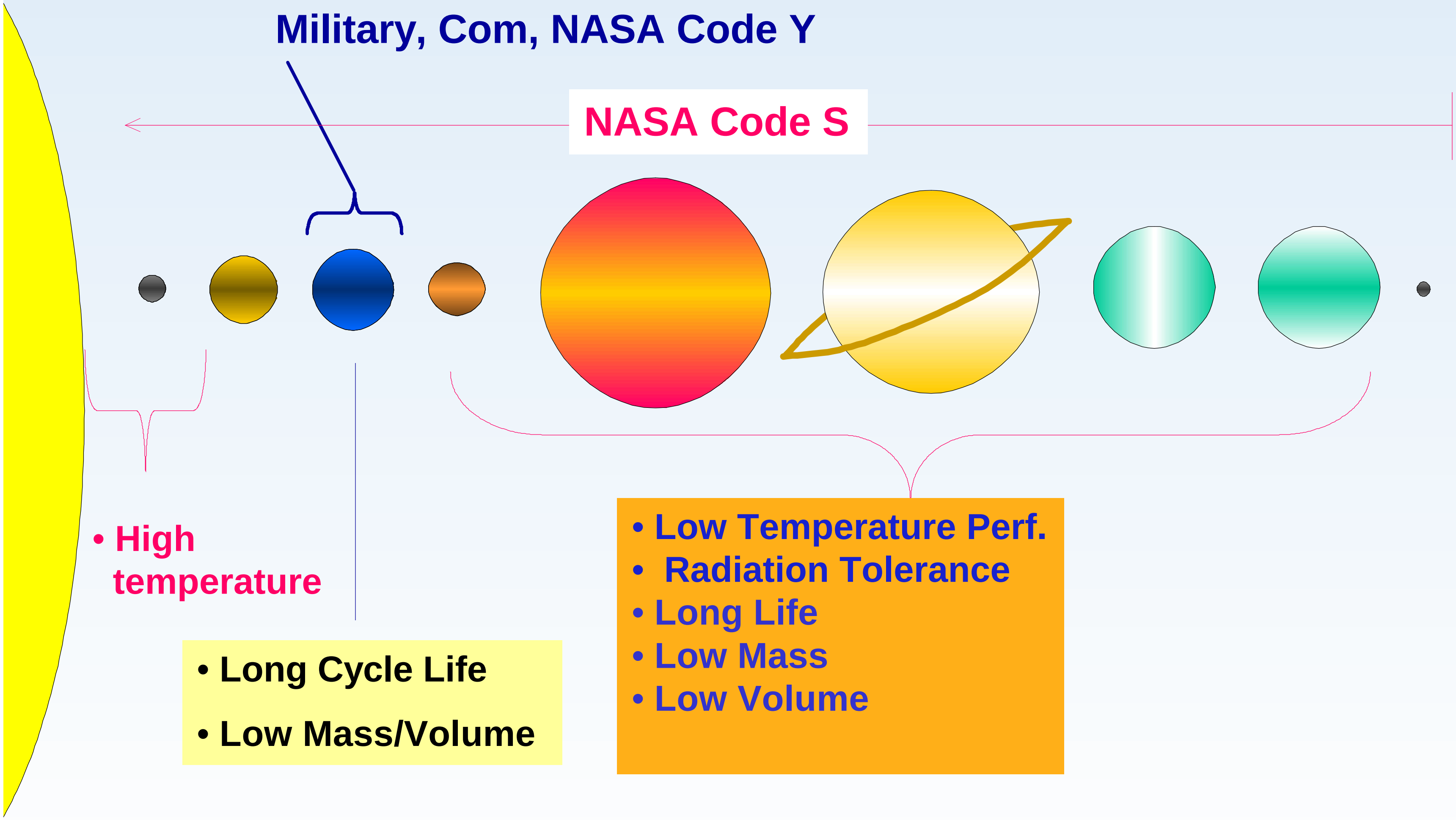

CBS-Energy Storage Subsystem

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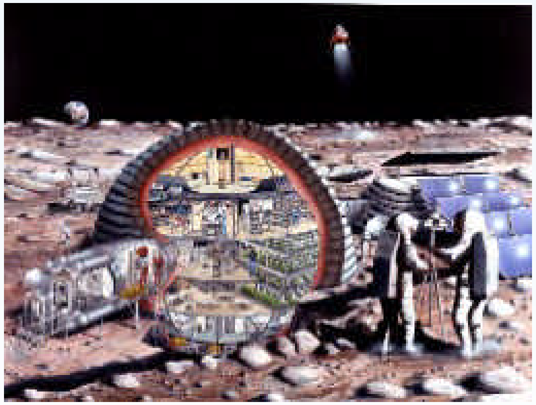
- Energy storage Subsystem Type title here
  - Surface Power Robotic Missions
    - Landers
    - RoversNuclear
    - Subsurface
    - Sensors
  - Surface Power Human Missions
    - Habitat
    - Astonaut
    - Mobile
    - ISRU
  - Spacraft Power Robotic Missions
    - Earth Orbital
    - Mars Orbital
    - Inner Planets
    - Outer Planets
  - Human Missions
    - CEV
    - CTV
    - EVA
  - Inspace Propulsion Robotic Missions
    - SEP
    - NEP
    - NTP
  - Inspace Propulsion Human Missions
    - SEP
    - NEP
    - NTP

Click to add title



Radioisotope Power System (RPS) Capability Roadmap Status

Backup Charts

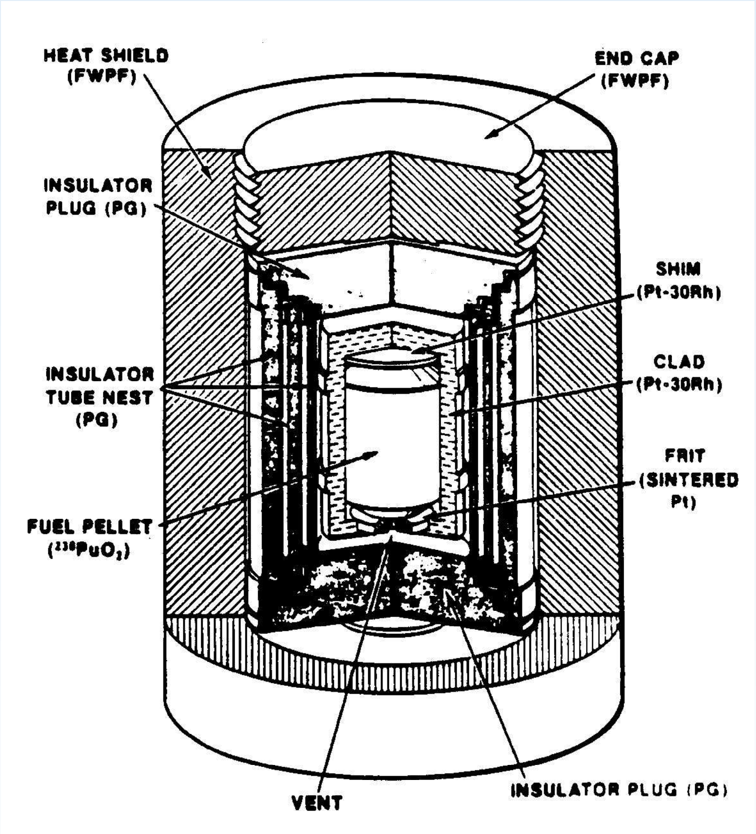
Disclaimer: This report presents the status of work-in-progress. The contents of this report represent a consensus opinion of the CR-2 XXX Sub-Team members, and is not the official view of NASA or DOE.

Classes of RPS

Advanced Planning & Integration Office

- Small RPS (milliwatt/multiwatt) class
  - Small probe and distributed lander applications
  - System design to begin in 2006
- 100 We class
  - Multiple Mars/solar system Science missions + Spiral 1-2 landers/rovers
  - State-of-the-art multi-mission generators
    - Multi-mission RTG (MMRTG under development)
    - Stirling Radioisotope Generator (SRG under development)
  - Advanced (lower mass than SOA + enables REP)
    - No system development planned
    - Low-mass, high-efficiency power conversion under NASA's Radioisotope Power Conversion Technology (RPCT) program
- Kilowatt class (1-2 kWe)
  - Flagship Science missions, REP, Spiral 2-5
  - No system development planned
- Multikilowatt class (5 kWe module)
  - Power/heat option for Spiral 3-5
  - No system development planned

State-of-the-Practice Light Weight Radioisotope Heater Unit (LWRHU)



- Recent uses for thermal control
  - MER 03 - 16
  - Mars Pathfinder (Sojourner) - 3
  - Cassini - 117
  - Galileo - 120
- ~ 70 LWRHUs stored at Los Alamos

DOE's Current RPS Production Infrastructure

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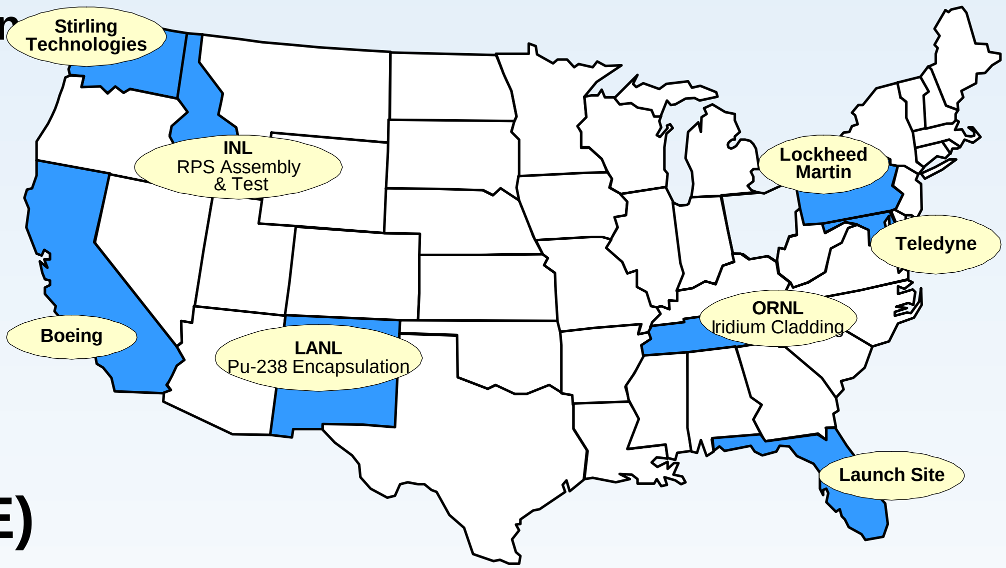
- DOE maintains infrastructure
  - Nuclear facilities
    - LANL and INL
  - Heat source hardware production
    - ORNL
  - Safety analyses
  - Pu-238 supply
    - Storing neptunium-237 (Np-237) at INL
    - Interim Russian purchase (using NASA funds)
- NASA funds (through DOE) mission-specific development
  - System design/development
  - Flight hardware
  - Production/acquisition cost of Pu-238



Proposed Consolidated Nuclear Infrastructure Capabilities

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- Consolidation would be complete and operational in late 2010 or 2011
- Storage of Np-237
- Domestic production of 5 kg/year of Pu-238
- Heat source production
  - Purification of Pu-238 for pellet fabrication
  - Encapsulation of pellets in Ir
- GPHS module assembly
- RPS assembly and testing
- RPS delivery to NASA
- Non-nuclear heat source hardware production

Enhanced Infrastructure to Support Expanded Exploration Missions

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- Increase quantity purchase of Russian Pu-238 to supplement the 5 kg/year domestic production
- Increased purification and encapsulation production rates
- Increased capabilities to assemble larger RPSs
- With appropriate planning and commitment of resources, RPS infrastructure could support expanded exploration missions

SUMMARY OF RADIOISOTOPE THERMOELECTRIC GENERATORS SUCCESSFULLY LAUNCHED BY THE UNITED STATES (1961 - 2003)

Launch Date	Spacecraft	Mission Type	User	Type of RTG	# of RTGs	Initial Average RTG Power (W)	Total Initial Spacecraft Power (W)
6/29/61	Transit 4A	Navigational	USN / APL	SNAP-3B7	1	2.7	2.7
11/15/61	Transit 4B	Navigational	USN / APL	SNAP-3B8	1	2.7	2.7
9/28/63	Transit 5BN-1	Navigational	USN / APL	SNAP-9A	1	>25.2	25.2
12/5/63	Transit 5BN-2	Navigational	USN / APL	SNAP-9A	1	26.8	26.8
4/14/69	Nimbus III	Meteorological	NASA / Goddard	SNAP-19B3	2	28.2	56.4
11/14/69	Apollo 12	Lunar	NASA / Johnson	SNAP-27	1	73.6	73.6
1/31/71	Apollo 14	Lunar	NASA / Johnson	SNAP-27	1	72.5	72.5
7/26/71	Apollo 15	Lunar	NASA / Johnson	SNAP-27	1	74.7	74.7
3/2/72	Pioneer 10	Outer Planets	NASA / Ames	SNAP-19	4	40.7	162.8
4/16/72	Apollo 16	Lunar	NASA / Johnson	SNAP-27	1	70.9	70.9
9/2/72	Triad	Navigational	USN / APL	Transit-RTG	1	35.6	35.6
12/7/72	Apollo 17	Lunar	NASA / Johnson	SNAP-27	1	75.4	75.4
4/5/73	Pioneer 11	Outer Planets	NASA / Ames	SNAP-19	4	39.9	159.6
8/20/75	Viking 1	Mars Lander	NASA / Langley	SNAP-19	2	42.3	84.6
9/9/75	Viking 2	Mars Lander	NASA / Langley	SNAP-19	2	43.1	86.2
3/14/76	LES-8*	Communications	USAF / Lincoln Labs	MHW-RTG	2	153.7	307.4
3/14/76	LES-9*	Communications	USAF / Lincoln Labs	MHW-RTG	2	154.2	308.4
8/20/77	Voyager 2	Outer Planets	NASA / JPL	MHW-RTG	3	159.2	477.6
9/5/77	Voyager 1	Outer Planets	NASA / JPL	MHW-RTG	3	156.7	470.1
10/18/89	Galileo	Jupiter System	NASA / JPL	GPHS-RTG	2	288.4	576.8
10/6/90	Ulysses	Solar Polar	NASA / JPL	GPHS-RTG	1	283	283
10/15/97	Cassini	Saturn System	NASA / JPL	GPHS-RTG	3	295.7	887

* Two Spacecraft on one Launch

RTGs = 21 Successful Launches with 22 Spacecraft containing 40 RTGs

		Aborted	Launches (All	Launch Vehicle	Problems)		
4/21/64	Transit 5BN-3	Navigation	USN / APL	SNAP-9A	1	25	25
5/18/68	Nimbus B-1	Meteorology	NASA / Goddard	SNAP-19B2	2	28	56
4/11/70	Apollo 13	Lunar	NASA / Johnson	SNAP-27	1	73	73

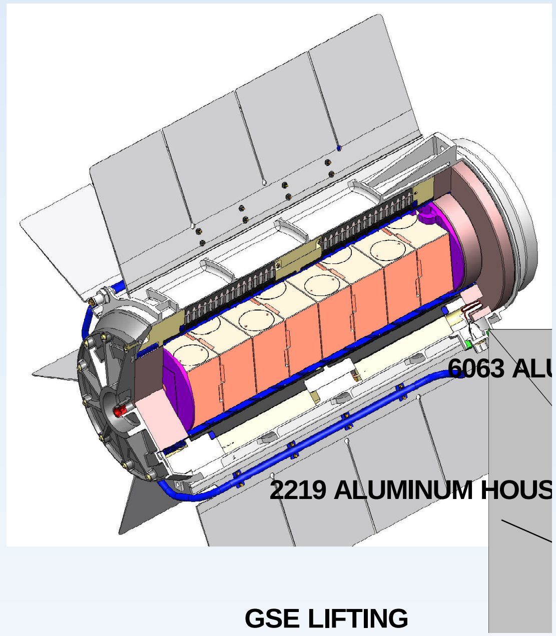
3 Aborted Launches / 3 Spacecraft / 4 RTGs – 1heat source burned up as designed (Pu metal), 2 heat sources recovered (fuel reused), 1heat source with graphite impact case on ocean floor

RHUs = Galileo (101in FSAR) , Cassini (117), Apollo 11 (2 – 15W RHUs), Mars Pathfinder (3), MER03A (8), MER03B (8)

"Multi-Mission" RTGs

	MMRTG	SNAP-19 Viking	SNAP-19 Pioneer
Beginning of life (BOL) power (We)	123	42.5	41.2
Voltage (volts)	28	4.4	4.0
Mass (kg)	43	15.2	13.6
Envelope (cm)	66 L x 64 D	40 L x 59 D	28 L x 51 D
BOL specific power (We/kg)	2.9	2.8	3.0
BOL thermal inventory (Wt)	2000	683	648
BOL system efficiency (%)	6.2	6.2	6.3
BOL T_{HJ}/T_{CJ} (ºC)	535/208	546/174	512/167
Number of couples	768	90	90
Couple dimensions (cm)			
N leg	0.589 D x 1.26 L PbTe	0.985 D x 1.27 L PbTe	
P leg	0.467 D x 0.531 L PbSnTe	0.686 D x 0.254 L SnTe	
	0.467 D x 0.711 L TAGS	0.686 D x 1.016 L TAGS	

Multi-Mission RTG



DESIGN METRICS

- Design Life: 14 Years + Storage

	Mars	Deep
Projected power	Noon	Space
– BOM (2000 Wt)	124 We	126 We
– BOM + 14 yrs	99 We	101 We

- Mass: 43.5 kg
- Size: 26” (66 cm) L x 25” (64 cm) D fin tip-to-tip

A

GPHS (Step 2)

thermocouples in 16 modules

PbTe

TAGS/PbSnTe

power at launch

helium cover gas

Eig

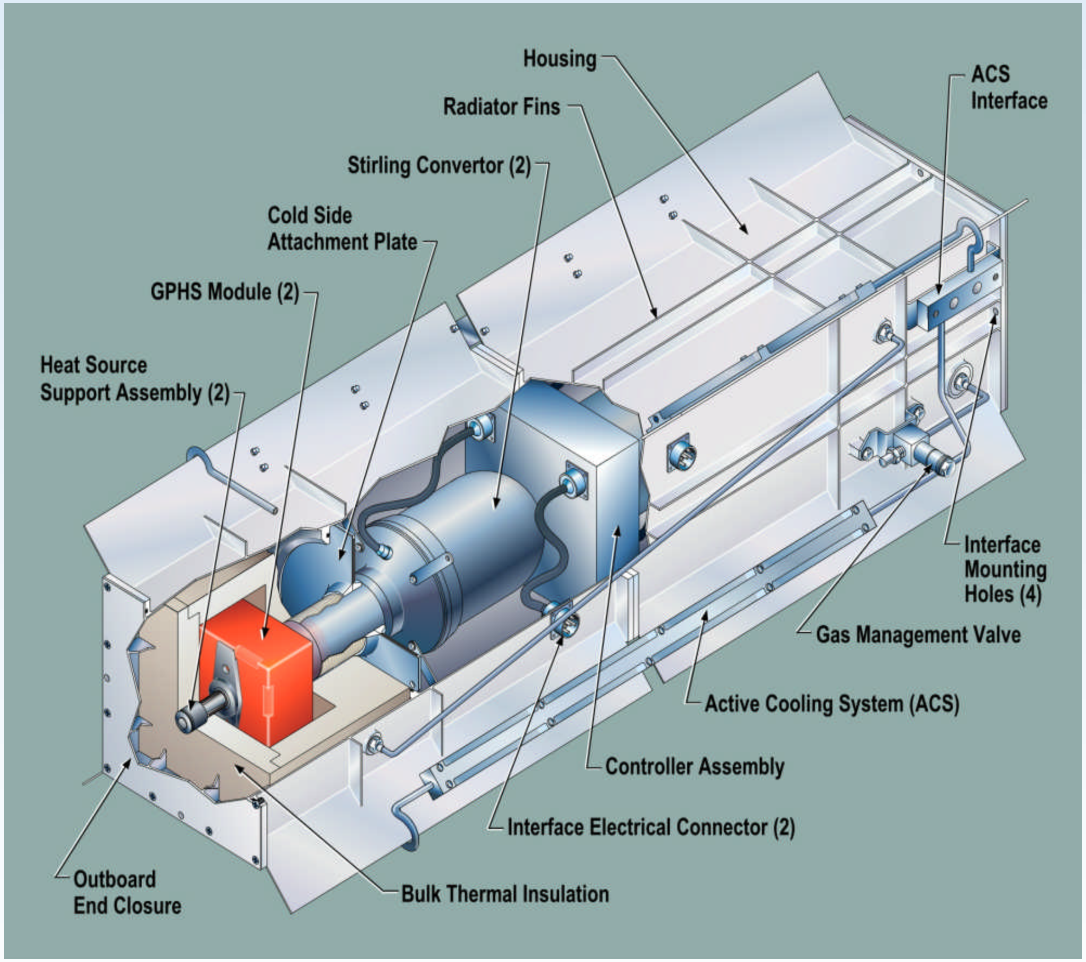
768

Ful

Arg

Alu

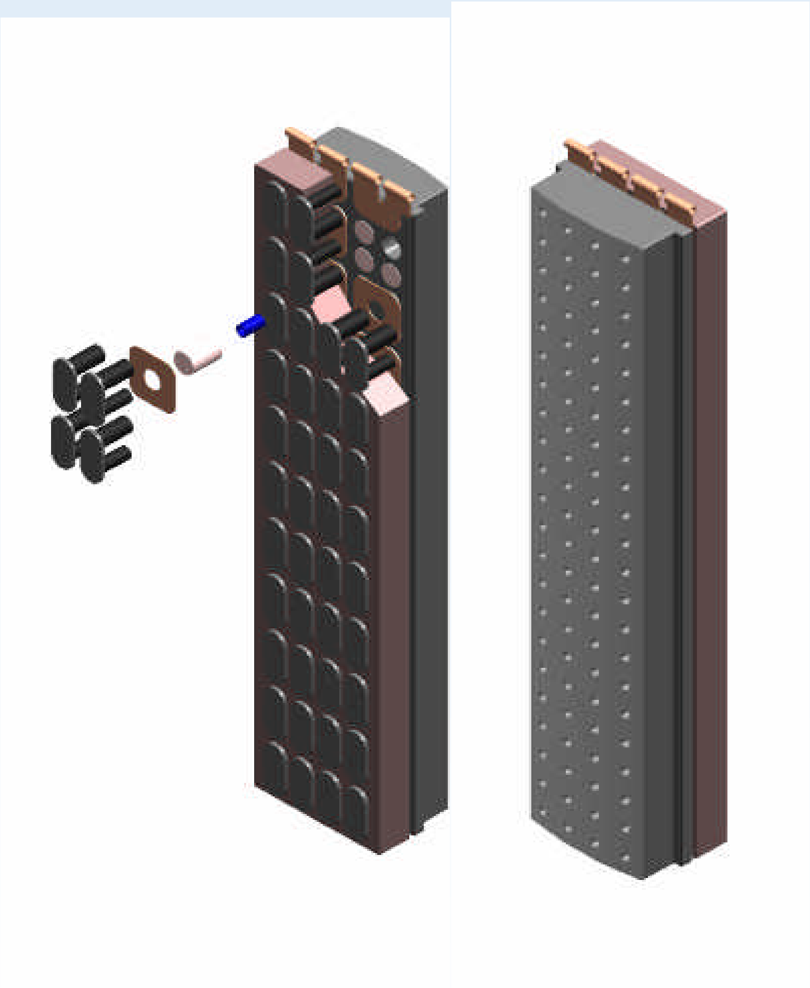
Stirling Radioisotope Generator (SRG110)

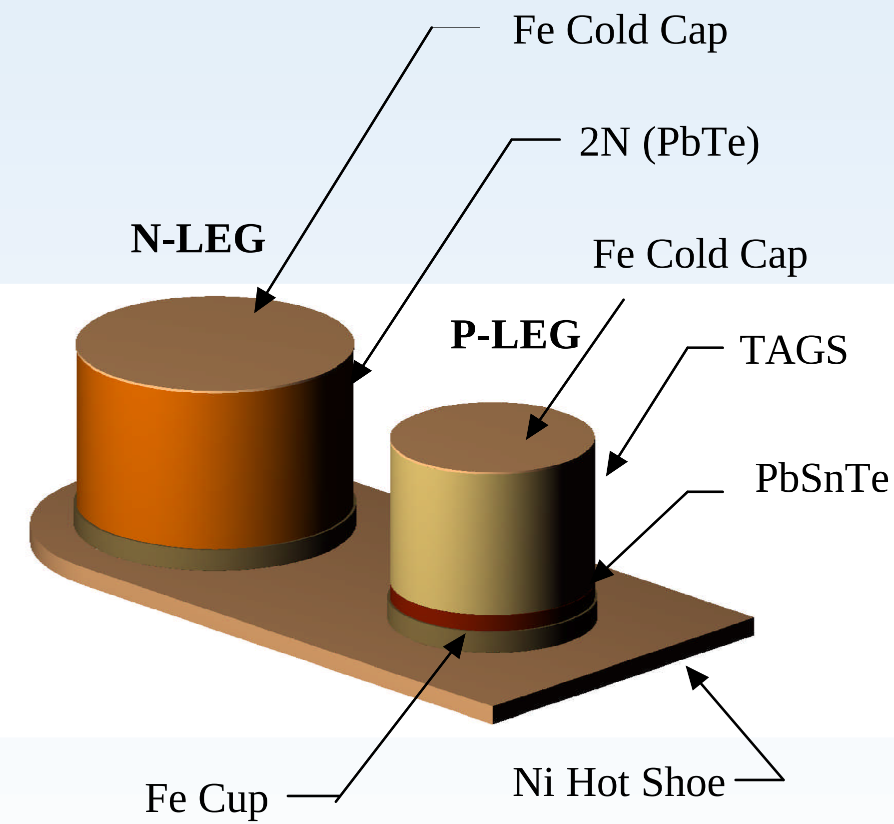


Projected power
- BOM 112 We
- 14 years 94 We

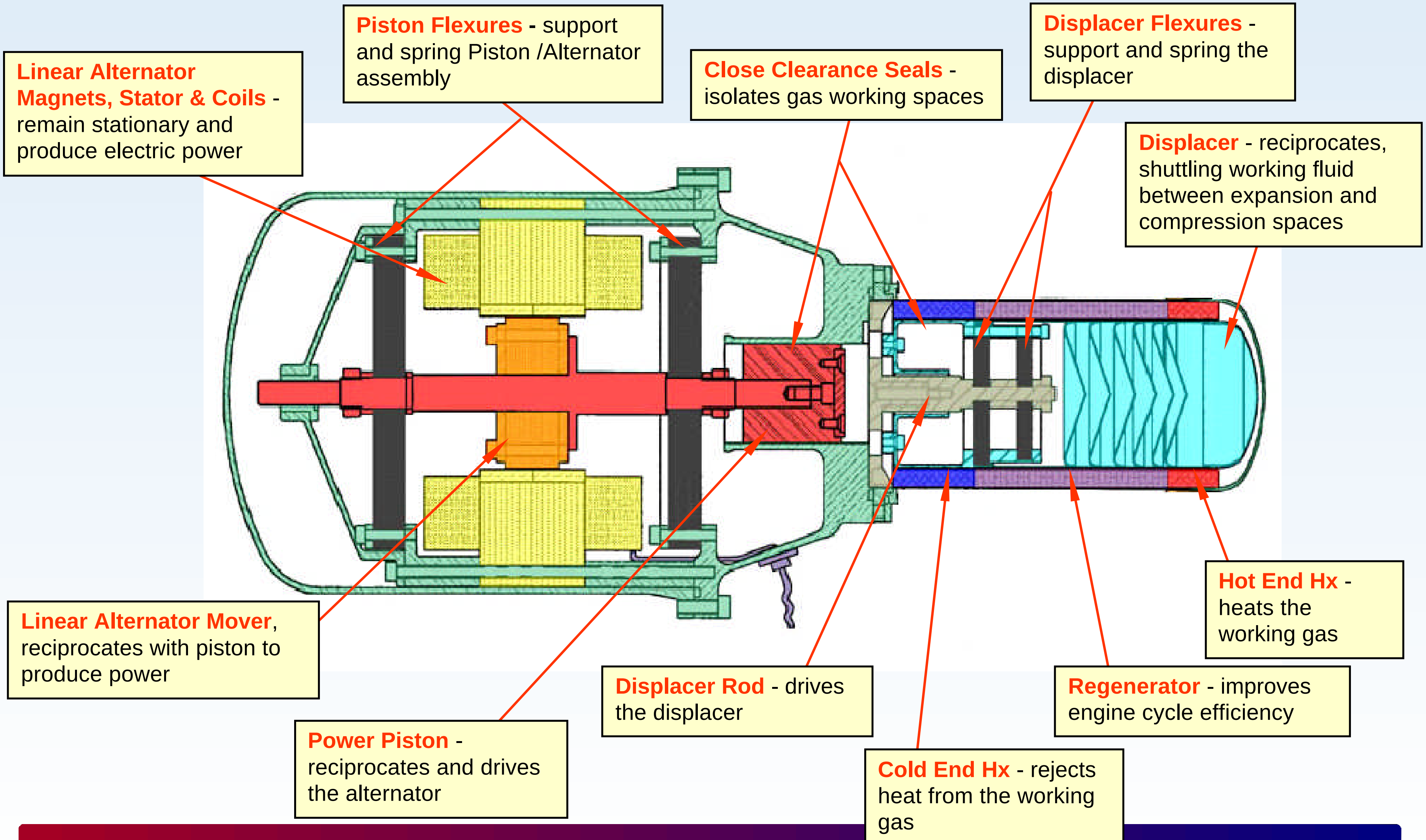
• Mass	34 kg
• Length	89 cm
• Diameter	27 cm
• Hot junction	650 •C
• Cold junction	80 •C
• Voltage	28 Volts dc
• Frequency	80 Hz
• Mean pressure	370 psia
• Design lifetime	14 years

PbTe/TAGS Thermoelectrics

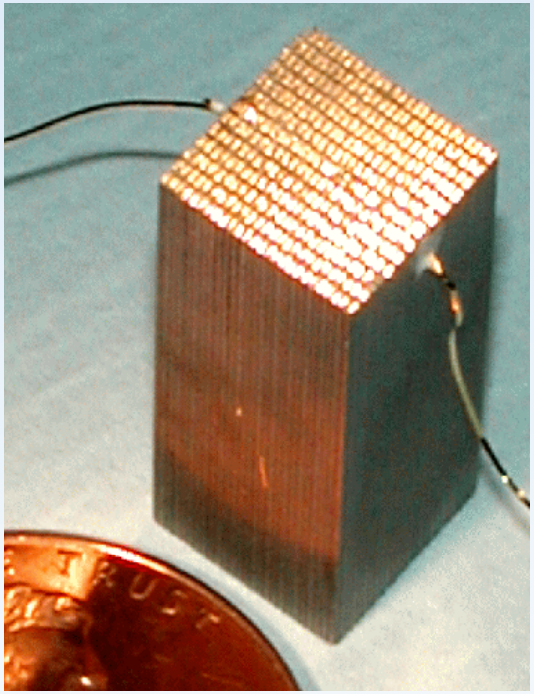


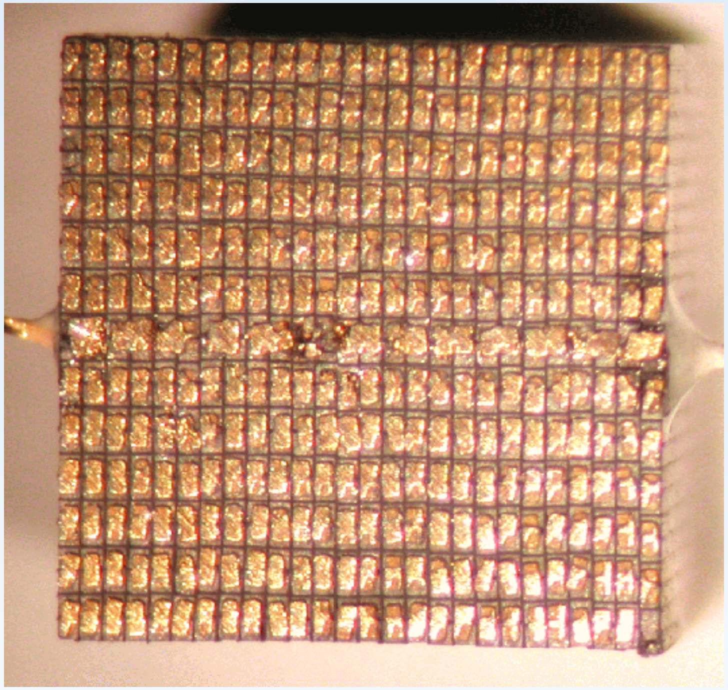


Major SCA Components and Functions



Hi-Z 676 Element Series-Parallel BiTe Module





Cold side showing series-parallel interconnects

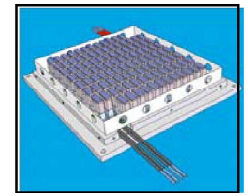
- 26 x 26 elements, 0.010” x 0.010” cross section
- Module size 0.29” x 0.29” x 0.9”
- Welded interconnects
- Series/parallel design

Development Projects

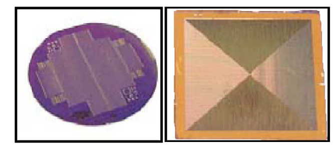
– Breadboard (TRL 5) demos funded at several $M/year

TE	Teledyne	Improve performance and manufacturability of segmented Bi-Te with PbTe, PbSnTe and TAGS unicouples. Demonstrate 10-12% efficiencies and >5 W/kg specific powers.
TPV	Creare	Demonstrate selective emitter-based TPV power generator with simulated radioisotope thermal source. Target 15-20% converter efficiency and ~15 W/kg specific power.
TPV	Edtek	Demonstrate TPV power generator employing improvements in GaSb PV cell, Frequency Selective

TE



TPV

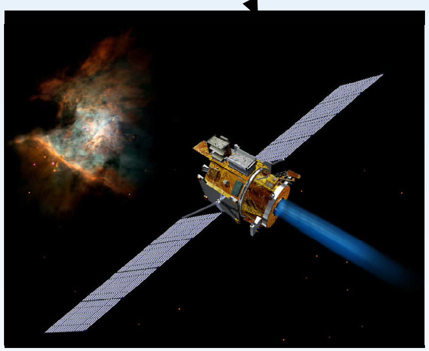


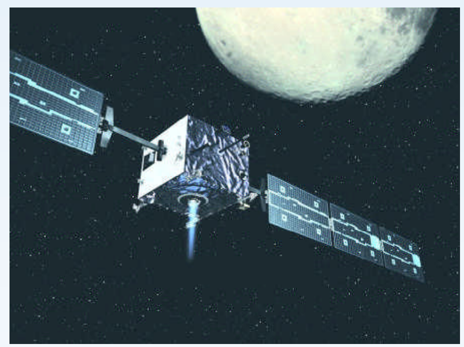
Stirling

Discontinued afte

State-of-the-Practice Electric Propulsion for REP

- **Missions:**
  - Routine use on US and foreign COMSATS (stationkeeping and final insertion)
  - Increasing use for planetary missions
    - Asia (HAYABUSA)
    - Europe (BELI-COLOMBO, SMART-1)
    - USA (DEEP SPACE-1, DAWN)

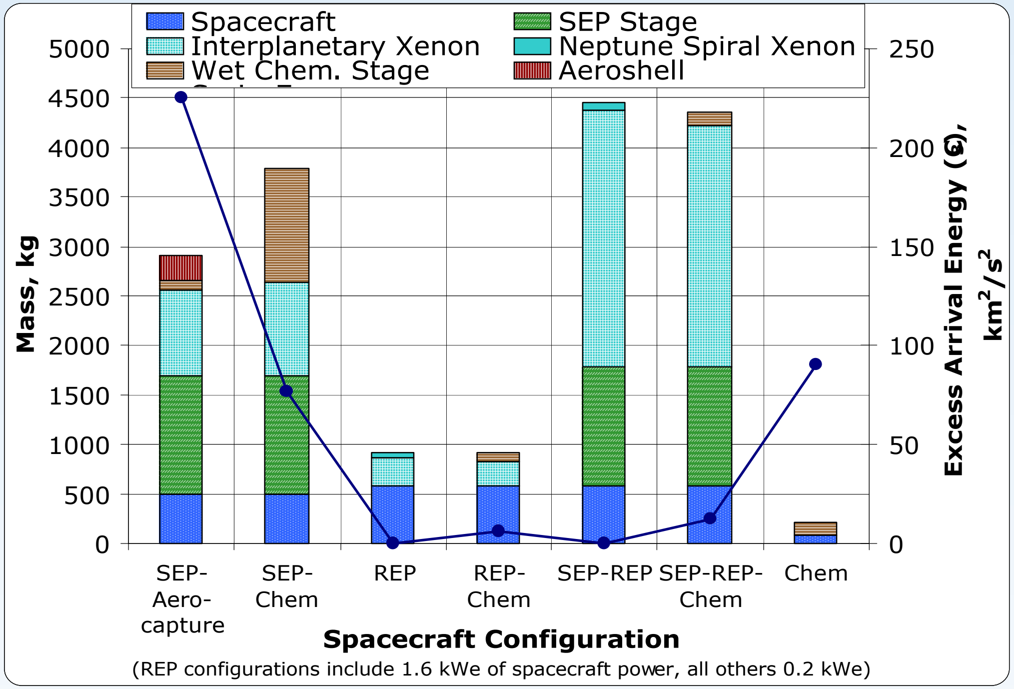




- **Systems (single string)**
  - Hall thrusters for Isp less than ~2500 sec
  - Ion thrusters for Isp greater than ~2500 to 3300 sec
  - Powers • 2.5 kWe
  - Efficiencies (thruster + PPU) • 60%
  - Specific masses (thruster + gimbal + PPU + cabling) • 15 kg/kWe

REP Performance – Total Spacecraft Mass

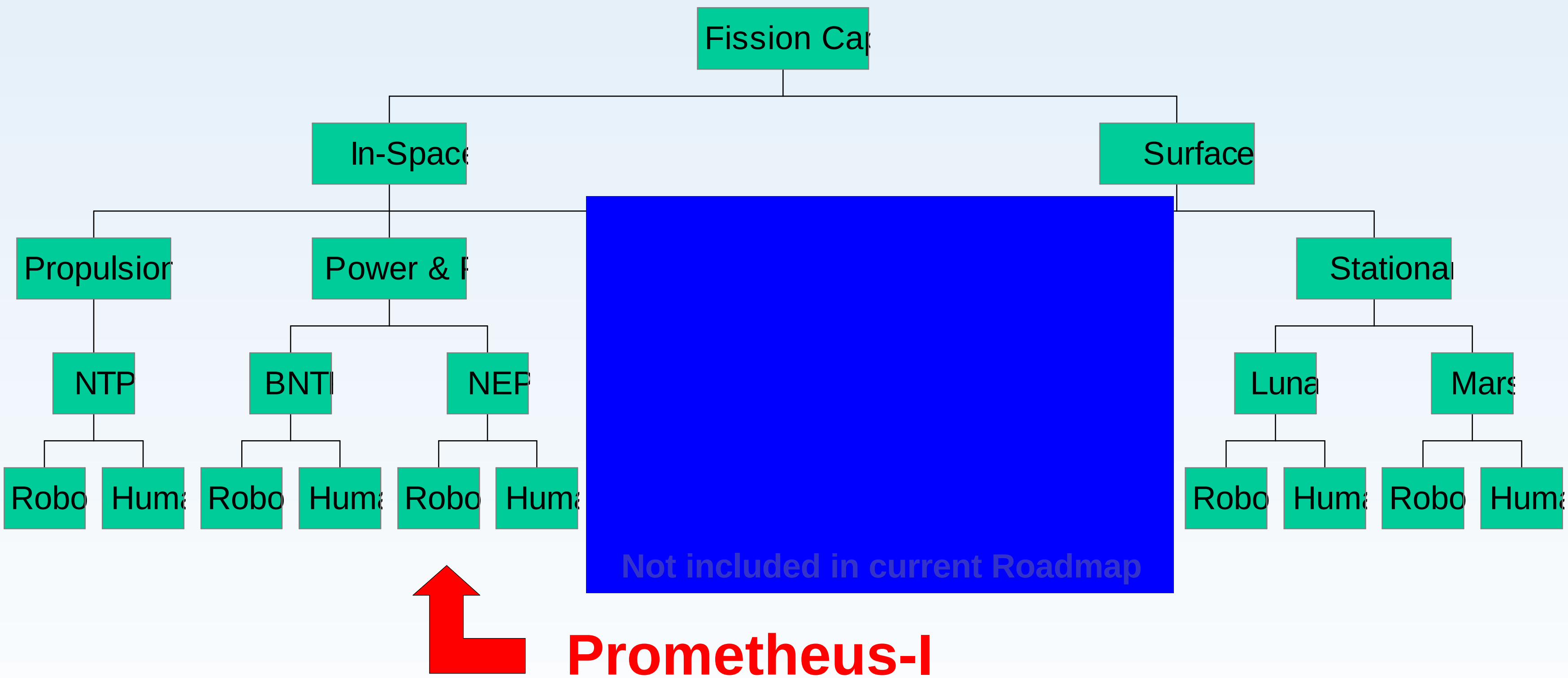
- Neptune Orbiter Mission
- ~ 500 kg spacecraft to Neptune Orbit (depending on power level)
  - Except for all-Chem (could only deliver 80 kg)
  - REP includes 1.6 kWe spacecraft power, all others 0.2 kWe
- Launch on Delta IV M+(4,2)



REP allows lowest total spacecraft mass

Backup Charts for Fission Systems

VSE Could Utilize A Diverse Set of Fission Power and Propulsion Systems



Exploration Spirals

- Spiral 1 (2008-2014)
  - Provide precursor robotic exploration of lunar environment
  - Deliver a lunar capable human transportation system for test and checkout in LEO
- Spiral 2 (2015-2020)
  - Execute extended duration human lunar exploration missions
  - Extend precursor robotic exploration of Mars environment
- Spiral 3 (2020+)
  - Execute a long-duration human lunar exploration campaign using the Moon as a testbed to demonstrate systems (e.g., lander, habitation, surface power) for future deployment at Mars
- Spiral 4 (~2025+)
  - Execute human missions to vicinity of Mars
- Spiral 5 (~2030+)
  - Execute initial human Mars surface exploration mission

Space Fission Systems Have Many Developmental Milestones (Demos)

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- All Fission Power and Propulsion Systems
  - Fuel performance
  - Mass, Power, temperature, lifetime, reliability
  - Radiation tolerance
  - Water- and sand-immersion kinetics (Safety Requirements)
  - Startup, power control, transient behavior
  - Shield performance
- NEP
  - PMAD / PPU
  - Thruster performance
- Surface Power
  - Landing
  - Environmental compatibility
  - PMAD
- NTP
  - Engine clustering (if small engine)
- BNTP
  - Bi-modal operation

Partial List

NASA Technology Readiness Levels

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TRL Level	Definition
9	Actual system "flight proven" through successful mission operations
8	Actual system completed and "flight qualified" through test and demonstration (ground or flight
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

NASA Capability Readiness Levels

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Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

NTR Reduces IMLEO by ~50% Compared To Chemical / Aerobrake & ~200-300% Compared To "All Chemical"

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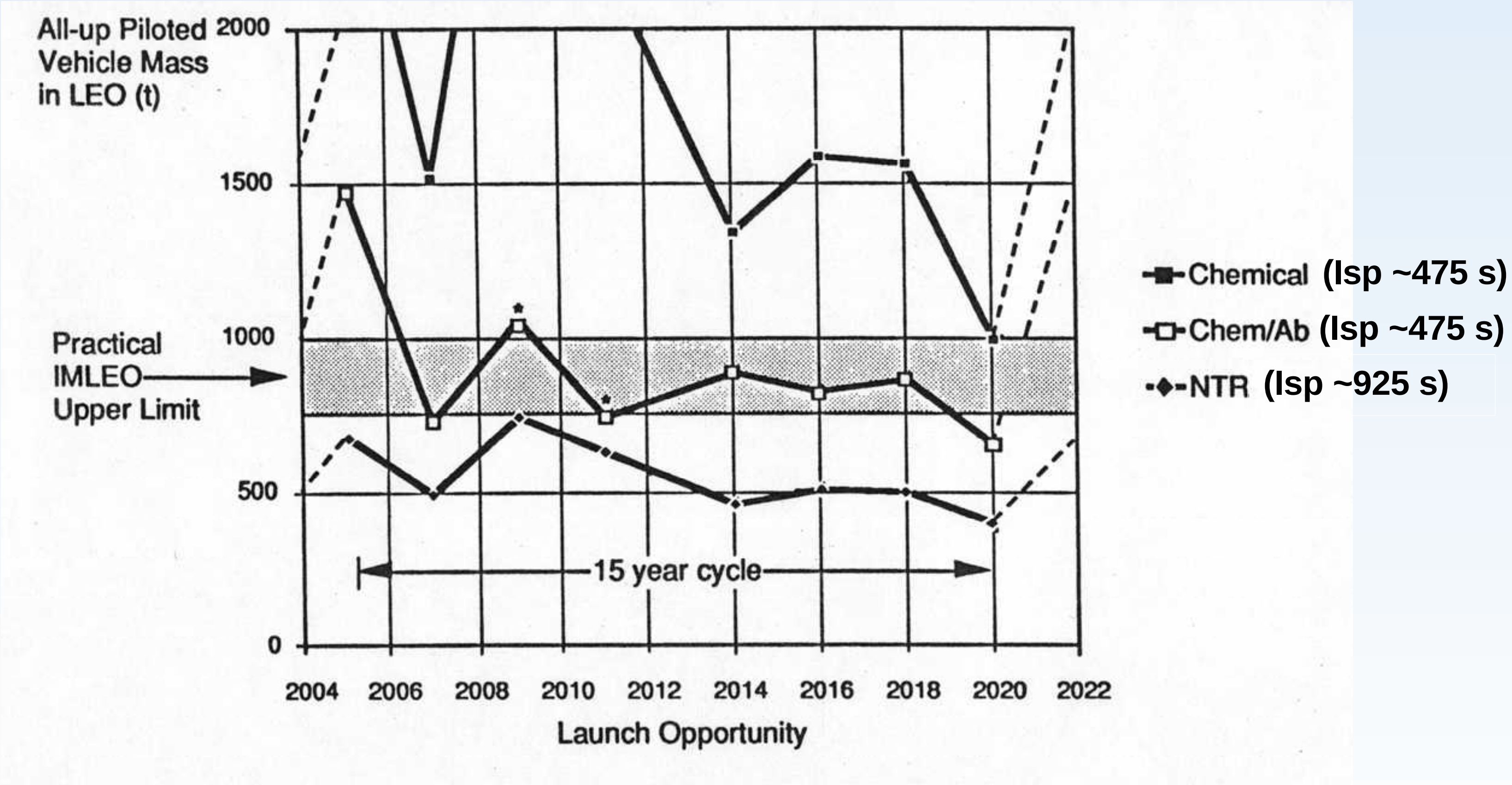
IMLEO Requirements for Mars "Opposition-class" Short Round-Trip Missions



*500-Day Constraint relaxed to 700 days (30 day stay)

Source: NASA's Office of Aeronautics, Exploration and Technology, presented to Stafford Synthesis Team in 1991

Opportunities Exist To Leverage Technology Investments – Example

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Entry-level NEP & SP Fuel — Entry-level NTP Fuel — High-Performance NTP Fuel — Bi-modal NTP Fuel — MMW NEP Fuel

UN
UO_2

Nerva-Derived
UC

Advanced Carbides
Coated Particle Fuels
Cermets

- *Limited commonality of entry-level NEP and NTP fuels*
- *Potential for common Hi-Po NTP, BNTP, and MMW fuels*

Entry-Level NEP & SP
- 1000 - 1500 K Fuel Temp
- Low burn-up (~ few %)
- Long Operation (5-15 yr)
- 100 kW_{th} - ~ 1 MW_{th}

NTP
- 2500 - 2700(?) K Fuel Temp
- Low burn-up (< 1 %)
- Short Operation (< 2 hr)
- 330 - 550 MW_{th}

Bimodal NTP
- 2500 - 2700(?) K Fuel Temp
- Low burn-up (~ few %)
- Short Operation (< 2 hr) @ high power (330 - 550 MW_{th})
- Medium Operation (< 3 yr) @ low power (~125 kW_{th})

MMW-NEP
- 1500 - 2000K Fuel Temp
- High burn-up (~ few %)
- Medium Operation (< 3 yr)
- 10 - 100 MW_{th}

National Research Council
Dialogue to Assess Progress on Development of NASA's

Advanced Telescopes and Observatories
&
Scientific Instruments and Sensors Capability Roadmaps

General Background and Introduction

Dan Coulter
Perry Bankston
March 15-16, 2005

Agenda

Advanced Planning & Integration Office

- General Background and Introduction of Advanced Telescopes and Observatories & Scientific Instruments and Sensors Capability Roadmaps
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

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National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	1. Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	6. Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	7. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	8. Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	4. Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	9. Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	5. Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	10. Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

Agency Goals and Objectives

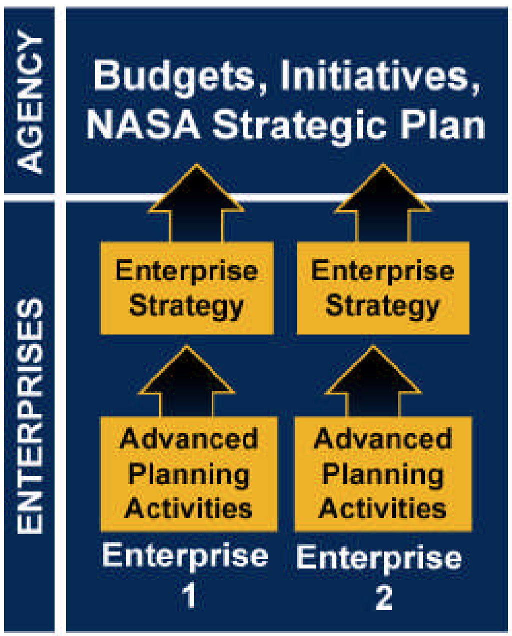
Advanced Planning & Integration Office

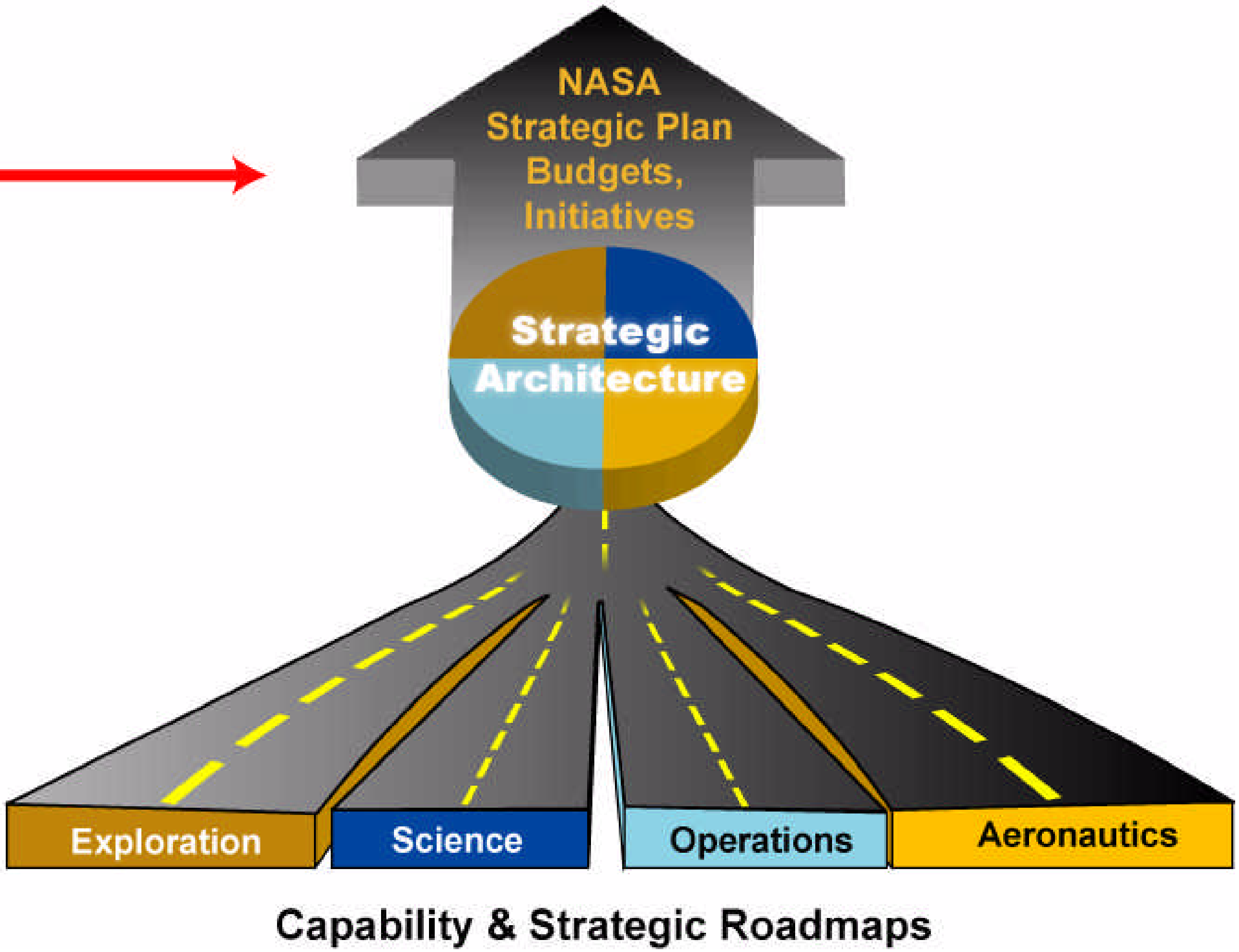
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	3. Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration.	4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	5. Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	11. Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	14. Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems. (SRM 9)	17. Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)
	12. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	15. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)	18. Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)
	13. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	16. Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	

Strategic Planning Transformation

ACHIEVING THE VISION

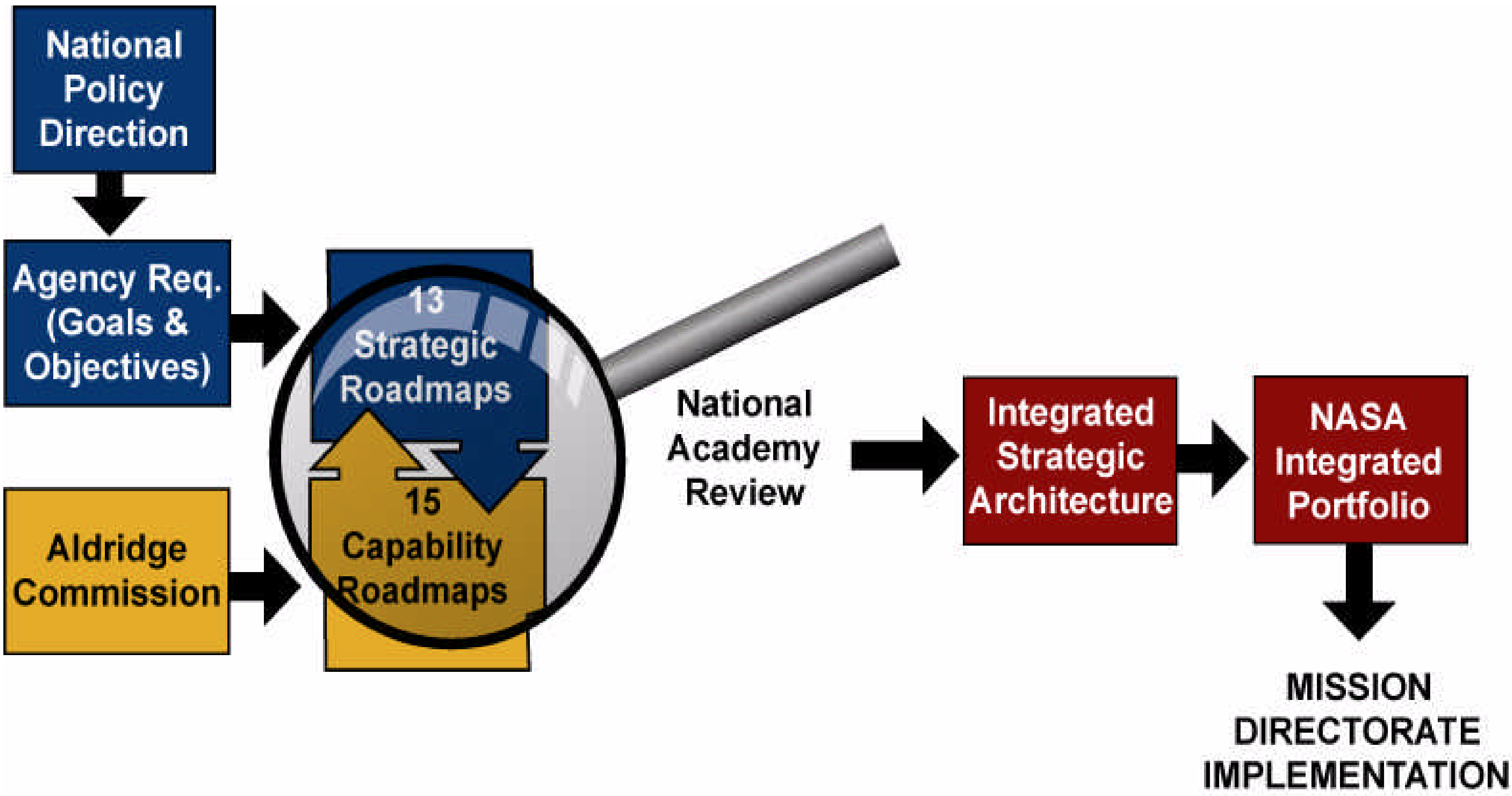
OLD vs. NEW





Strategic Planning Transformation - continued

Advanced Planning & Integration Office



Advanced Planning Organizational Roles

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- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Charles Elachi)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

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- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

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- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

- Broad human and robotic science and exploration goals, priorities, anticipated discoveries
- High-level milestones, options, and decision points
- Implementation approaches, suggested missions

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators Also with Each Team

= DoD Participation

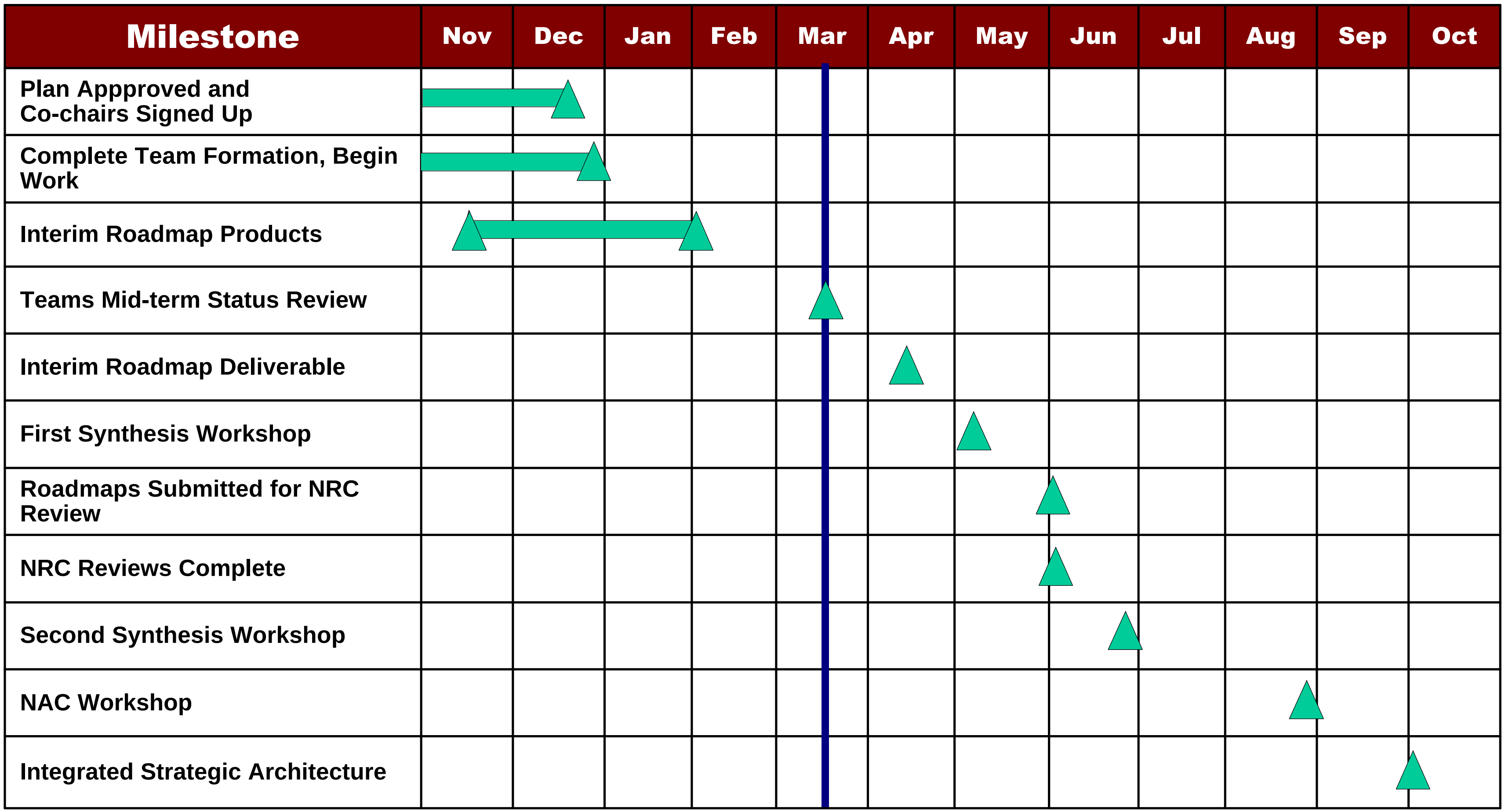
Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Directorate and APIO Coordinators Also with Each Team

= DoD Participation

Strategic Roadmaps Schedule



Capability Roadmaps

Advanced Planning & Integration Office

- Capability is defined as a <u>set of systems</u> (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

Advanced Planning & Integration Office

- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**

    1/3 Industry

    1/3 NASA & other Government Agencies

    1/3 Academia

- **Strategic Planning Council assigned roadmaps to Mission Directorate**

- **Mission Directorates assigned a NASA Chair with roadmap expertise**

- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

Capability Roadmaps - continued

Advanced Planning & Integration Office

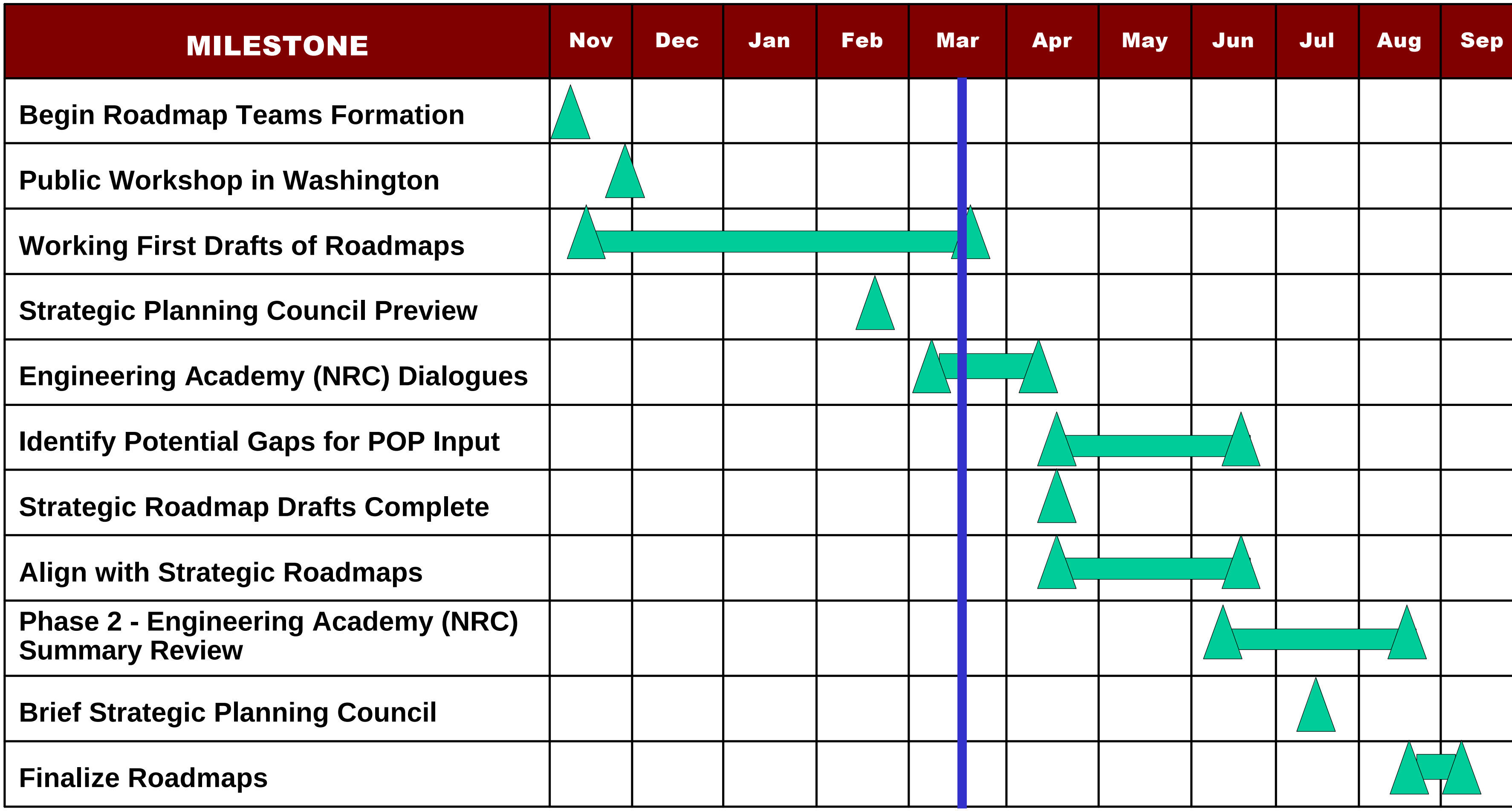
Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation (marked on the first four capabilities)

Capability Roadmap Development Schedule Overview

Advanced Planning & Integration Office



Purpose of NRC Review

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metrics for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate?

Technology Readiness Levels

Advanced Planning & Integration Office

9 Actual System Proven in Operation

8 Actual System Qualified by Demonstration

7 System Prototype Demonstration in an Operational Environment

6 System/Subsystem Model or Prototype Demonstration in a Relevant Environment

5 Component and/or Breadboard Validation in a Relevant Environment

4 Component and/or Breadboard Validation in a Laboratory Environment

3 Analytical and Experimental Critical Functions Characteristic Proof-of-Concept

2 Technology Concept and/or Application Formulated

1 Basic Principles Observed and Reported

Capability Readiness Levels

Advanced Planning & Integration Office

Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

Back-up charts

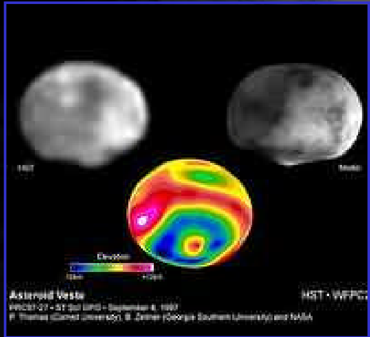
Capability Readiness Levels Defined

- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  - The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  - A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modelling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  - A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  - An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  - The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).

  -full scale flight articles
  -demonstration in appropriate operational 'envelope'
- **CRL 7: Capability Operational Readiness**
  - The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

Space Communications Capability Roadmap Interim Review

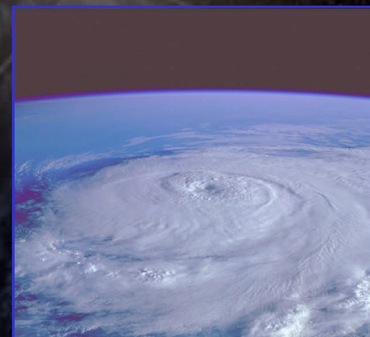
Robert Spearing
Michael Regan
March 24, 2005











NO COMMUNICATIONS

No Data

No Commands

No Pictures

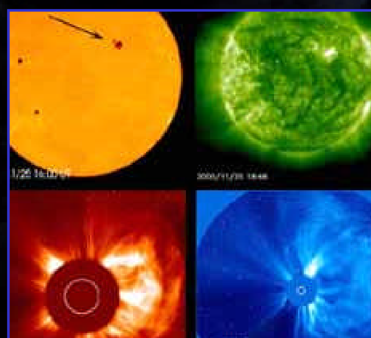
No Video

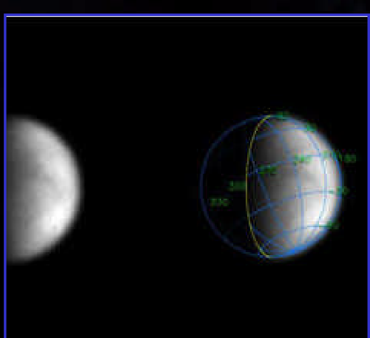
No Voice

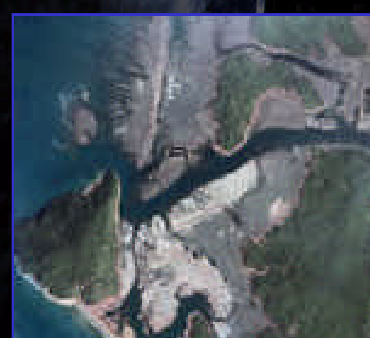
No Safety

NO SCIENCE

NO EXPLORATION

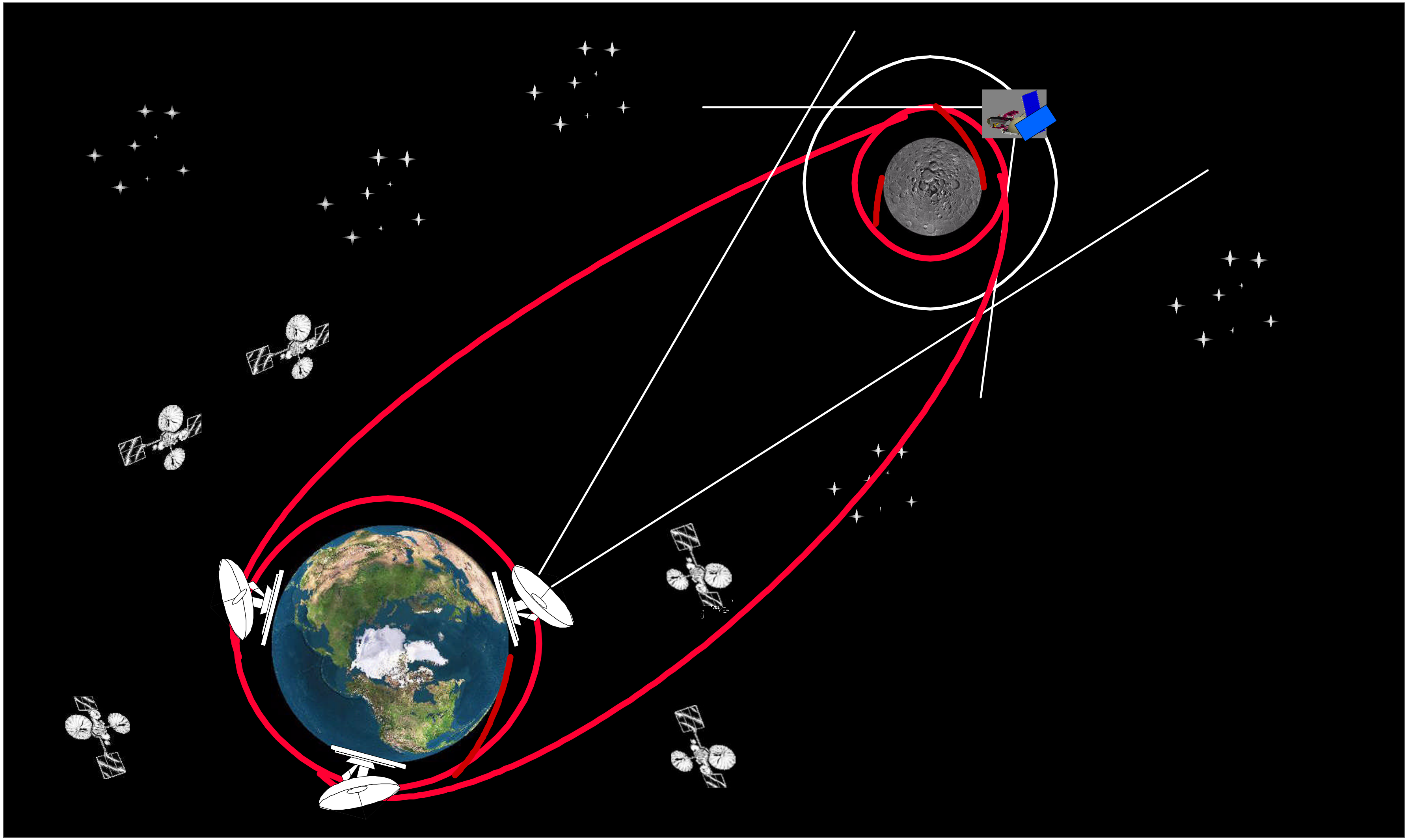







Comm Critical: All Phases of Flight…

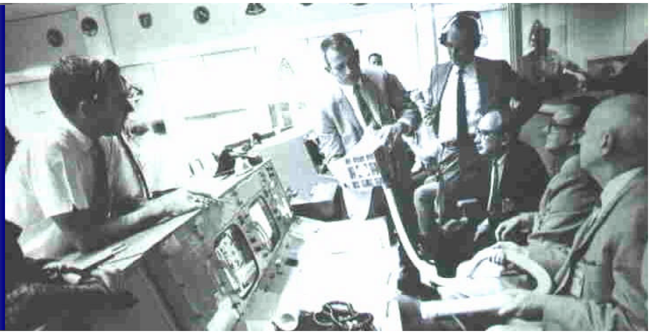
Advanced Planning & Integration Office



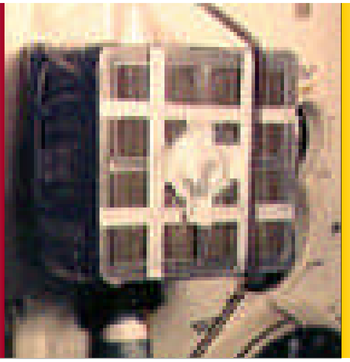
Comm-Critical Mission Safety: Apollo 13 Recovery

The Apollo 13 malfunction was caused by an explosion and rupture of an oxygen tank…All oxygen stores were lost within about 3 hours, along with loss of water, electrical power, and use of the propulsion system.

Communications with the ground support crew enabled dozens of engineers to work to find a solution



Mission Control devised a way to attach the CM canisters to the LM system by using plastic bags, cardboard, and tape- all materials carried on board.



Communications resources should be enabling, not constraining

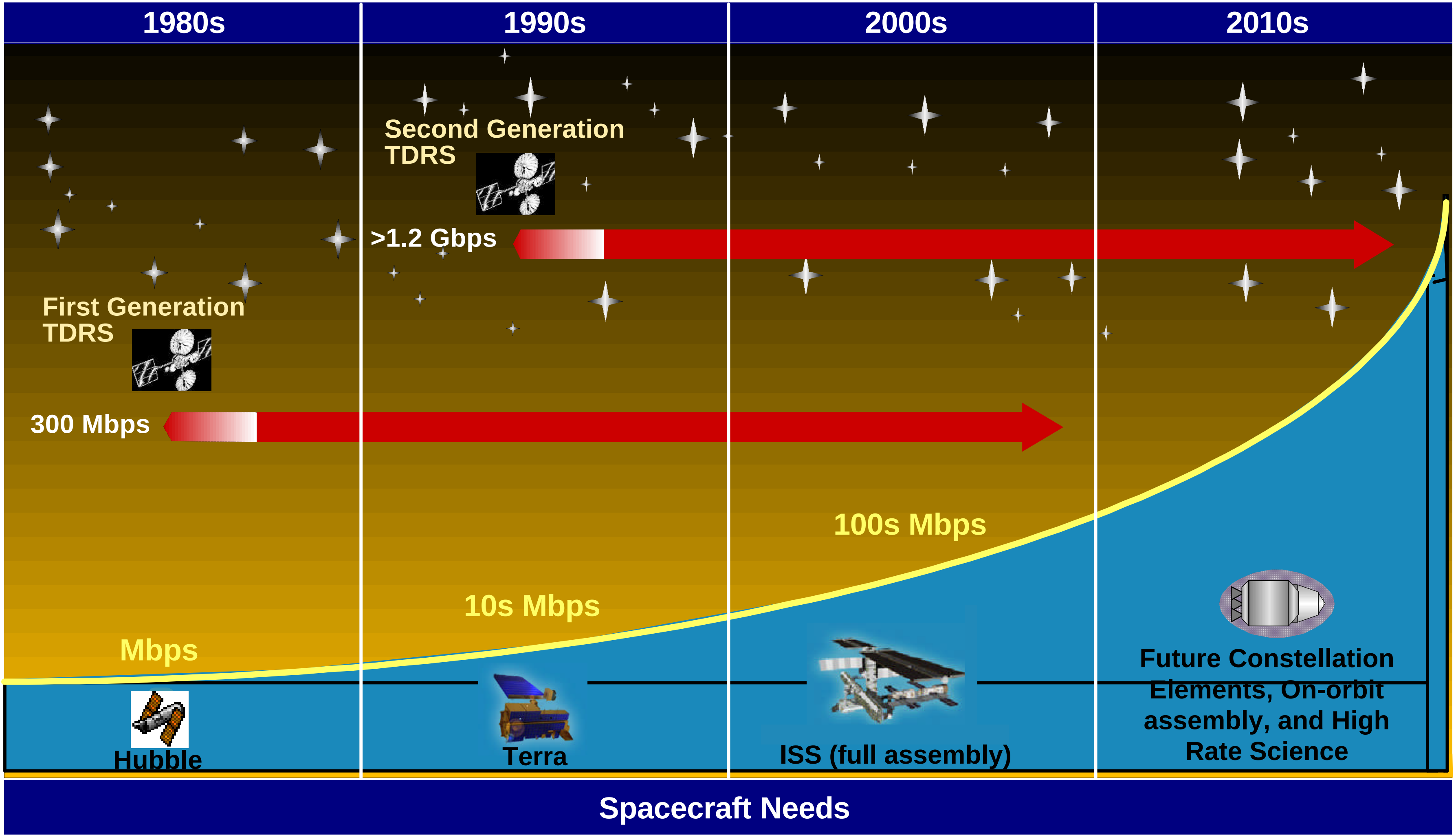
Photos: http://vesuvius.jsc.nasa.gov/er/seh/13index.htm

Timely Investment Remove Communications Constraints for Users

Advanced Planning & Integration Office

- **NASA has traditionally made strategic investments in communications capability ahead of user mission need**
  - **Must be available before mission operates**
  - **Long lead times to develop communication systems such as relays require advanced acquisition**
- **Goal for exploration and science communication capability: enable missions by providing ample, unconstraining capability**

Investing: The TDRSS Example



Executive Summary

Advanced Planning & Integration Office

- Identify the need for a robust communications and navigation architecture for the success of exploration and science missions
- Describe an approach for specifying architecture alternatives and analyzing them
- Establish a top level architecture based on a network of networks
- Identify key enabling technologies
- Synthesize capability, architecture and technology into an initial capability roadmap

Space Communication Capability Description

Advanced Planning & Integration Office

The space communication and navigation capability will fully enable evolution of the exploration and science programs.

- connectivity to exploration and science program vehicles
- spacecraft position
- transferring mission data
- vehicle telemetry
- voice and commands

Agenda

- Benefits of the Communications and Navigation Capability Roadmap
- Capability Roadmap Team
- Capability Description and Capability Breakdown Structure
- Roadmap Process and Approach
- Assumptions and Requirements, Current State-of-the-Art
- Communications and Navigation Capability Roadmap
- Sub-capability Descriptions and Relevant Technologies
- Description of Architecture Options and Recommendations
- Description of Technology Initiatives
  - Benefits
  - Current State of Art
  - Technology Roadmap
  - Technical Challenges
- Summary and Forward Work

Presentation Flow

- Speaker: Bob Spearing
- Subjects: Benefits, Roadmap Team, Capability Description
- Time: 30 min.

- Speaker: John Rush
- Subjects: Roadmap Process, Assumptions, Top-Level Roadmap, Sub-Capability, Architecture Options, Optical Communications Technology
- Time: 2 hrs 30 min.

- Speaker: Dan Williams
- Subjects: Spacecraft RF Technologies, Uplink Arraying, Programmable Communication Systems
- Time: 1 hr.

- Speaker: Bob Spearing
- Subject: Closing Remarks
- Time: 10 min.

Communications Roadmap Team

Co-Chairs

- NASA: Robert Spearing, Office of Space Operations
- Government: Michael Regan, National Security Space Office

Team Members

Government
- Michael Hawes, NASA
- Michael Luther, NASA

Ex Officio
- Pete Vrotsos, NASA
- Warren Wiley, NASA

Industry
- Greg Akers, CISCO
- Thomas Brackey, Boeing

Academia
- John Baras, UMD
- Patrick Smith, NSF

Coordinators

- NASA SOMD, Michelle Gates
- NASA APIO, Steve Mecherle

Technical Working Support

- Space Communications Architecture Working Group

Space Communications Architecture Working Group

Advanced Planning & Integration Office

John Rush (Chairperson)		NASA Headquarters
Dan Williams (Technology Assessment)	Dave Struba (Spectrum)	
Dave Graham (Cost Estimation)	Pete Vrotsos (Exploration)	
Barry Geldzahler (Science)	Donna Shortz (ISS / STS)	
Laura Hood (JSC)	Frank Stocklin (GSFC)	NASA Centers
Hugh LaMaster (Ames)	Bernie Edwards (GSFC)	
Ken Freeman (Ames)	Les Deutsch (JPL)	
Scott Sands (GRC)	Wallace Tai (JPL)	
Gene Fujikawa (GRC)	Fred Stillwagen (LaRC)	
Rich Nelson (KSC)	Bart Graham (MSFC)	

Space Communications Working Group

Advanced Planning & Integration Office

- Established prior to exploration program
- Goals:
  - Provide mission supporting communications & navigation system architectures for the agency
  - Identify key technologies needed to implement future architectures
- Architecture & technology recommended to Multi-Directorate Board
- Membership consists of representatives from both communication system providers (SN, GN, DSN) and consumers (All Space Missions)
- Approved architectures & technology initiatives provide guidance for budget formulation

Space Communication Capability
— Evolution

Advanced Planning & Integration Office

- **We have an architecture in place today; this distinguishes comm/nav from most other roadmaps**
- **Must evolve the architecture to meet the future needs of the exploration and science programs**
- **Developing communication/navigation capability requires analysis of architecture alternatives and the enabling technologies**

Comm/Nav Capability

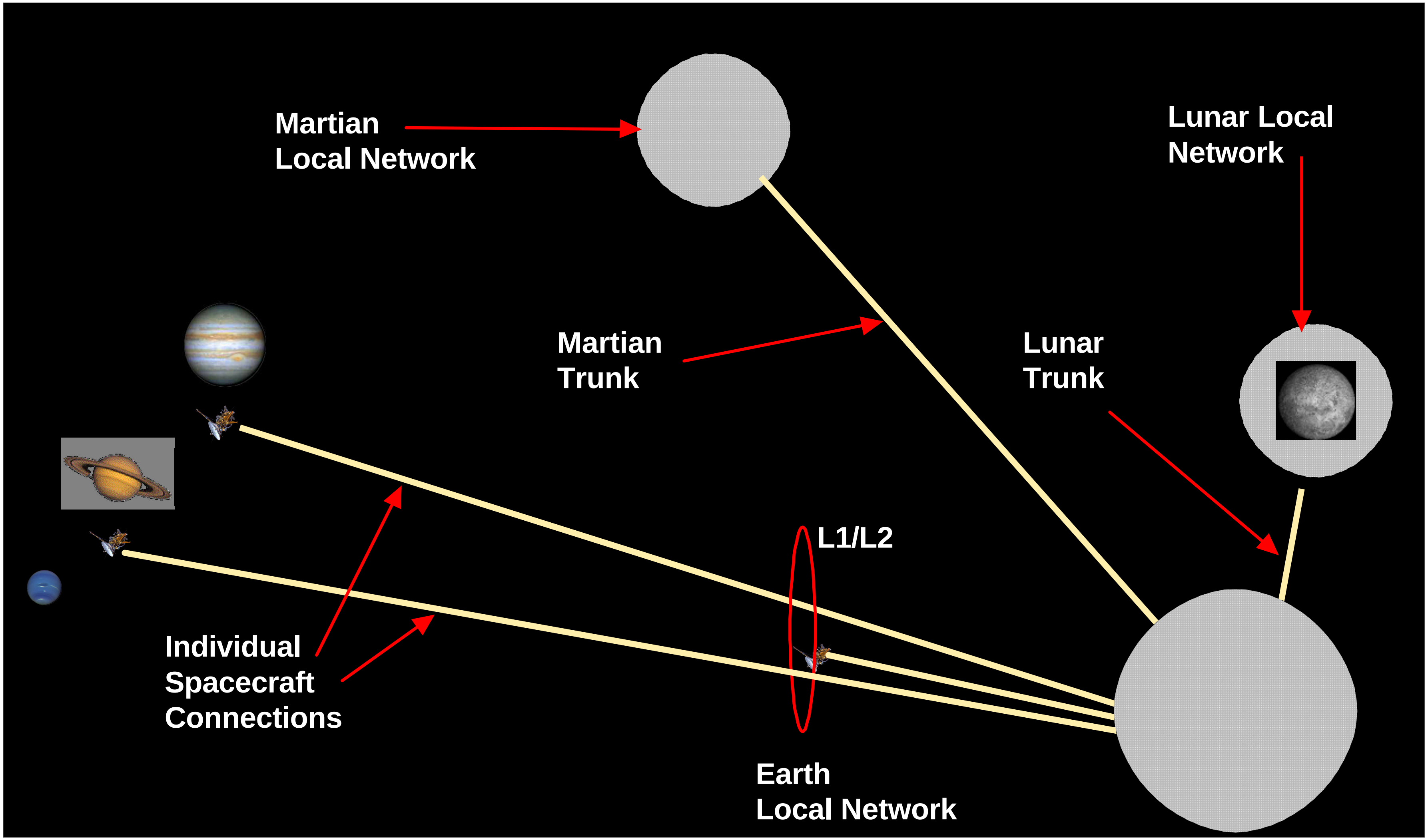
Architecture	Technology

Capability Breakdown Structure: a Services Based Approach

Advanced Planning & Integration Office

- **4.0 Communications and Navigation Architecture Capability to Support Science and Exploration**
  - 4.1 Launch
  - 4.2 Earth Orbit
  - 4.3 Transit
  - 4.4 Lunar
  - 4.5 Mars
  - 4.6 Solar System & Beyond

Top Level Conceptual Communication Architecture ~2030



National Research Council Dialogue to Assess Progress on

NASA's Communication and Navigation Capability Roadmap Development

General Background and Introduction

Steve Mecherle
Comm & Nav APIO Coordinator
March 24, 2005

Agenda

- General Background and Introduction of Communication and Navigation Capability Roadmap
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Communication and Navigation Dependencies on other Capability Roadmaps
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

Advanced Planning & Integration Office

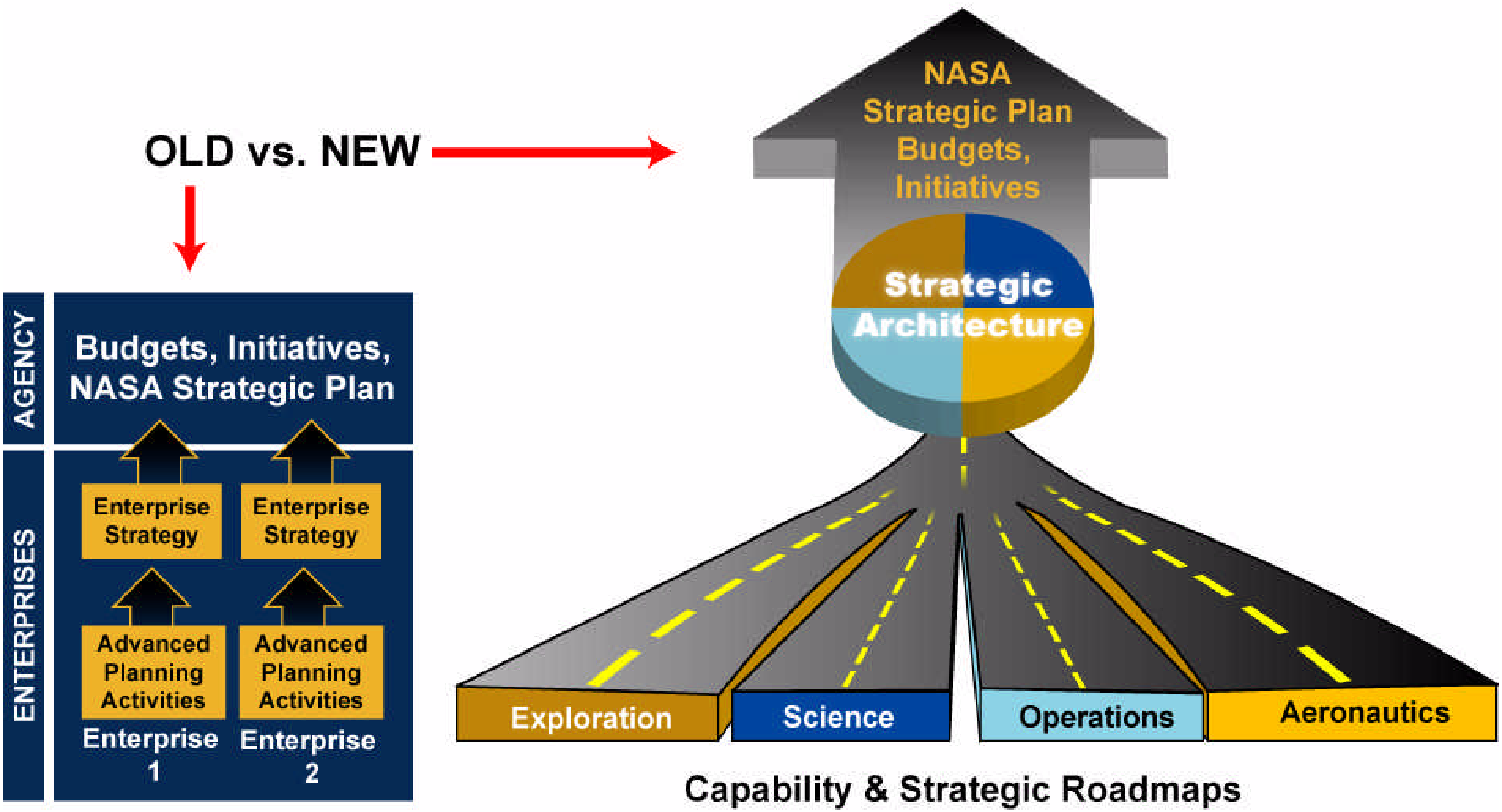
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	1. Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	6. Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	7. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	8. Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	4. Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	9. Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	5. Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	10. Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

Agency Goals and Objectives

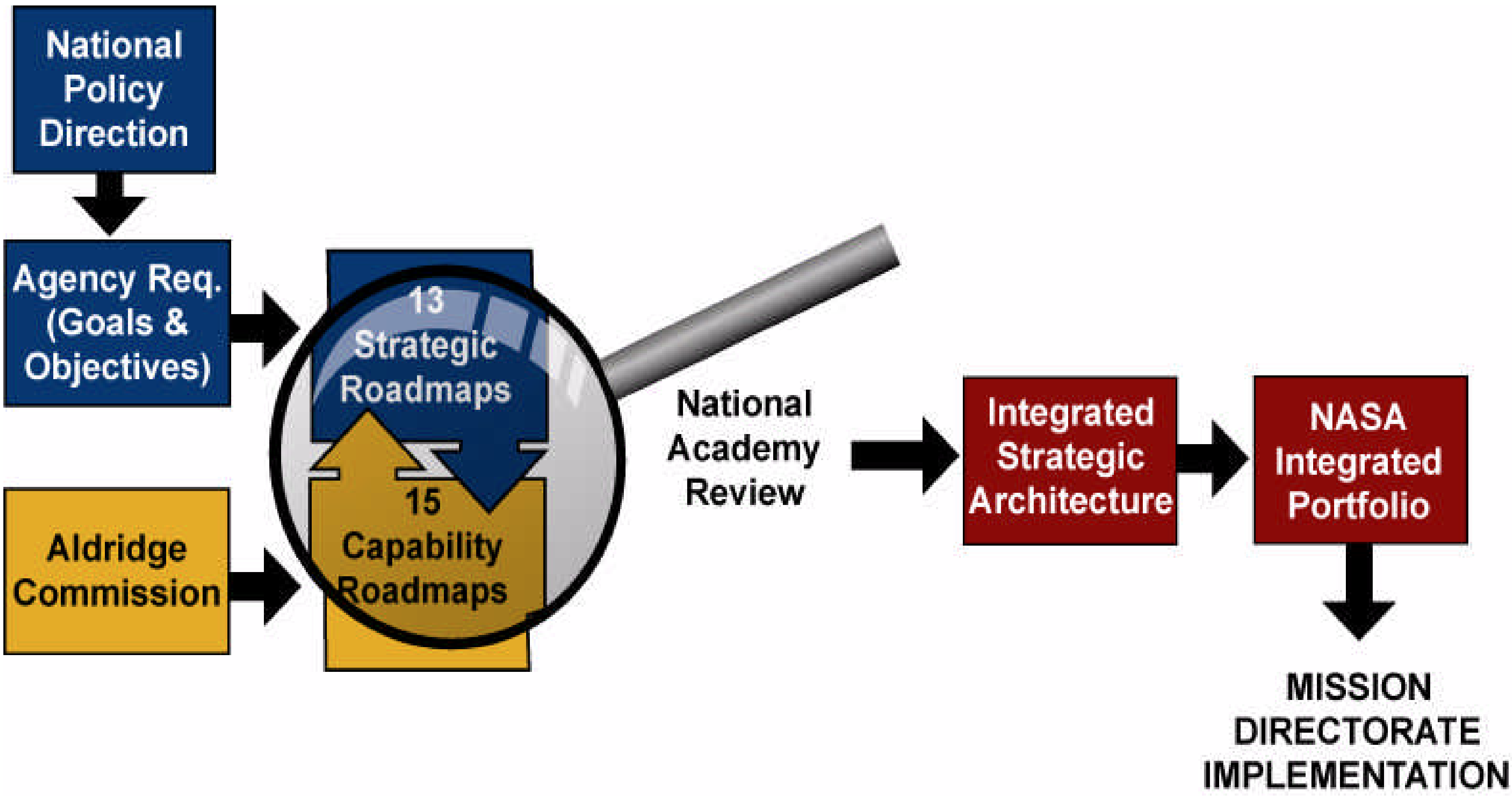
Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	3. Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration.	4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	5. Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	11. Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	14. Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems. (SRM 9)	17. Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)
	12. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	15. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)	18. Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)
	13. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	16. Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Charles Elachi)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

Advanced Planning & Integration Office

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

- Broad human and robotic science and exploration goals, priorities, anticipated discoveries
- High-level milestones, options, and decision points
- Implementation approaches, suggested missions

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators Also with Each Team

◤ – DoD Participation

Strategic Roadmaps - continued

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Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule

Advanced Planning & Integration Office

Milestone	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Plan Appproved and Co-chairs Signed Up	━	━▲										
Complete Team Formation, Begin Work	━	━▲										
Interim Roadmap Products	▲━	━	━	▲								
Teams Mid-term Status Review					▲							
Interim Roadmap Deliverable						▲						
First Synthesis Workshop							▲					
Roadmaps Submitted for NRC Review								▲				
NRC Reviews Complete								▲				
Second Synthesis Workshop								▲				
NAC Workshop										▲		
Integrated Strategic Architecture												▲

Capability Roadmaps

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- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**

    1/3 Industry

    1/3 NASA & other Government Agencies

    1/3 Academia
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Advanced Planning & Integration Office

Capability	NASA chair	External chair
High-Energy Power and Propulsion (DoD participation)	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation (DoD participation)	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories (DoD participation)	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation (DoD participation)	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility (DoD participation)	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators Also with Each Team

(marker) = DoD Participation

Capability Roadmaps - continued

Advanced Planning & Integration Office

Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

Advanced Planning & Integration Office

MILESTONE	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Begin Roadmap Teams Formation											
Public Workshop in Washington											
Working First Drafts of Roadmaps											
Strategic Planning Council Preview											
Engineering Academy (NRC) Dialogues											
Identify Potential Gaps for POP Input											
Strategic Roadmap Drafts Complete											
Align with Strategic Roadmaps											
Phase 2 - Engineering Academy (NRC) Summary Review											
Brief Strategic Planning Council											
Finalize Roadmaps											

Purpose of NRC Review

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

Technology Readiness Levels

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9 Actual System Proven in Operation

8 Actual System Qualified by Demonstration

7 System Prototype Demonstration in an Operational Environment

6 System/Subsystem Model or Prototype Demonstration in a Relevant Environment

5 Component and/or Breadboard Validation in a Relevant Environment

4 Component and/or Breadboard Validation in a Laboratory Environment

3 Analytical and Experimental Critical Functions Characteristic Proof-of-Concept

2 Technology Concept and/or Application Formulated

1 Basic Principles Observed and Reported

Capability Readiness Levels

Advanced Planning & Integration Office

Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

Comm / Nav Roadmap Crosswalk

Advanced Planning & Integration Office

High-energy power nd propulsion	In-space

Advanced Planning & Integration Office

All of the noted Capability Roadmaps below are dependent on Communication and Navigation Services (except Nanotechnology)

2.) High-energy power and propulsion (moderate)
- Electric propulsion dependence on navigation

3.) In-space transportation (critical)
- Requires TT&C link to Earth
- Critical dependence on TT&C during critical event coverage
- Vehicle-to-vehicle links needed for assembly and docking operations
- Comm security needed
- Navigation requirement is continuous
- Navigation provided by combination of autonomous and linked methods
- Requires time phasing of capability with missions

4.) Advanced telescopes and observatories (critical)
- Critical dependence on TT&C and mission data transport links to Earth (or Earth orbiting relay)
- Potential TT&C and mission data transport links to lunar or planetary orbiter
- Comm security needed
- Dependence on navigation critical for formation flying, VLBI, or scientific instrument pointing
- Navigation provided by combination of autonomous and linked methods
- May have crosslinks between array elements
- Requires time phasing of capability with missions

5.) Communication and Navigation (Same element)

Communication / Navigation Roadmap Dependencies (cont)

6.) Robotic access to planetary surfaces (critical)
- Dependent on TT&C and mission data transport links to Earth, Earth orbiter, or lunar or planetary orbiter
- May require surface-to-surface links or network
- Comm security needed
- Navigation provided by combination of autonomous and linked methods
- Requires time phasing of capability with missions

7.) Human planetary landing systems (critical)
- Critical dependence on assured TT&C, voice, and mission data transport links to Earth, Earth orbiter, or lunar or planetary orbiter
- May require surface to lander beacon link
- May require surface-to-surface links or network
- Comm security needed
- Critical dependence on highly reliable, highly available navigation
- Navigation provided by combination of autonomous and linked methods
- Navigation and communication required for rendezvous and docking
- May incorporate docking sensor on vehicle
- Requires time phasing of capability with missions

8.) Human health and support systems (moderate)
- Depends on vehicle TT&C, voice and mission data links for health status
- May require local wireless links
- May become a two-way communication driver to link crew to earth-based medical resources
- Special privacy issue on links

Communication / Navigation Roadmap Dependencies (cont)

Advanced Planning & Integration Office

9.) Human exploration systems and mobility (critical)
- Critical dependence on assured TT&C, voice, and mission data transport links to Earth, Earth orbiter, or lunar or planetary orbiter
- Astronaut EVA suits may require TT&C, voice and mission data links
- May require surface-to-surface links or network
- Comm security needed
- Potential mission data dependence on in-space deployable antennas
- Potential mission data dependence on surface-erectable antennas
- Critical dependence on highly reliable, highly available navigation
- Navigation provided by combination of autonomous and linked methods
- Requires time phasing of capability with missions

10.) Autonomous systems and robotics (critical)
- Critical dependence on system-to-system autonomous communication network for TT&C and mission data transport with systems located nearly anywhere
- May require links for critical event coverage
- May require communication on demand networking
- May require intervehicle communication for rendezvous / docking
- Navigation provided by combination of autonomous and linked methods

11.) Transformational spaceport/range (critical)
- Critical dependence on assured TT&C, voice, and mission data transport links to Earth or Earth orbiter
- Critical dependence on highly reliable, highly available navigation
- Tradeoff of range radar or space-based range (SBR increases dependence on comm/nav and GPS)
- Ramge radar can provide autonomous tracking w/out dependence on vehicle TT&C
- Comm security needed
- Navigation provided by combination of autonomous and linked methods
- Requires time phasing of capability with missions

Communication / Navigation Roadmap Dependencies (cont)

12.) Scientific instruments/sensors (critical)
- Critical dependence on TT&C and mission data transport links to Earth (or Earth orbiting relay)
- Potential TT&C and mission data transport links to lunar or planetary orbiter
- Comm security needed
- May have crosslinks between array elements
- May require inter-instrument communications
- Requires time phasing of capability with missions

13.) In situ resource utilization (moderate)
- May require surface communication network with fixed and possibly mobile elements

14.) Advanced modeling, simulation, analysis (moderate)
- Long haul, ultra-wide bandwidth
- Protocols
- Data access / virtual storage tools
- Comm architecture level simulation and modeling requirements
- Communication traffic load modeling
- Communication testbed

15.) Systems engineering cost/risk analysis (moderate)
- Utilization / development of interface standards (NASA / DoD / Int'l)
- Dave Graham is liason

16.) Nanotechnology (moderate)
- Potential communication devices
- Potential structural elements

Scope of the Comm and Nav Capability: Relating to the Other Roadmaps

Advanced Planning & Integration Office

Key Questions For Other Roadmap Teams

Category	Question
Data Rates	How much information (i.e., instantaneous rates) generated by mission elements for what types of information (e.g., voice, video, command, telemetry, mission data)?
Data Volume	How much information is expected to be generated (overall or in a certain time period)?
Distance	How far does the information have to be sent? (where are the mission elements located?)
Coverage	What portions of lunar/planetary bodies need coverage by C&N assets and when (how often) do missions need coverage? (e.g., periodic overhead passes at specific locations, scheduled passes over regions, or 24x7 coverage for the whole body)
Availability	How often does the communication connection have to be established to transmit desired information?

Key Questions For Other Roadmap Teams (continued)

Category	Question
Latency	Is the information time critical and, if so, what deadline(s) must be met? (e.g., telerobotic command and control loop constraints or human reaction times)
Connectivity	Do any missions need special connections such as inter-satellite links for cooperating spacecraft (S/C) (e.g., leader/follower, clusters, swarms, and cooperating rovers)?
Navigation Precision and Accuracy	How accurate does your arrival time, speed, and location have to be at your operational location or destination (e.g., landing within a crater or within 5m of a S/C; entry into a near circular orbit within 10 km of planned altitude or atmospheric interface within heat shield tolerances)?

Back-up charts

Capability Readiness Levels Defined

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- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  - The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  - A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modelling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  - A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  - An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  - The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).

  -full scale flight articles
  -demonstration in appropriate operational 'envelope'
- **CRL 7: Capability Operational Readiness**
  - The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

Advanced Telescopes & Observatories Capability Roadmap Presentation to the NRC

March 15th, 2005

Agenda

- Introduction– Lee Feinberg
- Capability Roadmaps
  - Optics – Phil Stahl
  - Wavefront Sensing and Control and Interferometry – Jim Fienup
  - Distributed and Advanced Spacecraft – Dave Miller
  - Large Precision Structures – Ron Polidan
  - Cryogenic and Thermal Control Systems – Jim Oschman
  - Infrastructure – Gary Matthews (for Jim Burge)
- Conclusion – Howard MacEwen

Capability Roadmap Team

Advanced Planning & Integration Office

Co-Chairs

NASA: Lee Feinberg, Goddard Space Flight Center
External: Howard MacEwen, SRS Technologies

Government
Jim Breckinridge, JPL
Pete Jones, AFRL
David Tratt, JPL/ESTO
H. Philip Stahl, MSFC

Industry
Jim Crocker, LMCO
Ron Polidan, NGST
Gary Matthews, ITT
Mark Stier, Goodrich
Jim Oschmann, BATC

Academia
Jim Fienup, UofR
Dave Miller, MIT
Jim Burge, UAz
Dan Inman, Va Tech

Center Reps (Ex-officio)
John Hong, JPL
Scott Smith, MSFC
Ray Boucarut, GSFC

Coordinators
Directorate: Harley Thronson, HQ
APIO: Dan Coulter, JPL

Capability Description

- The Advanced Telescope and Observatory Capability includes those sets of systems and associated technologies necessary to collect, concentrate and combine electromagnetic bands ranging from gamma-rays to radio waves, and including gravity-waves.
- The Committee does not consider technologies associated with the detection, conversion, or processing of observed signals into science data. These technologies are the responsibility of the Scientific Instruments and Sensors Roadmap Committee.

ATO Capability Breakdown Structure

Advanced Planning & Integration Office

- 4.0 Advanced Telescopes and Observatories — Lee Feinberg, Howard MacEwen
  - 4.1 Optics — Phil Stahl
    - 4.1.1 Cryogenic Normal Incidence Optics (IR, FIR, Submm, uwave)
    - 4.1.2 Precision Normal Incidence Optics (EUV, UV, Vis, etc.)
    - 4.1.3 Grazing Incidence Optics (X-ray, etc.)
    - 4.1.4 Diffractive, Refractive or Other Optics (Gamma Ray, X-Ray, etc.)
  - 4.2 Wavefront Sensing & Control & Interferometry — Jim Fienup
    - 4.2.1 Wavefront Sensing
    - 4.2.2 Metrology
    - 4.2.3 Wavefront Control
    - 4.2.4 WFSCI Testbeds
  - 4.3 Distributed and Advanced Spacecraft Systems — Dave Miller
    - 4.3.1 Platforms
    - 4.3.2 Systems
    - 4.3.3 Subsystems
  - 4.4 Large Precision Structures — Ron Polidan
    - 4.4.1 Structure Stability & Precision
    - 4.4.2 Materials Properties
    - 4.4.3 Implementation Capability
  - 4.5 Cryogenic & Thermal Control Systems — Jim Oschmann
    - 4.5.1 Passive Cooling
    - 4.5.2 Active Cooling
    - 4.5.3 Thermal Isolation
  - 4.6 Infrastructure — Jim Burge
    - 4.6.1 Integration & Test Facilities
    - 4.6.2 In-space Observ. Support/Servicing
    - 4.6.3 Workforce

Traceability of Key ATO Drivers

Advanced Planning & Integration Office

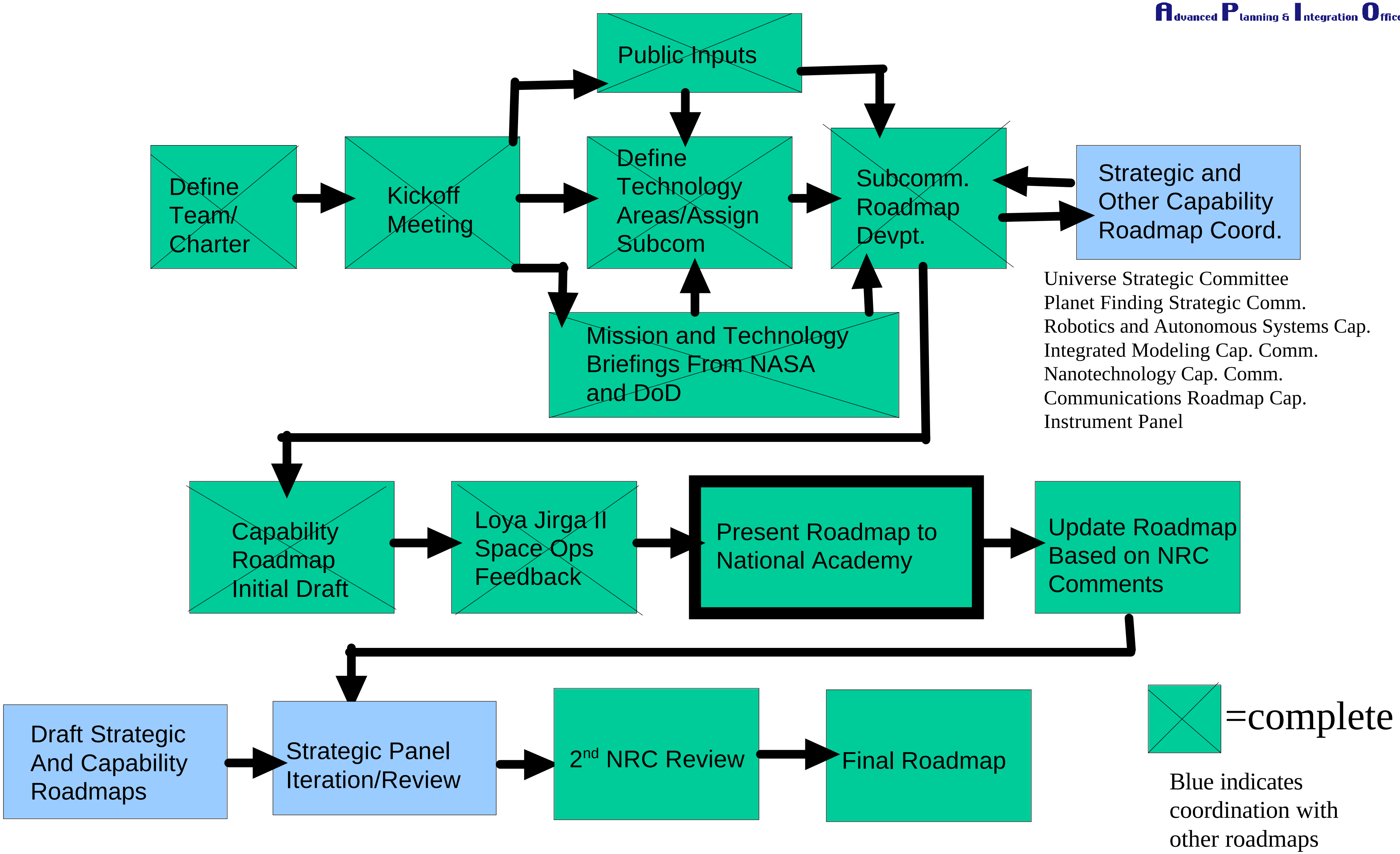
- Presidential Vision for Space Exploration "Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars"
- Aldridge Report: "The Commission finds implementing the space exploration vision will be enabled by scientific knowledge, and will enable compelling scientific opportunities to study Earth and its environs, the solar system, other planetary systems and the universe"
- NASA's Direction for 2005 and Beyond (budget supplement)
- National Academy Astronomy and Astrophysics Decadal Survey
  - High Priority Major (Space) Initiatives in Priority Order:
    - James Webb Space Telescope (formerly NGST)
    - Constellation X Observatory
    - Terrestrial Planet Finder/Single Aperture Far Infrared Observatory
  - Moderate (Space) Initiatives
    - GLAST
    - LISA
    - Solar Dynamics Observatory
    - EXIST (Black Hole Finder)
  - Note: SIM was included in the 1991 Decadal Survey Moderate Initiatives and was recommended for completion.
- Reference mission list provided by Science Directorate and being reviewed by strategic roadmapping (for post-NRC update)
  - Listed as assumptions for now

Committee Assessment of ATO Roadmapped Missions to Strategic Panels

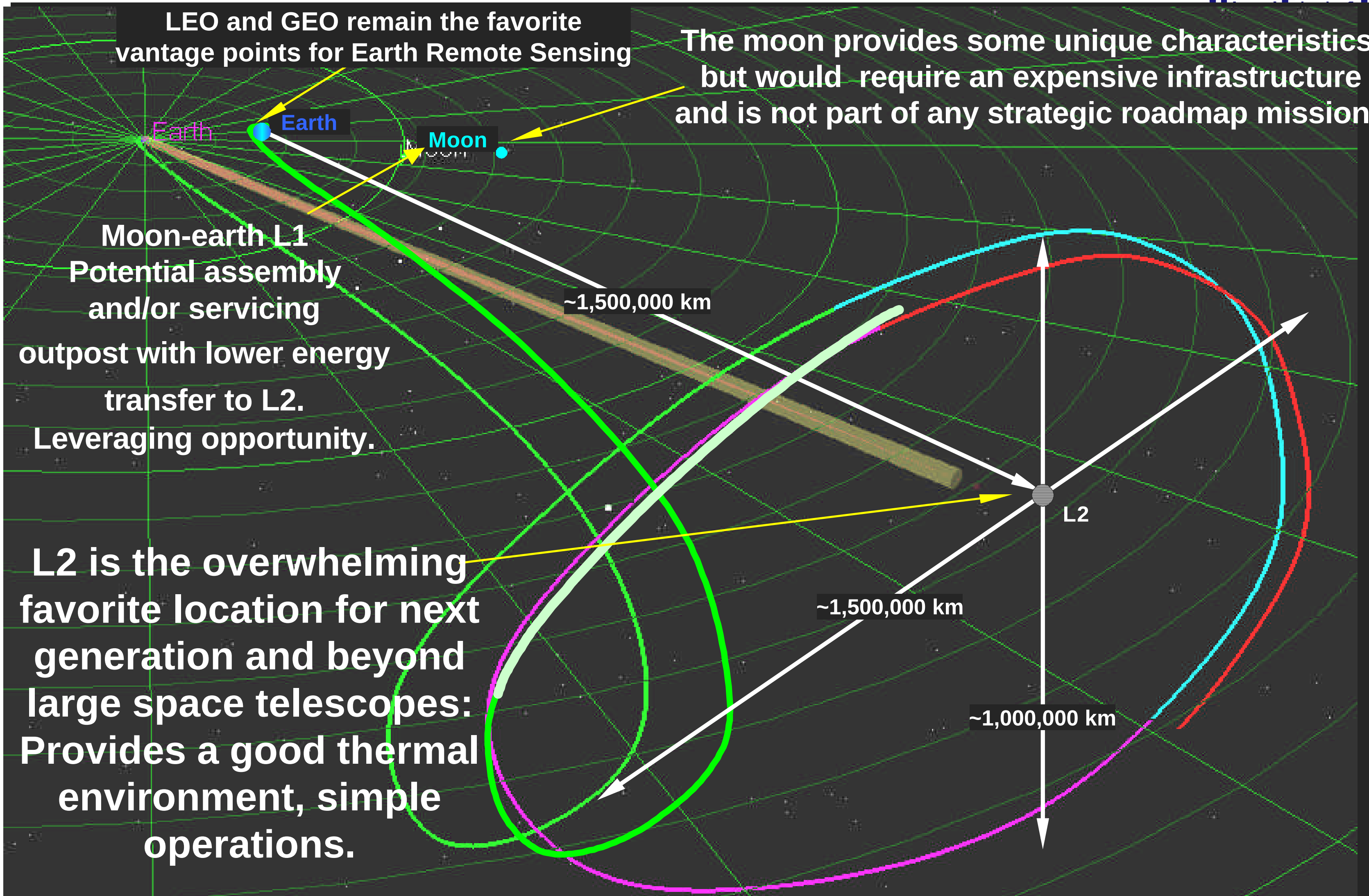
Advanced Planning & Integration Office

	Extrasolar Planet Science & Exploration	Universe Origins, Evolution, & Destiny	Earth System Science	Solar System Science & Exploration	Sun-Earth System Science
LUVO		X		X	
LF	X				
PI	X				
TPF-C	X				
TPF-I	X				
ConX		X			
DEM		X			
EUXO		X			
FISI	X	X			
IP		X			
LISA		X			
SAFIR	X	X			
UVOI		X			X
BHF		X			
BHI		X			
BBO		X			
EASI			X		
GEC			X		X
GSM			X		
HResCO2			X		
Leo LFSM			X		
LFFInSAR			X		
MMS					X
MTRAP					X
WS LIDAR			X		
LEO INSAR			X		
MEO INSAR			X		
GEO INSAR			X		
GEC					X
Mag Con					X
Mars EOR				X	
Telemachus					X
ASXI					X
RAM					X

ATO Roadmap Process

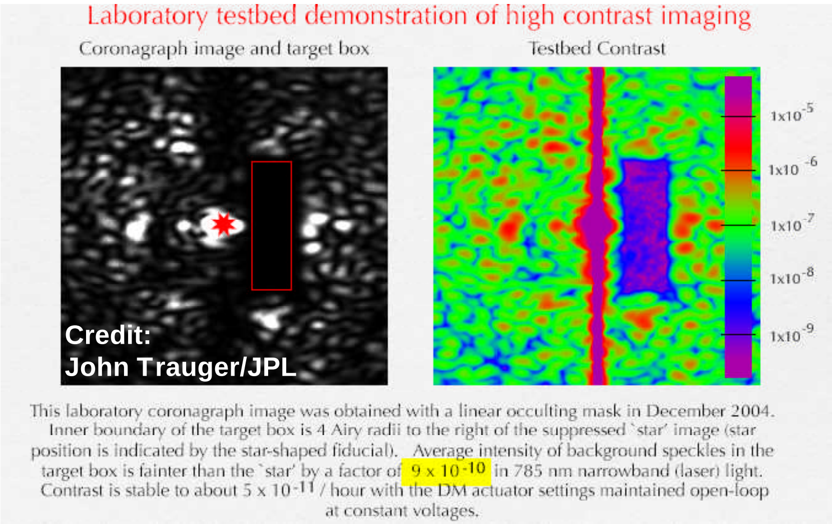


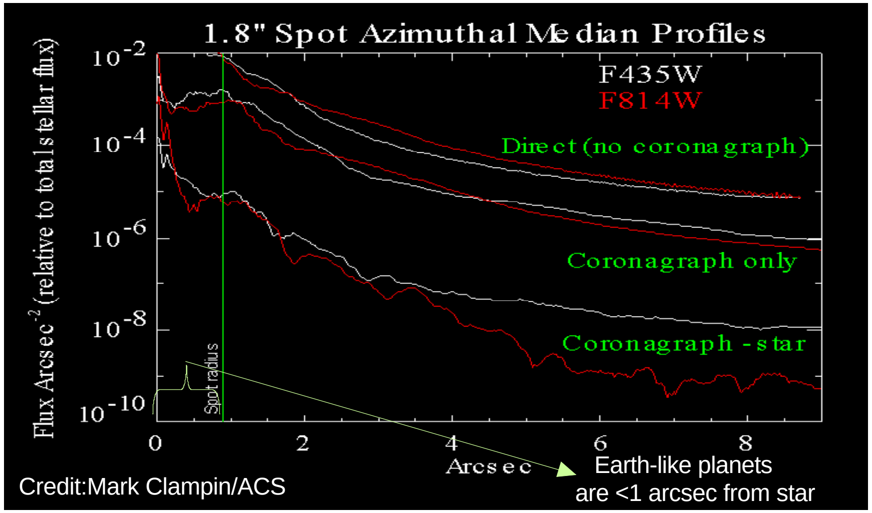
Key Vantage Points for Large Observatories



Large Observatories in the Future: Not Just Bigger, But Better

- Future Advanced Telescopes and Observatories won't just be bigger but also better. For example, if we want to study an extra-solar earth-like planet in the visible, then the amount of contrast of the system (a measure of how well an optical system can block a bright star) is critical

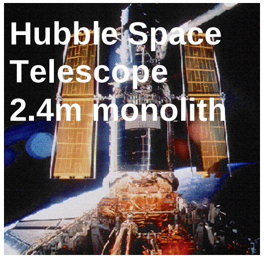




- Contrast is driven by the smoothness of the mirrors, the stability of the telescope system, and the basic architecture (eg, active control), optics and algorithms used to block the bright star and image the dim planet.
- Black Hole X-ray systems and gravity wave systems also need "better" optical systems (higher precision). For FIR and Submm systems, better usually means colder.

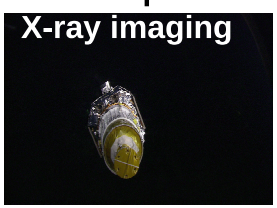
ATO Current vs. Future Capabilities

Advanced Planning & Integration Office

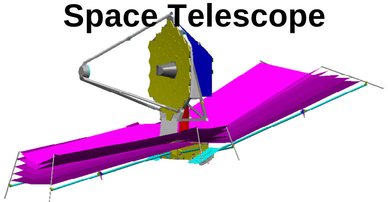

Hubble Space Telescope 2.4m monolith


Spitzer Space Telescope .8m Cryogenic telescope

Chandra X-ray Telescope: X-ray imaging



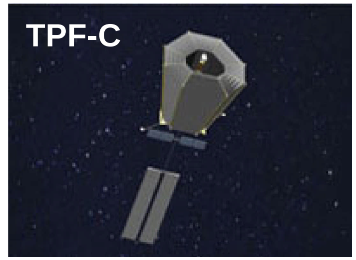
James Webb Space Telescope



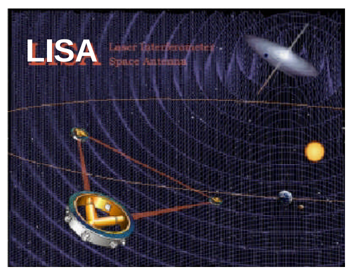
6.5m Segmented Telescope
Wavefront Sensing/Control
Sunshade Pass. Cooling to 35K
Large Deployables


SIM: Astrometry

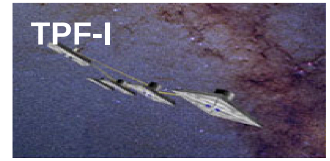
Precision Metrology Interferometry


TPF-C

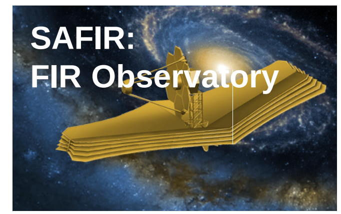
4x8 meter primary
Prec. Optics/occulters
Deformable mirrors/
Advanced Algorithms
Stable strucutres/
Active Control


LISA

Gravity Wave Detection:
3 space craft constellation.
Sub nm displacements measured by laser/interferometery
Mircro-thrusters


TPF-I

Nulling Interferometry
Formation Flying

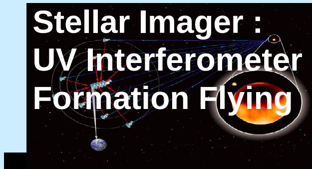

SAFIR: FIR Observatory

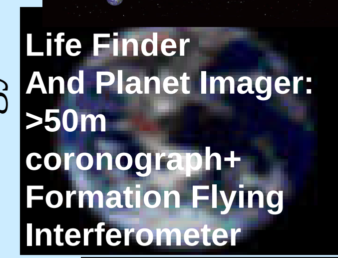
10-meter FIR Telescope
5-Kelvin Mirrors
Active/Passive Cooling

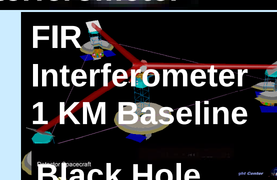

Constellation X: X-ray Spectroscopy

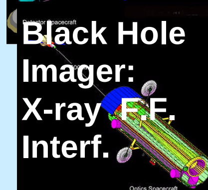
4 Co-pointed 1 meter
X-ray <15" Telescopes

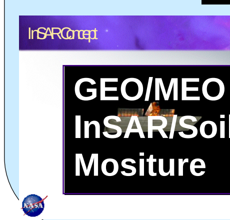
Sample Long Term Missions That Drive Technology


Stellar Imager : UV Interferometer Formation Flying

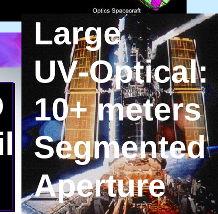

Life Finder And Planet Imager: >50m coronograph+ Formation Flying Interferometer


FIR Interferometer 1 KM Baseline


Black Hole Imager: X-ray F.F. Interf.



GEO/MEO InSAR/Soil Mositure


Large UV-Optical: 10+ meters Segmented Aperture

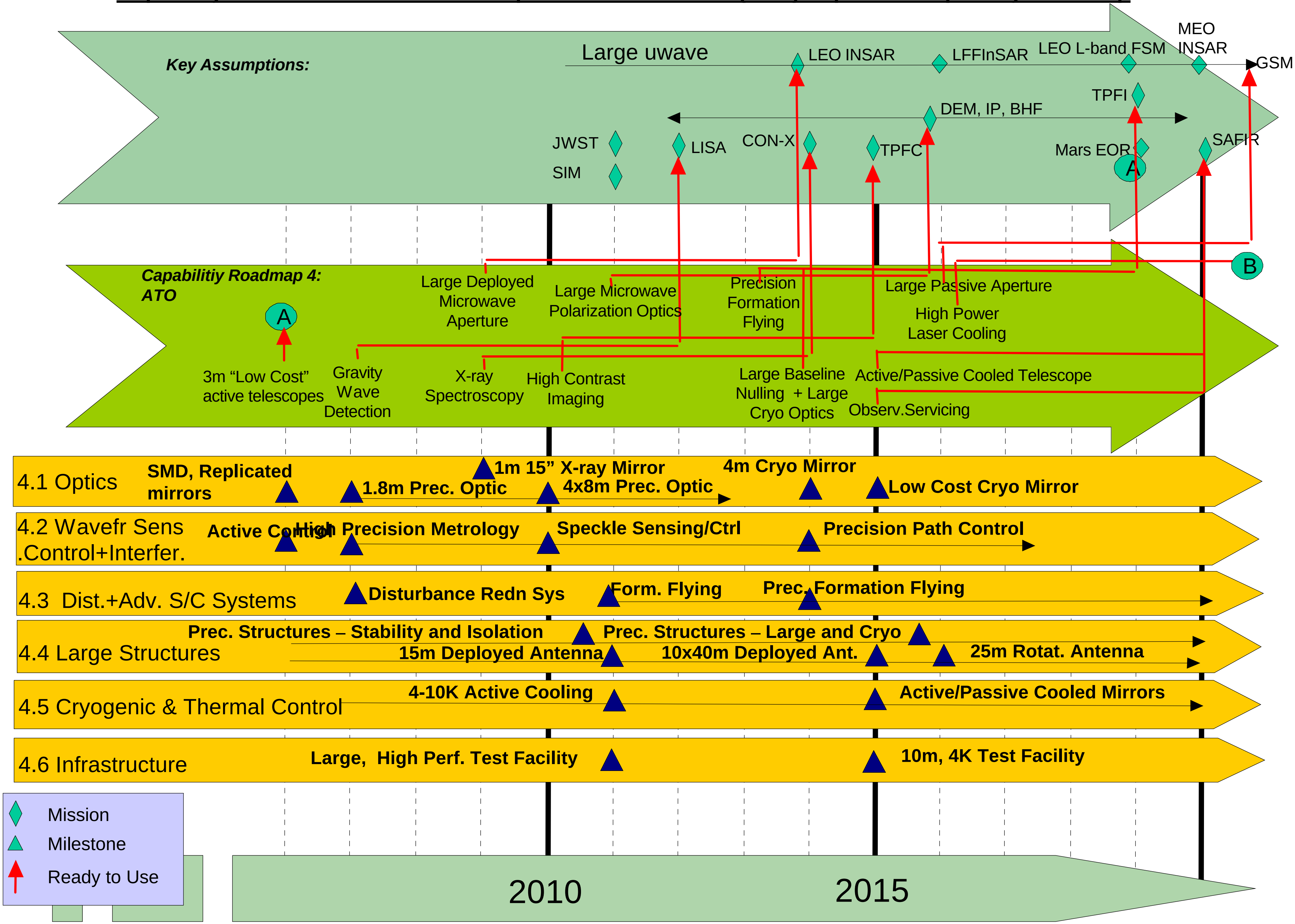
Current — **In Development** — **2005-2015** — **2015-2025** — **20+ Years**

Note: Architectures and technologies shown are current configurations and will likely evolve.

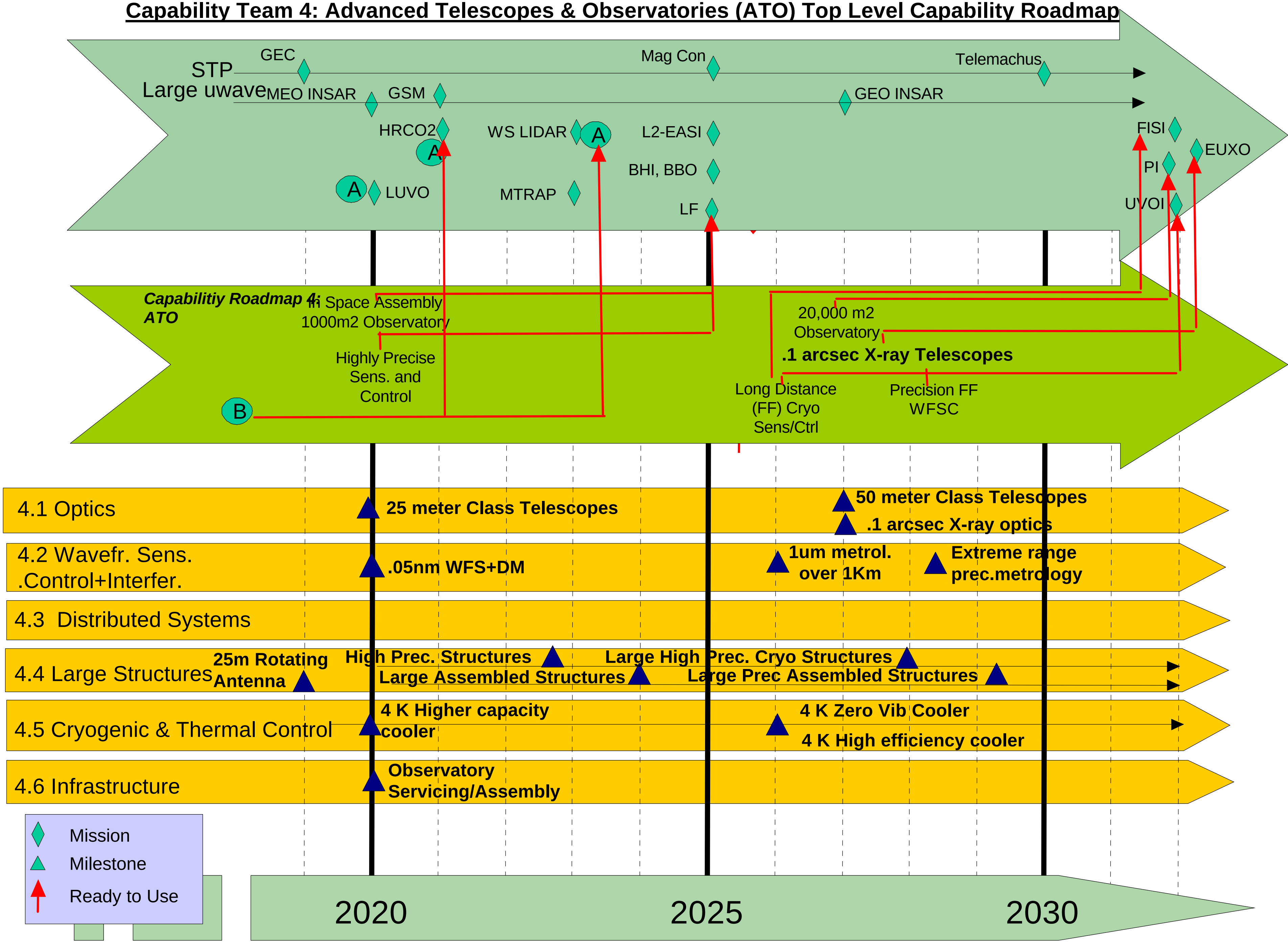
Top Level Assumptions for ATO

- Instrument panel covers cooling of instruments and sensors, including:
  - Black hole finder heat pipe cooling to radiators
  - Inflation Probe active cooling
    - Telescope passive cooling to 60 K
  - Optical bench cooling
  - CON-X detector cooler needs
- Instrument roadmap panel covers instrument optics
- Instrument roadmap panel covers lasers (including those used for LISA)
- Instrument panel covers microwave electronics and antennas/waveguides (ATO covers large deployed pieces)
- Modeling roadmap panel covers modeling and integrated modeling tools (included in backup slides)
- Do not roadmap JWST and SIM except to show as references where appropriate
- Key assumption was the list of missions and launch dates provided as reference missions. A summary of those missions show up on the timeline.
  - List is a subset of the reference missions provided by NASA HQ Science Mission Directorate divisions to APIO Capability roadmap teams
  - Some minor modifications to the list of missions was made at the suggestion or Strategic Roadmap Panels but we expect a future iteration of dates and missions with the strategic panels
- Mission technology needs based on NASA heritage roadmaps, presentation and reference material from missions

Capability Team 4: Advanced Telescopes & Observatories (ATO) Top Level Capability Roadmap



Capability Team 4: Advanced Telescopes & Observatories (ATO) Top Level Capability Roadmap



Capability 4.1
Optics

Presenter:

Phil Stahl, Team Lead

4.1 Optics Capabilities

- Optics Capability is defined as a system of components such as mirror substrates, coatings, actuators, and their respective manufacture & test processes necessary to enable the ability to collect and concentrate electromagnetic radiation.

- Four basic capabilities based upon wavelength region of the electromagnetic spectrum have been defined:

  - 1.1 Cryogenic Optics (for IR, Far-IR, Sub-MM, Microwave)
  - 1.2 Precision Optics (for EUV, FUV, UV, Visible)
  - 1.3 Grazing Incidence Optics (for X-Ray)
  - 1.4 Diffractive, Refractive & Novel Optics (for Gamma, X- ray or other)

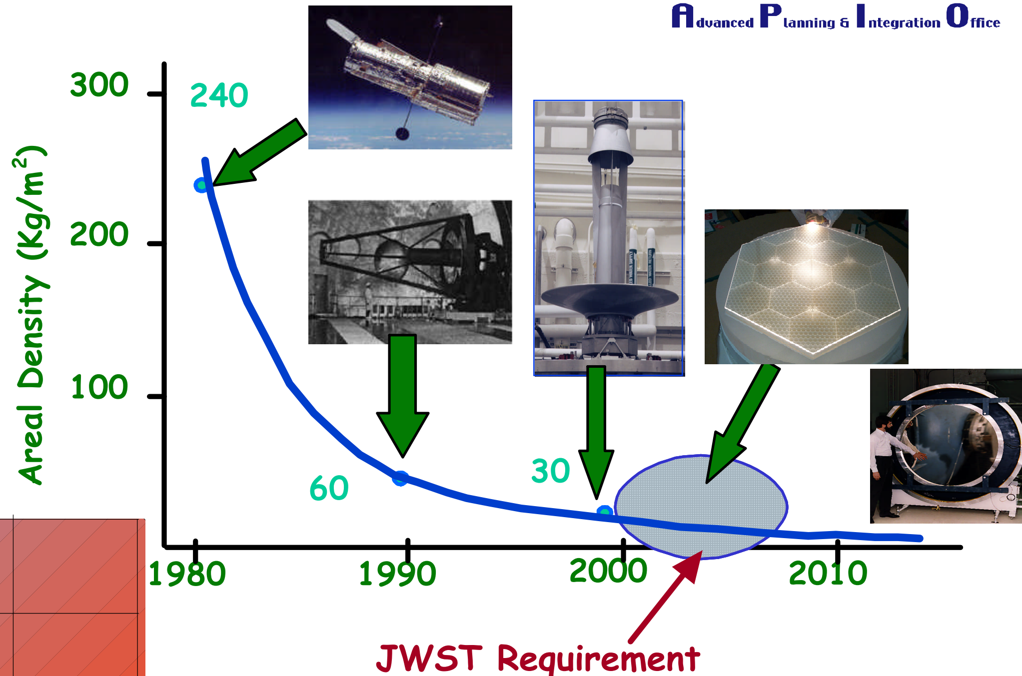
- Associated with each Capability are several Technology Figures of Merit which are closely related to system technical performance.

Space Telescopes need to Double in Size over Next 20 Years for NASA Science Missions

Challenges for Optical & X-Ray Telescopes:

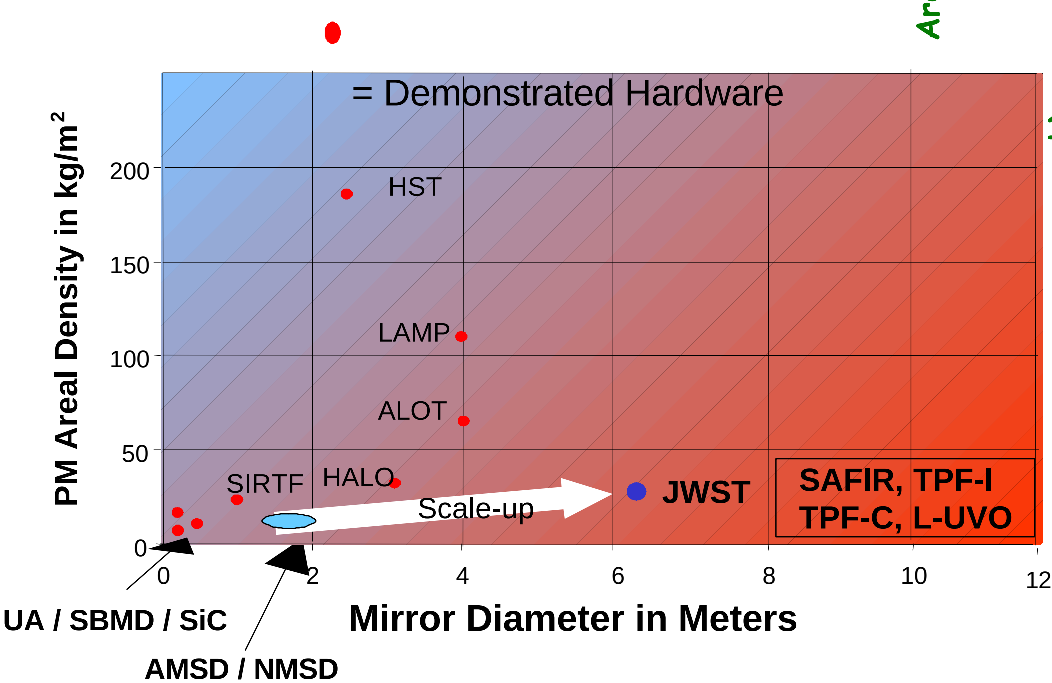
Areal Density to enable up-mass for larger telescopes.

Cost & Schedule Reduction.



Primary Mirror	Time & Cost	
HST (2.4 m)	• 1 m^2/yr	• \$10M/m^2
Spitzer (0.9 m)	• 0.3 m^2/yr	• \$10M/m^2
AMSD (1.2 m)	• 0.7 m^2/yr	• \$4M/m^2
JWST (6 m)	> 6 m^2/yr	< \$3M/m^2

Note: Areal Cost in FY00 \$



4.1.1 Cryogenic Optics

Description of Capability needed:

Large-Aperture Modest-Quality Mirrors that enable IR/FIR/SMM/MW science missions operating at temperatures from 4 to 40K.

Low Operating Cost Mirrors that enable mission affordability, i.e. lower areal cost, shorter fabrication schedules and lower areal density.

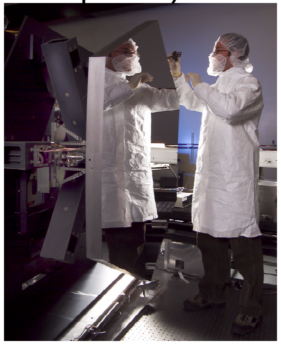
Need/Gap Assessment:

Manufacturing:
- 10X Decrease in Areal Cost
- 0 to 3X Increase in Mirror Segment Size
- 2X Decrease in Areal Density

Demonstrated Key Metrics:
- Figure Quality
- Thermal/Mechanical Stability
- Thermal Deformation

History/State-of-the-art:

- State-of-the-art/Mission History
  - Spitzer, WMAP, AMSD (flight/pathfinder)
  - JWST, Herschel, SPICA (in development)
- Leading Candidates
  - Beryllium (incumbent)
  - SiC
  - Glass – ULE, SiO2, Bk7
  - Others – Si, MgGr
- Current TRL
  - AMSD (TRL 5)
  - Various SBIR's (TRL 4)



JWST/AMSD Beryllium Mirror

Mission/Strategic Drivers:

- Potential Missions
  - SAFIR
  - Probes
  - TPF-I
  - FISI
- Key external requirement:
  - Cryo-Cooler Temp vs Aperture Dia
- Date: Continuous Cyclic Improvement

4.1.2 Precision Optics

Description of Capability needed:

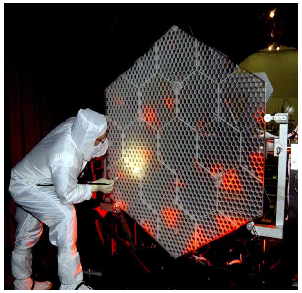
- Large-Aperture Extremely-Smooth Extremely-Stable Ambient-Temperature Mirrors that enable EUV/UV/O science missions.
- Edge Control and Phasing of Segmented Mirrors.
- Optical Test Instrumentation.
- Low Operating Cost Mirrors that enable mission affordability, i.e. lower areal cost, shorter fabrication schedules and lower areal density.
- High Reflectance Coatings from 90 to 1000 nm.
- Extremely Uniform Reflectance and Polarization Coatings from 400 to 1000 nm.

Need/Gap Assessment:

- Manufacturing:
  - Precision figure large low-stiffness mirrors
  - Polish all the way to Edges
  - Optical Testing – spatial, convex & fixture
  - 10X Decrease in Areal Cost
  - 2X Decrease in Areal Density
- Actuator Technology with 0.1 nm precision
- Coating Technology:
  - 2X Reflectivity Increase 90 to 120nm (80% Goal)
  - 10X Reflectivity Uniformity (0.1% Required)
  - 10X Polarization Uniformity
  - Dichroic, Spectral and Combiner Coatings

History/State-of-the-art:

- State-of-the-art/Mission History
  - HST, FUSE, SUMI, AMSD, TDM (flight/pathfinder)
  - KECK, ALOT (ground system)
- Leading Candidates
  - Glass (incumbent)
  - Actuated Hybrid Mirror (AHM)
  - Alternative substrate materials
- Current TRL
  - AMSD (TRL 5)
  - AHM (TRL 4)
  - Segmented Mirror Demo (TRL 5-6 FY 07)



Mission/Strategic Drivers:

- Potential Missions (Diameter)
  - TPF-C (4 x 8 meter)
  - Origin's Probes (JDEM, etc.) (2.4 meter)
  - EOR Lasercomm (3 meter)
  - MTRAP (5 meter)
  - Earth Science (2 to 5 meter)
  - UV/O Interferometer (1 meter)
  - Big Bang Observer (3 meter)
  - Life Finder (25 meter)
- Key external requirements:
  - Coatings & Aperture vs Detector Sensitivity
  - Passive Figure vs Active Control, i.e. DM
- Date: Continuous Cyclic Improvement

4.1.3 Grazing Incidence Optics

Description of Capability needed:

Large-Aperture Precision-Quality Grazing Incidence Mirrors that enable X-Ray/FUV science missions.

Radically Low Operating Cost Mirrors that enable mission affordability:

- –significantly lower areal cost,
- –shorter fabrication schedules and
- –radically lower areal density.

Need/Gap Assessment:

Manufacturing:

- 100X Decrease in Areal Cost
- 100X Decrease in Areal Density
- 0 to 2X Increase in Mirror Segment Size
- Replicated Surface Figure

Mechanical:

- Mounting, Support & Alignment
- Mechanical Stability

History/State-of-the-art:

- State-of-the-art/Mission History
  - Einstein HEAO-B, EUVE, TMA, XMM, Chandra
  - SXI, Solar B
- Leading Technology Candidates
  - Glass Slumping
  - Nano-laminate
  - Replication
  - Silicon Pore Mirrors
  - Active Mirrors
  - Revolutionary
- Current TRL
  - Glass Slumping (TRL 2/3)

Mission/Strategic Drivers:

- Potential Missions (Diameter)
  - Advanced Solar X-Ray Imager (ASXI)
  - ConX
  - Reconnection and Microscale (RAM)
  - EUXO
  - Black Hole Imager
- Key external requirements are:
  - Launch Vehicle Up-Mass vs Areal Density
- Date: Continuous Cyclic Improvement

4.1.4 Diffract., Refract. & Novel Optics

Advanced Planning & Integration Office

Description of Capability needed:

Diffractive/Refractive Optics for specific missions such as coded aperture & occulting imaging.

Revolutionary Optics to enable presently unachievable large-aperture science missions.

Revolutionary Optics for alternate implementations of planned future missions.

Need/Gap Assessment:

Manufacturing:

- 1000X Decrease in Areal Cost
- 1000X Decrease in Areal Density
- 100X Increase in Optic Size

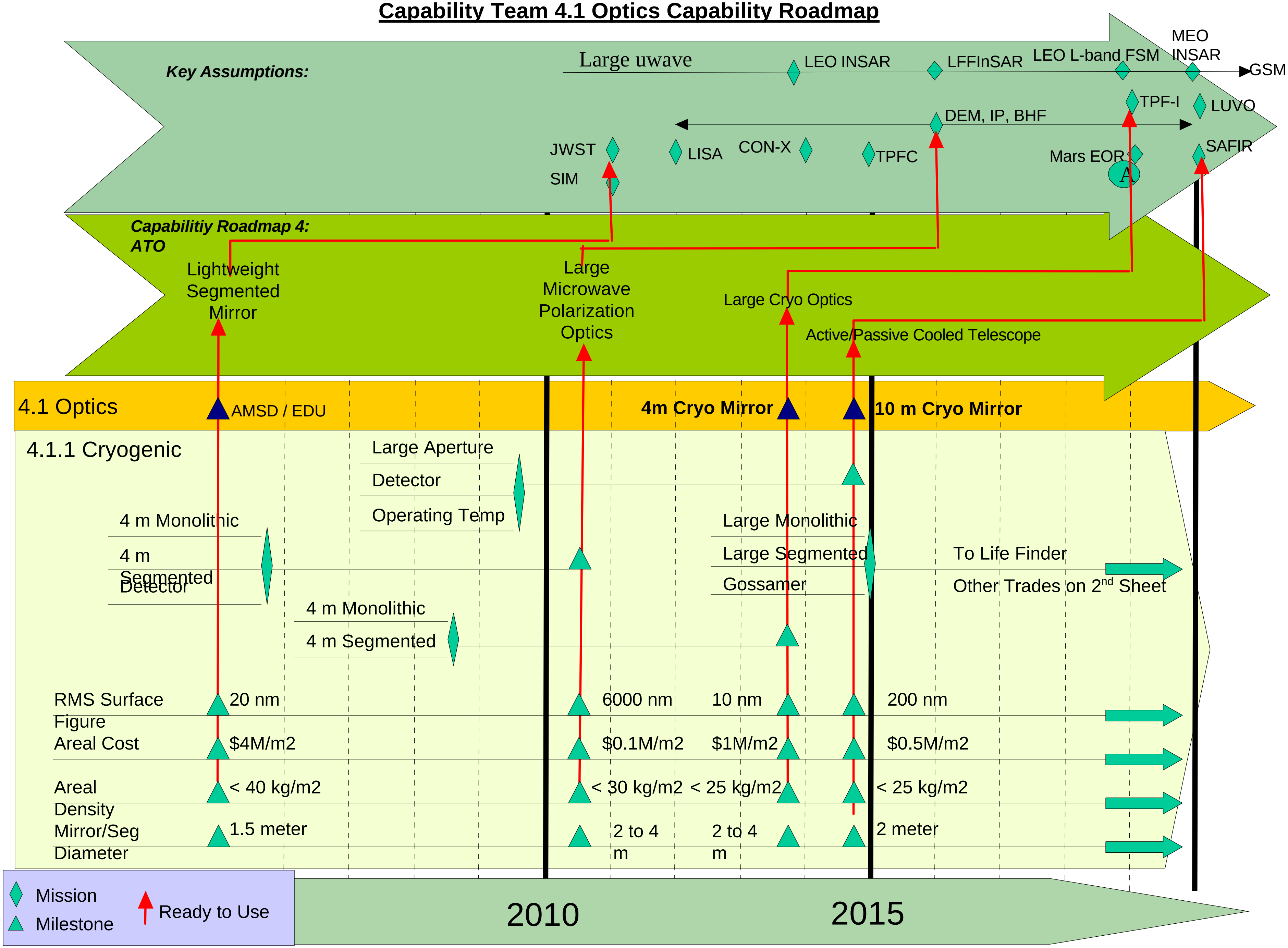
History/State-of-the-art:

- State-of-the-art/Mission History
  - Compton Telescope
  - Coronagraph
- Leading Technology Candidates
  - Laue Lens – Gamma Ray
  - Fresnel Lens – Gamma Ray, X-Ray, UV/O
  - Diffractive/Refractive X-Ray Lens
  - Occulting Screens, Pin Hole Camera
  - Gossamer/Membrane Mirrors
  - Laser Trapped or Magnetic Trapped Mirrors
- Current TRL = 1/2

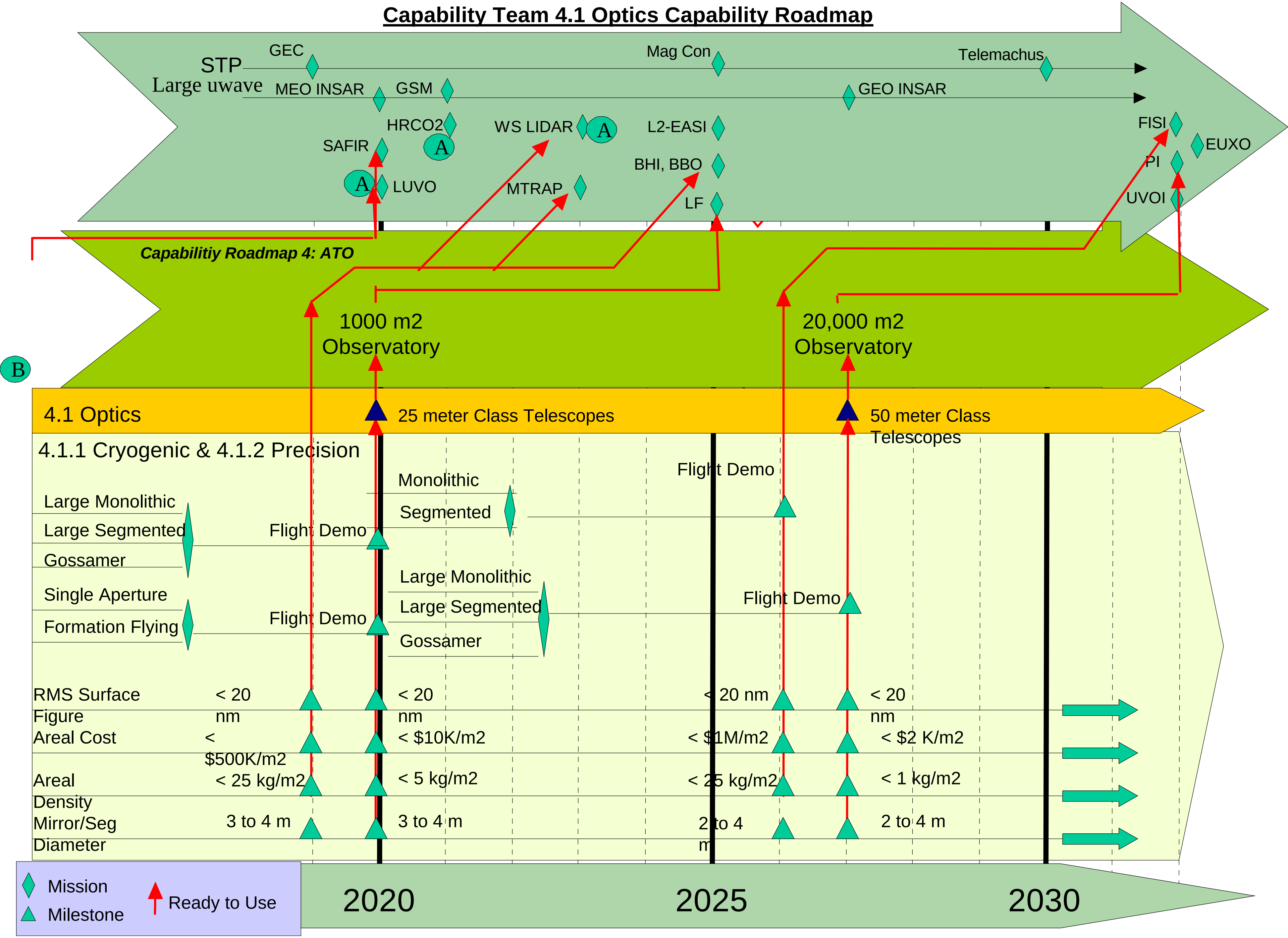
Mission/Strategic Drivers:

- Potential Missions (Diameter)
  - Life Finder (LF)/Planet Imager (PI)
  - Extreme Universe X-ray Observatory (EUXO)
  - Other Future Space Science Missions

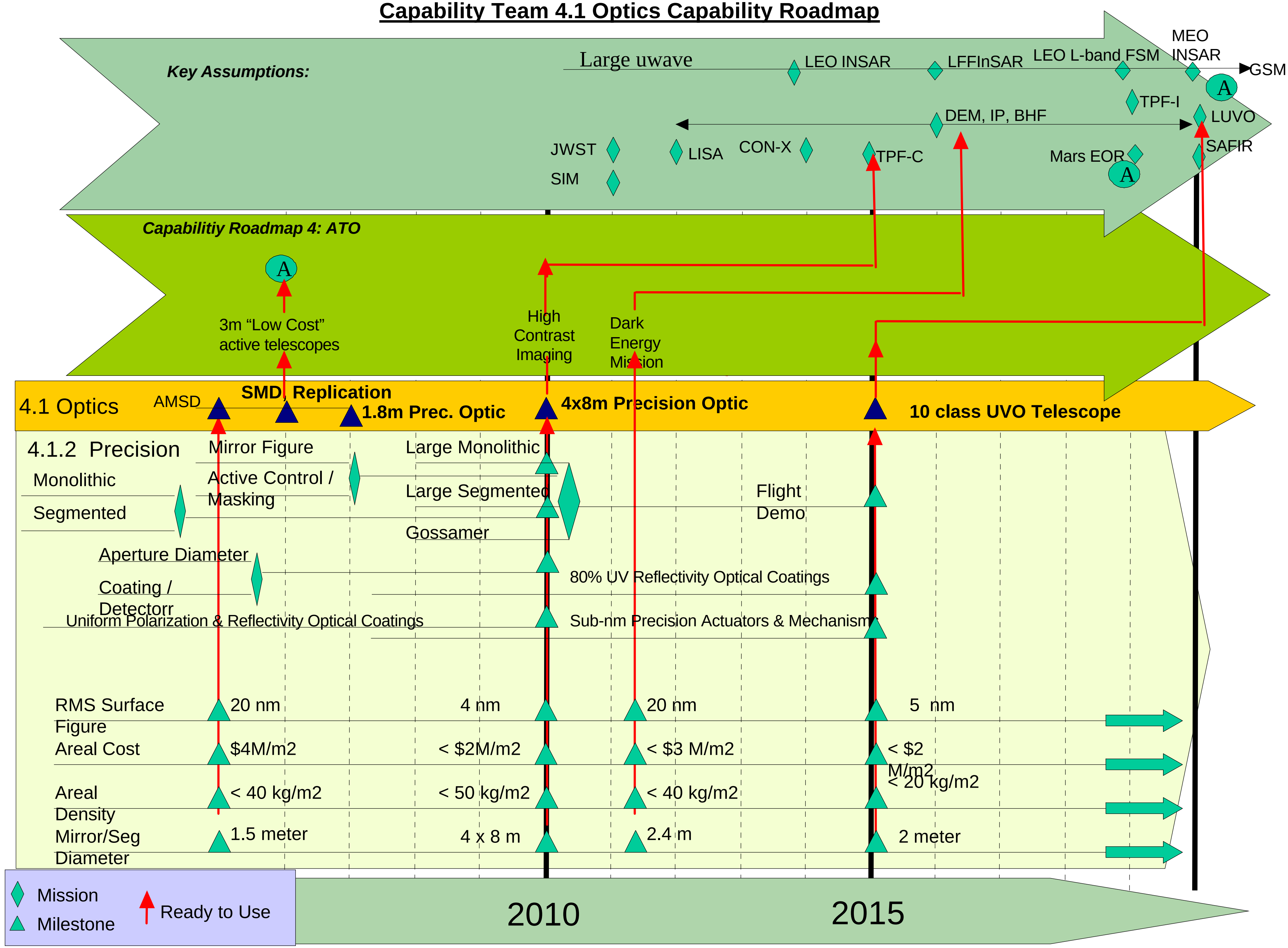
Capability Team 4.1 Optics Capability Roadmap



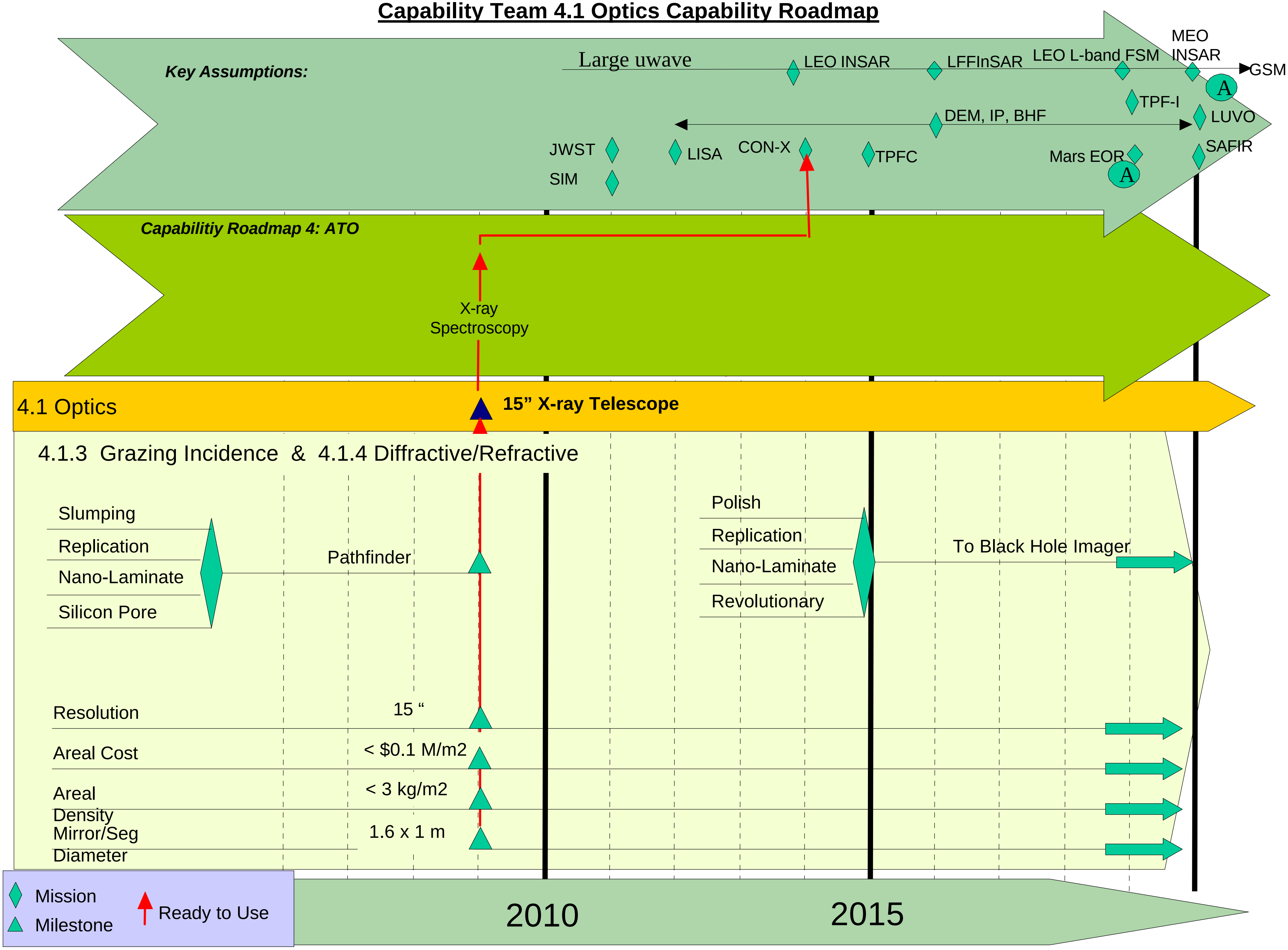
Capability Team 4.1 Optics Capability Roadmap

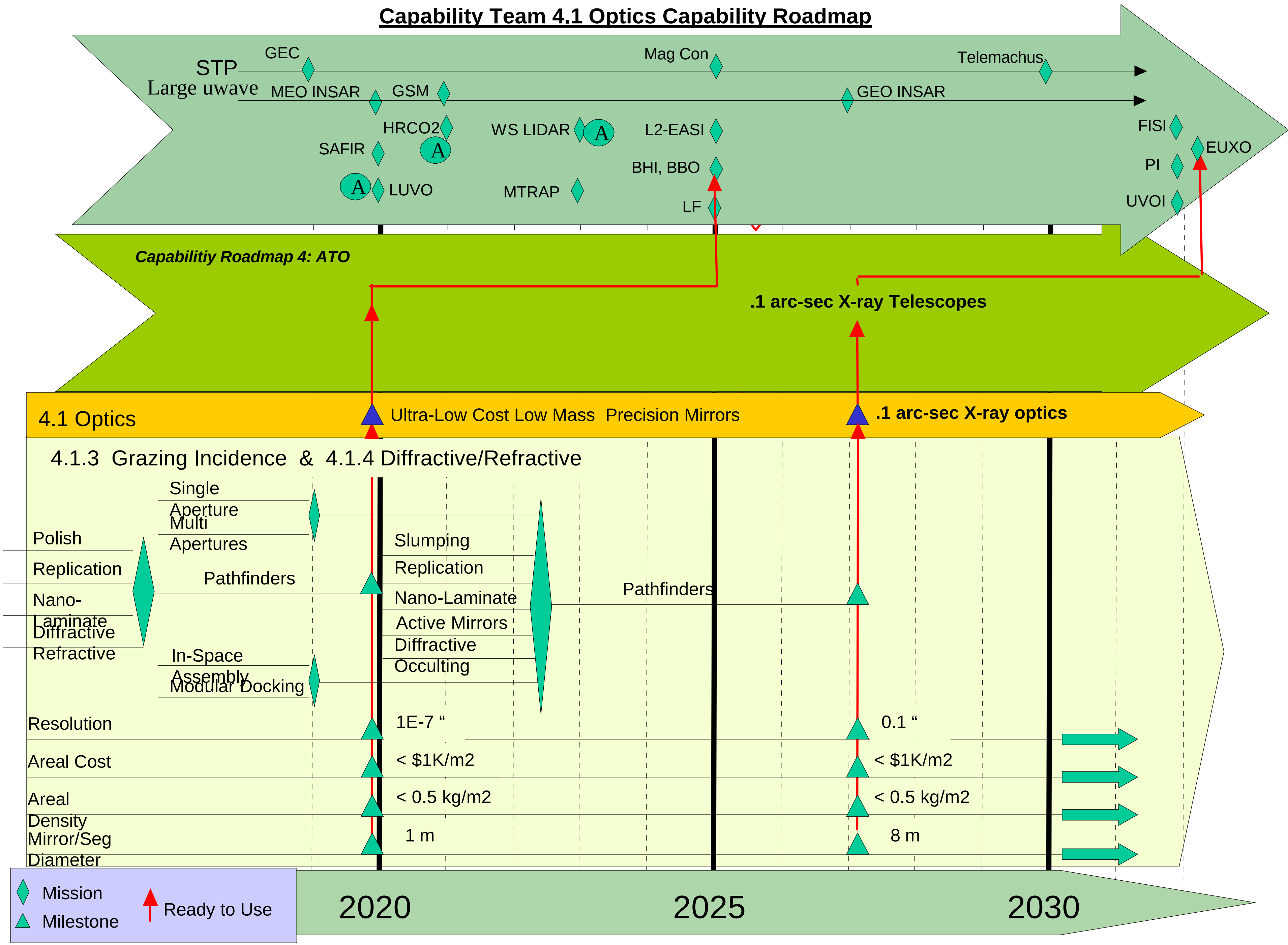


Capability Team 4.1 Optics Capability Roadmap



Capability Team 4.1 Optics Capability Roadmap





Capability Team 4.1 Optics Capability Roadmap
STP
Large uwave
GEC
MEO INSAR
GSM
Mag Con
Telemachus
GEO INSAR
HRCO2
SAFIR
LUVO
WS LIDAR
MTRAP
L2-EASI
BHI, BBO
LF
FISI
EUXO
PI
UVOI
A
Capabilitiy Roadmap 4: ATO
.1 arc-sec X-ray Telescopes
4.1 Optics
Ultra-Low Cost Low Mass Precision Mirrors
.1 arc-sec X-ray optics
4.1.3 Grazing Incidence & 4.1.4 Diffractive/Refractive
Single Aperture
Multi Apertures
Polish
Replication
Nano-Laminate
Diffractive Refractive
Pathfinders
In-Space Assembly
Modular Docking
Slumping
Replication
Nano-Laminate
Active Mirrors
Diffractive
Occulting
Pathfinders
Resolution
1E-7 "
0.1 "
Areal Cost
< $1K/m2
< $1K/m2
Areal Density
< 0.5 kg/m2
< 0.5 kg/m2
Mirror/Seg Diameter
1 m
8 m
Mission
Milestone
Ready to Use
2020
2025
2030

Capability 4.2
Wavefront Sensing & Control and Interferometry

Presenter:

James R. Fienup, Team Lead

Capability 4.2 WFSC&I

Advanced Planning & Integration Office

- **Description of the Capability Area**
- **Sensing the wave front from measured data, either from the object being imaged, from other nearby objects, or from beacons placed in front of the optical system. Mathematical algorithms, computer software (on-board or on the ground), and computer hardware for turning measured data into wave front information**
- **Metrology within and between telescope structures. Metrology lasers: multiple-wavelength-single-mode, long-lifetime, stable. Innovative optical test methodologies and interferometers. Edge sensors.**
- **Controlling the optics of a dynamic space structure to within a small fraction of a wave length is needed to satisfy mission objectives. Control issues include structures, active/adaptive optical surfaces, actuators, deformable mirrors, delay lines, damping, and software driving algorithms responding to an end-to-end optical system merit function such as image quality. On-board software and computing hardware to implement control algorithms at the bandwidths necessary to satisfy mission objectives**
- **Because of the relative immaturity of WFSC&I in space, testbeds are important to test the ability of hardware and software to work together under realistic conditions. Algorithms are also required for interferometry: aperture synthesis imaging, computing imagery, image restoration**

Advanced Planning & Integration Office

Description of Capability needed:

- Ultra high precision WFS
- Continuous sensing of segmented mirrors, continuous mirrors, or interferometer delay line adjustments for closed loop control
- Speckle nulling

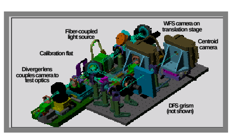
Need/Gap Assessment:

- 10^{-10} contrast for coronographic
- Innovation (e.g. speckle nulling, broadband nulling[1] multistep)
- $\lambda/20$ WFS for interferom. =8nm@ λ =155nm
- Test-beds, algorithm development[1]
- Continuous sensing for closed loop control
- Vector (polarization) optical modeling[3]
- Formation flying beacons

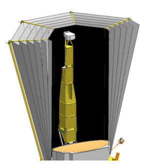
History/State-of-the-art:

- JWST testbeds: 3.5 nm WFS, 20 nm rms WFC[2] (TRL 5)
- HCIT: speckle nulling 10^{-9} contrast narrowband (TRL 3.5)
- Leading Technology Candidates: phase diversity, speckle nulling (TPF), plus others

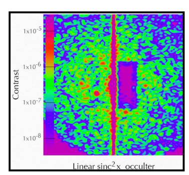
JWST



JWST Phase Retrieval Camera



TPFC



HCIT, Speckle Nulling

Mission/Strategic Drivers:

- WFSC needed for future missions to enable planet finding, stellar surface imaging
- JWST is tackling near term needs, but future missions require continuous improvements to meet future increasing precision and control for most optical/IR telescopes through planet imaging needs
- Driving missions: TPF-C, LISA, TPF-I, Large UVO, Life Finder, Planet Imager, Stellar Imager, SPIRIT, SPECS, BHI, BBO, Low Cost 3-meter telescopes for LIDAR/Lasercomm/Imaging

[1]Stapelfeldt, [2]Redding, [3]Lyon

4.2.2 WFSC&I: Metrology

Description of Capability needed:

Measure single aperture and distributed telescopes to enable the coherent performance necessary for high-angular resolution astronomy and exo-solar planet detection & characterization.

- Continuous metrology of segmented & continuous-surface mirrors, and interferometers.
- Interferometer delay line metrology(ambient and cryo temperatures) for closed loop control.
- Control unwanted radiation for to < 1:10E-12
- Frequency stabilized long life-time lasers
- Precision edge sensing & control for segmented mirrors

Need/Gap Assessment:

- Reject attitude control disturbances to < 80 dB, to give ~ 20 micro-arcsecond pointing
- Laser metrology gauge => repeatable measurements to 10's of picometers & absolute accuracy of microns over several 10's m.
- Accurate measurement of the structural and dynamic properties of mechanical subsystems & modeling to predict system performance: analysis, laboratory measurements, software, computational applications
- Measure & control optical wavefronts, to an accuracy < 0.001 wavelength, at spatial resolution of >~ 400 cycles/pupil, at correction frequency > 10 Hz
- Long OPD precision phase delay lines @ <70K

History/State-of-the-art:

SIM, JWST, TPF-C technology

- Measure optical surfaces to 0.005 waves rms
- 10 nm stability OPD control and picometer metrology
- Reject attitude control disturbances to < 60 dB, to give 20 milli-arcsecond pointing
- Laser metrology gauge => repeatable measurements to 10's of picometers & absolute accuracy of microns over several meters.
- Measure distances between optical fiducials on a 3-D truss to 10's of picometers
- Measure starlight angles to uas, detection position to +- 30 pm on CCD & control OPD to +- 1 nm.

Mission/Strategic Drivers:

- Direct detection and characterization of exo-solar planetary systems
- Determine the origins of the astrophysical universe
- TPF-I, TPF-C, Large UV Optical, Life Finder, LISA, BBO

4.2.3 WFSC&I: Wavefront Control

Advanced Planning & Integration Office

Capability Need:

–Adaptive real-time wave-front correction for space telescopes

- –High precision control of wave fronts for high contrast imaging
  - –DM's
  - –Innovative field and Lyot stops
- –On-board intelligent control systems to maintain performance with on-demand communications for commissioning and system diagnosis

Note: Active primary and secondary mirrors with actuators covered under optics

Need/Gap Assessment:

- –λ/10,000 rms =50pm control & stability for coronagraphic capability
- –Higher order, longer stroke, finer precision DM's
  - -Sampling, Stability
- - Cryogenic precision motion to Pico meter resolution
- –On board intelligent control systems
  - –Flight qualified DSPs
- –Architectures and test beds demonstrating closed loop intelligent control

History/State-of-the-art:

- –*Delay lines, actuators, mirror substrates and integrated DM systems for sub-nanometer control of alignment, phasing and figure*
- –*Many ground based systems using Adaptive Optics*
- –*Technology Candidates:*
  - – Actuated Hybrid Mirrors (JPL, LLNL, Xinetics) TRL 4-6
  - – Zonal Meniscus Mirrors (Xinetics) TRL ?
  - – Nanolaminate Mirrors (LLNL) TRL ?
  - –CAMELOT cryo actuated mirrors (Xinetics, JPL) TRL 3
  - –MEMs TRL ?

MEMs

Xinetics DMs

Mission/Strategic Drivers:

- –SIM requires Pico meter multi-baseline control
- –TPF-C #1 technology priority TRL X by 2007
- –TPF-I telescopes
- – Other large interferometers such as Planet Finder

Active system external requirement drivers:

Very difficult to scale up existing technology

- –Mass and volume limits on launch vehicles
- –Cost as system scale in size
- –Need different approach to meet tighter requirements

4.2.4 WFSC&I Algorithm Testbeds

Description of Capability Needed:

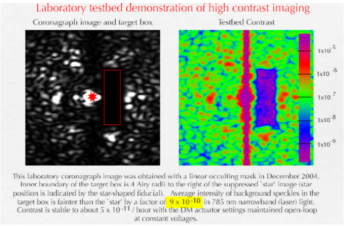
- Ground WFSC+I Algorithm Testbeds capable of demonstrating new measurement approaches and their key performance criteria
- Key to understanding key system trades, technology needs, algorithm development, model correlation/validation
- Need to continue work on many existing testbeds and make testbeds that are cryo-vacuum and vibration-free for more challenging requirements

Need/Gap Assessment:

- Leading Technology Candidates: Complete existing efforts on TPFC, TPFI, SPIRIT/FISI, SI, MAXIM/BHI testbeds, LISA/BBO, L2 EASI
- Need to fund low-TRL innovative architecture/algorithm testbeds (algorithms+testbeds)
- Need to make use of Pathfinders, including flight pathfinders when necessary
- Govt needs to fund contractor involvement in early government testbeds

History/State-of-the-art:

- JWST: Several few segment testbeds exist, a full 18 segment testbed in development
- SIM: Metrology testbeds
- TPF High Contrast Testbed: 10-9 contrast, monochromatic
- Wide-field Imaging Interferometry Testbed – 1-D imaging
- Stellar Imaging Testbed – Initial close loop control
- MAXIM – X-ray interferometry
- Fringes



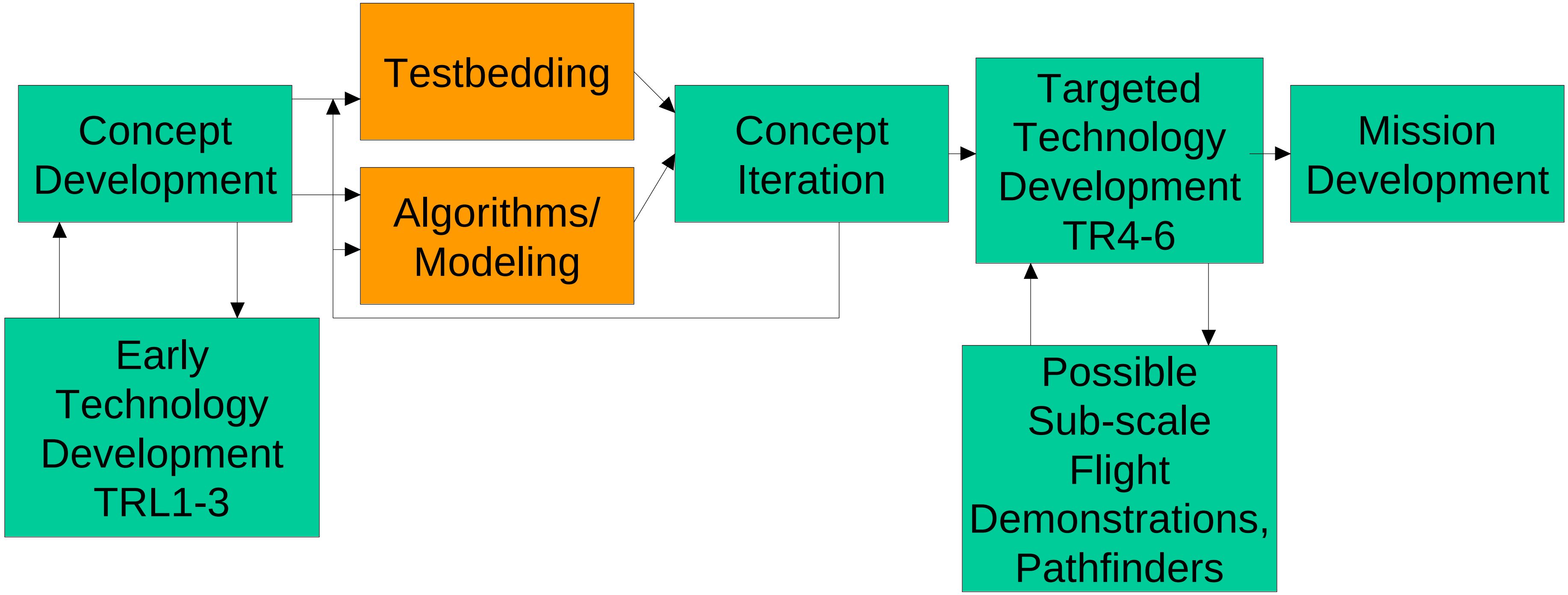
TPFC
High Contrast
Testbed Results

Mission/Strategic Drivers:

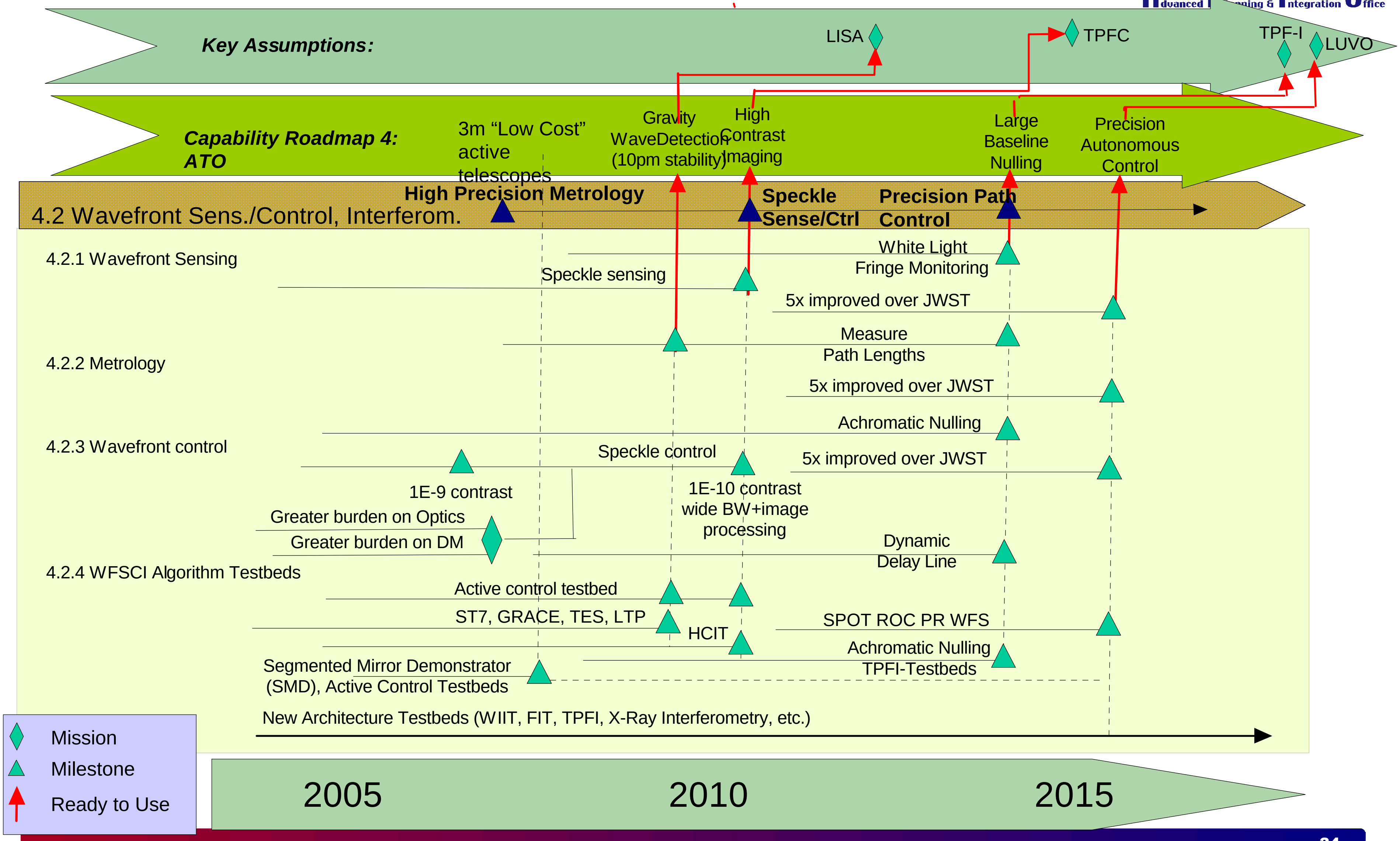
- Planet Finding: TPFC, TPFI, PI, LF
- L2 EASI – Earth Atmostpheric
- Low cost 2-3 meter LIDAR and comm telescopes
- Far-Infrared Interferometry – 2-D Spatial-Spectral wide field imaging interferometry
- Stellar Imager – Fizeau imaging interferometry
- Black Hole Imager – X-ray interferometry
- Recommend Funding Low TRL “Innovative Testbeds”

4.2.4 WFSC&I Algorithm Testbeds

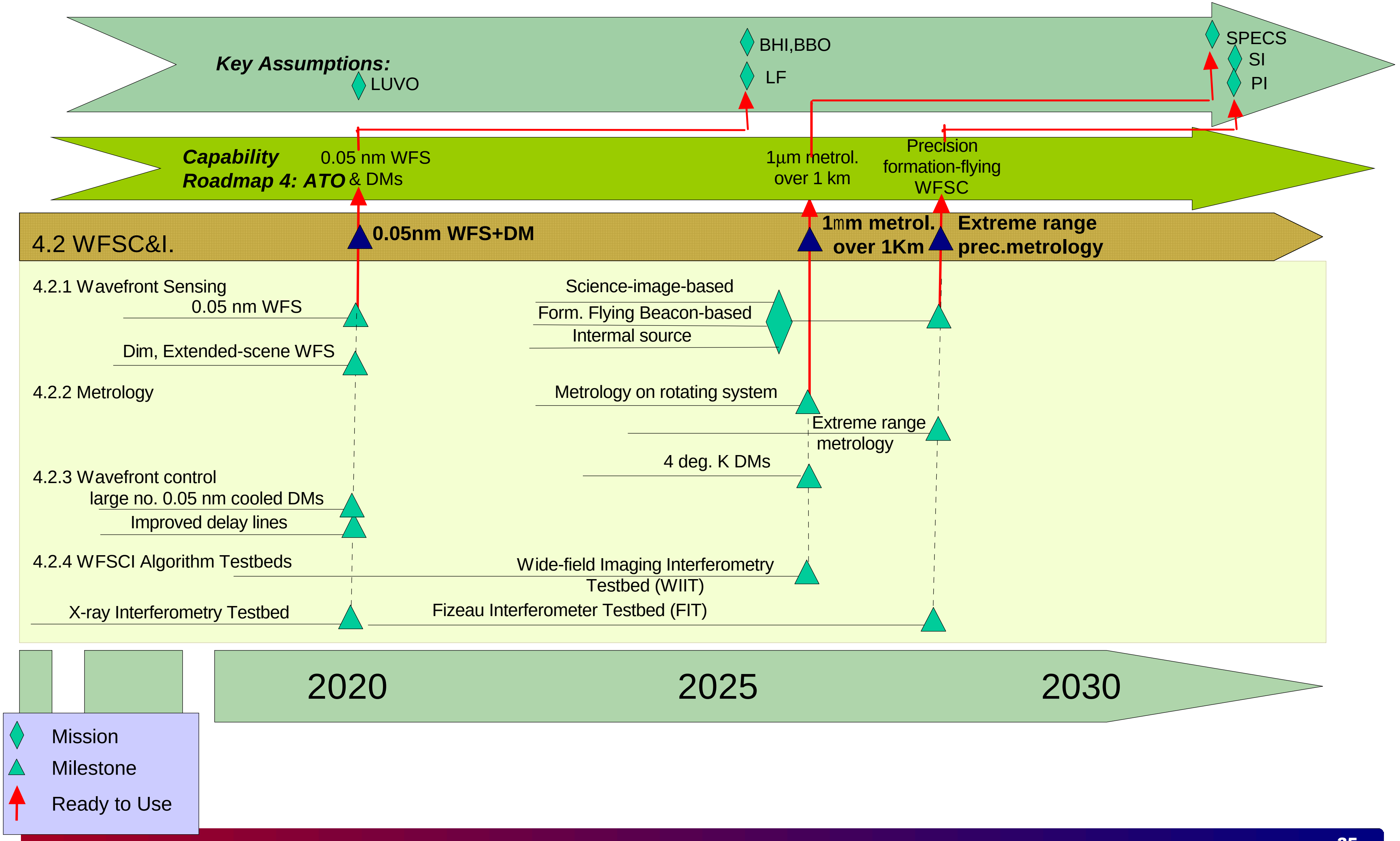
Because future observatories are often dependent on advanced algorithms, testbeds and algorithm modeling are critical during early phases to demonstrate feasibility and to perform system trades:



Capability 4.2 WFSC&I Roadmap



Capability 4.2 WFSC&I Roadmap



ATO Capability 4.3
Distributed and Advanced Spacecraft Systems
(DASS)

Presenter:

David W. Miller, Team Lead

ATO Capability 4.3 Distributed and Advanced Spacecraft Systems

- Distributed Spacecraft Systems correspond to any set of more than one S/C whose dynamics are coupled through sensing and control in order to enable the integration of a signal received from an observed target.
    - Inter-S/C sensing for radio & gravitational measurements.
    - Inter-S/C sensing & control for sub-millimeter through x-ray
  - Collectively, enables distributed network of individual spacecraft to act as a single functional unit that can operate more cost-effectively than a monolithic system.
  - Technical challenges include autonomy, control, path planning, contamination, metrology, propulsion, and technology maturation.
- Advanced Spacecraft Systems correspond to those architectural attributes necessary to enhance the cost-effectiveness of the distributed spacecraft system.
  - Technical challenges include S/C modularity and replication, high speed electronics and inter-S/C communications, graceful degradation and robust distributed sensing, communication and control architecture and algorithms.
- We partition DASS into Platforms, Formation Flight Systems, and Sub-systems

Requirements/Assumptions for 4.3 Distributed and Advanced Spacecraft Systems

- Roughly three-quarters of the proposed space science missions, not currently under development, drive DASS.
  - High production volume : UVOI, BHI, PI
  - Low production volume: LISA, Con-X, TPF-I, BBO, FISI
  - Long baseline: LISA, BHI, BBO, PI
  - Centimeter separation control: TPF-I, LF, UVOI, PI, FISI
  - Micrometer separation control: BHI, BBO
  - Earth-Sun L2 orbits: Con-X, TPF-I, LF, UVOI, PI, FISI
  - Heliocentric orbits: LISA, BBO

Space Science	SOA	LISA	CON-X	TPF-I	LF	UVOI	BHI	BBO	PI	FISI
Number of S/C	2	3	4	5	4 - 5	20-30	33	12	80 - 100	4
Geometry Maintenance	FF	FF	pointing	FF	FF	FF	FF	FF	FF	tether
Separation control	m	none	none	1 cm			5 um	1 um		
Separation knowledge	cm	<nm	coarse	1 mm			< 1 um	< 1um		
Thrust Range		1-100 uN				1 uN	uN - 0.1 N			
Min Baseline	100 m	5e6 km		75 m	100 m	100 m	1000 km	50000 km	100 km	100 m
Max Baseline	km			200 m	500 m	500 m	10000 km	~1 AU	3000 km	1000 m
Pointing Control				20 asec		10 uas	10-100 nas			
Mission Lifetime	5 yrs	10 yrs	5 yrs	5 yrs	> 5 yrs	> 10 yrs			5-20+ yrs	
Orbit	LEO	Helio	SE L2	SE L2	SE L2	SE L2		Helio	SE L2	SE L2
Launch Date		2005-2015	2015-2025	2015-2025	2025+	2025+	2025+	2025+	2025+	2025+

4.3.1 Platforms: Modularity and Replication

Advanced Planning & Integration Office

Description of Capability needed:

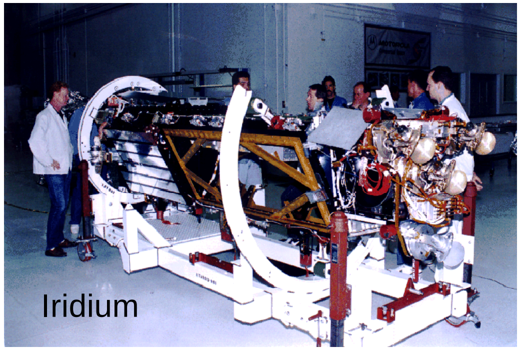
- Producing many S/C yields production savings. But, not enough S/C in most missions to justify 'assembly line'
  - Need BOTH subsystem and science payload designs that cross-cut several missions
  - Need architectures whose science productivity degrades gracefully under failures

Need/Gap Assessment:

- Need ability to extract efficiencies from small and large production volumes
  - Each poses different challenges
- Need functional redundancy where component or S/C can perform more than one role
  - Component redundancy prohibitive
  - Need associated design tools

History/State-of-the-art:

- Mission-optimized design w/customized I&T
  - Replication: GPS, Iridium (100 S/C) 25 day fab
- Several programs cancelled due to S/C costs



Iridium

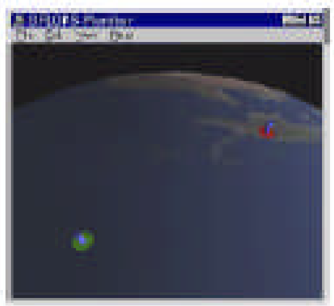
Mission/Strategic Drivers:

- Commonality across missions: *e.g., X-ray: Con-X, BHI*
- Extensibility of design: autonomy (e.g.): UVOI, BHI, PI
- Level of return on investment
  - TPF-I + LISA = 8 S/C
  - UVOI + BHI + BBO + PI = 157–187 S/C

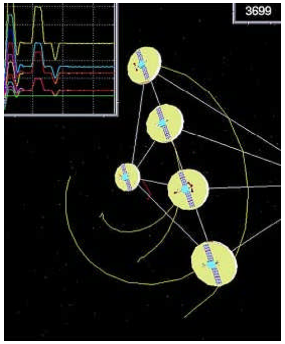
4.3.1 Platforms: Technology Maturation Programs

Description of Capability needed:

– Many programs share basic elements. Should share development costs
  – Need a reconfigurable, long duration, µ-g lab
  – Need multi-processor, regimented time mission simulation tools



MIT GFLOPS

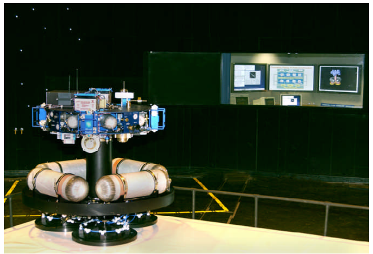


JPL HYDRA

History/State-of-the-art:

- JPL FCT, SPHERES, NRL-RSL
- HYDRA, GSFC FFTB, GFLOPS

MIT's SPHERES

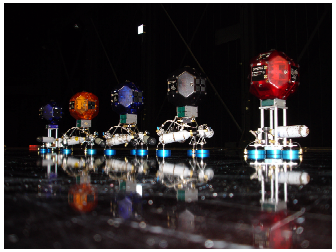


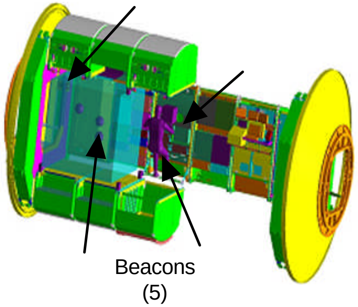
JPL Formation Control Testbed

Need/Gap Assessment:

Need more focus on
– Demonstrating robustness
– Component testing under representative conditions
– Large motion, 6 DOF, multi-S/C formation flight
– Calibration of end-to-end simulations with actual hardware test data

MSFC flat floor



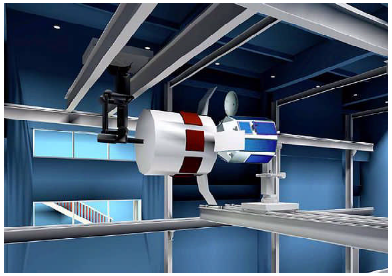


ISS Destiny Lab

Mission/Strategic Drivers:

– Multiple technologies need to reach TRL6 for mission insertion
- TPF-I, UVOI, BHI, BBO, LF, PI

GSFC Formation Flight Testbed



NRL Robotic Servicing Lab

4.3.2 Systems: Auto., Control, Contam, Ap. Synth. and supporting sub-systems

Advanced Planning & Integration Office

Description of Capability needed:

- Autonomy: effective 'safe modes' for close proximity, FDIR for inter-S/C faults
- Control: Robust & scalable formation control architecture (sensing, communication, control).
- Contamination mitigation, path planning for aperture synthesis, inter-S/C metrology (coarse/precision bearing & range) from deployment to instrument phasing
- Precision propulsion: m-Newton thrusters

Need/Gap Assessment:

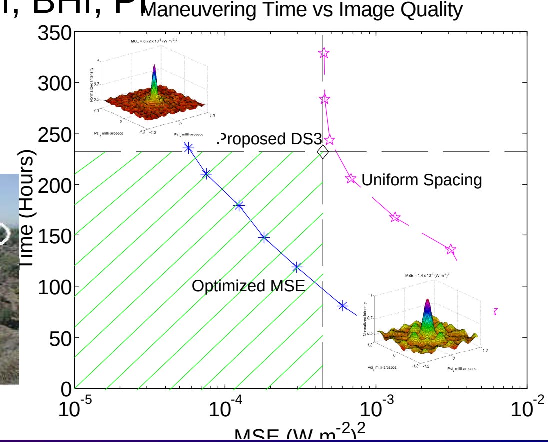
- Robust, on-line path-planning w/constraints, learning systems, high level reasoning
- Contamination reduction: propellant-less techniques, light baffling, imping. Avoidance
- Coarse metrology (reconfiguration): asec bearing/mm position, 4p sr FOV, 100km range. Precision (instrument phasing): mas bearing/mm position, ~deg FOV, 10km range
- RF multi-path

History/State-of-the-art:

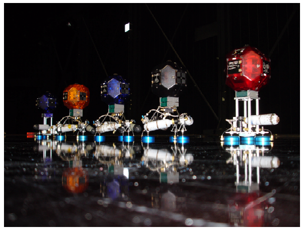
- Autonomy: Deep Space 1, UAVs.
- Earth rotation aperture synth. in RF (VLA).
  - Trade time & image quality (graph).
  - Metrology: AFF, DPCGPS ~cm range, MSTAR
  - ~km (EO-1), ~m (Shuttle), ~cm (STS & Prog)

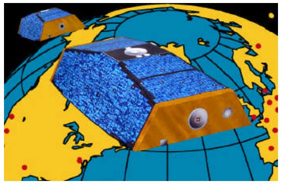
Mission/Strategic Drivers:

- Prox. ops, synth. Imag., many S/C
- TPF-I, LF, UVOI, BHI, PI

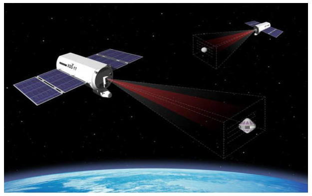


Five vehicle formations

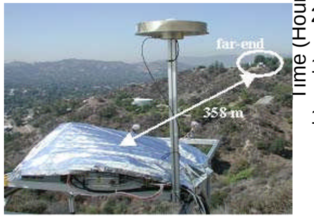




GRACE differential RF range sensor



ST6/XSS-11 range and bearing sensor



JPL AFF

4.3.3 Subsystems: Propellant-less Propulsion

Description of Capability needed:

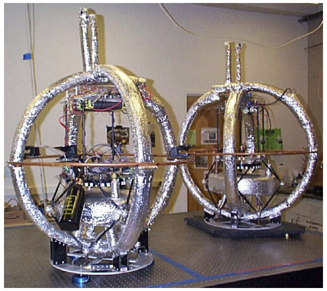
- Propellant consumption limits lifetime.
- Propellant-less formation control for high DV missions w/close proximity S/C
  - E.g. aperture synthesis, assembly & servicing, DJ2 perturbations, non-Keplerian orbits
- Options include orbital dynamics, electro-magnetics, electro-statics, and tethers

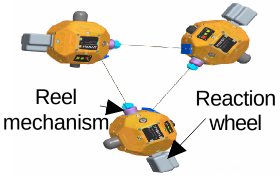
Need/Gap Assessment:

- Tethers: dynamics and controls
- EMFF and ESC need sub-system development
  - EMFF thermal management for high temperature superconductor

History/State-of-the-art:

- Tethers: 2 & 3 S/C tests (1-g flat floor)
- Electrostatic formation flight: theory
- EM formation flight: 2 S/C tests (1-g flat floor)
- Orbital dynamics: Hill's orbit ellipses

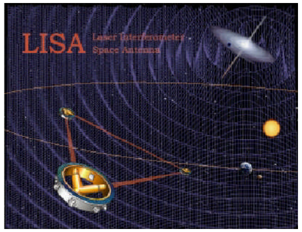

Electro-magnetics



Tethers

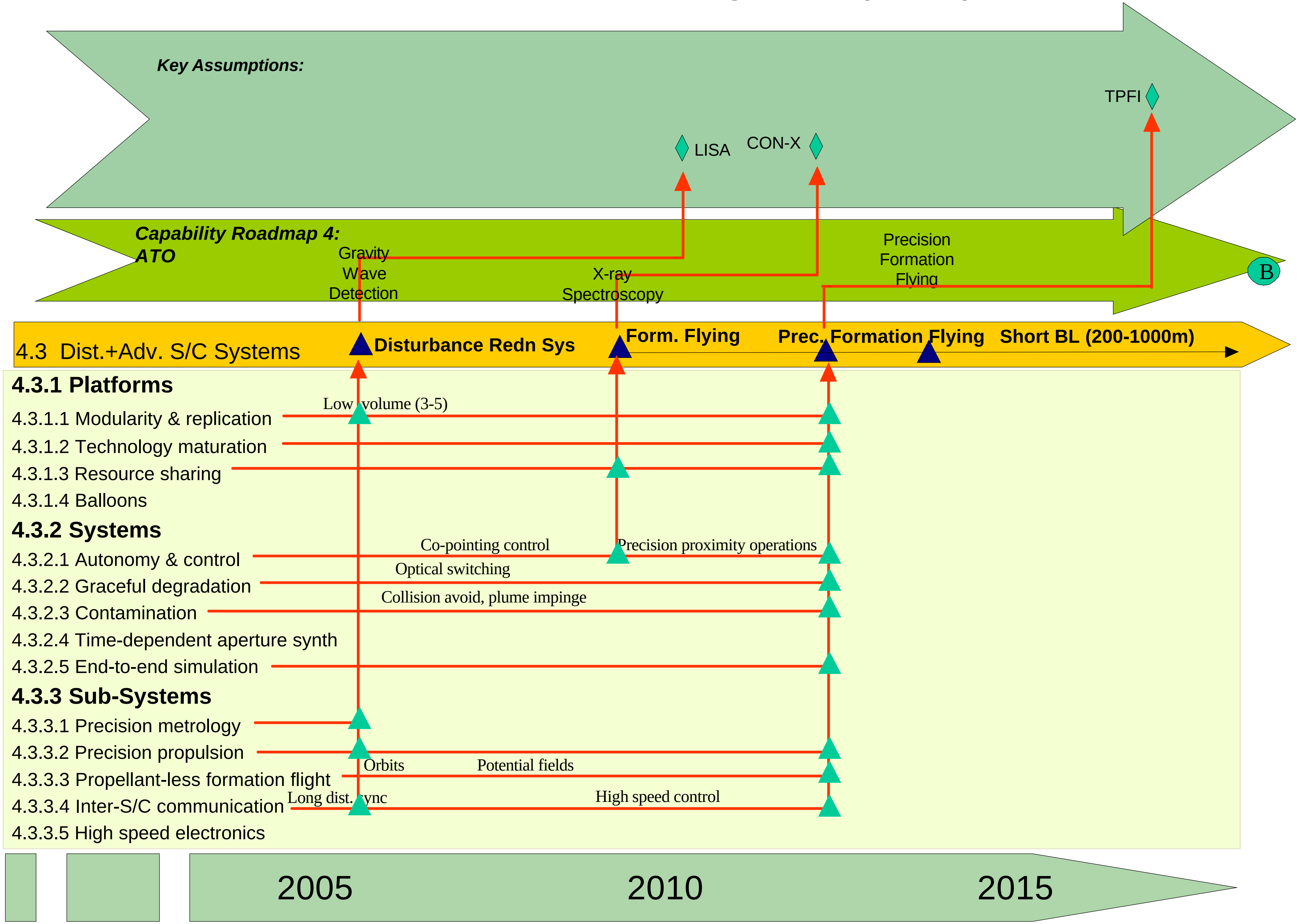
Mission/Strategic Drivers:

- LISA – orbits
- FISI – tethers
- TPF-I, UVOI – potential fields
- Propellant consumption severely limits Synthetic Imaging of UVOI & FISI

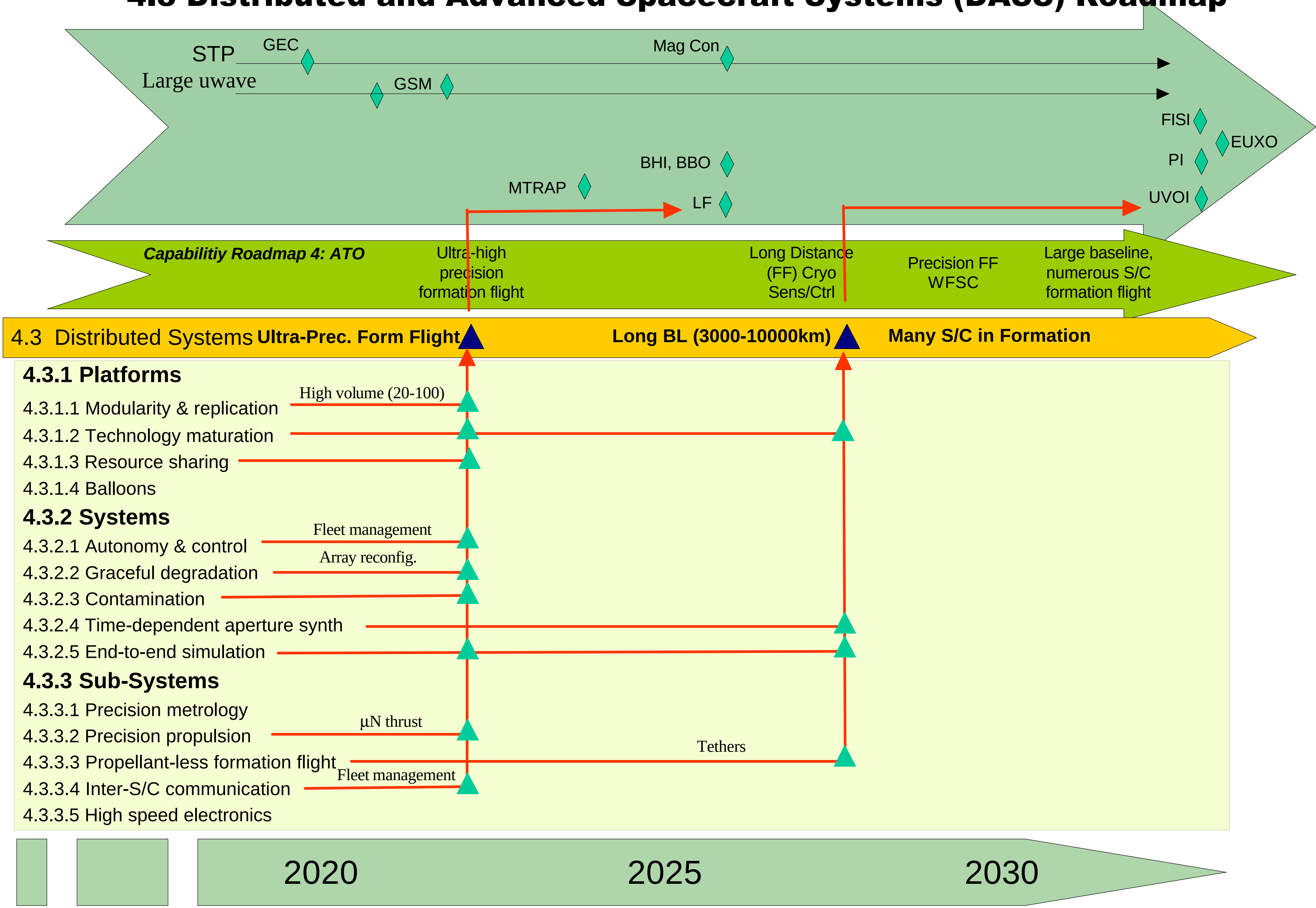



Orbital dynamics

4.3 Distributed and Advanced Spacecraft Systems (DASS) Roadmap



4.3 Distributed and Advanced Spacecraft Systems (DASS) Roadmap



4.4 Large Precision Structures for Observatories

Presenter:

R. S. Polidan / Northrop Grumman

Capability 4.4 Large Precision Structures

- Large Precision Structures for Telescopes are the structural elements that form/support the electromagnetic (g-ray through radio-wave) and gravity wave systems of telescopes and observatories. This capability includes:
  - Filled Apertures, Interferometers, and "Antennas (Radar, microwave, etc)"
  - Sunshields/Sunshades
- In order to support these large telescopes and observatories large *precision* structures are required to provide the
  - Basic optical structure elements that form the telescope
  - Sunshields that protect the telescope from solar light and heating
  - Modular elements and their connectors that allow these telescopes to fit within (small – at least relative to the telescopes) launch vehicle fairings, and be deployed or assembled in space
- Related capabilities covered in other CBS areas are:
  - Tethered systems: CBS 4.3 Distributed and Advanced Satellite Systems
  - Optical surfaces and substrates: CBS 4.1 Optics (CBS 4.4 Structures supplies the rigid body support for the optics)
  - Metrology systems: CBS 4.2 Wavefront Sensing and Control
  - Modeling and Simulation: CBS 4.6 Infrastructure

4.4.1 Stability and Precision

Advanced Planning & Integration Office

Description of Capability needed:

– Precision static, deployable, or assembled structures are required to enable all the large NASA observatories (> 4 m aperture).
– High stability/precision is a key enabling capability that overcomes size, packaging, and space environment issues to allow us to operate the advanced telescopes and observatories identified in NASA's strategic plan.

Need/Gap Assessment:

- Current in-space mechanical and thermal stability metrics are 2 or more orders of magnitude worse than what is needed for future observatory missions
- Technologies in both passive and active stability control are required

History/State-of-the-art:

– State-of-the-art/Mission History
  – *SIM-PlanetQuest and JWST* define the development current state of the (NASA) art for precision structures
  – There also exists programs in the classified environment
– Leading Technology Candidates
  – SIM Interferometer Beam
  – JWST Observatory structure
– Current TRL
  – SIM-PlanetQuest Interferometer Beam: TRL 6
  – Telescope structure systems: TRL 6 (JWST)

Mission/Strategic Drivers:

- Example Missions and Drivers
  - **TPF-C:** Size, Deployment, and Stability of large operational structure)
  - **Land Surface Topography Mission:** Large (3x15m evolving to 10x40m) L-band Radar antennae
  - **SAFIR:** Large deployable telescope structure and sunshade
  - **L2 EASI:** 8m interferometer boom
– Date: 2011 for TPF-C

4.4.2 Materials Technology

Description of Capability needed:

- Materials technology covers the physical properties of materials, outgassing & contamination control,cryogenic performance, response to space environment, coatings, charging, and smart materials.
- This is a basic enabling capability that supplies the technical/physical information that allows us to build the precision structures and operate them in the space environment.

Need/Gap Assessment:

- Need a comprehensive set of laboratory and space test data on the properties and performance of applicable structural materials in appropriate environments
- Need properties of materials at space-cryogenic temperatures
- Need to incorporate developments and information on nanomaterials into space structures development

History/State-of-the-art:

- -History
  - Materials information for in-space large precision structures is patchy and incomplete
  - New materials (e.g. nanotechnology) are just beginning to appear
  - Cryogenic performance of many materials are not well known
- State-of-the-Art: JWST example
  - Issue: Accurate data on material properties at JWST temperatures are generally not available and will require testing to generate and not the test data will not be available in time.
  - Potential Impact: The performance of the integrate observatory may not be accurately predicted and the uncertainty of the predicted performance may not be understood.

Mission/Strategic Drivers:

- Example Missions and Drivers
  - **TPF-C:** Size, Deployment, and Stability of large operational structure)
  - **Land Surface Topography Mission:** Large (3x15m evolving to 10x40m) L-band Radar antennae
  - **SAFIR:** Large deployable telescope structure and sunshade
  - **EASI:** 8m interferometer boom
- Key external requirements are:
  - Robust laboratory materials program to populate needed database
- Date: First version: 2008

4.4.3 Implementation Capability

Description of Capability needed:

- Implementation technology spans the range of application of the large precision structures:
  - Launch Load Reduction & Fairing Technology
  - Deployed structures
  - Assembled structures
  - Inflatable and "Growable" Structures
- Each implementation path has it own unique needs.

Mission/Strategic Drivers:

-Example Missions and Drivers

TPF-C: Size, Deployment, and Stability of large operational structure

Land Surface Topography Mission: Large (3x15m evolving to 10x40m) L-band Radar antennae

SAFIR: Large deployable telescope structure and sunshade

EASI: 8m interferometer boom

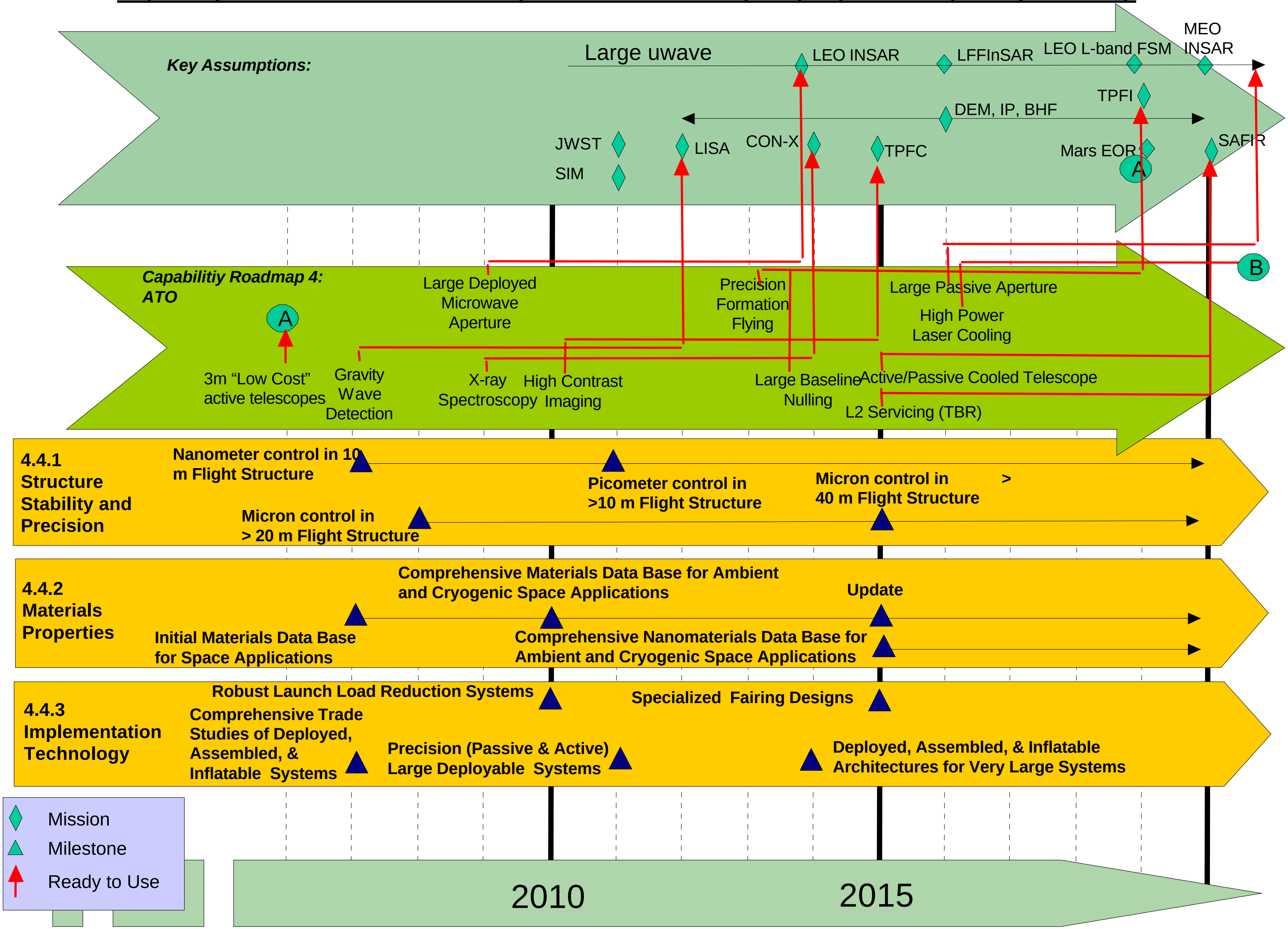
History/State-of-the-art:

- AFRL/Boeing have produced initial systems for vibrational and acoustic dampers
- Deployed structures have been flown but not close to the combined size/precision needed for observatories
- Space station is the state of the art for assembled structures but it is far from the precision structures that are needed for observatory structures
- Initial inflatable antenna structures have been flown but do not have the size and performance required for large telescopes

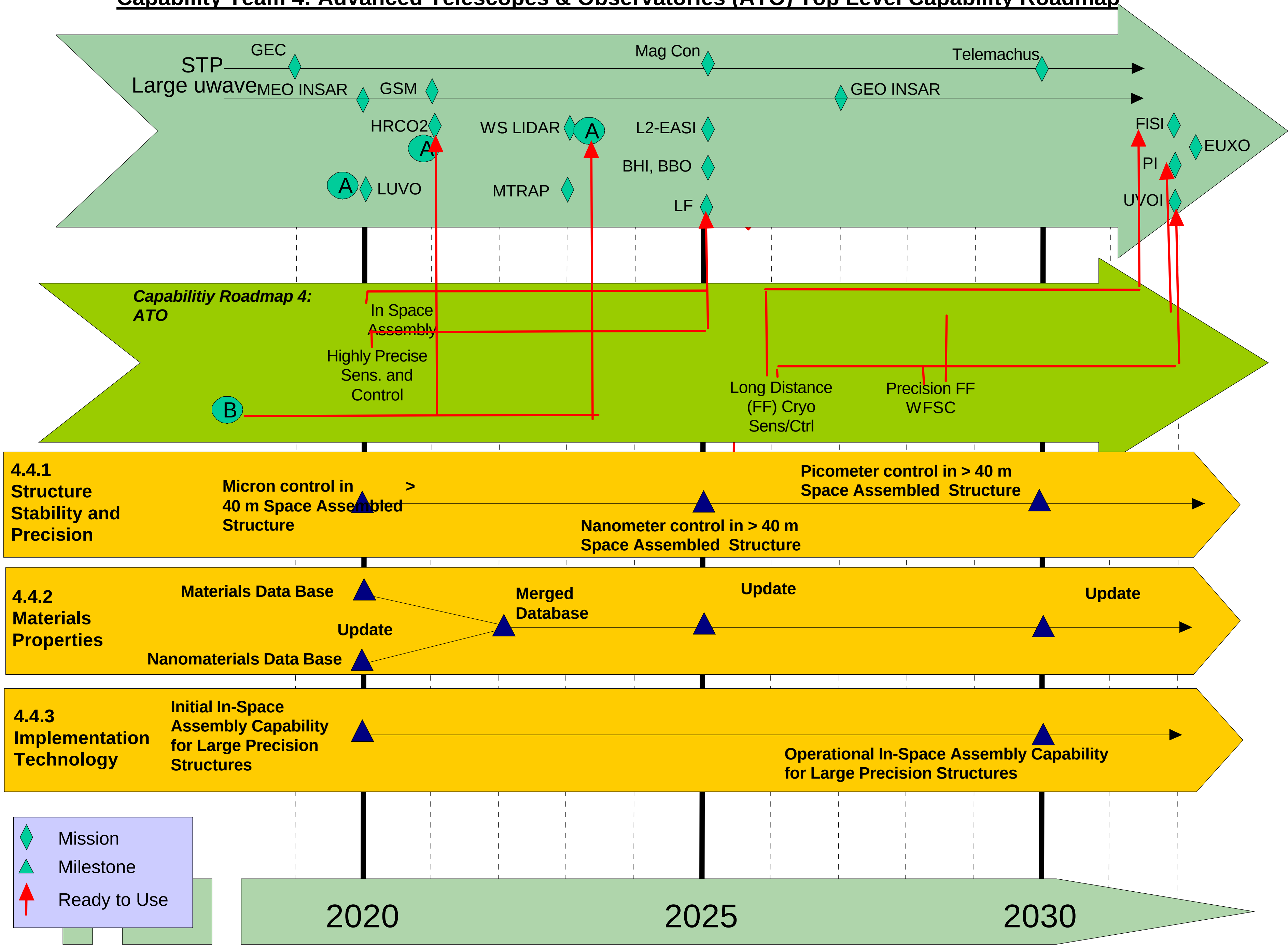
Need/Gap Assessment:

- Launch Loads and Fairings
  - Low cost production of fairings, custom fairings, load alleviation technology
- Deployable, Assembled, Inflatable Systems
  - Understanding of system trades and risks across implementation approach
  - System level assessment of size and stability (mechanical & thermal) properties from both passive and active approaches

Capability Team 4: Advanced Telescopes & Observatories (ATO) Top Level Capability Roadmap



Capability Team 4: Advanced Telescopes & Observatories (ATO) Top Level Capability Roadmap



Capability 4.5 Cryogenic and Thermal Control Systems

Presenter:
Jim Oschmann / BATC

Team Members:
Peter Jones / AFRL
Ron Polidan / NGST

Capability of Cryogenic and Thermal Control Systems

- Enabling technology for mid to far IR through mm wave telescopes
  - 4 - 50 K for large deployed optics and structures
  - 10 K - Milli-kelvin for sensors
    - Technology overlaps with sensors
      - Need system level designs
      - Includes other wavelengths
      - Tie in to sensors road mapping needed
  - Needs both active and passive improvements to realize goal
  - Isolation of warm and cold spacecraft areas needs improvement
- Large fraction of future IR missions require this thermal performance to reach their stated scientific goals

4.5.1 Passive Cooling

Advanced Planning & Integration Office

Capability Needed

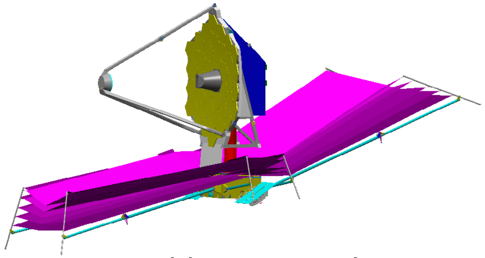
- Passively cool large and/or distributed optics (30 to 80 K, depending upon mission)
  - Reduce thermal background on sensors
  - Precool optical bench
  - Precool optics that are actively cooled to lower temperatures
- Improved sunshade, radiators, heat distribution, thermal materials, coatings, and assembly

Need/Gap Assessment

- Need temp of sunshade on cold side ~15 K
  - Eases requirement on cryocoolers
- More sunshade layers and/or new materials
  - Newer composites
  - Enhanced emittance at very low temp
- Improved MLI isolation (lower conductance)

History/State-of-the-art

- Spitzer (0.8 m) at ~35 K passively
- JWST (6.4 m) at >35 K with passive sunshade/isolation
  - In design phase



James Webb Space Telescope

Mission/Strategic Drivers

- SAFIR
- TPFI
- Any cryogenic system

Spitzer Space Telescope

4.5.2 Active Cooling

Advanced Planning & Integration Office

Capability Needed

Cool optics below temp limits of radiators w/o life- and mission-limiting cryogens

Pre-cooling for sensors (6 K - milli K levels)

30-100 mW cooling @ 4 K

Simultaneous 150-400 mW @ 18 K & 1-2 W @ 40 K

Low vibration, mass, & power

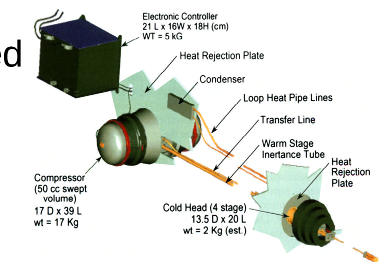
Need/Gap Assessment

Demo ACTDP electronic controls at TRL 5 by FY10

No high capacity zero vibration cooler for coronagraphs – need TRL 5 by FY10

Extend cooler operation to 5 K with 0.1 W thermal load (TRL 5 by FY14)

Space demo ~ FY08 needed



History/State-of-the-art

Multiple coolers (50 – 80 K) developed by DoD & NASA are operating in space

DoD 10 K & multistage 35 K coolers at TRL 5 in FY07

ACTDP 6 K/18 K cooler at TRL 5 in FY07

Planck sorption 18-20 K cooler launch FY07
No other flight electronics <30 K at TRL>3

Mission/Strategic Drivers

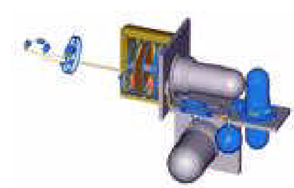
–SAFIR (8-10 m aperture at 4 K)

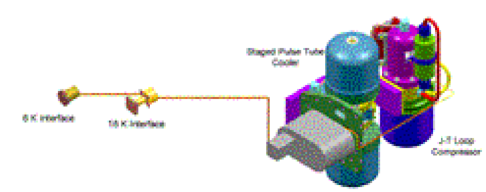
TPF-I for instruments, maybe telescopes

Several missions beyond

Probes, other large 4 K telescopes

DoD has complementary needs > 10 K





4.5.3 Thermal Isolation Capability

Advanced Planning & Integration Office

Capability Needed

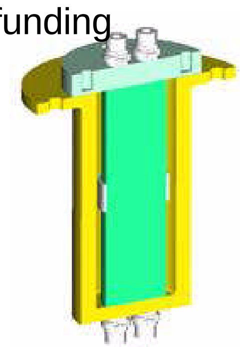
– Thermal isolation of payloads & components
– Reduce risk, cost, and mass, extend mission lifetimes, and enable new missions
– Key enabling technologies reduce thermal flow across an interface
  – Structural struts, straps, passive/active disconnects, thermal switches, and electrical thermal isolation systems

Need/Gap Assessment

– Large area 5 ± 0.1 K temp control by FY08
– System studies to better define needs
– Reversible heat switches for redundant coolers
– Reduce heat switch conductance to 0.1 W/K @ 6 K
– T-zero disconnect

History/State-of-the-art

– Spitzer heat switch allowed warm launch with stored cryogens
– Very little progress due to lack of funding
– Lack of focus and technology development
  – Some at Goddard, JPL, USAF

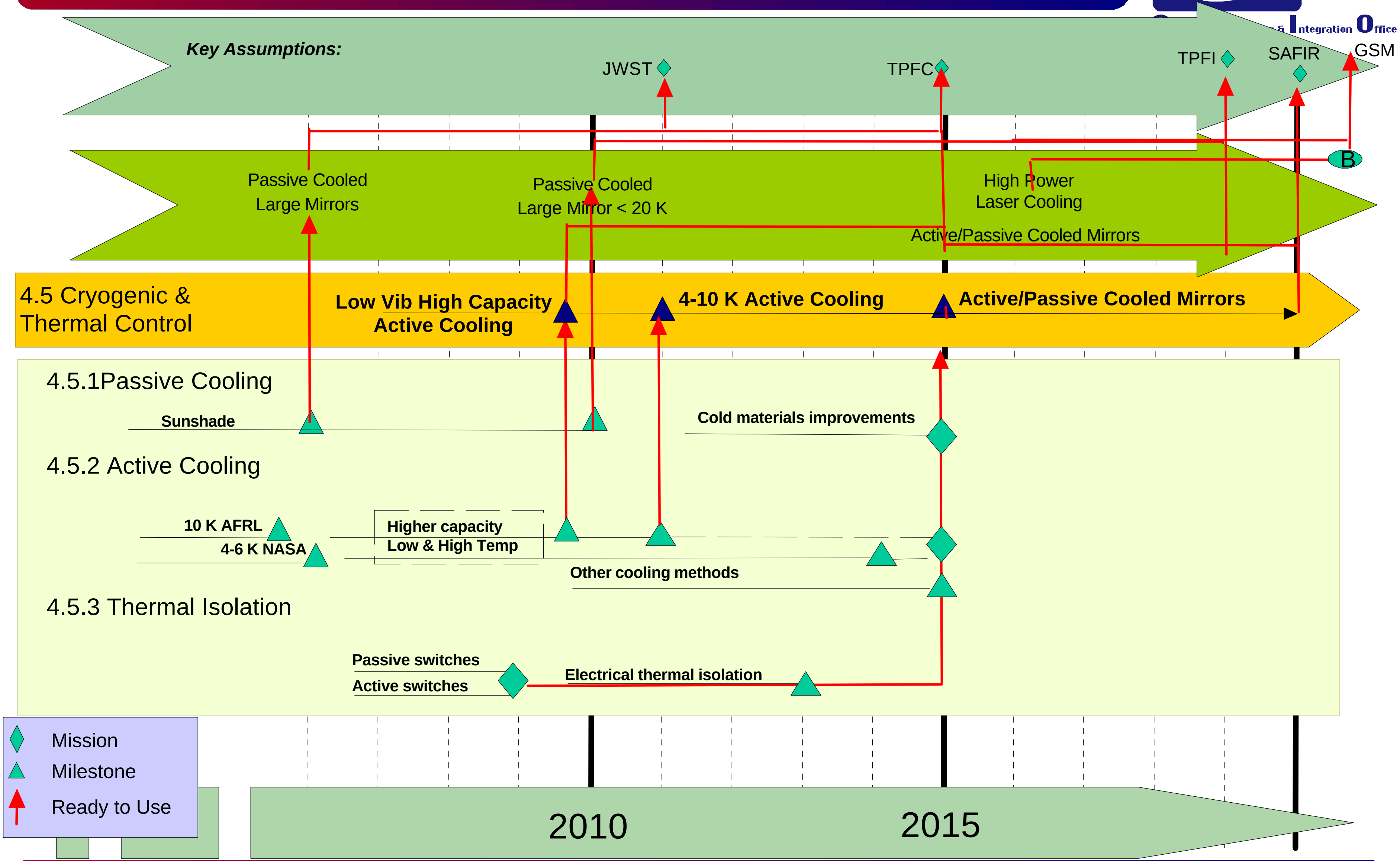


SWALES passive heat switch

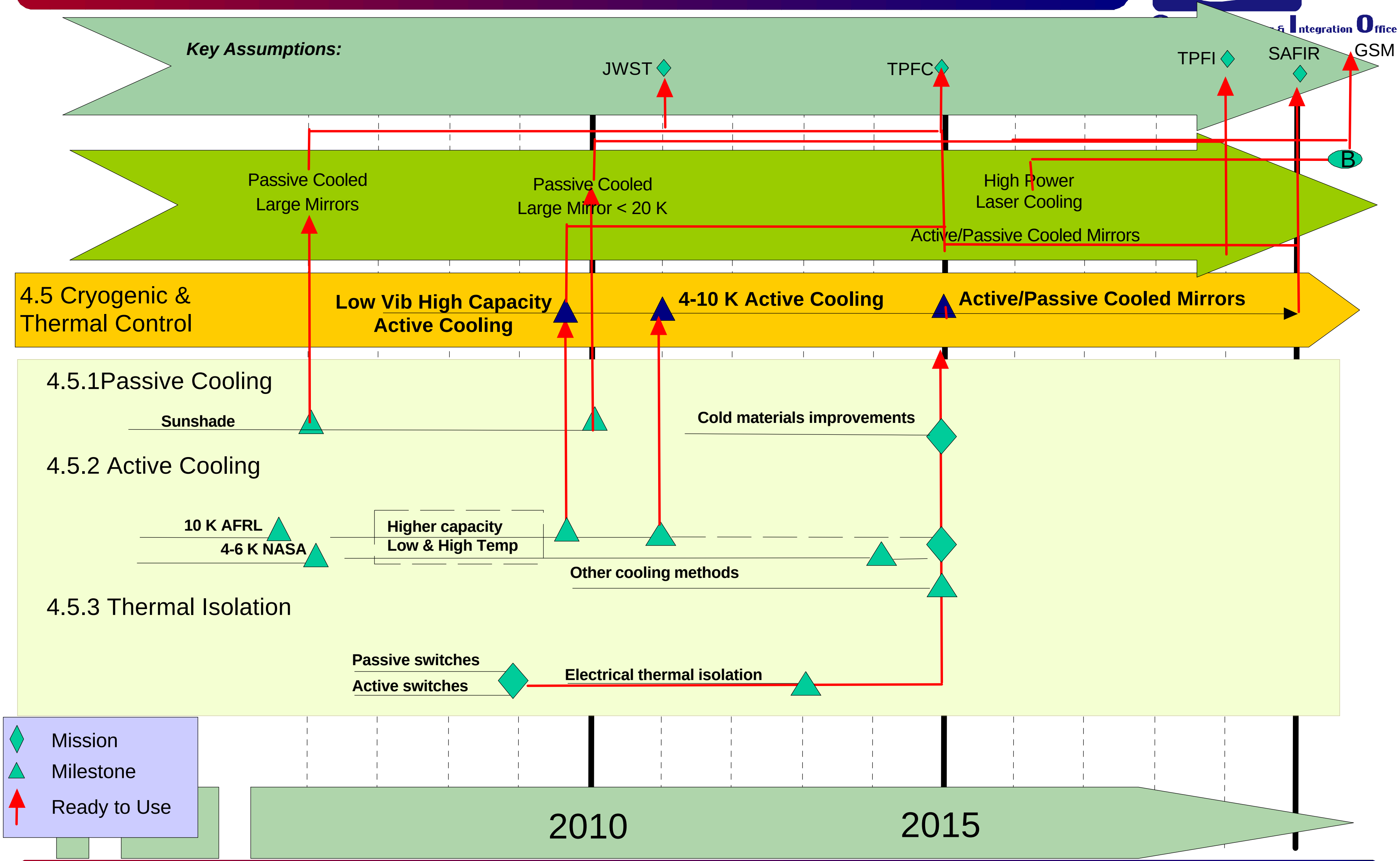
Mission/Strategic Drivers

– Most future cryogenic observatory missions
  – SAFIR
  – TPF-I
  – SPIRIT
  – SPECS

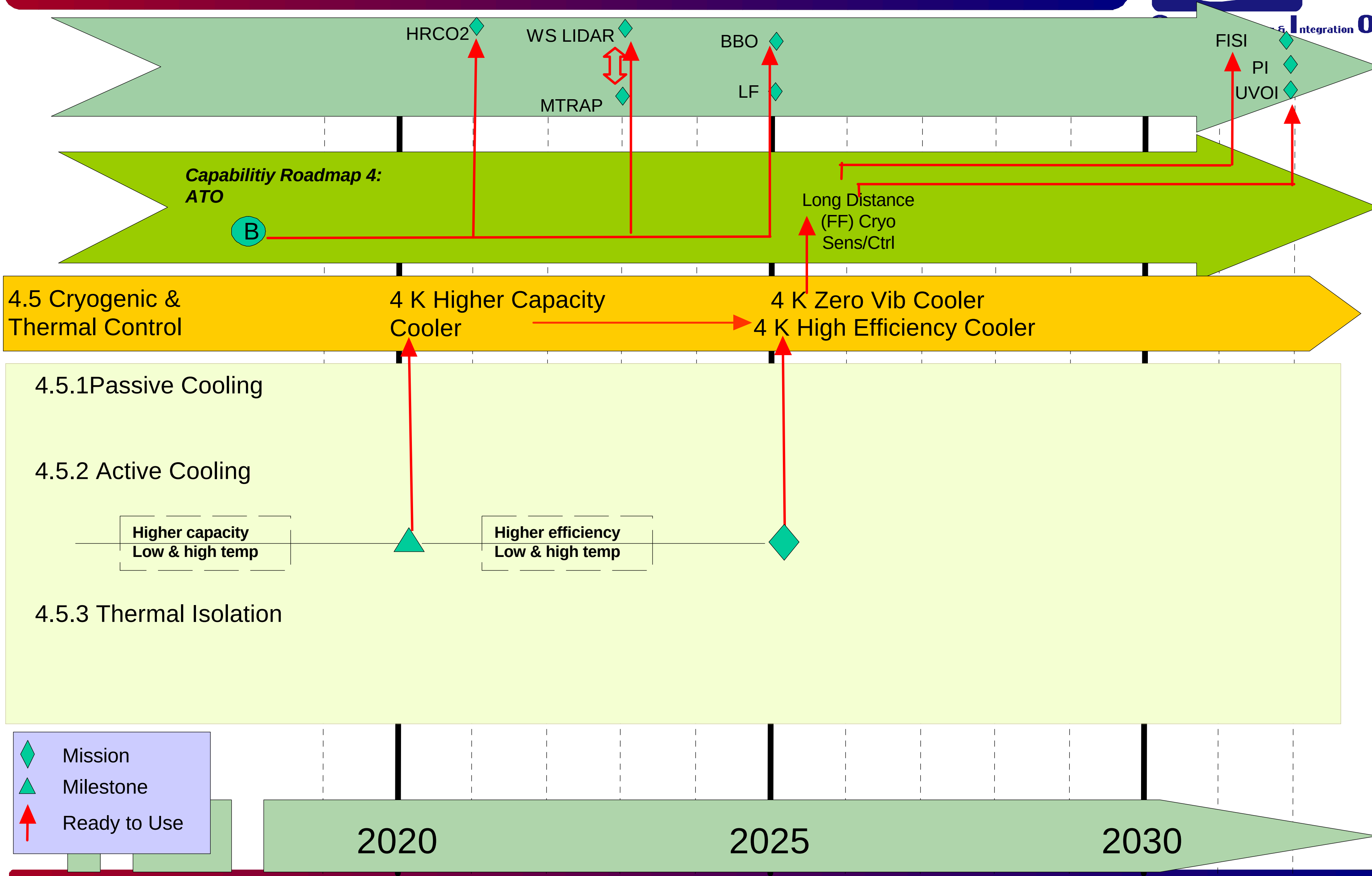
Capability for Cryogenic and Thermal Control Systems Roadmap



Capability for Cryogenic and Thermal Control Systems Roadmap



Capability for Cryogenic and Thermal Control Systems Roadmap



Advanced Telescopes & Observatories Capability Roadmap

4.6 Infrastructure

Gary Matthews, ITT

Infrastructure for ATO

Advanced Planning & Integration Office

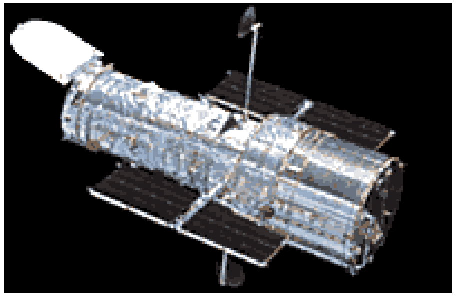
The ATO roadmap identifies technology developments necessary for future Advanced Telescopes and Observatories. This information will be used to guide long range planning that can make these programs possible. In addition to key technological advancements, we recognize the need to invest in the development and sustenance of infrastructure, which would be shared across multiple missions.

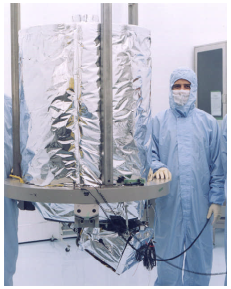
We consider infrastructure as:

- Necessary for development or operation of missions, but not explicitly part of the mission
- Requiring significant, long term effort to implement
- Ideally, infrastructure should be shared by multiple missions

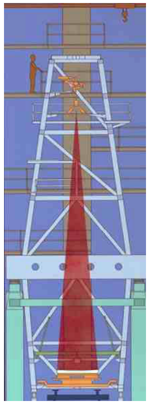
1960's – 2005	2005 – 2025	2025 – 2035
Large systems to 2.5m	Large systems to 8-10m	Large systems > 15m

Full Aperture Verification Using Standard Vacuum Chambers





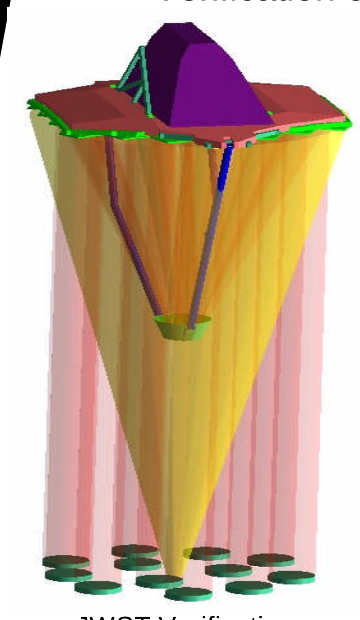
IKONOS



Verification Test Tower

Sampled Full Aperture Verification of Observatory

JWST



JWST Verification

Verify Subassemblies on Ground, Certify Performance After Launch(s) and Potentially On-orbit Assembly

Robust Analytical Tool Set Insures On-orbit Performance

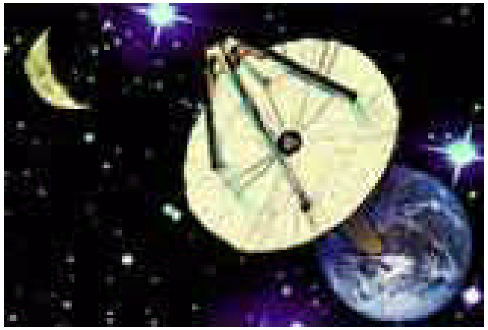
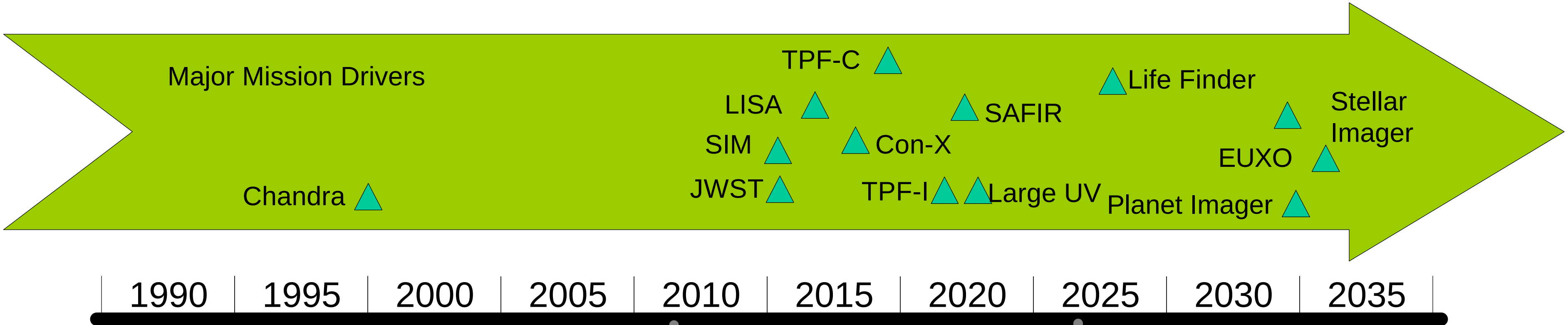


Photo: Space.com

4.6.1 Facilities (cont.) – transition of system testing full ground testing on- orbit verification



Full system testing and verification on the ground prior to launch:

- Vibration
- Static Loads
- Optical
- Thermal Balance
- Acoustic

Robust tool development and verification

Emphasis on system testing is reduced, Sub-scale testing

Larger, higher performance test facilities required

On-orbit system verification for giant systems

Verifications completed at subsystem level

Rely on smarter systems to accommodate system errors

4.6.1 Facilities

Advanced Planning & Integration Office

Description of Capability Needed

- Dedicated high performance optical test facility required to verify systems up to 8-10m
- Even larger facilities will be required if modeling tools are not developed
- (independent subsystem verification becomes important)

Need/Gap Assessment

- Large, dedicated facility required to test large and complex optical payloads while robust tools are being refined
  - Thermal, vacuum, dynamics, cleanliness
  - Consider location relative to Ambient I+T
  - Consider modification of existing vs. new facility
- Long term, subsystem testing and on-orbit performance flexibility will allow observatory testing to be eliminated
- Robust design/analysis/test tools needed

History/State of Art

- Full observatory verification required
- Robust tools and active on-orbit correction are not available to eliminate observatory testing
- Structure Vibration Modeling Verification (SVMV) has attacked modeling tools for prediction obviates need for full scale dynamic testing

Mission/Strategic Drivers

- Sample missions: TPFC, TPFI, SAFIR, LUVO, FISI, BHI
- Full system verification will be difficult/impossible due to gravity and thermal effects on very large systems

4.6.2 Assembly/Servicing Capability

Description of Capability needed:

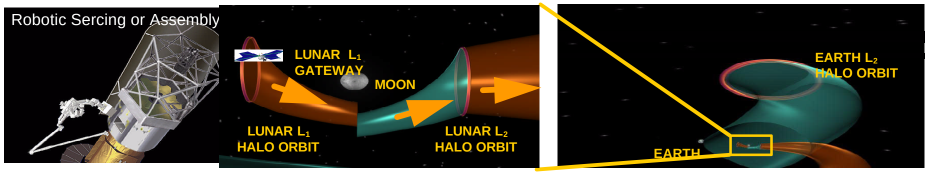
- Capability to provide on-orbit servicing, replenishment, repair/maintenance, and construction of observatory systems
- The benefit of this capability is to reduce risk, extend mission lifetimes, and enable new missions
- Key enabling technologies are architectures and components that develop standard interfaces and component/system modularity.

Need/Gap Assessment:

- Key gaps between state-of-art and needed performance is end-to-end mission system-level architectures that accommodate servicing and mission requirements are needed before we can assess gaps, technology needs, critical flight and ground tests required to ensure capability readiness, etc
- This capability should concentrate on large number of near term observatories going to L2 and should leverage off of Exploration infrastructure

History/State-of-the-art:

- Various missions have fluid transfer concepts and other subsystem needs, but there has been no significant system level technology effort
- Leading Technology Candidates - None
- Current TRL
  - Subsystem components: TRL 1-6 depending on subsystem
  - Architecture: TRL 1



Mission/Strategic Drivers:

- Most future cryogenic observatory missions, including
  - SAFIR, TPF-I, FISI
  - Large UV-Optical: LUVO, LF
- Key external requirements are:
  - Standardized interfaces that include the human/robotic servicing requirements, safety, and priorities
  - Development of mission architectures that enable efficient and affordable servicing
- Date: SAFIR mission need date (~2016)

Potential Approach for Exploration Servicing Vehicle

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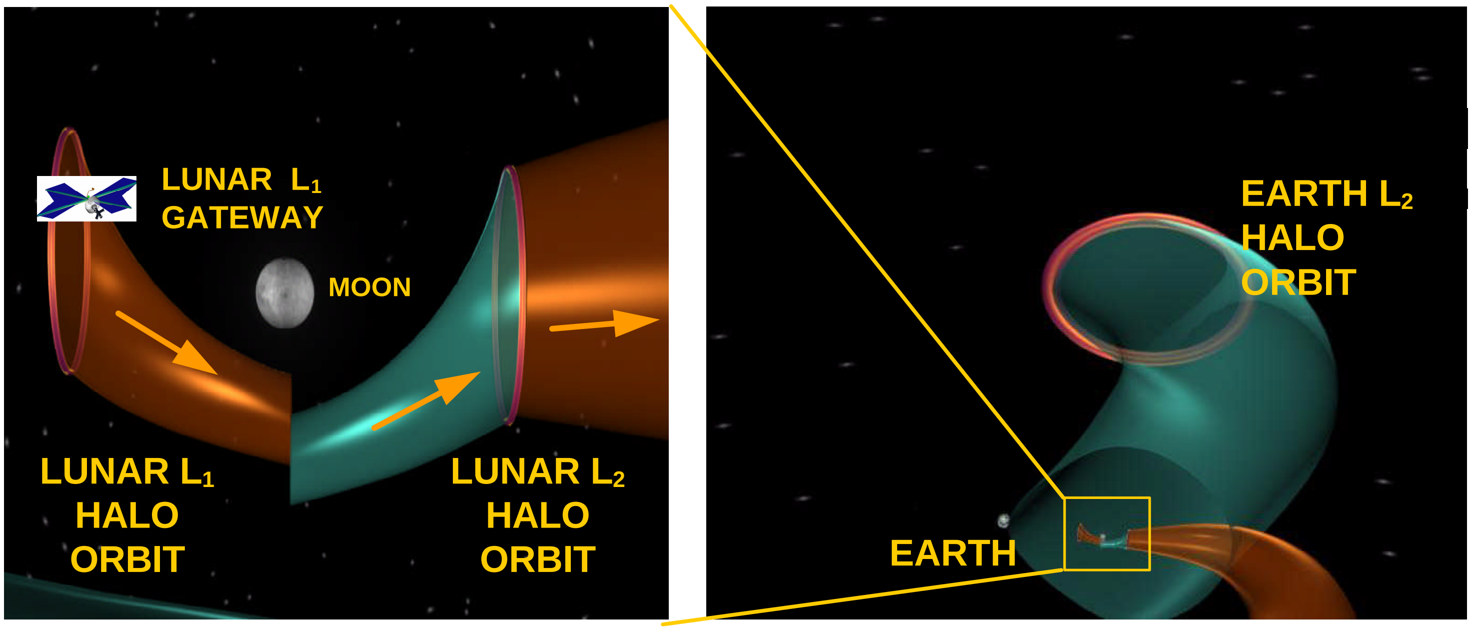
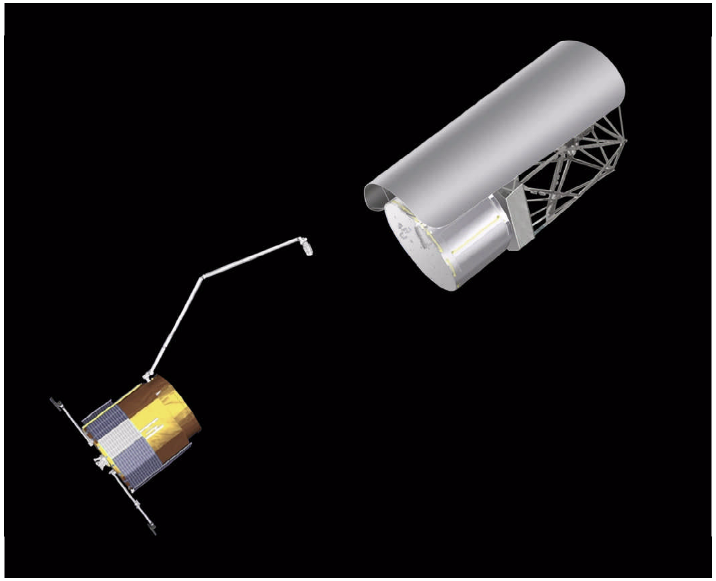
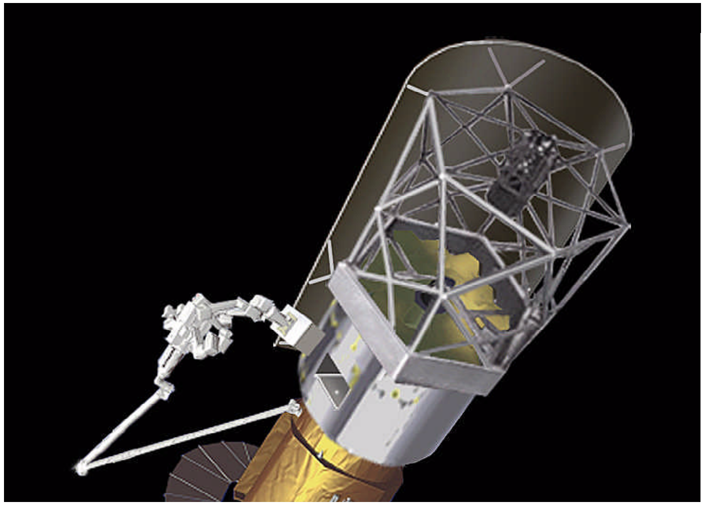
- Small Delta v (~11m/s) required to navigate between lunar gate way and L1 and L2.
- Exploration Vehicle can service and support multiple vehicles thought out earth-moon and Lagrange space.
- Argues for assessing leveraging opportunities from Exploration program



Potential Approach for Exploration Service Vehicle

- Use Lunar Gateway as a staging point
- Collect new instruments and repair modules at gateway for installation at Observatories located at L1 and L2
- Service and assemble through out vast volumes
- Utilize as a general purpose exploration tool





4.6.3 Workforce

Capability needed:

Specialized work force with the necessary work ethic, scientific understanding and experience to create space optics

- Optical design concepts
- New high-sensitivity, low noise detectors and electronics
- Mirrors and uniform coatings
- Metrology and large light-weight space structures for telescopes
- Thermal control
- Precision formation flying

Need/Gap Assessment:

- Need research grant program (NSF, NASA, AFOSR, ARL, etc) focused on the interdisciplinary field: Optical System Science & Engineering.
- Need technology development funds for instrument subsystem testbed demonstration as a training ground.
- Need $25M/yr. University research grant program focused on space-based remote sensing science telescopes, devices, components.
- Need funding to initiate focused programs for training technicians in optics and precision mechanics

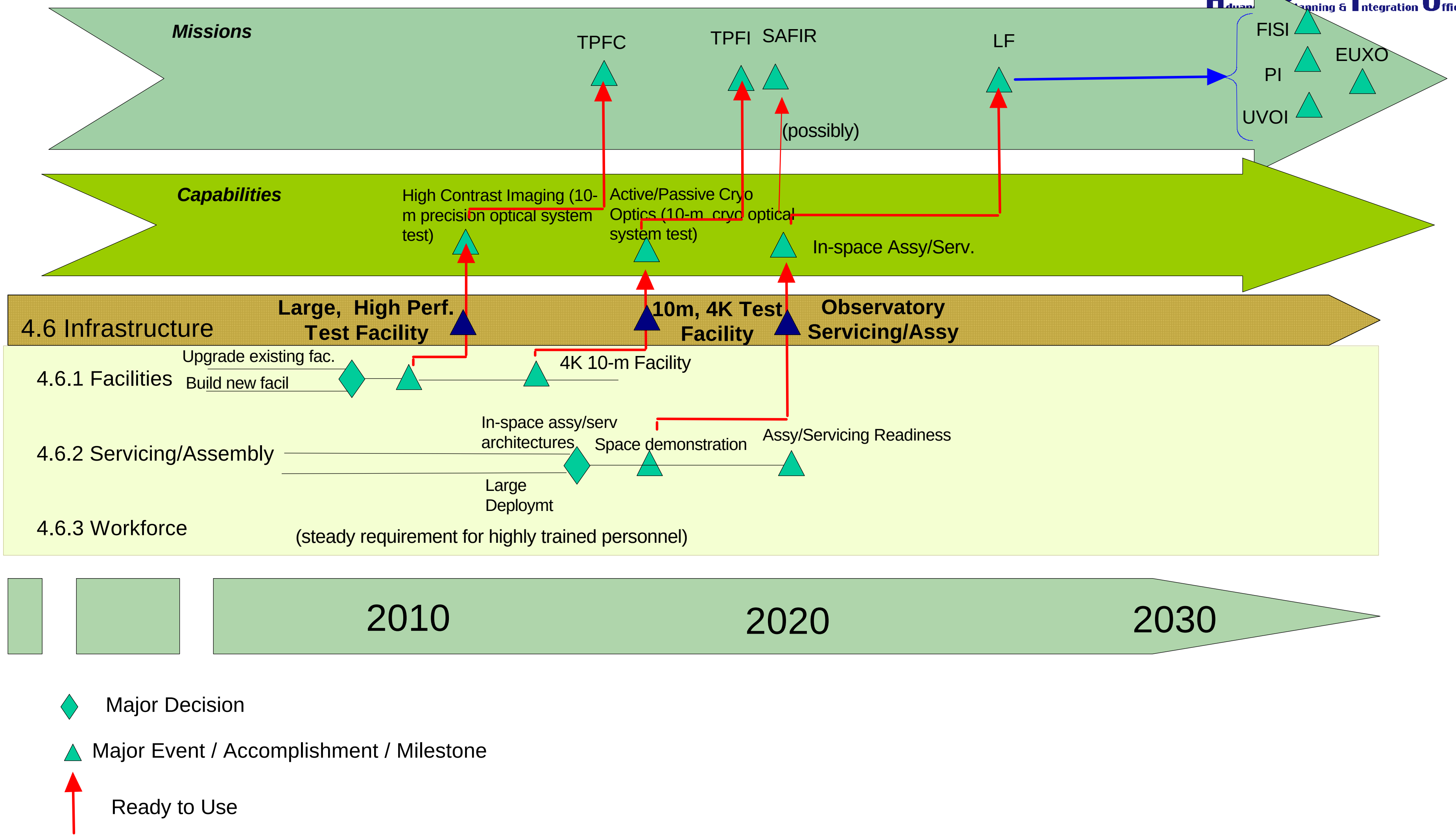
History/State-of-the-art:

- Classical telescopes were designed and built by astronomers with support from technologists and engineers
- The new complex advanced telescopes require full partnership between astronomers, technologists and engineers
- Historically Optical engineering has been divided among physics, structural, mechanical, electrical, and materials engineering. Limited educational programs in US in this area. (National capability for such PhD optical engineering graduates is <10 per year.)

Mission/Strategic Drivers:

- ATO development requires increasing skills for workers of all levels: technician, engineer, manager
- We must cross-train to retain core competency through project and employment cycles
- Coordination with Education Strategic Roadmap

4.6. Infrastructure Timeline



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Concluding Charts

Howard MacEwen, SRS, External Co-chair
Lee Feinberg, NASA Chair

Partnering Possibilities

- Program in replicated, lightweight hybrid mirror technology aimed at UV/Visible options
  - Candidate technologies include nanolaminates, SiC, carbon composites, and MgGrEp
  - Flight demonstration/missions enabled by 3-m class UV-optical deployable telescope
    - Potential for Probe science
    - One-for-one replacement of Hubble capabilities
    - Laser communication telescope capabilities
    - Earth sensing missions
    - LIDAR (Earth, Mars, Io, Titan…..)
  - 3 X Scale-up: New approach to 9 – 10 meter class telescopes
- Launch Load Alleviation approaches
  - Synergistic with lightweight mirrors for affordability
- International partnership:
  - Formation flying via Smart 2/Darwin
- Servicing and refueling
- Material databases

External Roadmap Coordination

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- Large Optics Working Group (LOWG)
  - LOWG an element of the Space Technology Alliance (STA)
  - Developing a “Bottoms-up” space telescope technology roadmap
  - Major LOWG players: NRO, NASA, DOD (including DARPA), DOE
  - ATO and LOWG Roadmaps provide complementary approaches to space telescope technologies: very active coordination ongoing
  - Cross-membership ATO/LOWG
    - MacEwen, ATO external co-chair, supports LOWG Chair (Howerton/NRO)
    - Multiple additional members (Stahl, Breckinridge, Smith, Jones, Tratt)
- ATO Roadmap will also coordinate with National Academy Large Optics in Space (LOIS) study
  - Co-sponsored by NASA and NRO (possible Air Force participation)
  - 12-18 month study: Begins early 2005
  - Will also be coordinated with NRC review of ATO Roadmapping

Comments/Challenges

- Optics and WFSC
  - Critical enablers for many missions, near and far term
  - Direct linkage with Science Enabled
- Distributed/Advanced Spacecraft capabilities (inc formation flying)
  - Enable a majority of longer term missions
  - Spiral technology development approach needed
- Test Facilities
  - New facilities already needed to test next generation observatories
  - Future larger space telescopes will not be ground testable
  - Requires investment in modeling and validation approaches
- Complex space telescopes may benefit from servicing and assembly/testing
  - Leveraging opportunities from Exploration need to be explored
- Current Partnering Possibilities provide opportunity for national approach to multiple missions
  - Includes potential line of low cost 3-meter class telescopes
- Strategic planning process must recognize need for continuity in key core competencies and technological capabilities
  - During the current transition to the new strategic process
  - Long term

ATO Crosswalk to Other Capability Roadmaps

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	2. High-energy power propulsion	3. In-space transportation	4. Advanced telescopes and observatories	5.Communication & Navigation	6. Robotic access to planetary surfaces	7. Human planetary landing systems	8. Human health and support systems	9. Human exploration systems and mobility	10. Autonomous systems and robotics	11. Transformational spaceport/range technologi	12. Scientific instrume and sensors	13.*In situ* resource utilization	14. Advanced modeling, simulation, analysis	15. Systems engineering cost/risk analysis	16. Nanotechnology
2. High-energy power and			[blue]												
3. In-space transportation			[red]												
4. Advanced telescopes and observatories			[yellow]	[red]	[blue]	[gray]	[blue]	[red]	[red]	[red]	[red]	[gray]	[red]	[blue]	[blue]
5. Communication & Navigation															
6. Robotic access to planetary surfaces															
7. Human planetary landing systems															
8. Human health and support systems															
9. Human exploration systems and mobility															
10. Autonomous systems and robotics															
11. Transformational spaceport/range technologies															
12. Scientific instruments and sensors															
13. *In situ* resource utilization															
14. Advanced modeling, simulation, analysis															
15. Systems engineering cost/risk analysis															

Same element [yellow]

Critical Relationship (dependent, synergistic, or enabling) [red]

Moderate Relationship (enhancing, limited impact, or limited synergy) [blue]

[gray]

Summary/ Forward Work

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- Make changes to roadmaps based on verbal feedback from NRC review
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for ATO capabilities
  - Suggest possible opportunities for Strategic Roadmaps
- Make changes to ATO roadmaps to ensure consistency with Strategic Roadmaps requirements
- Continue to work with other Capability roadmaps to ensure consistency and completeness
- Develop rough order of magnitude cost estimates for the ATO Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Acronyms

- ConX= Constellation X
- DEM= Dark Energy Mission
- EASI=Earth Atmospheric Space Interferometer
- EUXO= Early Universe X-ray Observer (formerly Gen X)
- FISI= Far Infrared and Sub-millimeter Interferometer (formerly SPECS)
- GEC=Geospace Electrodynamics Connections
- GSM=Global Soil Moisture
- HResCO2
- IP=Inflation Probe (formerly CMB Pol)
- ISC=In-space Construction/Servicing
- Leo LFSM=Leo Low Frequency Soil Moisture
- LF=Life Finder
- LFFInSAR=L-band Formation Flying InSAR
- LISA=Laser Interferometer ??
- MMS=Magnetospheric Multiscale
- MTRAP=Magnetospheric Transition Region Probe
- PI=Planet Imager
- SI=Stellar Imager
- SMD=Segmented Mirror Demonstrator
- UVOI=UV Optical Interferometer (formerly Stellar Imager)
- WS LIDAR=Wide Swath LIDAR

Crosswalk Tool Example -for backup

In-Space Transportation		**Advanced Telescopes and Observatories**	
Sub-Topic or Subsidiary Capability	**Capability Flow & Criticality**	**Sub-Topic or Subsidiary Capability**	**Nature of Relationship**
GN&C/AR&D	↔ (red)	Distributed and Advanced Spacecraft Systems; Large Precision Structures	All advanced telescope and observatories will require guidance, navigation, attitude, reaction control and determination
Structures	→ (blue)	Large Precision Structures	Primary structures will interface with large precision and potentially deployable telescope structures.
Propulsion Systems (Chemical)	↔ (red)	Distributed and Advanced Spacecraft Systems	All advanced telescope and observatories require Attitude / Reaction Control Systems, Main Propulsion System (including Propellant Pressurization System), and Orbital Maneuvering Systems. This is particularly applicable to formation flying arrays.
Non-Chemical Propulsion Systems	↔ (red)	Wavefront Sensing & Control & Interferometry, Distributed and Advanced Spacecraft Systems; Large Precision Structures	Some Interferometers may require tethers. Some large telescopes may require solar sails for momentum dumping (eg TPF-C). Precision formation flying interferometers require precision low thrust propulsion for on-orbit maneuvers. All advanced telescopes
Thermal Systems	↔ (red)	Cryogenic and Thermal Control Systems	Infrared telescopes require cooling to cryogenic temperatures. Almost all advanced telescopes and observatories require significant thermal management to minimize thermally induced distortions.
Avionics	→ (red)		All advanced telescope and observatories require avionics
Cryo-fluid Management	↔ (blue)	Cryogenic and Thermal Control Systems	Infrared telescopes require cooling to cryogenic temperatures which may require transport of cryo-fluids to cool various parts of the system.
Vehicle Health Management	→ (blue)		All advanced telescope and observatories will require instrumentation/software for monitoring vehicle health and status
Robotic Craft Earth Departure Stage	→ (red)		All advanced telescope and observatories will require launch vehicles
Red - Critical			
Blue - Moderate			

Robotic Access to Planetary Surfaces Capability Roadmap

RAPS Team

June 3, 2005

Agenda

0930-1000	Introduction	Mark Adler
1000-1045	Atmospheric Transit	Neil Cheatwood
1045-1100	Break	
1100-1130	Surface Mobility	Samad Hayati
1130-1200	Accommodation of Instruments and Access to Samples	Steve Gorevan
1200-1300	Lunch	
1300-1345	Aerial Flight	Henry Wright
1345-1415	Cross-Cutting	Joe Parrish
1415-1445	Facilities and Conclusions	Bobby Braun
1445-1500	Margin	

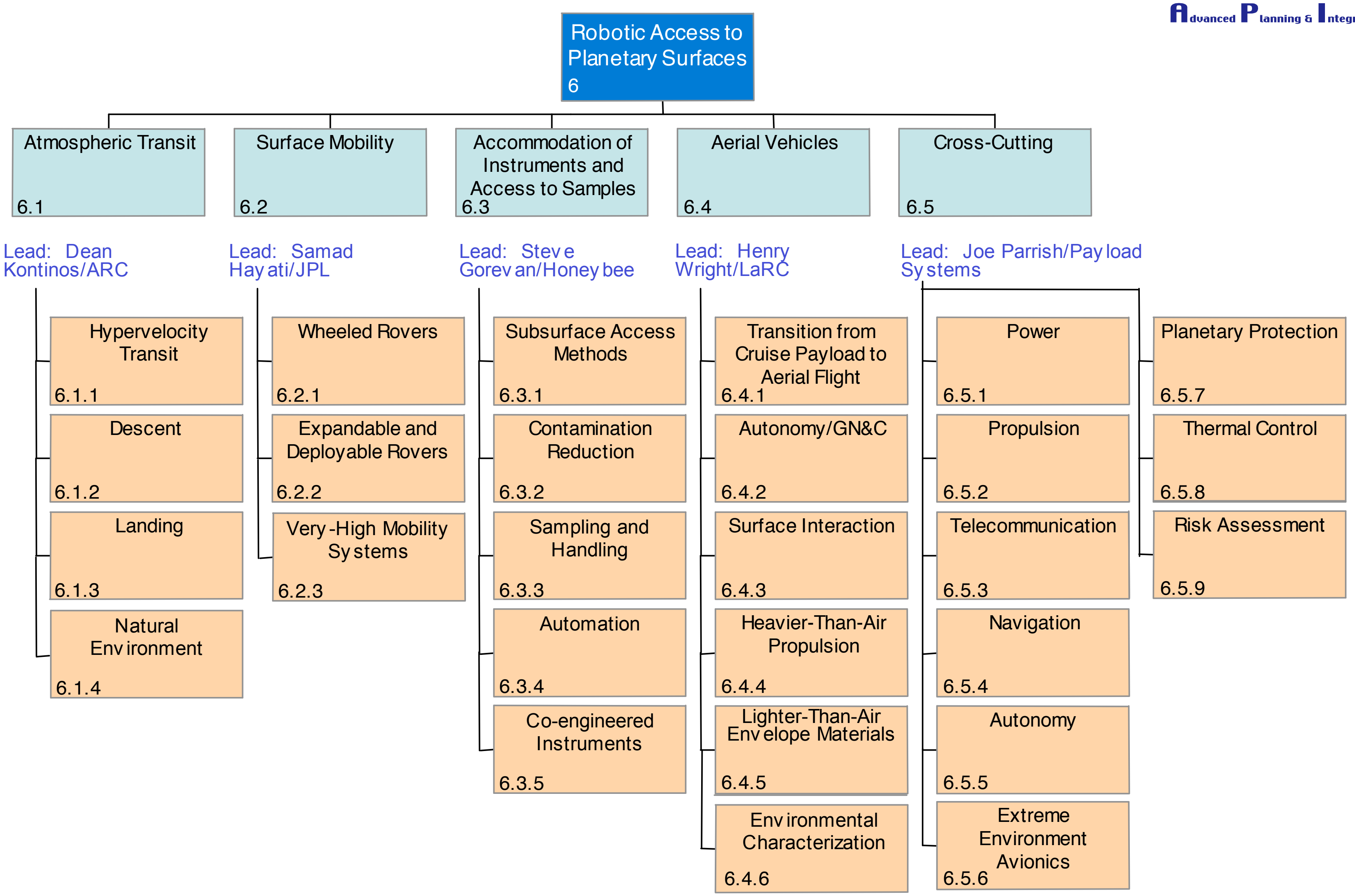
Capability Roadmap Team

- Co-chairs
  - Mark Adler, JPL
  - Bobby Braun, GaTech
- NASA
  - Debora Fairbrother, GSFC
  - Claude Graves, JSC
  - Samad Hayati, JPL
  - Dean Kontinos, ARC
  - Tom Rivellini, JPL
  - Brian Wilcox, JPL
  - Henry Wright, LaRC
- Academia
  - Dave Miller, MIT
- Industry
  - Ben Clark, Lockheed-Martin
  - Steve Gorevan, Honeybee Robotics
  - Joe Parrish, Payload Systems
  - Al Witkowski, Pioneer Aerospace
- Coordinators
  - Harley Thronson, NASA HQ SMD
  - Carl Ruoff, APIO

Capability Description

- Land, Fly, Rove, Dig
  - Operating on (and under) planetary surfaces and in planetary atmospheres
  - Includes aerocapture
  - Includes planetary protection
- On Large Solar System Bodies
  - Moon, Mars, Venus, Titan, Europa, Gas Giant atmospheres
  - Earth landing for sample returns
  - (not small bodies, asteroids, comets)

Capability Breakdown Structure



Roadmaps

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"Roads? Where we're going, we don't need roads."

Dr. Emmett L. Brown (Christopher Lloyd) in *Back to the Future*

Strategic Roadmaps

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- **Robotic Access directly driven by and supports:**
  - Solar System Exploration Roadmap
  - Mars Exploration Roadmap
  - Lunar Exploration Roadmap

Other Capability Roadmaps

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- Scientific Instruments and Sensors
  - RAPS brings the instruments to the samples and the samples to the instruments
  - SIAS provides integrated instruments, e.g. down-hole
- Human Planetary Landing Systems
  - Continues EDL evolution from RAPS
- Autonomous Systems and Robotics
  - Provides high-level autonomy for surface robots
- Communication and Navigation
  - Provides relay communications and radio-location services
- High Energy Power and Propulsion
  - Provides nuclear power sources for in situ vehicles
- In-space Transportation
  - Provides in-space systems for sample returns
- In situ Resource Utilization
  - ISRU can provide propellant for very-long-range traverse

Coverage Assumptions

- Human mission drivers
  - Robots as assistants to humans in space and on planetary surfaces (Human Exploration Systems and Mobility)
  - ISRU and resource extraction (In situ Resource Utilization)
- High-level autonomy (Autonomous Systems and Robotics)
  - Automated planning and sequencing — flight and ground
  - On-board science analysis
  - Proximity cooperation of multiple surface assets
  - Machine perception, including vision to support pinpoint landing and hazard avoidance
  - Mobility and articulation goal seeking
- Robotic sample-return capabilities (In-space Transportation)
  - Planetary ascent
  - Autonomous rendezvous and capture
- Communications and Navigation (High-capacity Telecom and Information Transfer)
  - Surface relay communication and radio location determination
  - Proximity communication between surface assets
  - Approach navigation, including optical data types
  - EDL and other critical event communication
  - Post-entry EDL navigation aids (orbital and surface)

Roadmap Process

1. Define scope of roadmap, Oct 14, 2004
2. Select team members to cover scope, Nov 1, 2004
3. Conduct public session to solicit input, Nov 30, 2004
4. Conduct three workshops with invited experts
   1. Dec 15-17, 2004, JPL
   2. Feb 2-4, 2005, ARC
   3. Mar 3-4, 2005, Georgia Tech
5. Construct roadmap messages (3rd workshop)
6. Detail roadmap actions (April)
7. Executive Summary (May)
8. *External Review (June)*
9. Final Report (July)

Roadmap Approach

- Define scope and preliminary reference missions
  - Establish relations with other roadmaps
- Canvas community for capability status, plans, and hopes
  - Significant overlap with HPLS in atmospheric transit, held common workshops
- Construct roadmap messages
  - What we think NASA should do, action-oriented
- Fill in details of the actions
  - Metrics
  - Applicable reference missions, or push missions
  - Current and required capability readiness (descriptive)
  - Key resources, e.g. facilities
  - Rough cost and schedule estimates
- Lay out a representative implementation plan

Europa Ldr

NASA 2005 Strategy

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NASA Strategic Objectives (first 3 of 18):

1. Undertake robotic and human lunar exploration to further science and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. The first robotic mission will be no later than 2008.
2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration.
3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore the moons of Jupiter, asteroids, and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources.

All require robotic access to planetary surfaces

The Real Justification

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Design Reference Missions (1)

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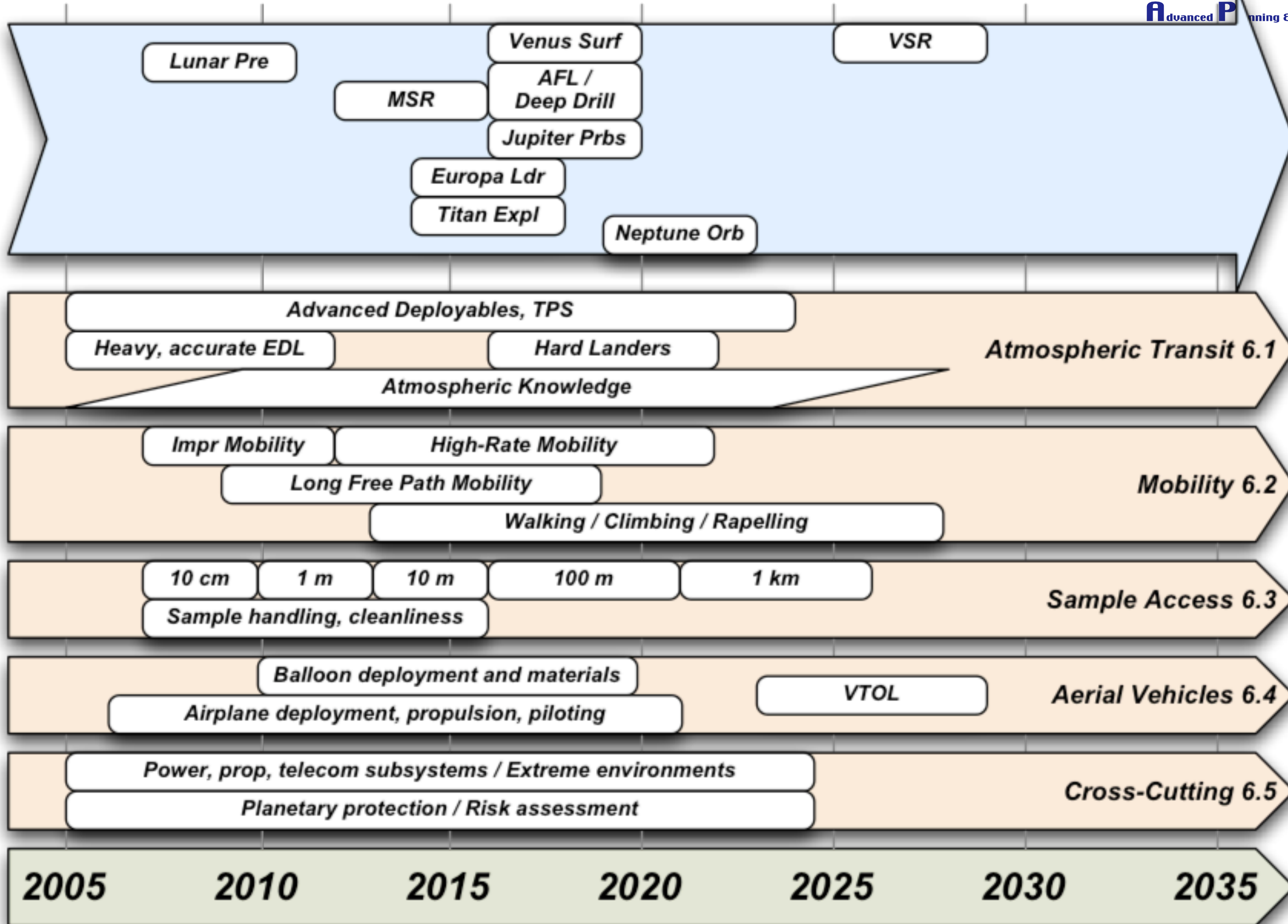
- Derived from:
  - Solar System Strategic planning
  - Mars Exploration Program planning
  - Robotic Lunar Exploration planning
- Subset of conceived missions chosen:
  - To involve the scope of this roadmap
  - To drive capability developments in time
    - Does not include all applicable missions, only schedule drivers
- Pathways
  - Missions on separate pathways are included in the capability development to enable the choice
- Schedule
  - Assumed capability readiness required in all cases four years before launch

Design Reference Missions (2)

- Lunar Precursor Lander 2011
- Mars Sample Return 2016
- Titan Explorer (airship) 2018
- Europa Astrobiological Lander 2018
- Mars Deep Drill 2020
- Mars Astrobiological Field Laboratory 2020
- Venus Surface Explorer 2020
- Jupiter Atmospheric Probes 2020
- Neptune Orbiter (aerocapture) 2023

Top-Level Roadmap



Key Architectural Decisions

Key Architecture/Strategic Decisions	Date Decision is Needed	Impact of Decision on Capability
Decision to launch Mars Sample Return.	9 years before the intended launch.	Latest date to start planetary protection, Earth entry, heavy Mars EDL, advanced mobility, and sample handling capabilities.
Decision to launch an in situ life-detection laboratory to Mars, either rover-borne or on a fixed platform deep drill.	7 years before the intended launch (though see next row).	Latest date to start contamination reduction and sterilization, and complex sample handling.
Decision to launch a deep drill life-detection laboratory to Mars.	8 years before the intended launch.	Latest date to start an autonomous deep drill, and down-hole instrumentation.
Decision to continue the exploration of Titan with a long-lived airship capable of surface sampling.	8 years before the intended launch.	Latest date to start airship materials, guidance and control, propulsion, and surface interaction.
Decision to explore the Venusian surface with a long-lived laboratory.	7 years before the intended launch.	Latest date to start extreme environment survival system studies and component development.
Decision to deliver deep atmospheric probes to Jupiter, or decision to conduct an aerocapture at Neptune.	12 years before the intended launch.	Latest date to start thermal protection materials, refurbish test facilities, and analysis capabilities.

Cost and Schedule

- Cost estimates have been provided where available
  - All are considered to have an uncertainty of a factor of three in the up direction, unless otherwise stated
  - Many areas require further definition since the cost is strongly dependent on the requirements of the capability, or the duration of the maintenance of a capability
  - The costs are provided for top-level conceptual planning only. Detailed cost estimates should be requested from providing organizations. Your mileage may vary.
- Schedule estimates are shown in the roadmap graphics
  - Similarly, detailed schedule estimates should be requested, given more detailed scope definitions

6.1 Atmospheric Transit

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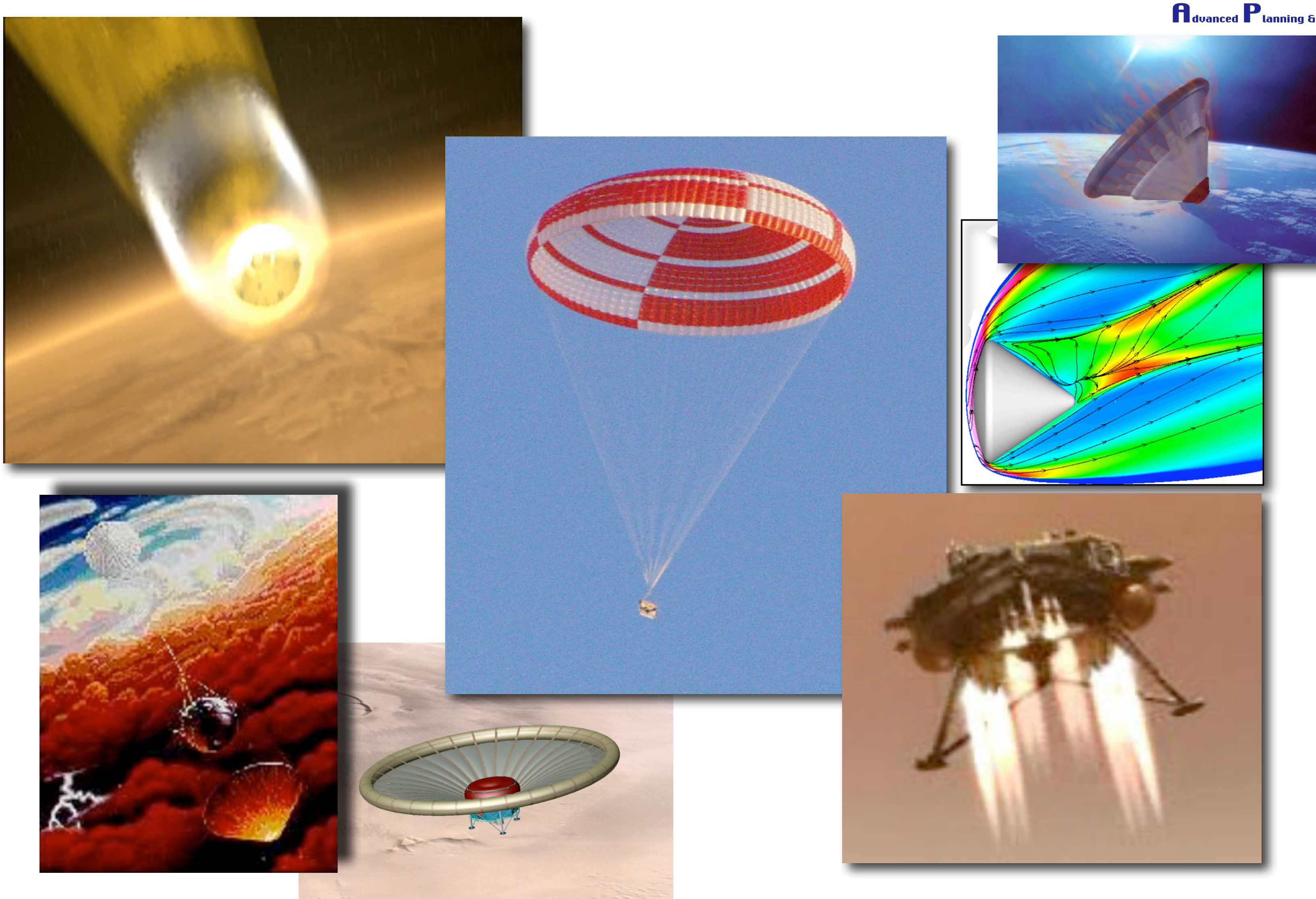


6.1 Atmospheric Transit

- Entry, descent, and landing
- Entry: thermal protection and controlled hypersonic flight in atmospheres, guidance in hypersonic flight for precision landing and aerocapture
- Descent: non-thermal supersonic and subsonic deceleration and control in atmospheres, guidance for pinpoint landing
- Landing: sensing and reaction for hazard avoidance and controlled surface impact, structure and mechanisms for surface impact survival and stability
- Descent guidance and landing also apply to bodies without atmospheres

6.1 Benefits

- Placement of instrument packages and vehicles on planetary surfaces
  - Landers / stations
  - Rovers
  - Sample returns (both ends)
- Atmospheric measurements and sampling
  - Atmosphere probes
  - Atmosphere samplers (hyperbolic exit for return)
- Deployment of aerial vehicles in the atmosphere
  - Vehicles covered in 6.4
- Aerocapture of orbiters

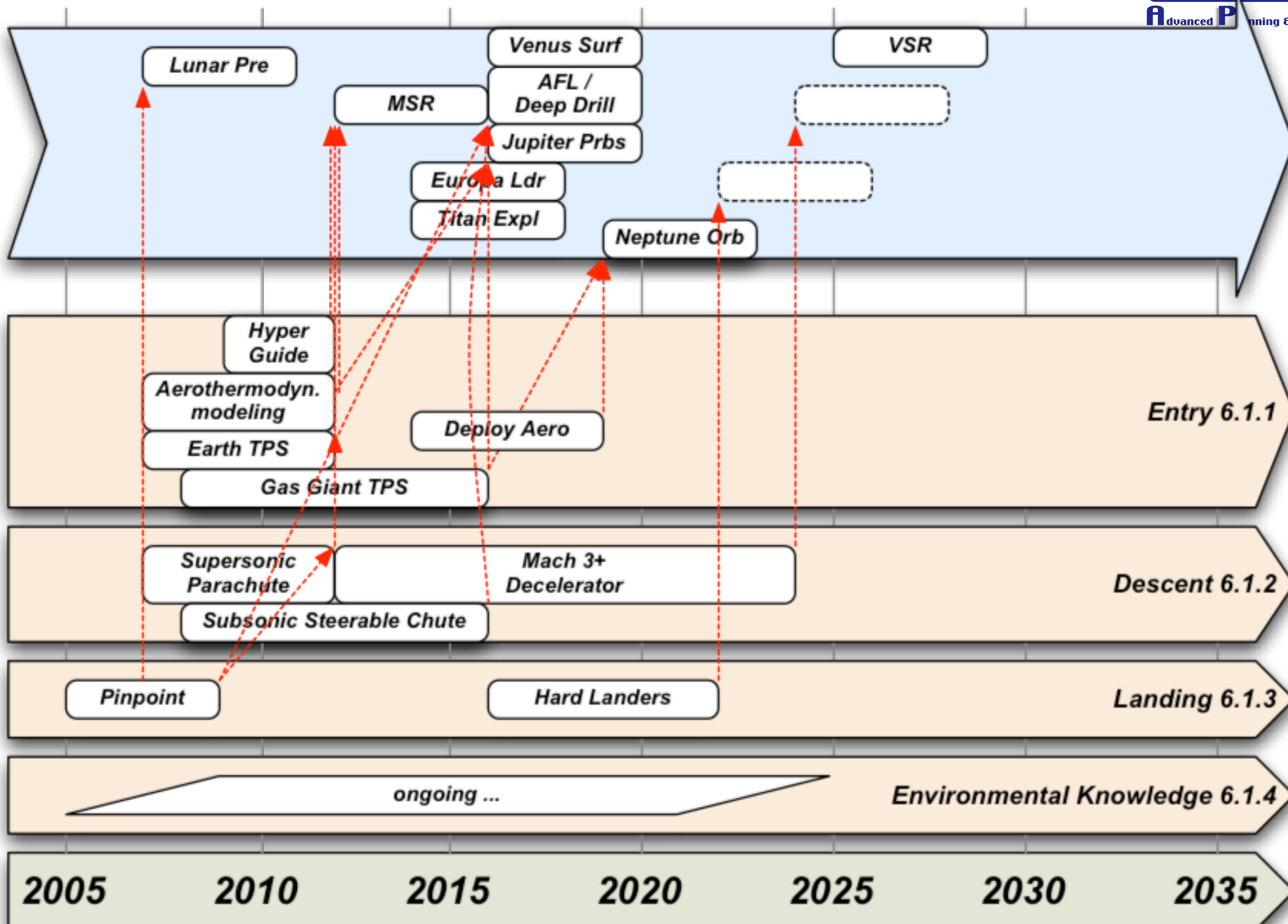
6.1 State of Practice

- Mars entry and descent (Viking, Pathfinder, MER)
- Legged soft landing (Surveyor, Apollo, Viking)
- Airbag rough landing (Pathfinder, MER)
- Atmospheric probes (Pioneer Venus, Galileo)
- Earth return (Apollo, Genesis, Stardust en route)
- Other countries:
  - Luna landers at the Moon (USSR)
  - Luna sample returns to Earth (USSR)
  - Mars 3 lander? (USSR)
  - Vega 1/2 landers at Venus (USSR)
  - Vega 1/2 balloon deployments at Venus (USSR/France)
  - Huygens atmosphere and surface probe at Titan (ESA)

6.1 Driving Mission Assumptions

- Assume sky crane technology developed for MSL
- Large (> 1 mt) payloads to Martian surface
- Moon and Mars precision and pinpoint landing
- Gas giant atmosphere probes and aerocapture
- Venus atmosphere probes and surface landers
- Titan aerial vehicle delivery to pre-deployment conditions
- Europa landing
- Earth landing for Mars Sample Return
  - With very high reliability

6.1 Atmospheric Transit Roadmap



6.1.1 Atmospheric GN&C

- Advanced GN&C algorithms must be brought from the simulation & analysis realm to flight readiness with sufficient reliability to enable precision (< 10 km) landing, pinpoint (< 100 m) landing and aerocapture.
- Derivatives of Apollo GN&C algorithms exist but have not been flight proven for aerocapture. Advanced GN&C algorithms offer significant performance and robustness advantages.
- Metrics: Landing precision, software complexity, compute time and robustness
- Resources: GN&C expertise within NASA, industry and academia.
- Applicable at multiple planetary destinations (Mars, Venus, Titan, Neptune, Earth).
  - MSL, MHP, MSR, AFL
- Cost: $10M

6.1.1 Aerodynamics

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- Retain aerodynamic performance prediction capability.
  - Knowledge of static aerodynamics to within 3% and dynamic aerodynamics to within 10% will allow reduced design margin and high reliability atmospheric transit.
- Aerodynamics expertise exists within the Agency and in industry. Facilities for aerodynamic testing are operated by NASA and are under threat of closure. Little to no flight data for validation.
- Metrics: Aerodynamic coefficient uncertainty
- Resources: NASA LaRC Hypersonic Complex, Transonic Dynamics Tunnel, and Vertical Spin Tunnel, Eglin and ARC Ballistic Ranges
- All missions with trans-atmospheric flight: Mars, Venus, Sample Return, Titan, Gas Giants
  - MSL, MHP, MSR, AFL
- Cost: $40M

6.1.1 Aerothermodynamic Modeling

- **Accurate prediction of entry heating environments for TPS sizing, mission design, and risk management.**
  - **Understand radiating shock layer uncertainty to within ±50%, boundary layer transition time to seconds, shock-boundary layer heating predictions to ±25%, while reducing simulation time for multi-physics interactions to hours.**
- **Expertise resides primarily within NASA.**
  - **Currently able to predict forebody convective heating to ±15% and forebody turbulent heating to ±25%. Radiative heating ±300%, transition to turbulence time (minutes), aft-body heating ±100%, and ablative shock layers ±200%. Insufficient flight data to validate models.**
- **Metrics: Aerothermodynamics uncertainty and computational time**
- **Resources: LaRC Aerothermodynamics Laboratory, ARC shock tube and ballistic range, Calspan-University of Buffalo Research Center LENS facility, Cal Tech T5, Supercomputing Facilities, high-fidelity CFD analysis/codes**
- **All missions with trans-atmospheric flight: Mars, Venus, Sample Return, Titan, Gas Giants: MSL, MHP, MSR, AFL**
- **Cost: $25M**

6.1.1 Ablative TPS

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- Develop reliable mid/high-density ablative TPS for specific entry and aerocapture environments.
  - Reduce mid-density TPS mass fractions from 25-30% to 15-20%. Reduce high-density TPS mass fractions from 50-100% to 30-50%. High fidelity TPS response modeling: surface temperature to within 100 deg C, in-depth temperatures to within 10% and 10 s, surface recession to within 20%, char thickness and depth to within 10%.
- Few existing, poorly characterized mid-density ablative materials. Heritage high-density materials needed for Gas Giants no longer manufactured, recipe lost
- Metrics: TPS mass fraction and thermal response prediction
- Resources: ARC and JSC arc-jets, ARC Giant Planet Facility (reconstituted) for Gas Giants.
- Sample return missions (Mars, Lunar), aerocapture missions (Venus, Neptune), entry probes (Venus, Saturn, Jupiter)
  - MSR, Moonrise
- Cost: $30M for mid-density, $30M high-density

6.1.1 Deployable Decelerators (Inflatable Hypersonic)

- Develop deployable entry systems that package on existing launch vehicles and experience extremely low entry heating (1-10 W/cm2).
- Current planetary program relies on rigid aeroshells and ablative thermal protection systems. The Russians have flown, unsuccessfully, an inflatable system. In the US, system studies for deployables and inflatables are ongoing.
  - Key challenges are materials, deployment, aerostability, and control.
- Metrics: Materials characterization, aerostability, integration
- Resources: NASA LaRC Hypersonic Complex and Transonic Dynamics Tunnel, High altitude balloon flight testing (NASA WFF), Sounding rocket flight testing (NASA WFF, strategic assets), Super-computing facilities for dynamic aero-thermal-structural simulation.
- Applicable to Venus, Titan, and Nepture aerocapture, Heavy Mars landers and Earth return.
- Cost: $75M to $150M

6.1.2 Supersonic Parachute

- Develop supersonic parachute to support Mars entry masses ~4000 kg, Mach 2.5 deploy
- Currently limited to Viking heritage, ~1000 kg entry mass, Mach 2.1 deploy
  - Have been living off of the Viking parachute qualification for over 30 years
- Metrics: drag area, deploy Mach, mass, stability
- Resources: High altitude balloon flight testing (NASA WFF), NASA LaRC TDT, NASA GRC 10x10, Sounding rocket flight testing (NASA WFF, strategic assets)
- Needed for MSR, AFL, Deep Drill
- Cost: $140M (within 30%)

6.1.2 Deployable Decelerators
(Inflatable Supersonic)

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- Develop supersonic deployable drag device for enabling large entry mass (> 4000kg) to Mars.
- Parachute systems are prohibitive due to size and Mach number constraints. Numerous studies and experiments of inflatable supersonic decelerators. Devices are not flight tested, and will require additional subsonic decelerator for adequate performance.
- Metrics: drag area, deploy Mach, mass, stability
- Resources: High altitude balloon flight testing (NASA WFF), NASA LaRC TDT, NASA GRC 10x10, ARC NFAC, Sounding rocket flight testing (NASA WFF, strategic assets), Supercomputing facilities
- May be applicable to MSR, AFL, MHP

6.1.2 Subsonic Parachute

- Develop subsonic parachute to support large Mars entry mass > 4000 kg. Guidance enhancement enables wind drift compensation for pinpoint landing
- One test in relevant environment of single ringsail with no steering
- Metrics: drag area, mass, stability, L/D
- Resources: High altitude balloon flight testing (NASA WFF), NASA LaRC TDT, NASA GRC 10x10, ARC NFAC, Sounding rocket flight testing (NASA WFF, strategic assets), Supercomputing facilities
- May be applicable to MSL, MSR, AFL, MHP
- Cost: $20M (within 30%)

6.1.3 Landing Airbags

- Develop low mass (60-80 kg), high reliability, rock-tolerant airbag systems for MER class Mars landing.
- MER and Pathfinder used Vectran bags (125 kg). Zylon and its variants offer potential mass savings but no work has been done to explore its applications to airbags.
- Metrics: Airbag system mass, reliability
- Resources: NASA Glenn Research Center Plum Brook Station (Space Power Facility and B2 vacuum chambers)
- Applicable to Mars Scout or MER-class and lunar missions.
- Cost: $20M

6.1.3 Terrain Sensing

- Develop high performance terrain sensing customized for the unique requirements of spacecraft landing.
- Recent lander missions have used modified military radars with limited performance. Advanced technologies are in development, but not ready for flight qualifiction
- Metrics: Acquisition altitude, Velocity error, Map resolution
- Resources: Industry
- Applicable to Mars Scout, MSL, MSR, AFL, Europa lander, lunar landers, Venus lander, Venus sample return, Titan explorer, small body/comet sampling and rendezvous missions.

6.1.3 Descent Propulsion

- Develop a high reliability, throttleable descent propulsion system
- Current technologies are variants of 1960's technologies and span a limited thrust range. Pulse-mode work arounds add control interaction complexity and risk.
- Metrics: Control authority, thrust range
- Resources: Industry
- Applicable to MSL, MSR, AFL, Europa lander, lunar landers, Venus lander, Venus sample return, Titan explorer, small body/comet sampling and rendezvous missions.

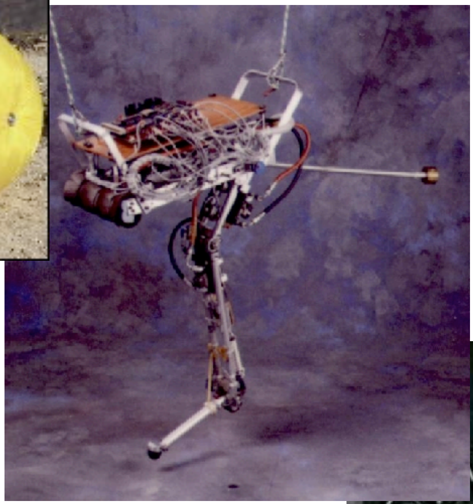
6.1.3 Surface Penetrators

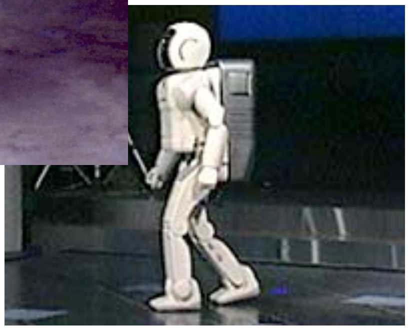
- Develop low mass, high reliability, single-stage entry to impact system capable of penetrating at least 1-3 m below Mars surface
- Space exploration application limited to DS-2 Mars Microprobe (failed), Soviet mission (failed), Japanese mission (postponed). Extensive military application of penetrators.
- Metrics: System mass, impact depth & g's, terrain type
- Resources: Sandia National Laboratory air guns and test facilities.
- Applicable to Mars, Lunar and small body missions
- Cost: $30M

6.1.4 Atmosphere Characterization

- Develop planetary atmosphere modeling capability that yields predictions of density within 10% and a credible basis for wind and atmospheric opacity estimation.
- Flight through a planetary atmosphere is complicated by our lack of atmospheric knowledge (density, winds and dust content) at hypersonic maneuvering (20-60 km) and terminal descent altitudes (0-10 km).
- Metrics: Atmospheric uncertainty, Quantifiable entry system margin reduction.
- Resources: Atmospheric science expertise within Agency and academia. May require atmospheric observer orbiter, probe or network science (micro probe) missions as well as instrumentation reqts for all entry systems.
- Applicable to MSL, MSR, AFL, Venus sample return, Titan explorer, Gas Giant entry missions
- Cost: $10M per project for entry instrumentation, unknown cost for atmospheric instrumentation piggyback or on dedicated orbiter

6.2 Surface Mobility





6.2 Surface Mobility

Advanced Planning & Integration Office

- Mobile platforms on planetary surfaces
  - Traversal over the surface
- Wheeled vehicles
- Expandable deployed vehicles
- High-mobility non-wheeled vehicles
  - (Swimming considered but not covered in this roadmap due to number of decades away and lack of characterization of potential environments)

6.2 Benefits

Advanced Planning & Integration Office

- Access to features away from landing location (a la Opportunity in Eagle crater)
- Exploration of multiple geological units
- Access across and beyond landing ellipse
- Combined with precision/pinpoint landing and high-mobility, access to any selected point on the surface

6.2 State of Practice

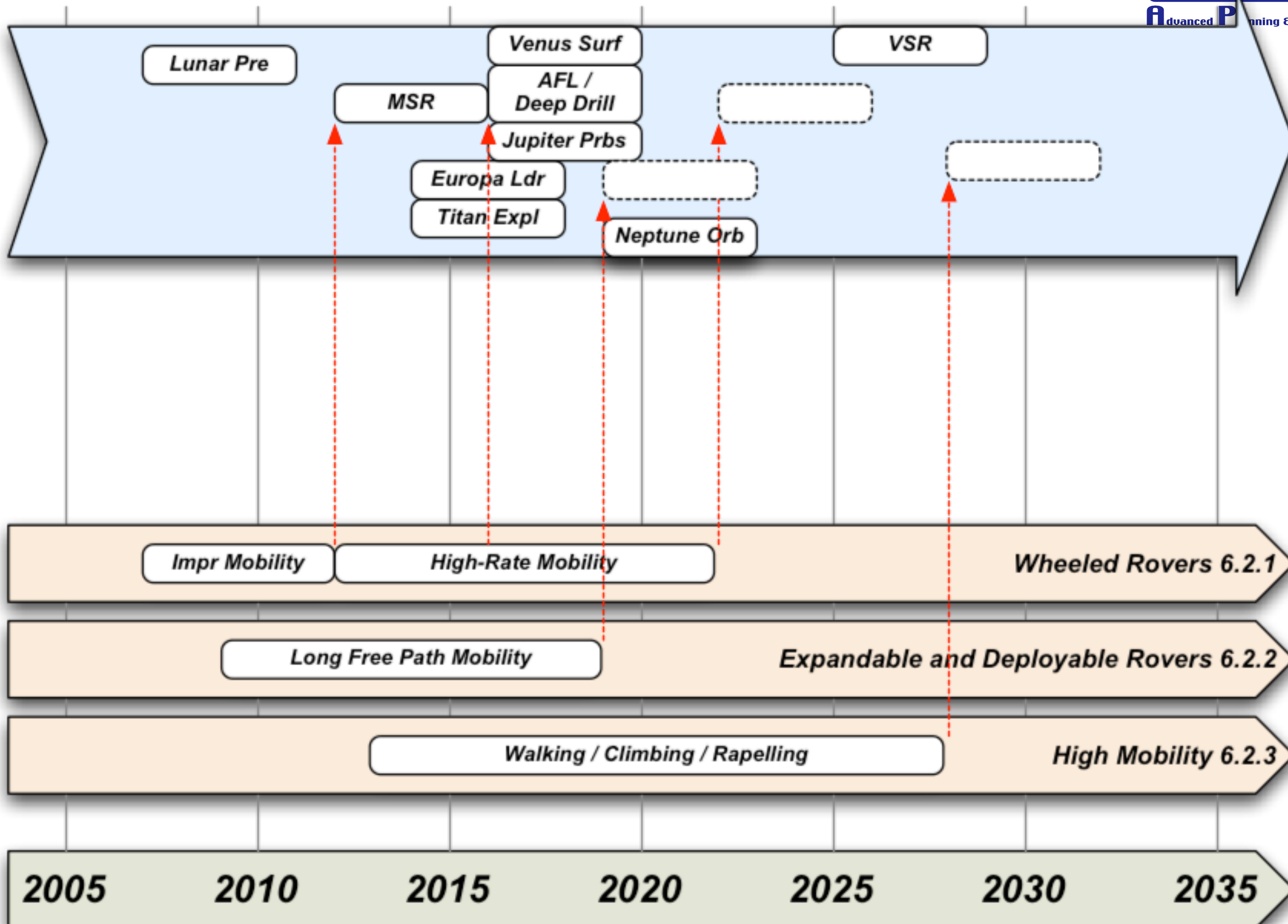
Advanced Planning & Integration Office

- Apollo lunar rover (human operated)
- Sojourner rover on Mars
- Mars Exploration Rovers
- Other countries:
  - Lunakhod, teleoperated on the Moon (USSR)

6.2 Driving Mission Assumptions

- Mars Sample Return
  - Rapid sample collection and delivery
- Mars Astrobiological Field Laboratory
  - Long traverse, increased autonomy
- Lunar Precursor Lander
  - New terrain for our robotic rovers

6.2 Mobility Roadmap



6.2.1 Wheeled Rovers

- Develop more capable wheeled rovers (longer life, modular architectures, increased computer throughput, and robust navigation sensors)
- Currently limited to MER capabilities; i.e, heavy dependency on human-in-the-loop and designed for 90 sols (cannot be guaranteed to operate for several years)
- Metrics: Long life, modularity, and increased navigation and compute power (to accommodate more autonomous operation)
- Resources: NASA (JPL and ARC), university testbeds
- Needed for MSL, MSR, and AFL
- Cost: $2M/yr for technology and $1M/yr for maintenance of testbeds, for the next 5-15 years

6.2.2 Expandable and Deployable Rovers

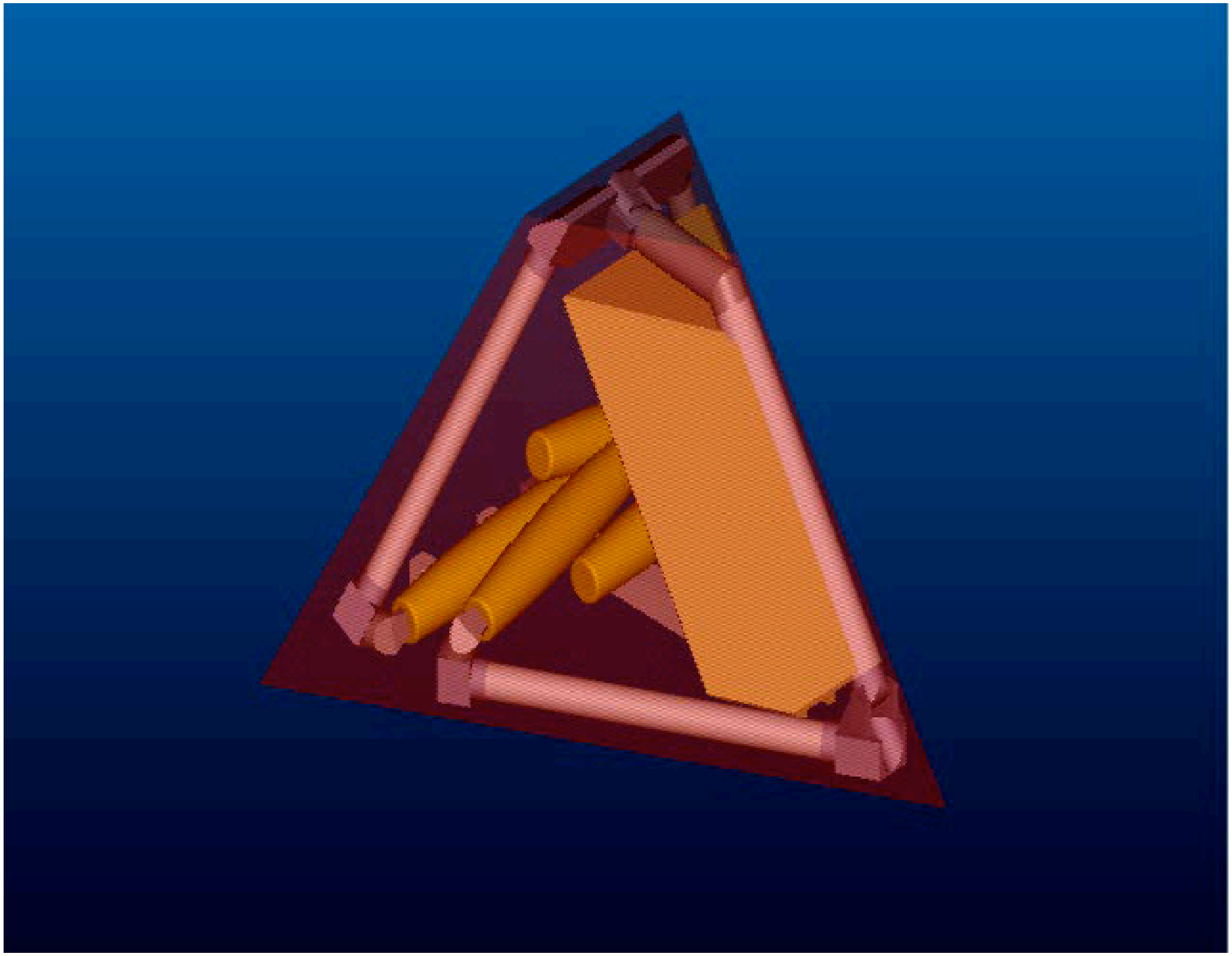
- Develop rovers that have high vertical climb to stowed ratio (increase from 0.3 to 0.8) and ability to traverse steeper slopes (increase from 30° to 60°)
- Currently limited to MER capability of ~0.3 and ~30°
- Metrics: Vertical climb to stowed ratio. Traverse on steep slopes
- Resources: Some component technologies and materials exist. Non flight-like prototypes have been developed
- Needed for Mars scouts and Mars, Solar System, and Lunar SRMs
- Cost: $1-2M/yr for 10 years

Expandable Rover Capabilities

Advanced Planning & Integration Office

inflate-demo movie

Expandable Rover Deployment



6.2.3 Walking, Rappelling, Hopping

Advanced Planning & Integration Office

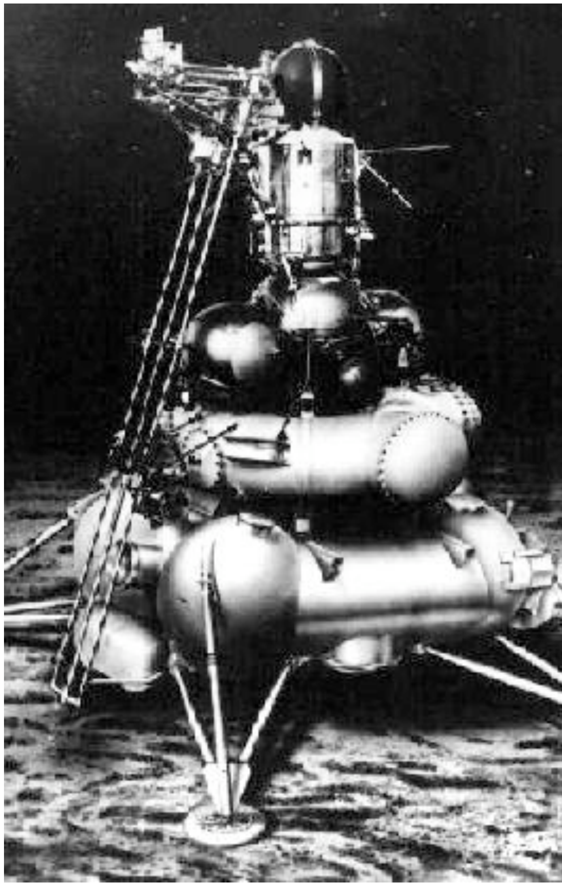
- Develop mobility systems that are capable of exploring very difficult to access regions (gullies, cliffs, and very rough terrain)
- Currently limited to MER capability; moderate terrain roughness, no capability to explore cliffs or gullies
- Metrics: Terrain roughness and slope
- Resources: Technologies in an early stage of development exist at universities and NASA
- Will enable missions in Lunar, Mars and Solar System SRMs
- Cost:
  - $1M/yr first 5-year, $2M/yr 2nd 5-year, $3M/yr 3rd 5-year

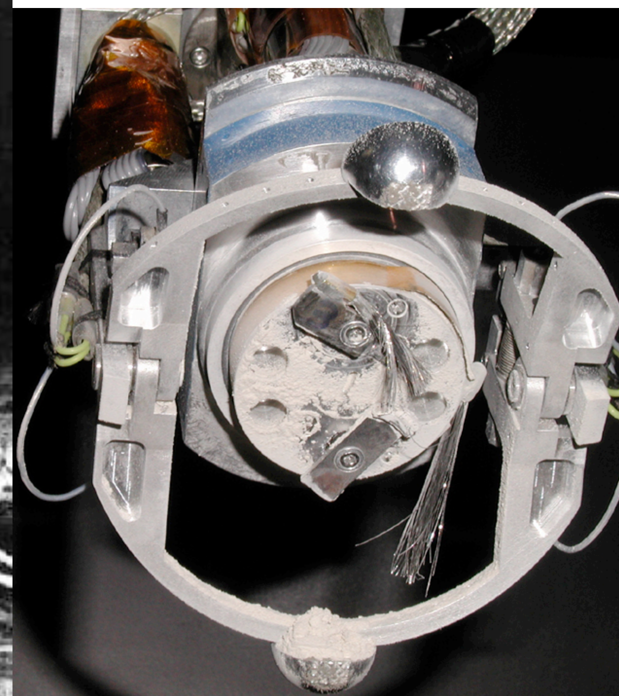
Climbing Mobility

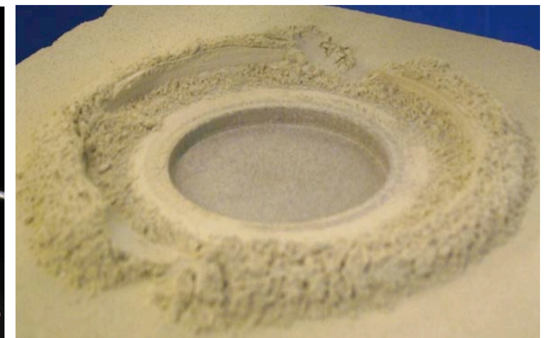
Advanced Planning & Integration Office

climber-demo movie

6.3 Accommodation of Instruments and Access to Samples







6.3 Accommodation of Instruments and Access to Samples

Advanced Planning & Integration Office

- Access to subsurface (mm to km)
  - Grinding, digging, drilling, melting
- Sample contamination avoidance
- Acquisition and transfer of samples to instruments or containers for return
  - Processing and preparation of samples for instruments
- Automation of sample access sensing and control
- Integrated design of sensors with access approach

6.3 Benefits

- Access older samples below newer surfaces
- Access material protected from environment and contamination
- Access different geological units at depth
- Access pristine samples
- Transfer samples to laboratory instruments
- Transfer samples to container for sample return
- Enable operations on irregular natural objects of unknown composition with reactive automation
- Integrate instruments into access devices

6.3 State of Practice

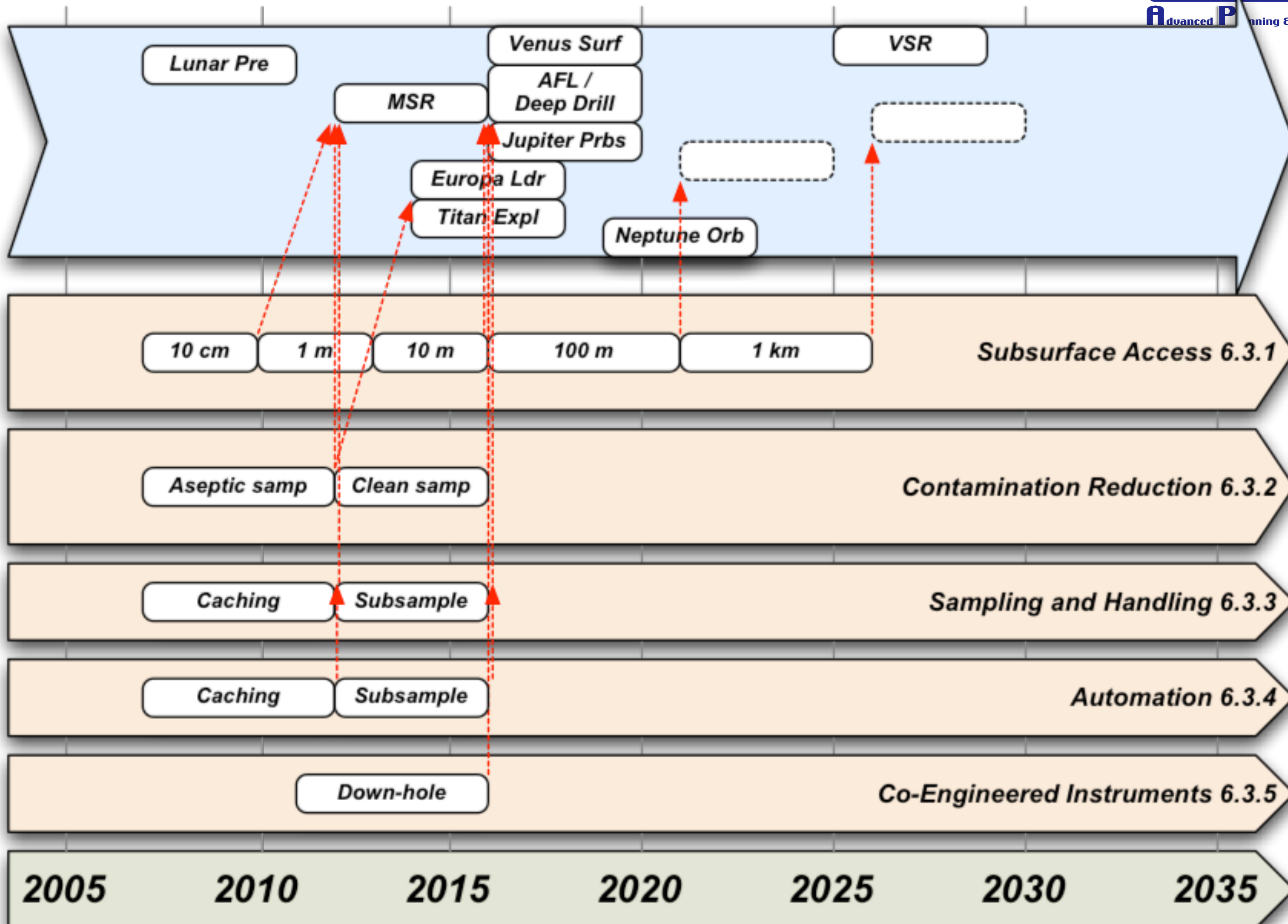
- Apollo drill (human operated and powered)
- Viking scoop
- Mars Exploration Rover rock abrasion tool
- Mars Exploration Rover trenching

- Other countries:
  - Luna, Venera, Vega drills (USSR)

6.3 Driving Mission Assumptions

- Mars Sample Return
- Mars Deep Drill
- Europa Astrobiological Lander
- Venus Sample Return

6.3 Sample Access Roadmap



6.3.1 Subsurface Access

- Reliable, flexible, and repeatable access from millimeter to kilometer range in rocks, ice, ice mix, and regolith.
- Currently limited to MER RAT (1-13 mm), shallow trenching using wheels or scoops, and past Lunar drills.
- Metrics: Depth of penetration, mass, power, and volume
- Resources: Capabilities exists mostly at industry. NASA and universities have some capabilities.
  - Unfortunately, very little can be leveraged in this area from terrestrial drilling technologies
- Needed by Mars (MSL, MSR, AFL, Deep Drill), Solar System (Venus In-situ and Surface Explorer missions), and Moon Reference Lander
- Cost: 10 cm - $7M, 1 m - $10M, 10 m - $20M, 100 m - $45M, 1 km+ $130M

6.3.2 Contamination Reduction

- Develop forward and cross contamination control, localized barriers, in situ sterlization, and hermetic seals capabilities for sample return canisters
- Capabilities in an early stage of development exist at NASA and industry
- Metrics: PPM of containment in samples, bio-load vs. non-organic contaminants
- Resources: NASA, university, and industry to a limited extent.
- Needed by MSR, greater degree by Mars AFL/Deep Drill and Europa lander
- Cost: $5M

6.3.3 Sampling and Handling

- Develop capabilities to acquire precision samples (powder, solid, soils, and fluids), preserve ingredients, and manipulate, process, and transfer samples
- Sample handling and transport systems have been demonstrated in laboratory settings
- Metrics: Number of transfers (hand-offs of sample)
- Resources: Industry leads. NASA is developing systems, universities to lesser degree
- Needed by all reference missions
  - MSL is now struggling with complex sample handling requirements, in retrospect more such development should have been done earlier
- Cost: $20M

6.3.4 Automation

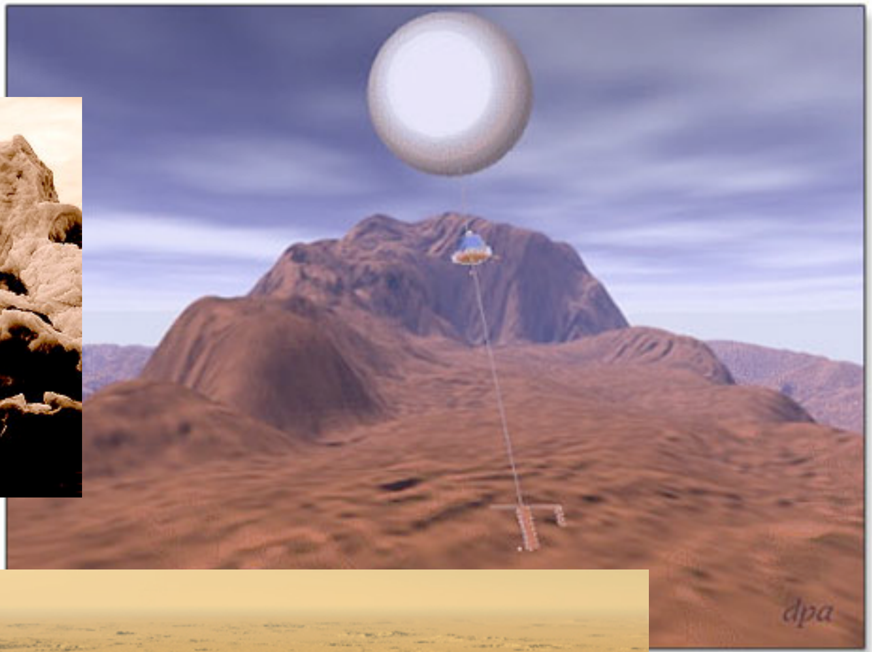
Advanced Planning & Integration Office

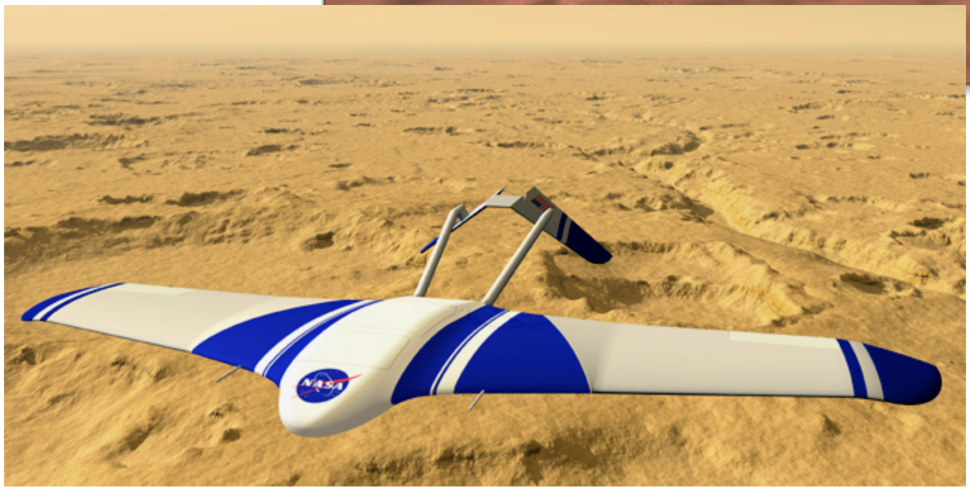
- Develop capabilities to autonomously operate sampling systems safely and efficiently in a highly unstructured environment
- Current capability is at the level of laboratory demonstration for various technologies. Significant new capabilities are required.
- Metrics: Number of ground loops required, hours of continuous operations
- Resources: Industry, NASA, and universities
- Needed by almost all missions in Mars and Solar System SRMs
- Cost: $15M

6.3.5 Co-engineered Instruments

- Develop capabilities for sub-surface instrument access via integrated and embedded instruments into subsurface access systems
- Current capability is at the level of laboratory demonstration, not yet in flight-like configurations
- Metrics: Mass, volume, power, allowable vibration level, and instrument sample requirements
- Resources: Industry, NASA, and universities
- Needed by almost all missions in Mars and Solar System SRMs
- Cost $15M (highly dependent on requirements)

6.4 Aerial Flight





6.4 Aerial Flight

- **Heavier than Air Systems**
  - Airplanes
  - Gliders
- **Lighter than Air Systems**
  - Balloons
  - Airships

6.4 Benefits

- **Aerial vehicles fill a unique planetary science measurement gap, that of regional-scale, near-surface observation, while offering a new perspective for potential discovery.**
  - **Regional-scale science (hundreds to thousands of km)**
  - **In-situ atmospheric measurements in the near-surface planetary boundary layer**
  - **Atmosphere-surface interactions (photochemical sources/sinks)**
  - **High-spatial resolution**
  - **Flight over inaccessible surface terrain**

6.4 State of Practice

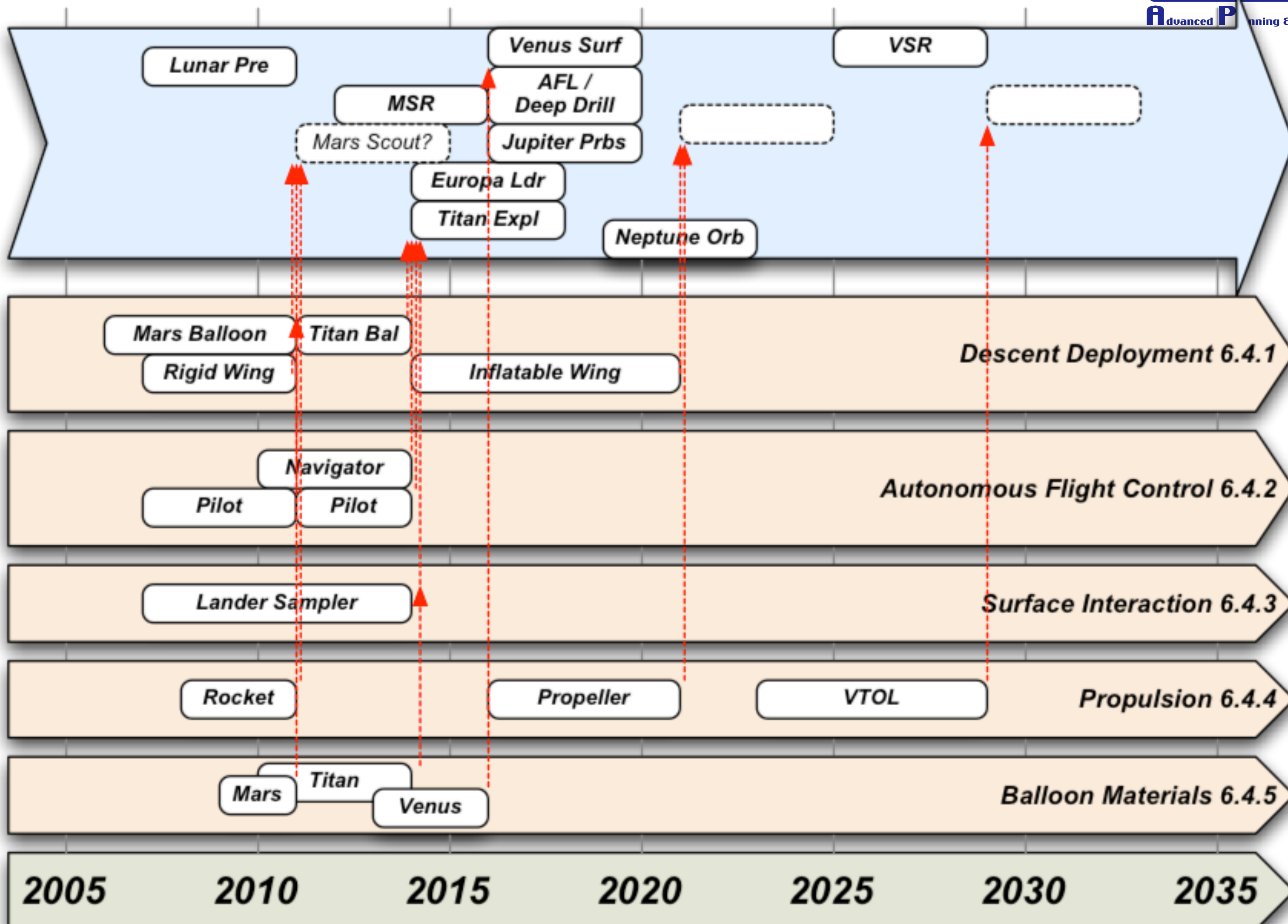
- **Heavier than Air Platforms:**
  - No planetary flight experience
  - Today's airplane technology is sufficient to enable "first flight" on another planet.
  - Inertially propagated navigation uncertainty is the limiting factor for autonomous aerial flight.
  - Four critical technology investment areas: Transition, Autonomy, Surface Interaction, and Propulsion.
- **Lighter than Air Platforms:**
  - Balloon flight has been successfully demonstrated on Venus
  - Specific technologies for flight at Mars or Titan require development.
  - Key technology issues for airships and balloons revolve around the trade between mission endurance and payload capacity.
  - Four critical technology investment areas for extended duration flight: Transition, Autonomy, Surface Interaction, and Envelope Materials.

6.4 Driving Mission Assumptions

Advanced Planning & Integration Office

- At the current time, NASA's core science missions do not include aerial vehicles.
- Design Reference Missions
  - Titan Explorer: the NRC Decadal survey recommended consideration of an aerial exploration of Titan as a follow-on to the Cassini-Huygens mission.
  - Venus In Situ Explorer
  - Venus Sample Return
- Science teams from around the country are intrigued with the potential for observations of Mars and Venus via aerial vehicles.

6.4 Aerial Flight Roadmap



Potential Capability Timeline

Destination	Today	+10 Years	+20 Years	+30 Years
Mars	• **Rocket Airplane (500 – 800 km)** • **Glider (40–100 km)**	• **Propeller Airplane (10,000 km)** • **Balloon – 90 days**	• **Propeller Airplane (global)** • **Balloon (global)** • **VTOL**	• **Airplane (unlimited range)** • **Airplane (local reconnaissance)**
Venus	• **Balloon (100 hours – high altitude)**	• **Rocket Airplane** • **Balloon (global)** • **Balloon (low altitude)**	• **Propeller Airplane** • **Airship (global)**	
Titan	• **Balloon**	• **Airship (90 days)**	• **Airship (global)** • **VTOL**	• **Airship (unlimited range)**

6.4.1 Transition

- Develop reliable strategies for mid-air transition from a stowed payload to a flying platform
- Current HTA vehicle transition methods rely on rigid wings and empennages with hinges, latches, and energy absorbing devices, demonstrated with high-altitude balloon Earth-based testing. LTA flight has been demonstrated on Venus (Soviet Vega) and in high-altitude balloon Earth-based testing.
- Metrics: Reliable/repeatable deployments, mass
- Resources: High altitude balloon flight testing (NASA WFF and industry), NASA LaRC TDT, NASA GRC Large Vacuum Chamber
- Applicable to Venus, Mars Scout and Titan missions
- Cost: $10M rigid wing, $20M inflatable wing, $8M Venus/Titan balloon, $10M Mars balloon

6.4.2 Autonomous Navigation

- Improve long term navigation knowledge to < 1 km, enabling exploration of unique science features.
- IMU propagation errors limit near-term flights to a few hours duration. Promising navigation solutions include: use of orbital assets for 2-way range and Doppler tracking, feature recognition, and reduced power radar or laser altimeters .
- Metrics: Position knowledge, Mission duration
- Resources: Captive carry testing and integrated low altitude flight testing - NASA and Industry; Integrated High Altitude Flight Testing - NASA WFF and Industry
- Applicable to Venus, Mars Scout and Titan missions
- Cost: RF $5M, optical $9M, active $5M

6.4.2 Autonomous Flight Control

Advanced Planning & Integration Office

- Development of a robust flight control architecture which allows self-diagnosis and problem resolution will allow long duration (> 10 days for HTA, >30 days for LTA) aerial flight.
- Terrestrial systems have demonstrated end-to-end autonomy. Soviet Vega balloon demonstrated autonomous mission. High altitude flight testing on Earth in relevant environment have demonstrated precursor GN&C methods.
- Metrics: Flight control robustness, aerial mission duration
- Resources: High altitude balloon flight testing (NASA WFF and industry), NASA LaRC TDT, NASA GRC Large Vacuum Chamber
- Applicable to Venus, Mars Scout and Titan missions
- Cost: $12M first flight, $25M long duration

6.4.3 Surface Interaction

- Develop reliable strategies to survive planetary (Mars) surface landing.
- Dropping a science package while in flight is current state of the art. Technologies for soft landing under study include hazard detection and avoidance, precision navigation, and airplane propulsion.
- Metrics: Surface approach speed and terrain type, mass, acquisition altitude
- Resources: NASA and industry
- Applicable to Venus, Mars Scout and Titan missions
- Cost: package drop $5M, airship touch $12M, airplane one soft landing $15M, airplane multiple landings $30M (Mars)

6.4.4 Heavier than Air Propulsion

- Improve aerial traverse range (to 10,000 km) and duration (to days).
- Current systems are limited to rocket powered vehicles with ranges up to ~1000 km and 90 minutes duration. Propellers and turbo-jets provide the highest near term promise for improving conversion efficiency to enable longer duration flight. Reducing the mass and increasing the robustness of the gearbox between the motor or engine and the propeller is an additional enabling technology.
- Metrics: Aerial performance: range and duration
- Resources: High altitude balloon flight testing (NASA WFF and industry), NASA LaRC TDT, NASA GRC Large Vacuum Chamber, NASA ARC NFAC
- Applicable to Venus, Mars Scout and Titan missions
- Cost: rocket $3M, propeller $18M, VTOL $20M

6.4.5 Lighter than Air Materials

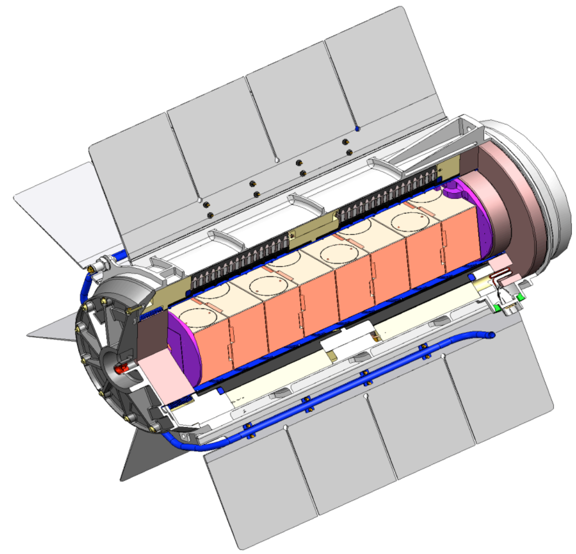
Advanced Planning & Integration Office

- Develop low mass, strong and reliable materials for LTA vehicles
- Materials selection must balance toughness, pliability and mass. Floating over Mars drives the need for lightweight materials which are resistant to UV degradation with mild cryogenic conditions. Risk mitigation drives system design to multi-layer materials with higher strength. For Titan, there is a need for cryogenic materials; whereas materials for Venus are driven towards elevated temperature characteristics and sulphuric acid resistance.
- Metrics: Aerial mass, longevity in extreme environments, abrasion and tear resistance
- Resources: High altitude balloon flight testing (NASA WFF and industry), NASA GRC Large Vacuum Chamber
- Applicable to Venus, Mars Scout and Titan missions
- Cost: Venus $7M, Titan $10M, Mars $4M

6.4.6 Atmosphere Characterization

- Develop planetary atmosphere modeling capability that yields predictions of density within 10% and a credible basis for wind and atmospheric opacity estimation.
- Flight within a planetary atmosphere is complicated by our lack of atmospheric knowledge (density, winds and dust content) at aerial traverse altitudes (0-5 km).
- Metrics: Atmospheric uncertainty, Quantifiable margin reduction.
- Resources: Atmospheric science expertise within Agency and academia. May require atmospheric observer orbiter, probe or network science missions as well as instrumentation reqts for all entry systems.
- Applicable to Venus, Mars Scout and Titan missions

6.5 Cross-Cutting Systems



6.5 Cross-Cutting Systems

- Subsystems and generic vehicle requirements for atmosphere and surface operations
  - Power
  - Propulsion
  - Telecom
  - Navigation
  - Autonomy
  - Extreme Environments
  - Planetary Protection
  - Thermal Control
  - Risk Assessment
- Interfaces with other capability roadmaps

6.5 Benefits

- New throttled liquid propellant engines for sample returns
- Small radioisotope power systems for small explorers
- Black box for hard impact data return
- Extreme environments capabilities required for Venus and Europa surface missions
- Planetary protection and risk assessment capabilities required for Mars Sample Return
- Higher performance subsystems enable existing and new mission concepts

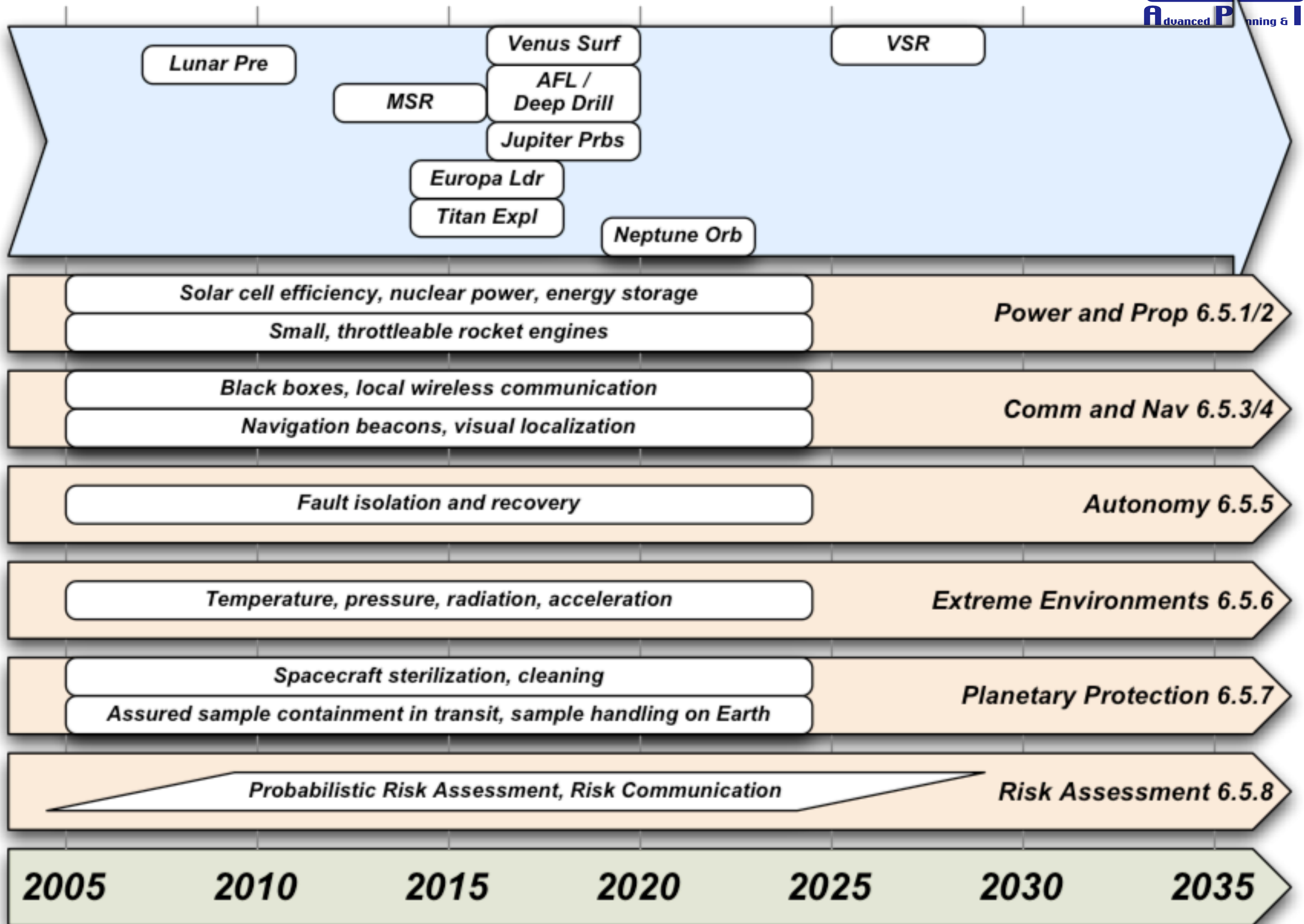
6.5 State of Practice

- Solar power at 23% efficiency
- Nuclear radioisotope power at 6% efficiency
- Solid propellant and pulsed liquid thrusters
- Survival in Martian, Titan surface environments
- Planetary protection forward contamination at class IVA
- Autonomous waypoint surface navigation

6.5 Driving Mission Assumptions

- Mars Sample Return
  – Planetary protection
- Venus Surface Explorer
  – Extreme environments
- Europa Astrobiological Lander
  – Extreme environments
  – Planetary protection
- All landers
  – Propulsion

6.5 Cross-Cutting Roadmap



6.5.1 Solar Power

- **Develop crystalline cells with efficiency ≥ 45%, thin-film cells with efficiency ≥ 15% for longer mission durations**
- **Status: Triple junction crystalline cells limited to 27% efficiency, thin film cells <10%; no dust mitigation**
- **Metrics: efficiency, output degradation, mass**
- **Resources: Plum Brook Testing Facility**
- **Needed for: small Mars landers**
- ***Power and Propulsion CRM should cover***

6.5.1 Radioisotope Power

Advanced Planning & Integration Office

- **Develop small (~1-10 We) radioisotope power systems for small spacecraft and planetary surface missions, use in hard landers**
- **Status: Current systems have ≥ 100 We output and mass ≥ 20 kg**
- **Metrics: Power output, mass, impact G survival**
- **Needed for: small, long-life landers at any body, surface network missions**
- ***Power and Propulsion CRM should cover***

6.5.1 Power Storage

- **Develop primary (non-rechargeable) power storage with energy densities ≥500 W-hr/kg; secondary (rechargeable) energy density ≥200 W-hr/kg**
- **Status: primary energy density is 250 W-hr/kg; secondary is 90 W-hr/kg. Other advanced technologies have been infrequently utilized.**
- **Metrics: Energy density; safety**
- **Enhancing for all missions**
- ***Power and Propulsion CRM should cover***

6.5.2 ISRU-based Mobility

Advanced Planning & Integration Office

- Develop capabilities for using propellants produced in situ from local resources for local transport
- Status: No existing capability
- Metrics: transport system mass vs. range
- Needed for multiple sorties of very long range on any body

6.5.2 Chemical Propulsion

- **Develop small throttleable rocket engines for sample return ascent**
- **Status: Throttleable rocket systems have been used (Surveyor, Viking), but capability needs to be rebuilt, non-trivial development**
- **Metrics: maximum thrust, Isp, minimum thrust fraction**
- **Needed for: Mars, Venus Sample Return**
- ***In Space Transportation CRM should cover***

6.5.3 Wireless Telecom

Advanced Planning & Integration Office

- Develop high-data-rate wireless communication through liquid and solid materials to enable exploration of extremely remote regions
- Status: ELF (80Hz) to LF (100kHz) and blue-green laser communication used with submarines; seismic or acoustic communication is possible in solid media
- Metrics: Depth of transmission; data rates
- Needed for: deep subsurface/ice missions at Mars or Europa

6.5.3 Black Box

- Develop robust, survivable onboard data storage and playback for post-mission data delivery to avoid data loss (black box)
  - Depending on the application, a challenge will be how to communicate through wreckage or extract self from wreckage
- Status: Aircraft use robust black boxes; no dedicated data relay subsystems available for space mission planners
- Metrics: G-level endurance, data storage; data return bandwidth, mass
- Enhancing for aerial missions without landing capability, failure diagnosis for landed missions

6.5.4 Navigation Beacons

- Develop high precision (10 cm, 1 degree), low mass, short range (~ 100 km) navigation beacons that offer both range and bearing information
- Status: Radio beacons and VHF Nav Systems (VOR) used terrestrially to provide both range and bearing information. ~15 nautical mile range
- Metrics: range and bearing precision, beacon mass/operational range, required power, lifetime
- Enhancing for landed missions returning to the same site, e.g. surface rendezvous MSR

6.5.5 Autonomous Localization

- **Develop autonomous localization capability using locally-sensed surface features, thus reducing mission infrastructure requirements**
- **Status: Localizing current rover systems requires significant interaction with ground controllers, reducing mission throughput**
- **Metrics:Location estimation accuracy, time**
- **Enhancing for all mobile surface and aerial missions**
- ***Autonomous Systems and Robotics CRM should cover***

6.5.5 Autonomous Fault Handling

- **Develop Capabilities for On-Board Autonomous Fault Detection, Isolation, and Recovery**
- **Status: Current systems require either interaction with ground controllers or react in a pre-scripted manner**
- **Metrics: Percentage of S/C faults addressable through autonomous FDIR**
- **Enhancing for all missions**
- ***Autonomous Systems and Robotics CRM should cover***

6.5.6 Extreme Temp. Components

- Develop actuators and avionics capable of operating under extreme temperatures to enable missions in extreme temperatures (down to -270C or up to +460C)
- Status: Most ruggedized components are suitable for MIL-SPEC temperature range of -40 to +85°C, which is unsuitable for most planetary applications.
- Metrics: Flight-allowable storage and operating temperature ranges, lifetime
- Needed for: Venus Surface Explorer, Venus Sample Return, Titan Explorer, Jupiter Probes

6.5.6 Extreme G Avionics

- Develop avionics capable of operating under extreme (1,000 G to 100,000 G) deceleration levels, to enable penetrator missions for subsurface access
- Status: Avionics ruggedness is generally limited to 10s or 100s of Gs; Some high-G DoD applications
- Metrics: survivable acceleration levels and profiles
- Needed for: Jupiter Atmospheric Probes, Penetrators

6.5.6 High Radiation Avionics

Advanced Planning & Integration Office

- Develop avionics capable of operating in extreme radiation environments (> 180 krad/day) to enable Jupiter atmospheric probe and icy moon missions
- Status: Radiation-rugged COTS devices exist, but are typically for nuclear events, not total dose
- Metrics: total dose storage survival, total dose operating survival, error-free operation dose rate
- Needed for: Jupiter Atmospheric Probes, Europa Lander

6.5.6 Extreme Pressure Avionics

- Develop avionics capable of operating under extreme (>100 bar) pressure to enable long-duration missions, such as probes, to planets with high atmospheric pressure
- Status: Significant technology available for terrestrial applications (e.g., oil exploration); limited space flight qualification
- Metrics: Pressure, temperature tolerance, lifetime, mass
- Needed for: Venus Surface Explorer, Jupiter Atmospheric Probes, Venus Sample Return

6.5.7 Spacecraft Sterilization

Advanced Planning & Integration Office

- Develop Forward Planetary Protection Capabilities for Whole-Spacecraft Sterilization and Cleaning
- Status: Viking-level capability decommissioned. New facility must account for sensitive avionics and instruments
- Metrics: Spacecraft size; spores or bio-remnants per unit area; decades of reduction, cost impact to spacecraft to use components qualified to the process
- Resources: Whole-Spacecraft Sterilization Facility
- Needed for: Mars Sample Return, Mars AFL/Deep Drill, Europa Lander
- Cost: $15M for selective cleaning and transport analysis approach, if viable. If not, $60M for whole-spacecraft sterilization process qualification and facility

6.5.7 Assured Containment

Advanced Planning & Integration Office

- Develop back planetary protection capabilities for assured containment of returned samples (≤10E-6 loss of containment risk) to enable sample return missions
- Status: Technology development underway; not yet flight qualified
- Metrics: Probability of containment loss
- Needed for: Mars Sample Return, other Class V return missions
- Cost: $46M technology development + > $20M Earth Entry vehicle flight test

6.5.7 Returned Sample Handling

- **Multidirectional containment/contamination control for returned samples to permit returned sample analysis and to prevent sample contamination**
- **Status: Limited technology development underway for clean sample handling; Sample Receiving Facility (SRF) architecture design, etc.**
- **Resources: Sample Receiving Facility**
- **Needed for: Mars Sample Return, other Class V return missions**
- **Cost: $120M for basic capabilities and facility, another $240M for outfitting facility with instruments, facility operations, and separate curation facility and its operations (within 30%)**

6.5.8 Thermal Control

- Increase capability for insulation and active thermal control (heating) for missions to cold environments; temperature tolerance and heat rejection (cooling) for missions to hot environments
- Status: Limited capability for Mars missions - inefficiency drives large power requirement
- Metrics: Heat transfer, heat rejection
- Needed for: Venus Surface Explorer, Mars Sample Return, Astrobiology Field Lab, Europa Lander

6.5.9 Risk Assessment

- Increase capability in risk assessment to permit more rigorous, consistent design trades
- Status: Probabilistic Risk Analysis, experience, and other methods are used in projects
- Metrics: Statistical accuracy and consistency of risk assessments across projects
- Resources: Expertise spread across academia, industry and NASA
- Needed for: All missions
- *Systems Engineering CRM should cover*

Facilities

Required Resources (Facilities and Human Capital)

Advanced Planning & Integration Office

- Robotic access technology development and flight system qualification requires access to numerous unique facilities across the country as well as support of the resident engineering talent that has honed a unique skill set.
- A small set of facilities exist which are vital for RAPS applications.
- Most of these same facilities also have direct application to the Human Planetary Landing Systems Capability Roadmap #7.

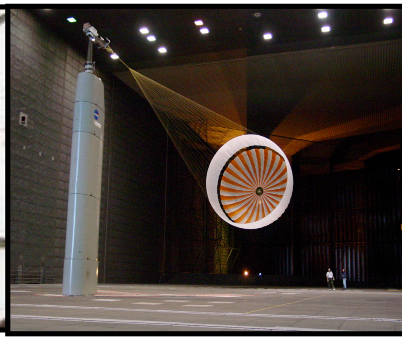
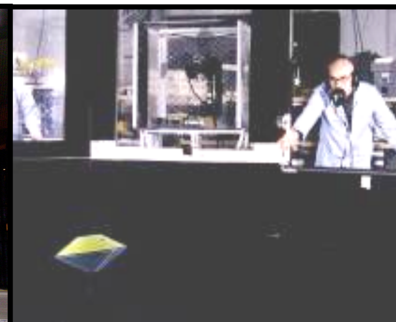
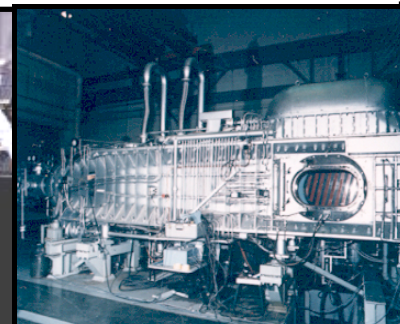
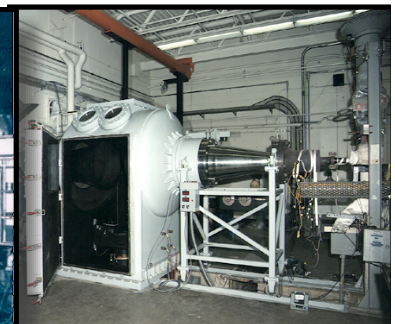
Required Resources (Facilities and Human Capital)

Advanced Planning & Integration Office

- **No ground-based facility exactly replicates high energy flight conditions. Instead, individual facilities have been developed that replicate a particular aspect of hypervelocity flight.**
- **When combined with analysis and flight test capabilities (e.g., sub-orbital balloon and sounding rocket programs), these ground-based facilities anchor robotic access technology development and flight system qualification.**

Ground-Based Facility Type and Use (1 of 6)

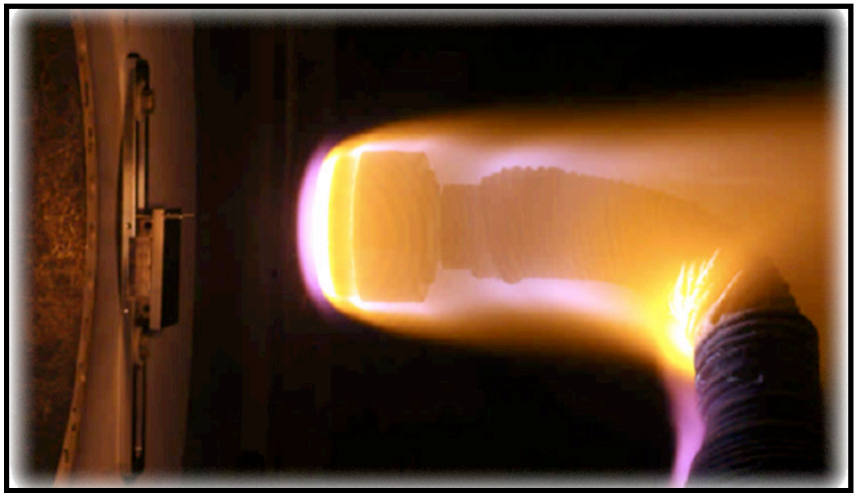
- **Wind-tunnels** achieve fluid dynamic similarity to flight. These facilities are used to obtain aerodynamics across a large range of relevant Mach number regimes, patterns of heating to the vehicle, and the behavior of transition to turbulence for the specific vehicle shape. Because these facilities do not replicate the energy of the flow, flight heat transfer conditions are not obtained.

- Subscale parachute testing in the LaRC TDT
- Full scale parachute testing in the Ames NFAC
- Entry stability testing in the LaRC VST
- Entry system aerodynamic characterization in the LaRC Aerothermodynamics Complex (2)

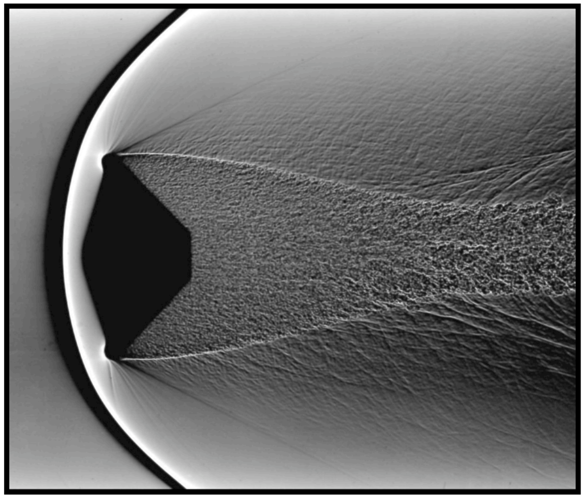
Ground-Based Facility Type and Use (2 of 6)

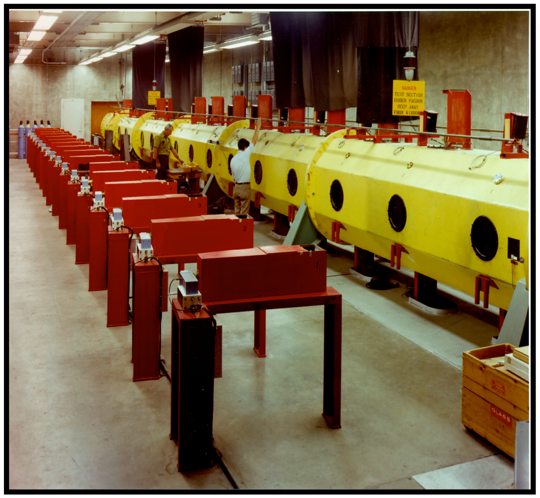
- **Arc-jets** are used to understand thermal protection system response during hypersonic entry. These facilities can deliver flight-like heat rate, temperature, heat load, and shear to a test sample. In this manner, the thermal response of flight hardware can be determined.

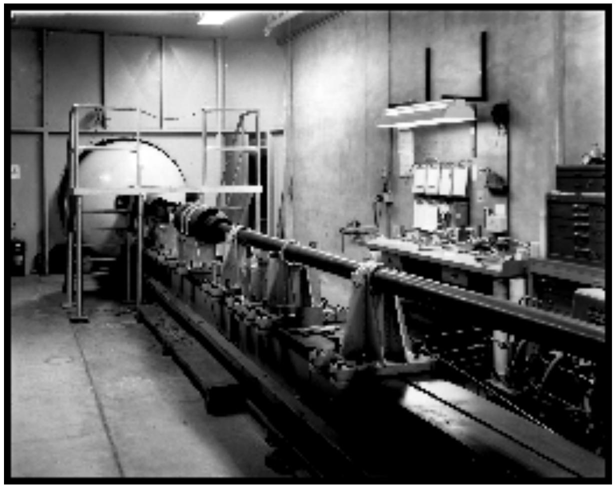


- The existing ARC facilities are required for qualification of Mars entry and Earth return thermal protection systems. For missions to the gas giants, the Giant Planet Facility, a leg on the ARC arc-jet complex which is no longer operational would need to be refurbished.

- **Ballistic range** facilities operate by firing a small projectile into a test chamber. Such testing is useful for determining aerodynamic stability and transition characteristics.



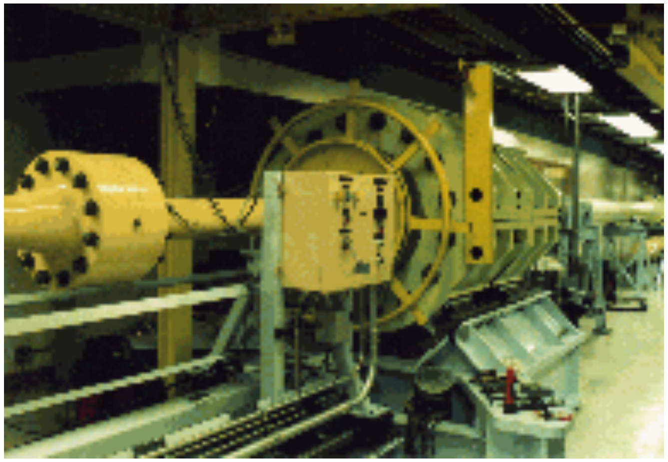




- The Eglin AFB ballistic range is typically used by current robotic Mars and Earth programs. The ARC ballistic range offers the advantage of controlling the gas composition and pressure, albeit for smaller models.

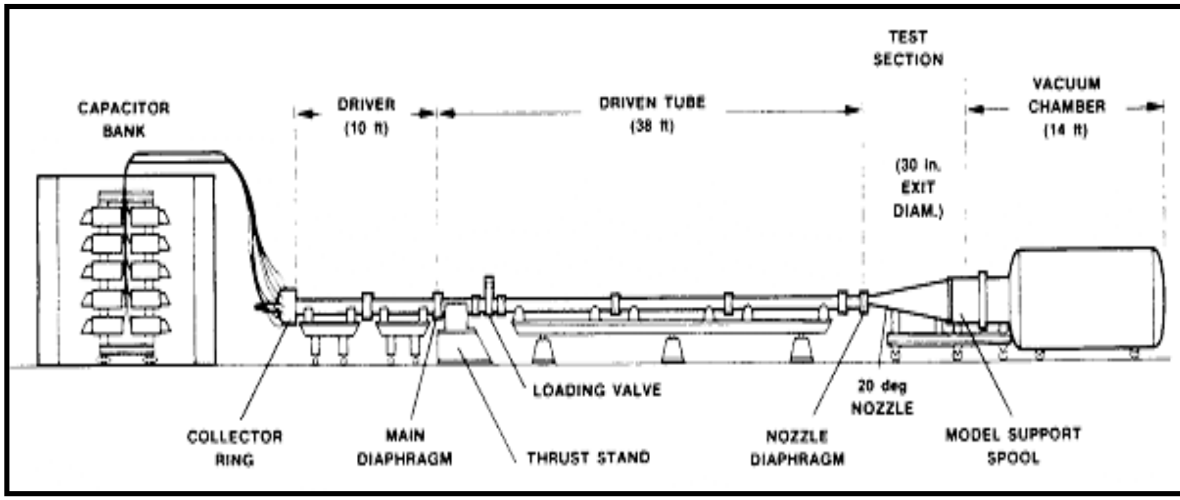
Ground-Based Facility Type and Use (4 of 6)

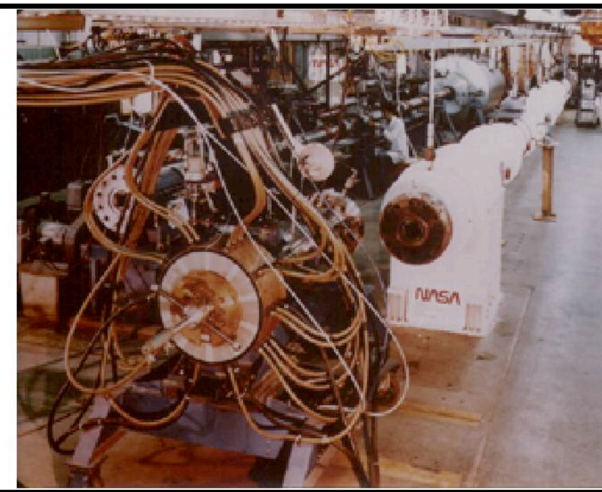
- **Shock tunnels** can combine fluid dynamic and energy similarity in some cases.



- The T5 facility at Cal Tech and LENS at University of Buffalo Research Center can be used to understand hypersonic convective heating and transition to turbulence.

- **Shock Tubes** are used to understand the high temperature atomic, chemical kinetic, and gas dynamic behavior of the atmospheric gases at high temperature, which is essential for shock layer radiation modeling.





- The ARC Electric-Arc Driven Shock Tube is the sole remaining facility of its kind in NASA.

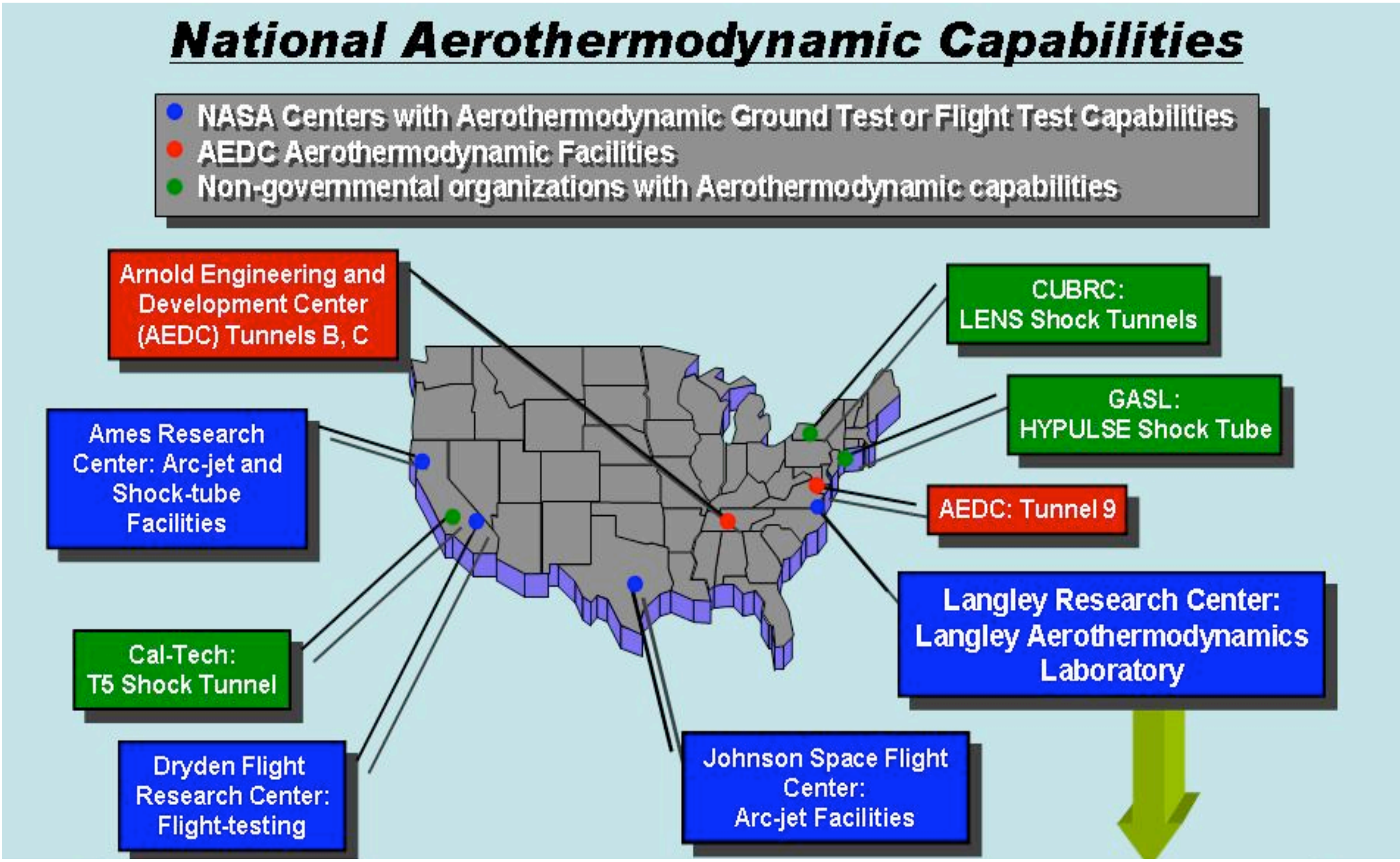
Ground-Based Facility Type and Use (6 of 6)

- **Relevant Environment Structural Test Facilities** are used to replicate the relevant environment for structural design and qualification

- The National Science Balloon Facility, WFF Sounding Pr Vacuum Chamber are unique national assets.

National Aerothermodynamic Capabilities

Advanced Planning & Integration Office



Required RAPS Ground-Based Facilities (1 of 2)

Facility	Location	Role
Aerothermodynamics Complex	NASA LaRC	Understanding hypersonic aerodynamics and convective heating, including transition to turbulence
Aeroballistic Research Facility	Eglin AFB	Gather free-flight aerodynamic data using shadowgraph and laser interferometry
Arc-Jet Test Facility	NASA ARC	Development and qualification of TPS under flight-like thermo-structural conditions.
Transonic Dynamics Tunnel (TDT)	NASA LaRC	Perform sub-scale developmental testing of supersonic decelerators and planetary aerial platforms in relevant conditions
National Full-scale Aerodynamics Complex (NFAC)	NASA ARC	Perform full-scale load testing at representative loads and Reynolds number for Mars & Titan supersonic decelerators and full-scale testing of Mars airplane propeller drive systems.
National Science Balloon Facility (NSBF)	NASA WFF (Palestine TX)	Perform high altitude balloon drop testing essential for scaled flight testing at relevant conditions (Mach and Reynolds Number) for supersonic decelerators. NASA suborbital balloon and sounding rocket programs mitigate risk for planetary aerial platforms.

Required RAPS Ground-Based Facilities

Facility	Location	Role
Plum Brook Facility (Vacuum Chamber)	NASA GRC	Allow full-scale testing of landing systems at Mars surface pressures. Allows scale testing of balloons and airships at representative (Mars and high-altitude Venus) pressures.
Vertical Spin Tunnel	NASA LaRC	Perform sub-scale testing of entry systems and planetary aerial platforms to investigate subsonic stability characteristics.
T5 facility	Cal Tech	Understand hypervelocity convective heating, including transition to turbulence
LENS	CUBRC	Understand hypervelocity convective heating, including transition to turbulence
Ballistic Range	NASA ARC	Gather free-flight aerodynamic data using shadowgraph and laser interferometry. Quantifying transition effectiveness of ablated materials.
Electric-Arc Driven Shock Tube	NASA ARC	Understand the high temperature atomic, chemical kinetic, and gas dynamic behavior of the atmospheric gases at high temperature for developing radiative heating models.
Arc-Jet Test Facility	NASA JSC	Development and qualification of TPS under flight-like thermo-structural conditions.

Facility Costs

- **Facility cost information can be obtained from the appropriate point-of-contact at each facility**
- **Because of the range of cost assumptions in use by these facilities, cost information is not provided herein**
- **Additional information on these and other test facilities can be obtained at:**
  - http://wte.larc.nasa.gov/
  - http://facility.hq.nasa.gov/
- **Recommendation: NASA should form a test facilities team to develop a uniform cost basis for these facilities. Because of the critical nature of the test facilities and the resident expertise, this cost information is vital for planning RAPS (and other Capability Roadmap) technology development.**

Wrap-Up

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Long-Term Breakthrough Concepts

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- We identified some ideas not included in the roadmap, but worthy of system studies:
  - Micro-probes system design (incorporating high-G, small RPS capabilities outlined here)
  - Lightweight, low-power, high-capacity, reconfigurable avionics
  - High-capability Tele-operated Robotic Explorers for Mars with Virtual Presence (for global Mars access by human explorers)
  - Melter/Drill for Mars and Europa
  - Swimmer for Europa

Conclusions (6.1, 6.4)

- The capabilities for entry, descent, and landing are complex and interrelated at the system level, and will require significant coordination as mission plans change, including the coordination of developments between robotic and human planetary landing systems
- Small landers can be enabled with high-G systems and small nuclear power sources, to permit consideration of networks of landers
- A modest amount of Earth testing of aerial systems as part of an organized program can open up new ways to take advantage of planetary atmospheres for regional and global observation
- EDL and aerial vehicle development depend heavily on NASA test infrastructure and expertise — special attention is needed to determine how to maintain that infrastructure and develop new infrastructure, and how that will be funded

Conclusions (6.1, 6.4 cont'd)

- For both landed and aerial missions, precursor environmental observations will enhance and possibly enable the design and test of viable systems for those environments. The performance of systems in those environments need to be well-characterized to reduce risk for subsequent missions.
  - This must be considered at the program level so that instrumentation for these purposes can be incorporated in orbiters and landers, and so that requirements can be imposed for performance measurements of key systems so that each mission can feed into the next
  - Analogous to the telecomm infrastructure, we need a sustained Mars atmosphere observation infrastructure
  - These objectives should be balanced against the design margin alternatives to reduced uncertainty

Conclusions (6.2, 6.3)

- New surface mobility systems should be developed to access difficult and treacherous terrain, and would need to be coordinated with developments for human exploration robotic assistants – this long-term investment will enable a new class of missions not currently envisioned
- Sampling capabilities will initially be driven and developed by missions. However, deep drilling and down-hole instrumentation will require considerable development and demonstration before mission applications can be considered

Conclusions (6.5)

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- Radioisotope power systems need to be scaled down in size for use in small systems – rovers, ground penetrators, etc.
- Extreme environment systems are essential for the envisioned strategic missions, yet there is no comprehensive program in place to develop them. An organization needs to be assigned this task, and the system engineering trades performed for these missions to define the requirements
- More robust means of communication are required – to provide data from, e.g., post-landing events, deep subsurface (liquid and solid)
- New degrees of contamination control for both science and planetary protection is required for life-detection missions (e.g. MSR), but is currently at a low capability level
- Assured containment may be the single most vexing requirement Mars Sample Return faces, for which a chain of events can all be drivers, and for which most have no qualified capabilities at this time

Summary

- A set of robotic access to planetary surfaces capability developments and supporting infrastructure have been identified
  - Reference mission pulls derived from ongoing strategic planning
  - Capability pushes to enable broader mission considerations
  - Facility and flight test capability needs
- Those developments have been described to the level of detail needed for high-level planning
  - Content and approach
  - Readiness and metrics
  - Rough schedule and cost
  - Connectivity to mission concepts

Review Objectives

1. Are the products connected in a logical progression and are they linked to credible missions or mission classes?
2. Was the proper set of capabilities identified to address the mission needs? Are there any alternative approaches that were not considered?
3. Does the capability roadmap provide a clear pathway to (or process for) technology and capability development?
4. Are technology development decision points identified, described and justified?
5. Does the roadmap describe competently the products planned for the technology development? Is the roadmap written and presented in a manner understandable to the non-specialist?
6. Are proper metrics for measuring the advancement of technical maturity included?
7. Is there a clear and correct understanding of the technical risks, 1/2 order of magnitude costs, and schedule estimates to within a year?

National Research Council Dialogue to Assess Progress on

NASA's Human Planetary Landing Systems Capability Roadmap Development

General Background and Introduction

Rob Mueller
NASA APIO Coordinator
May 04, 2005

Agenda

- General Background and Introduction of Capability Roadmaps
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

Advanced Planning & Integration Office

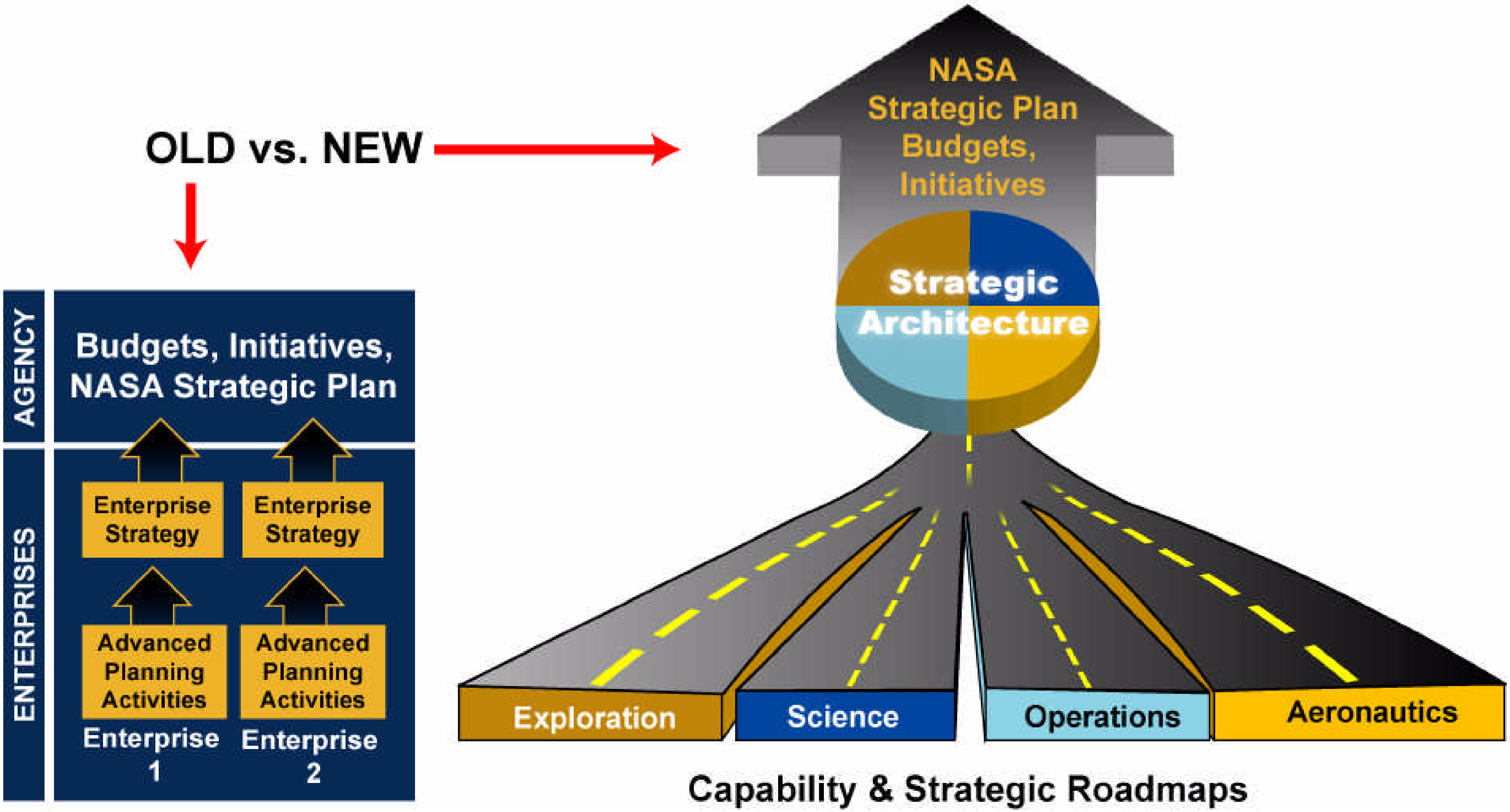
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

Agency Goals and Objectives

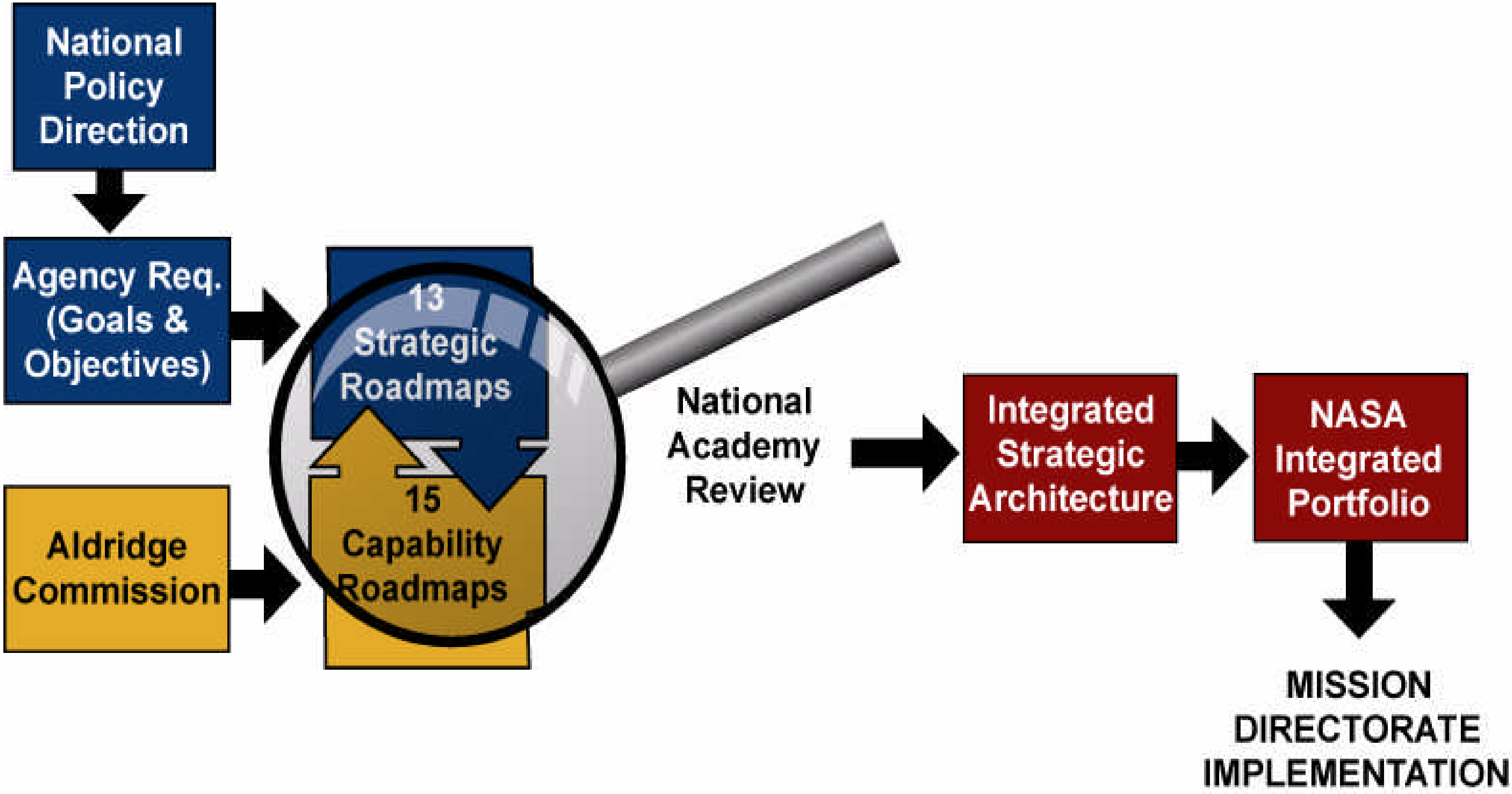
Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	Develop innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.	Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	Conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems. (SRM 9)
	Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)	Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)
	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)	

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

Advanced Planning & Integration Office

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Mary Kicza)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

Advanced Planning & Integration Office

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

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- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

- Broad human and robotic science and exploration goals, priorities, anticipated discoveries
- High-level milestones, options, and decision points
- Implementation approaches, suggested missions

Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators Also with Each Team

= DoD Participation

Strategic Roadmaps - continued

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Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule

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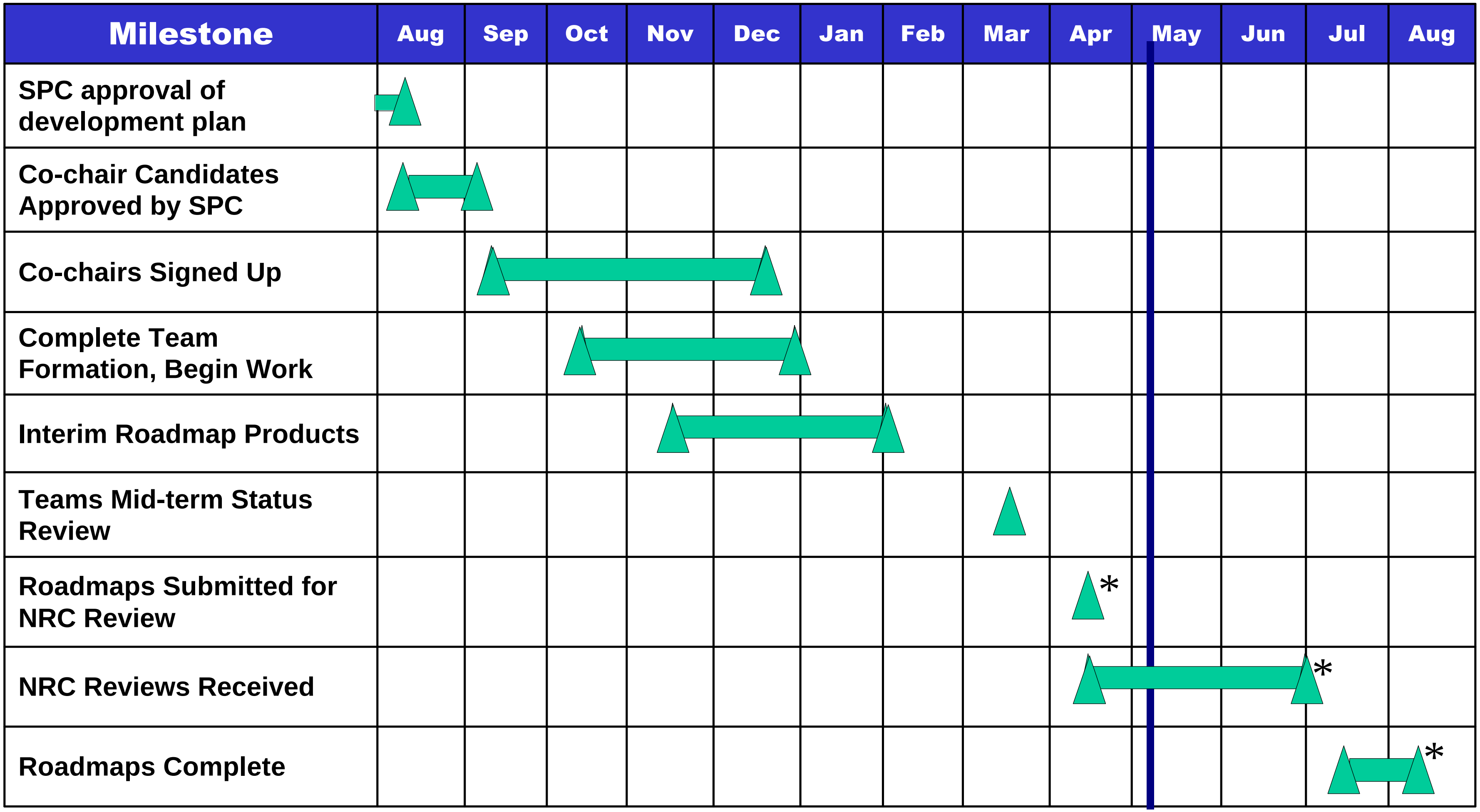

* Schedule Under Review

Capability Roadmaps

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- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

Advanced Planning & Integration Office

- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**

    1/3 Industry

    1/3 NASA & other Government Agencies

    1/3 Academia
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

Capability Roadmaps - continued

Advanced Planning & Integration Office

Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

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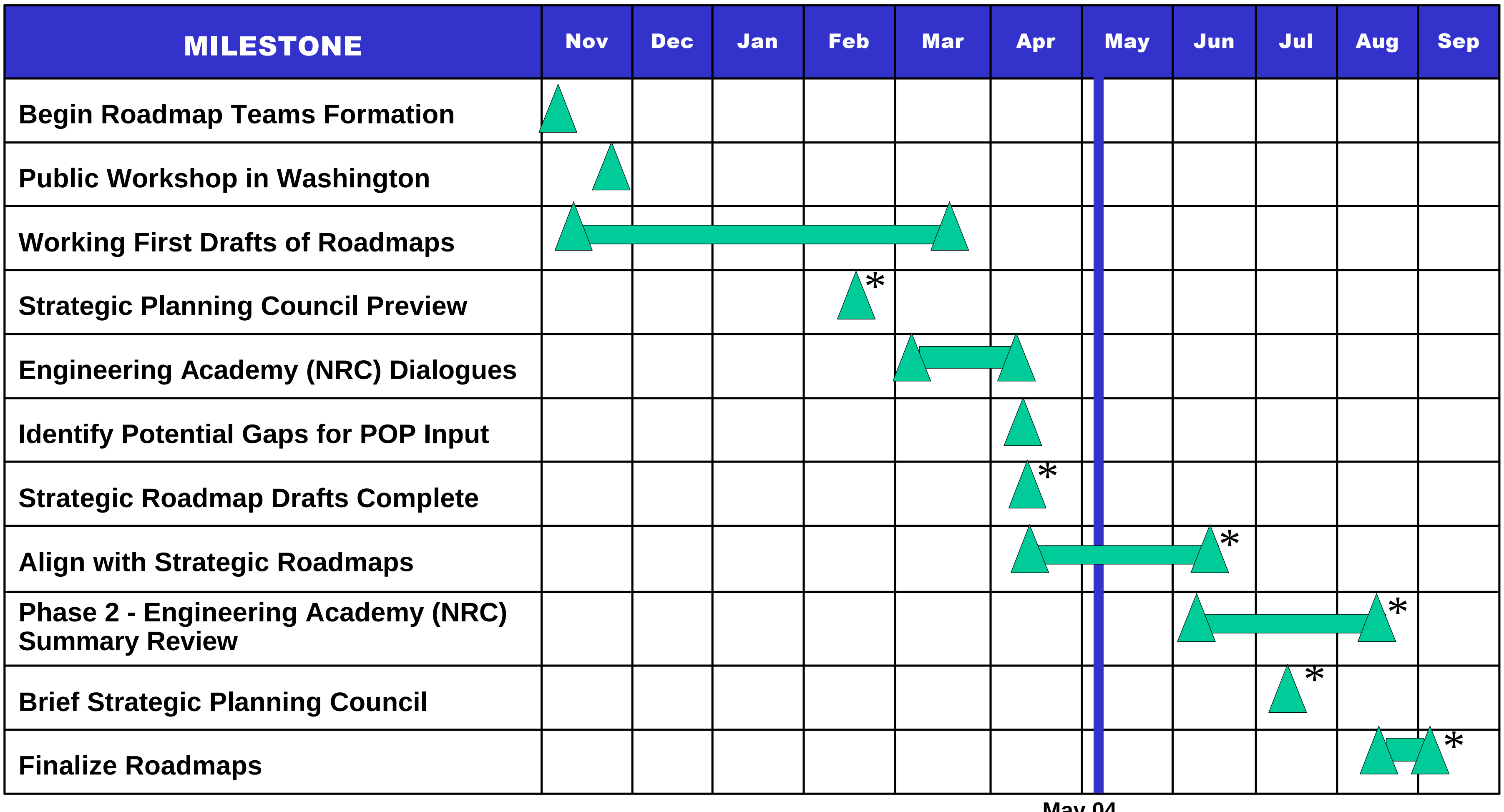

*Schedule under review

Purpose of NRC Review

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- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

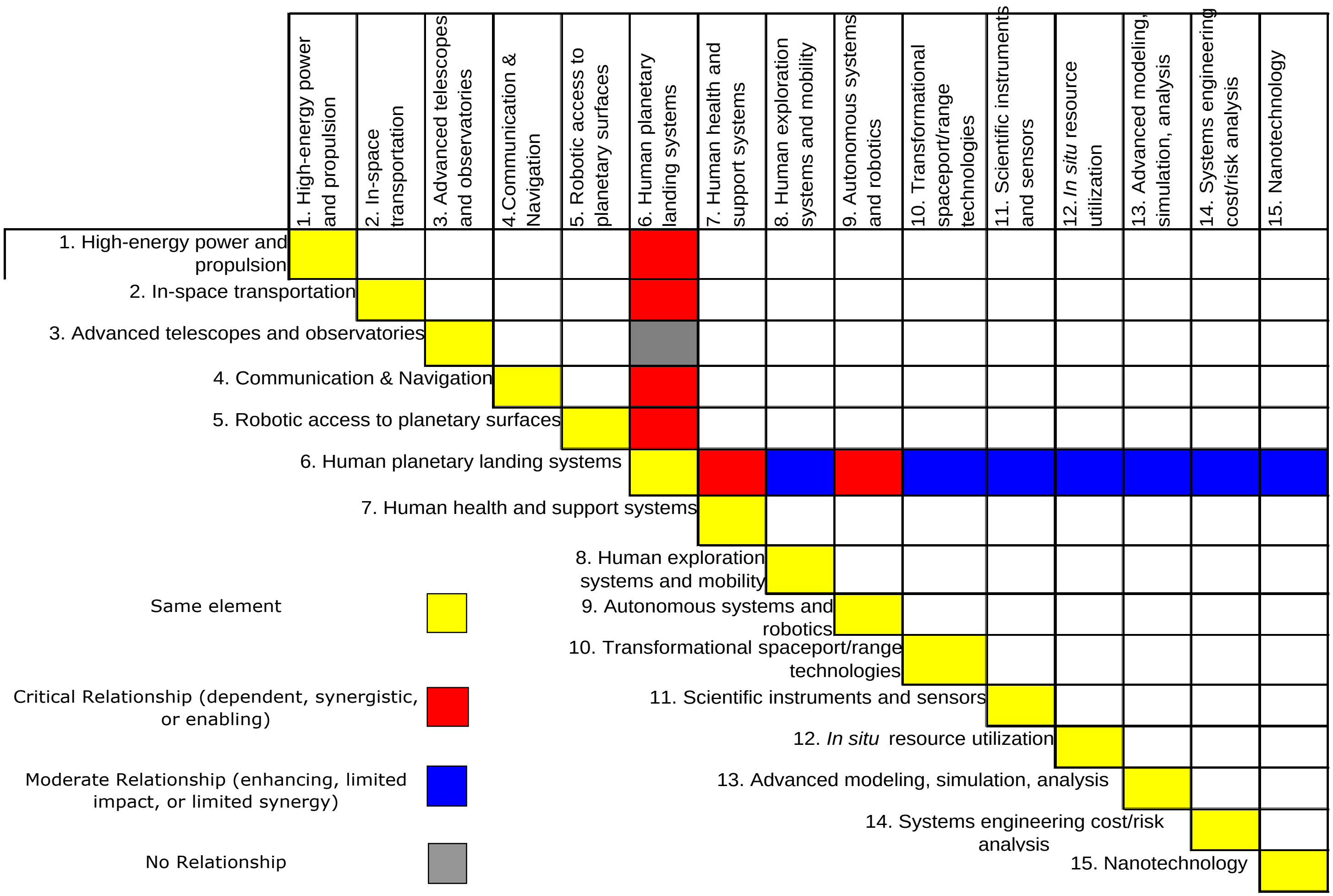
Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

Backup Charts

HPLS CRM Crosswalk



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Examples of Crosswalk Data

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5. Robotic access to planetary surfaces		6. Human planetary landing systems	
Entry: Hypervelocity Transit	⟷	Hypersonic Entry/AeroCapture Aerothermal TPS Systems	Robotic Entry methods may be applied to Human Entry
Descent	⟷	Transonic decelerators	Robotic Descent methods may be applied to Human Descent
Landing	⟷	Terminal Descent Propulsion Touchdown Systems Terrain Relative Sensing	Robotic Landing methods may be applied to Human landing
Observations	⟷	Observations	Orbital reconnaissance requirements for surface site characterization and atmospheric characterization. Precursor surface-mission engineering observational requirements (meteorology, dust characterization, TPS/parachute performance).
Entry, Descent & Landing	⟷	Robotic-human interactions	Human interaction with Robotic systems during EDL
Navigation- Beacons & Orbital Assets	⟷	Communications and Navigation Infrastructure	Common assets can be shared for navigation
Extreme Environment Avionics	⟷	Hypersonic Entry/AeroCapture Aerothermal TPS Systems	Avionics must function in extreme environment of Mars Entry
Planetary Protection	⟷	EDL Systems Engineering, Guidance, Nav & Control Analysis & Rqmnts	Landed mass must adhere to Planetary Protection Rules Robotic methods may be employed in Human landings
Mobility	→	Touchdown Systems	Successful Landing includes deployment of surface asset - robotic methods may be used
Propulsion	⟷	Terminal Descent Propulsion	Robotic propulsion methods may be applicable to Human landing

CRM X SRM Crosswalk (Part 1)

SR-#	Short	Full Name	Chartered Objective	Flow	CRM #7 Human Planetary Landing Systems	Relationship	CRM Communications with SRM
1	Moon	Robotic and Human Lunar Exploration	Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.	↔		Use common methods for landing on the Moon and on Mars where possible. These common technologies include Terminal descent systems, deep throttling propulsion engines, aerocapture Earth return systems, human systems & instrumentation for data during Earth return.	- Co-Chair (Harrison Schmitt) attended Meeting #2 - Potential invititation to present at Meeting #3 - Reviewing SRM presentations on Docushare
2	Mars	Robotic and Human Exploration of Mars	Exploration of Mars, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration; human expeditions to Mars after acquiring adequate knowledge about the planet using these robotic missions and after successfully demonstrating sustained human exploration missions to the Moon.	↔		Very Large (30-60 MT) landed masses on Mars will require new Aerocapture, Entry, Descent, Landing and Ascent (AEDLA) technologies/capabilites with long development/test times. Human factors, operations & training must be factored into AEDLA Mars mission planning and human rated design in order to safely land and return human crews from Mars. Aeroassist technologies will dramatically reduce the amount of propellant/mass that is required for human travel to Mars and safe return to Earth.	-Chair (Rob Manning) presented at Meeting #2 -Chair presented at Meeting #3 -Team Member (Bobby Braun) is on SRM Committee - Reviewing SRM presentations on Docushare
3	Solar System	Solar System Exploration	Robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.	NA		Not Applicable	-Reviewing SRM presentations on Docushare
4	Earth-like Planets	Search for Earth-Like Planets	Search for Earth-like planets and habitable environments around other stars using advanced telescopes.	NA		Not Applicable	NA
5	CEV / Constellation	Exploration Transportation System	Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.	↔		Efficient and feasible CEV/Constellation designs and configurations will require close coordination, systems engineering and packaging of Aerocapture, Entry, Descent, Landing and Ascent (AEDLA) technologies, capabilities and systems. Very Large (30-60 MT) landed masses on Mars will require new AEDLA technologies/capabilites with long development times. Aeroassist technologies will dramatically reduce the amount of propellant/mass that is required for human travel to Mars and safe return to Earth. Large volume & area payload launch fairings will be required. Heavy Lift will be required for full scale earth based testing and actual missions	-Reviewing SRM presentations on Docushare - Chairs presented at Meeting #2
6	Space station	International Space Station	Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures.	→		ISS will provide human health and performance data, human factors and interfaces data, training opportunities & test bed, on orbit assembly experience.	-Reviewing SRM presentations on Docushare
7	Shuttle	Space Shuttle	Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the Space Shuttle to a new exploration transportation system.	→		Space Shuttle will provide human health and performance data, human factors and interfaces data, training opportunities & test bed, Earth Entry Descent & Landing (EDL) data, Thermal Protection System (TPS) Data & Earth atmospheric conditions data.	-Reviewing SRM presentations on Docushare

Critical Relationship

Moderate Relationship

Minimal or No Relationship

CRM = Capability Road Map

SRM = Strategic Road Map

CRM X SRM Crosswalk (Part 2)

8	Universe	Universe Exploration	Explore the universe to understand its origin, structure, evolution, and destiny.	NA		Not Applicable	NA
9	Earth	Earth Science and Applications from Space	Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.	NA		Not Applicable	NA
10	Sun-Solar System	Sun-Solar System Connection	Explore the Sun-Earth system to understand the Sun and its effects on the Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.	NA		Forecasts of dangerous solar events and on board solar activity monitoring to preserve human health & performance in Aerocapture, Entry Descent & Landing (AEDL)	-Reviewing SRM presentations on Docushare
11	Aero	Aeronautical Technologies	Advance aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.	⇔		Direct Entry, Aerocapture, Aerobraking, Guided Hypersonic Flight, Supersonic deceleration, and Aerogravity Assist all require aeronautical technologies/capabilities & test facilities to successfully use the Mars atmosphere.	-Reviewing SRM presentations on Docushare
12	Education	Education	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the nation's scientific and technological capabilities.	⇔		Use Aeronautics, Science & Engineering principles to educate, inspire and motivate, which provides a skilled labor force for Human Planetary Landing Systems implementation	-Reviewing SRM presentations on Docushare
13	Nuclear	Nuclear Systems	Utilize nuclear systems for the advancement of space science and exploration.	⇒		Use of advanced nuclear propulsion systems could reduce the transportation vehicle's arrival velocity at Mars alowing for reduced orbital capture delta velocity (Delta V) requirements	-Reviewing SRM presentations on Docushare
	Cross Cutting		HUMAN PLANETARY LANDING SYSTEMS ARCHITECTURAL ISSUES				

(red)	Critical Relationship
(blue)	Moderate Relationship
(grey)	Minimal or No Relationship

CRM = Capability Road Map

SRM = Strategic Road Map

SRM X CRM Example Data

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Mars

Go Back

Capability	Requirement	Date Required	Investment Start	Rationale for Capability	SRM Concurrence
Aerocapture, Entry, Descent & Landing (AEDL) Architecture Asessment	Decide what AEDL methods/technologies could work	2008	2006	Trade studies and research to define an ensemble of Evaluation architectures and AEDLA methods/technologies	
At Earth Sub Scale AEDL Component Development & Architecture Evaluation Testing	Technology development and testing to define & answer questions about AEDL architectures	2015	2009	Technology options & capabilities must be explored in order to get data for rationale of down selection	
Scaled Mars AEDL Validation Flights	4 MT Landing Capability at Mars: Validate AEDL Models	2022	2015	Use Robotic Mars program to validate scaleable Mars Human AEDL methods	
Earth Based Full Scale Development Program	Develop & Qualify the Full Scale Hardware	2028	2020	Use mostly Earth based Sub-Orbital qualification tests to develop the full scale of the hardware	
Prepare & Fly Cargo & Piloted Human Missions to Mars	Fly first Human Missions to Mars > 40 MT AEDL Systems Qualified & Flown	2032	2025	Deliver Cargo & Humans to Mars.	
Validate Mars Surface Models	Mars Odessy and MRO Surface Assessment	2010	2006	DTM's and Site Hazard Maps for Human Scale Site Selection	
Utilize Mars Robotic Overlap Technology	MSL, MSR, MTO, MSR Data Analysis	2015-2034	2006	Develop Pin Point Landing Radar, Terrain Relative Navigation, Guidance, Hazard Avoidance Sensors	
Validate Mars Atmosphere Models	Entry, Descent & Landing (EDL) In Situ Measurements & 3 Mars Years Atmosphere Monitiring Mission	2022	2010	Mars Atmospheric variations and dust characteristics must be understood in order to successfully design high reliability EDL systems.	
Interaction with Lunar & Earth Return Development	Component Development & Architecture Evaluation Testing	2008-2015	2008	Use Lunar program and CEV to gain data and test common hardware	
Shuttle & ISS Return Human Physiological Performance Data	Human Performance Data	2006-2015	2006	Use empirical human performance data to drive designs and enable Human landings on Mars	
Special Test facilities and knowledge	Specialized supersonic and large scale wind tunnels for aerodynamic testing & Other Test Facilities for Terminal Descent Landing	2015	2009	Test Facilities are required to efficiently develop Aerocapture, Rntry, Descent & Landing Hardware on Earth	

Technology Readiness Levels (TRL)

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- Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA.

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 9 Actual system “flight proven” through successful mission operations

Capability Readiness Levels

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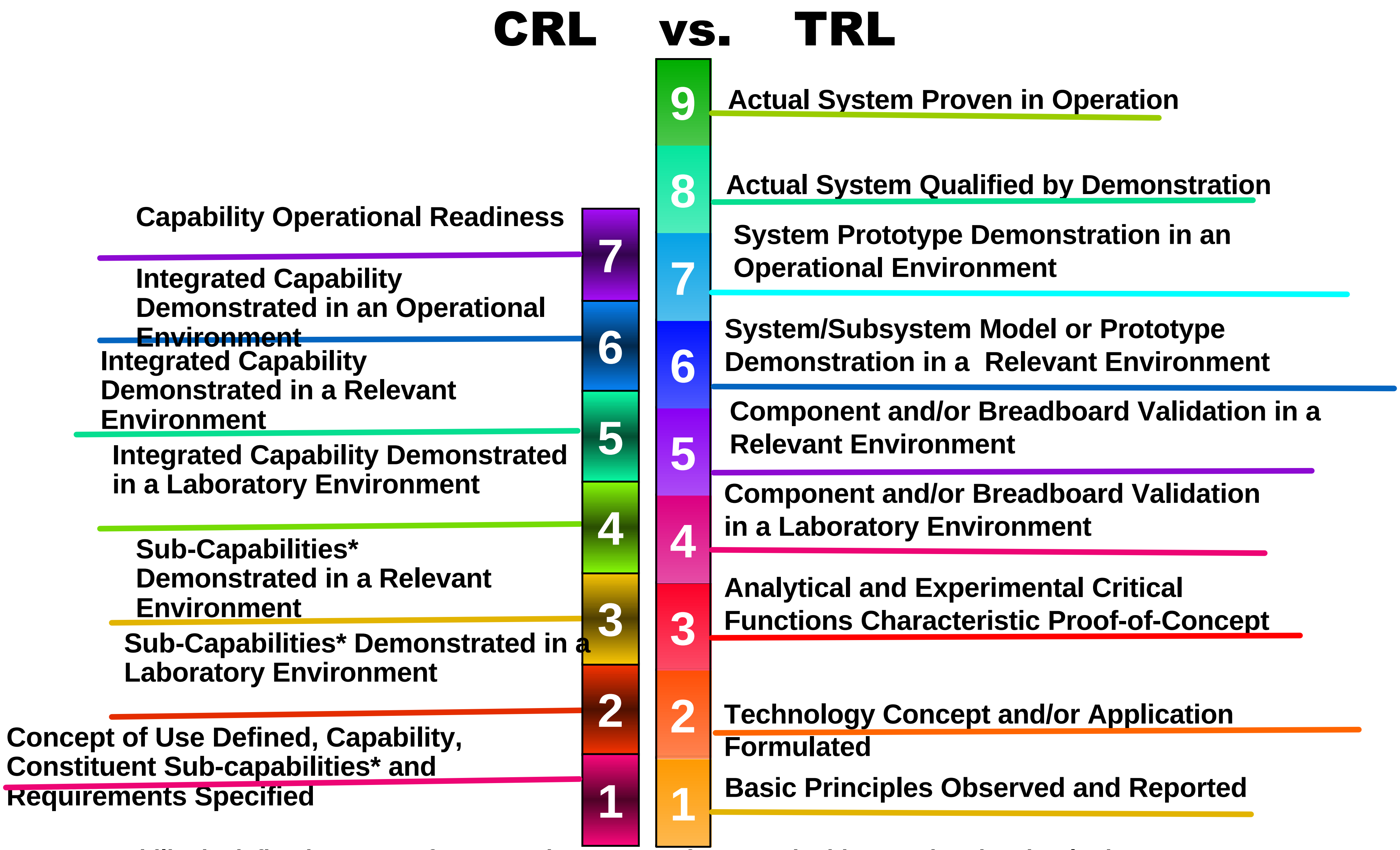
- **7** Capability Operational Readiness
- **6** Integrated Capability Demonstrated in an Operational Environment
- **5** Integrated Capability Demonstrated in a Relevant Environment
- **4** Integrated Capability Demonstrated in a Laboratory Environment
- **3** Sub-Capabilities* Demonstrated in a Relevant Environment
- **2** Sub-Capabilities* Demonstrated in a Laboratory Environment
- **1** Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Guidelines for Using CRLs

- A Capability is defined as a set of systems with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.
- The scope of a Capability includes the knowledge or infrastructure (process, procedures, training, facilities) required to provide the Capability.
- A Capability needs to be demonstrated and qualified, just as a technology does, in both laboratory and relevant environments.
  - The infrastructure and knowledge (process, procedures, training, facilities) of the Capability needs to be:
    - Demonstrated and qualified in both laboratory and relevant environments
    - Available in order for the Capability to be considered mission-ready.
- A minimum level of TRL 6 is required to integrate technologies into a Sub-capability.
- Sub-capabilities are required to reach CRL 3 before integration into a full Capability.



A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge

that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

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1 **Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**

The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

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2 Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

Advanced Planning & Integration Office

3 Sub-Capabilities* Demonstrated in a Relevant Environment

Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

- -of appropriate scale
- -functionally equivalent flight articles
- -major system interactions and interfaces identified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

4 Integrated Capability Demonstrated in a Laboratory Environment

A representative model or prototype of the integrated Capability is tested in an ambient laboratory environment. Performance of the constituent Sub-capabilities is observed in addition to the Capability as an integrated system. Analytical modeling of the integrated Capability is performed.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

Advanced Planning & Integration Office

5 Integrated Capability Demonstrated in a Relevant Environment

An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

- -of appropriate scale
- -functionally equivalent flight articles
- -all system interactions and interfaces identified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

Advanced Planning & Integration Office

6 Integrated Capability Demonstrated in an Operational Environment

The Capability is near or at the completed system stage. The integrated Capability is demonstrated in an operational environment with the intended user organization(s).

- -full scale flight articles
- -demonstrated in the intended operational 'envelope'

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

7 Capability Operational Readiness

The Capability has been proven to work in its final form under expected operational condition. This level represents the application of the Capability in its operational configuration and under “mission” conditions.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

2.0 AEDL Systems Engineering

Presenter: Claude Graves

Team Lead

2.0 AEDL Systems Engineering Topics

- Some Initial Thoughts
- Capability Description
- Capability State-of-the-Art
- Capability Requirements
- Systems Engineering
- Capability Roadmap
- Capability Maturity
- Candidate Technologies
- Metrics

Flight Phases

- **Mars AEDL**
- Earth Return Lunar and Mars
- Lunar Landing

2.0 Some Initial Thoughts

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- This part of the discussion is about AEDL from a system level perspective
  - Subsystems such as Structures, TPS, GN&C are discussed in subsequent sections
- AEDL capability roadmaps will evolve as the Exploration Initiative architecture and the resulting AEDL requirements mature
  - This AEDL capability roadmap is based on anticipated AEDL capabilities that accommodate a range of Exploration architectures but include core capabilities, such as Mars EDL, that are common to all of the architecture options
- A credible Mars EDL concept does not exist for the very large masses and volumes needed for human Mars exploration – perhaps 30 times present Mars EDL capabilities
  - Deceleration in the supersonic through terminal descent flight regime in the thin Mars atmosphere is the key to development of an EDL capability for human Mars missions
    - Robotic mission capability is not scalable to human mission size
  - "Minimize the Mars EDL mass" must be an objective of the Exploration architectures
    - The EDL system mass, and hence landed mass, will be limited by the size of the aeroshell that can be accommodated by the launch vehicle and by the TransMars injection system
  - Limited assessment of human scale EDL capability has identified candidate AEDL systems capabilities that may be combined to provide the EDL capability needed for human exploration
  - This EDL capability will be the driver for development of a combined AEDL capability for human Mars missions

2.0 Some Initial Thoughts (Con't)

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- **The technology for aerocapture into low energy orbits is ready for exploitation**
  - Aerocapture is an essential element of some exploration architectures and must be included in the Human Planetary Landing Systems (HPLS) capability development until the Exploration architecture matures and the need for aerocapture is resolved
  - Aerocapture has not been flown at any destination, but Apollo experience and other significant work has established aerocapture as a viable technology
  - Aerocapture technology must be developed into an aerocapture system capability for specific applications
- **Lunar landing will be much like Apollo but with 2 to 4 times the Apollo mass**
  - The initial lunar landing capability will be based on the Apollo experience but incorporating modern technologies and capabilities – both analytical and hardware – but with much larger descent mass
  - Capability for autonomous hazard avoidance may be included as an enhancement to the Apollo capability
  - Experience with the larger landed mass, throttleable engines, and autonomous hazard avoidance and landing systems will be an asset in the development of these systems and capabilities for Mars missions

2.0 Some Initial Thoughts (Con't)

- Return to Earth will build on the Apollo experience for lunar return and this capability will be expanded for the more demanding Mars return
  - Initial return to Earth capability will be based on the Crew Exploration Vehicle (CEV) capability and may include Earth aerocapture into a low energy orbit
  - Return from Mars will have about 40% more energy than return from the moon for long duration Mars missions
- Short duration Mars missions are difficult for several reasons including an increase in the Mars and Earth arrival speeds
  - One year Mars missions increase the maximum Mars entry speeds to from 7^{+} km/s to 10.0 km/s and Earth entry speed from 13.0 km/s to 15.0 km/s, respectively
  - For 580 day Mars missions the maximum Mars entry speed is the same as for long duration and the maximum Earth entry speed is 14^{+} km/s
- The human element provides challenges and opportunities
  - Safety and risk challenges particular for the remote Mars operations with long transit times
  - Humans limit the aerodynamic and propulsive loads that can be accommodated, particularly after long periods of weightlessness – limit believed to be about 5 g's for sustained loads
  - Crew capabilities can be used to enhance mission success
- Systems Engineering
  - HPLS capability development depends on the integration of complex, high performance systems into AEDL capabilities that must perform in a wide range of environments – Earth, Moon, and Mars
  - An effective HPLS systems engineering effort is a key to successfully developing this capability

Capability Description

Click to add subtitle

2.0 AEDL Capability Description – at Mars

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- Mars EDL
  - Mass 50 to 60 Mt at entry interface
  - Land at up to 2.5 km above the mean surface throughout the Mars year – Mars has a wide variation of density profiles with season
  - Pin Point landing (accuracy of 100 m)
- Aerocapture into Mars orbit
  - Needed for some candidate exploration architectures
  - Mass 70 to 100 Mt
  - Mars arrival speeds
    - 6 to 7^{+} km/s for long duration missions and for missions of about 580 days
    - 8^{+} to 10^{+} km/s for 1 year missions
  - Orbit altitude about 500 km or 17,000 km for a stationary orbit
- Mars AEDL Capabilities
  - Human and cargo missions and cargo only missions
  - Sustained loads limited to about 5 g's for AEDL with a flight crew
  - Autonomous operation capability
  - Use human capabilities to enhance success for crewed missions
- Candidate Mission Scenario at Mars
  - Mars cargo aerocapture
  - Mars cargo aerocapture followed by EDL
  - Mars human and cargo aerocapture followed by EDL

2.0 AEDL Capability Description - Return to Earth

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- **Lunar return – much like Apollo but may include aerocapture at the Earth**
  - Crew Exploration Vehicle (CEV) or enhanced CEV – mass 5^+ Mt
  - Return speeds of about 11.0 km/s
  - Options include short range direct entry, extended range with atmospheric exit and subsequent reentry and landing, or aerocapture followed by EDL
- **Mars return**
  - Mass 5 to 10 Mt without return of the crew transit vehicle
  - Return speeds
    - Up to about 13.0 km/s for long duration missions (40% increase in spacecraft energy compared to lunar return missions)
    - Up to 14^+ km/s and 15.0 km/s (86% increase in spacecraft energy compared to lunar return missions) for 580 day and 1 year missions, respectively
    - Increased aerodynamic heating results in more severe TPS environment
    - Effects entry corridor, aerodynamic loads, L/D requirement
  - Options include short range direct entry, extended range with atmospheric exit and subsequent reentry and landing, or aerocapture followed by EDL
    - Aerodynamic loads constraints for crewed vehicles may preclude direct entry
- **Earth return Scenarios**
  - Human missions with cargo
  - Sustained loads limited to about 5g's after long periods of weightlessness
  - Autonomous operations
  - Use human capabilities to enhance success

2.0 AEDL Capability Description - Lunar Landing

Advanced Planning & Integration Office

- **Lunar Landing**
  - **Concept Apollo like but with 2 to 4 times the mass at start of powered descent**
  - **Human and cargo missions**
  - **Pin Point landing capability**
  - **Autonomous operations**
  - **May include autonomous hazard avoidance capability**

State-of-the-Art

Click to add subtitle

2.0 Current State-of-the-Art – Mars EDL

Advanced Planning & Integration Office

- **Systems Capabilities of Current Mars Landers (Through 2009 MSL)**
  - Limited entry mass capability – currently 2 Mt and may evolve to 4 to 6 Mt
  - Blunt body, rigid aeroshells
    - Blunt body, rigid aeroshells – 70 deg sphere cone
    - Maximum entry body diameter ~ 4.5 m
    - No movable aerodynamic surfaces
    - 3-axis control or spinning ballistic entry
    - Direct entry or entry from orbit
    - Maximum design deceleration ~ 16 g's
    - L/D = 0.18 (constrained by angle of attack limits at parachute deployment)
  - Maximum landing site altitude ~ 2.0 km above MOLA (direct entry, no dust storm)
  - Parachute capability is based on Viking technology
    - Disk Gap Band design
    - Max diameter – 16.15m
    - Dynamic pressure deploy envelope 239 - 850 pa
    - Mach deploy envelope 1.13 - 2.2
    - Max deploy angle of attack – 15 deg

2.0 Current State-of-the-Art – Mars EDL (Con't)

Advanced Planning & Integration Office

- Systems Capabilities of Current Mars Landers (Through 2009 MSL)
  - Precision trajectory control to parachute deployment
    - Autonomous guided entry guidance to parachute deployment
      - Passive center-of-mass control to achieve low angle-of-attack
      - Bank angle modulation only for trajectory control
      - Position accuracy perpendicular to the radius vector at parachute deployment ~10 km and is driven by navigation accuracy – the effects of low altitude winds while on the parachute must be accommodated to attain precision landing
      - Control trajectory to density altitude at parachute deployment – results in large variation in geometric altitude
    - Autonomous flight control system
    - No hazard detection or avoidance capability

2.0 Current State-of-the-Art - Aerocapture

Advanced Planning & Integration Office

- The technology for aerocapture into low energy orbits is at a TRL of 6 – Based on Apollo experience and subsequent aerocapture assessments and experience
  - Never been done into any planetary atmosphere but a significant body of work shows that technology for aerocapture into low energy orbits is ready for program application
    - Apollo program human rated the capability for a controlled skip out of the Earth's atmosphere followed by a re-entry into the atmosphere and a precision landing in less that one orbit.
      - This capability was available on every Apollo lunar mission to fly over late developing bad weather in the landing area but was never needed or used.
      - This provided the atmospheric flight technology needed for aerocapture
      - The propulsive capability for orbit adjustment was not included
    - The Soviet Union returned two spacecraft from the moon – Zond 6 and Zond 7 in 1968 and1969, respectively with aerocapture like maneuvers in the Earth's atmosphere
      - The spacecraft entered the Earth's atmosphere, exited the atmosphere, and reentered the atmosphere to land in the Soviet Union in less than one orbit of the Earth

2.0 Current State-of-the-Art - Aerocapture (Con't)

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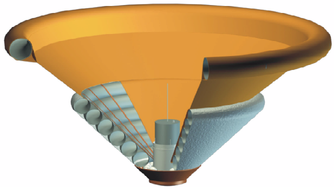
– Never been done… (Con't)
  - Since Apollo many programs and detailed systems studies have shown the viability of aerocapture for Earth and other destinations
    - Aerocapture Flight Experiment (AFE) program analytically demonstrated aerocapture in the Earth's environment in the early 1990's – guidance algorithm ready for flight software coding and some hardware built.
    - Aeroassist Orbital Transfer Vehicles studies in 1980's (Industry and NASA) showed aerocapture feasibility at Earth – some hardware built.
    - Mars Atmospheric Knowledge Working Group in 1991 with NASA and industry participants concluded that aerocapture was a viable option for Mars orbit insertion.
    - Original Mars 2001 orbiter planned to use aerocapture – NASA, industry, and academia team completed a controlled rigorous assessment of aerocapture guidance algorithms before orbiter switched to aerobraking after failures of MPL and MCO.
    - CNES/NASA Mars Premier Orbiter was to use aerocapture in 2007.
      - CNES/NASA team evaluated aerocapture risk and concluded aerocapture was feasible with significant mass savings compared to all-propulsive capture, or all-propulsive capture followed by aerobraking.
    - Detailed NASA inter-center systems studies have demonstrated the viability and benefit of aerocapture at multiple destinations (Mars, Titan, Neptune, and Venus)

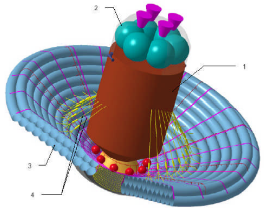
2.0 Current State-of-the-Art – Earth EDL

- **Extensive experience with rigid aeroshells in the Earth's atmosphere for a wide variety size, shapes, and applications**
  - Blunt Bodies
    - Human mission – Mercury, Gemini, Apollo, Vostok, Soyuz
    - Robotic missions – Zond 6 and 7, Discoverer, Genesis, Atmospheric Reentry Demonstrator
  - Slender bodies and winged vehicles
    - Human capability – Space Shuttle Orbiter, Buran, X-38
    - Fly at high angle-or-attack until aerodynamic heating has reduced to low levels. This creates a blunt body effect at high speeds to minimize aerodynamic heating.
  - Autonomous operation
  - Precision trajectory control and landing
  - Vertical and horizontal landings
  - Mass up to 105 Mt

- **Very limited experience with inflatable aeroshells, particularly in the United States**
  - **Russian experience**



    - **Mars '96 Mission**
      - **The Soviet Union designed, developed, and launched a small two stage, inflatable aeroshell in 1996 intending to use the aeroshell for Mars EDL as part of a surface penetrator mission.**
      - **Propulsion system failure prevented the system from leaving earth orbit**
    - **Have a flight test program, Inflatable Reentry And Descent Technology (IRDT) to further develop inflatable aeroshells based on Mars '96 technology and test in the Earth's atmosphere at near low energy orbital speeds**
      - **Two flight tests completed with very limited success**
      - **Ballistic entry, no data link, limited ground tracking, recovery beacon**
      - **Re-flight of IRDT-2 scheduled for 2005**
    - **Concept analytically assessed for Mars AEDL for 6 Mt and 60 to 70 Mt vehicles**



2.0 Current State-of-the-Art – Earth EDL (Con't)

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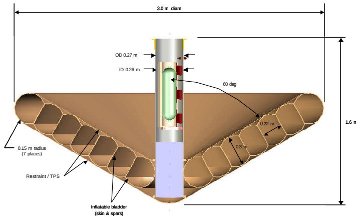
- Very limited experience….. (Con't)
  - United States experience
    - Inflatable Re-entry Vehicle Experiment (IRVE)



      - Project led by LaRC
      - Low speed, ballistic flight test of 3 m diameter inflatable aeroshell
      - First flight of inflatable aeroshell in the United States scheduled for 2005
    - Aerossist Inflatable Reentry System (AIRS)
      - Project led by JSC with LaRC and ARC major contributors
      - Three low speed flight test of inflatable aeroshells – follow on to IRVE
        - Flight test 1 – 3 m aeroshell with non-zero angle-of-attack, aerodynamic lift, and attitude maneuvers or possible closed loop GN&C – Sept 06
        - Flight 2 – 8 m aeroshell scaled from flight 2 with closed loop GN&C – Aug 08
        - Flight 3 – 8 m aeroshell provided by open competition to provide design and construction innovation also with closed loop GN&C – Oct 08
    - Very low ballistic coefficient, high altitude inflatable decelerators
      - Technology development program led by Ball Aerospace Corp.
        - Demonstrate light weight decelerator construction methods and materials survivability
        - Structural testing
        - Validation of coupled hypersonic aerodynamics and nonlinear structural analysis
        - Demonstrate vacuum deployment

2.0 Current State-of-the-Art – Lunar Landing

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- Apollo Lunar Module is the system level experience base but subsystems for the Exploration Initiative will use available technologies
- Apollo Lunar Landing characteristics:
  - Two person crew for short stay
  - Mass at start of powered descent about 15 Mt
  - Limited landing site accessibility
  - Abort to orbit capability during powered descent
  - Landing radar provided altitude and 3 axis speed information – altitude and speed lock-up at about 8.5 km and 2.0 km altitude, respectively. Speed lock-up limited by geometry
  - Precision landing accuracy (accuracy of 10’s of meters)
  - Hazard avoidance capability used crew-in-the-loop to detect hazards and to retarget to avoid hazards
  - No prediction of accessible landing area from a performance perspective - propellant remaining and T/W

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Mars AEDL Capability Requirements

Click to add subtitle

2.0 Mars AEDL Capability Requirements

Aerocapture

- Mass 70 to 100 Mt
- Arrival speeds 6 to 7^{+} km/s
- Orbit altitude about 500 km or 17,000 km to achieve a stationary orbit

EDL

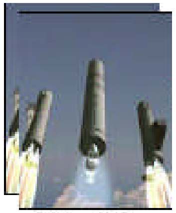
- Mass 50 to 60 Mt at entry interface
- Land at up to 2.5 km above the mean surface throughout the Mars year
- Pin Point landing (accuracy of 100 m)
- Hazard avoidance

Mars AEDL

- Human and cargo and cargo only flights
- Constrained loads to accommodate flight crew
- Autonomous operations
- Use human capabilities to enhance success for crewed missions

Launch

- Packaging
- Thermal control
- Communications
- Launch loads

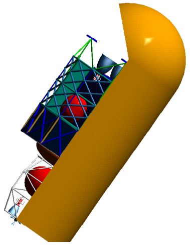


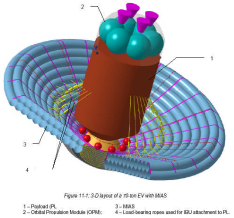
Trans Mars Injection & Transit

- Packaging
- Thermal control
- Communications
- AEDL preparation

Mars Aerocapture

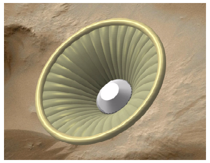
- Packaging
- Thermal control
- Communications
- Orbit adjustment after atmospheric exit

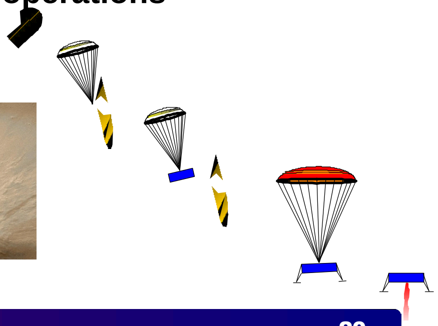




Mars EDL

- Packaging
- Communication
- Deorbit
- Decelerator deployment
- Safe disposal after use of unneeded and obstructing systems
- Pin Point landing near assets
- Emergency ascent and Earth return
- Surface operations





Systems Engineering

Click to add subtitle

2.0 HPLS Systems Engineering Description

AEDL Systems Engineering function ….

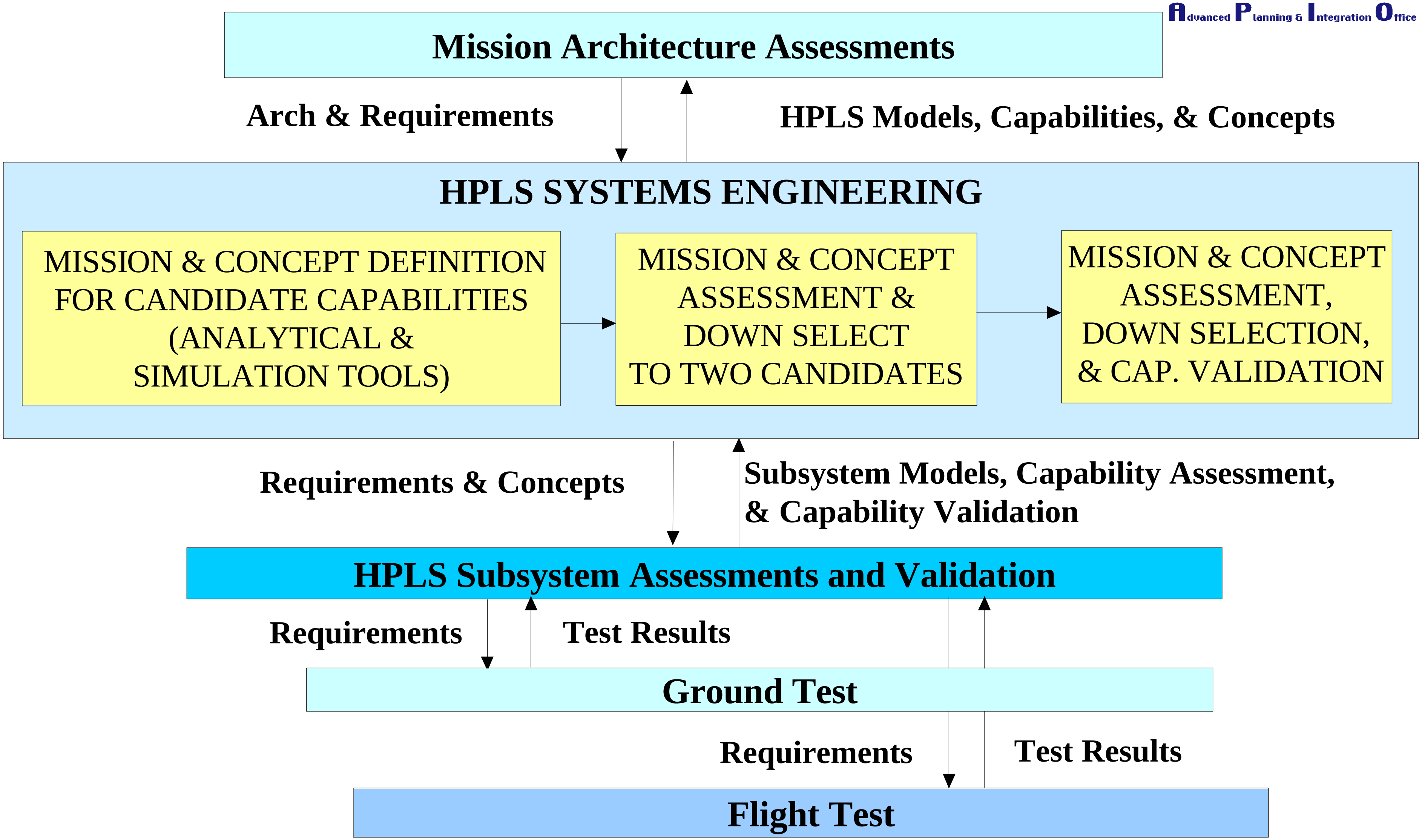
provides analysis and direction for the development of the demanding, complex, and interrelated AEDL capabilities for the Exploration Initiative....

This is essential to avoid the pitfall of developing AEDL system and sub-system capabilities that may be significant achievements in themselves, but add little to achieving the Exploration Initiative objectives

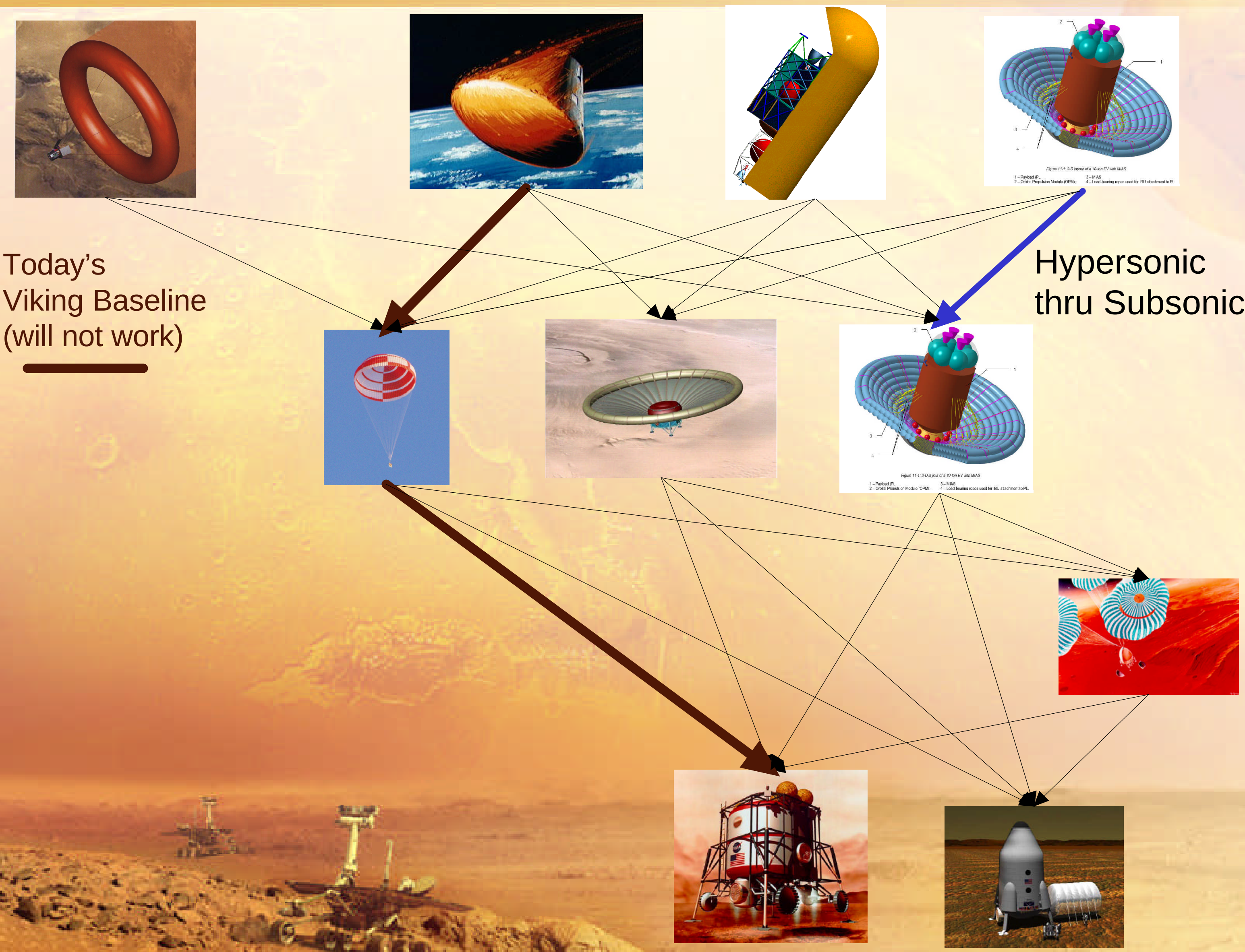
2.0 HPLS Systems Engineering Description

- Is an interactive process…
  - Inputs…
    - Requirements from Exploration Initiative (EI) architecture assessments
    - Subsystem and system models and capabilities
      - Sub-systems specialists
      - Lunar missions, Robotic exploration missions, and precursor missions
      - CEV program
    - Operations concepts
    - Human capabilities and limitations
    - Natural environment models
  - Define AEDL mission and system concepts….
    - Iterative process with the EI architects, other capability development elements, AEDL sub-systems, mission operations, and the flight crew
  - Define AEDL subsystem requirements
  - AEDL mission and system concept down selection
  - Validate the AEDL capabilities
    - Analytical assessments at both the system and sub-system level
    - Ground and flight test
      - Define test requirements
      - Assess test results
  - Update models and reassess concepts and capabilities

2.0 Systems Engineering Process



Which will it be?



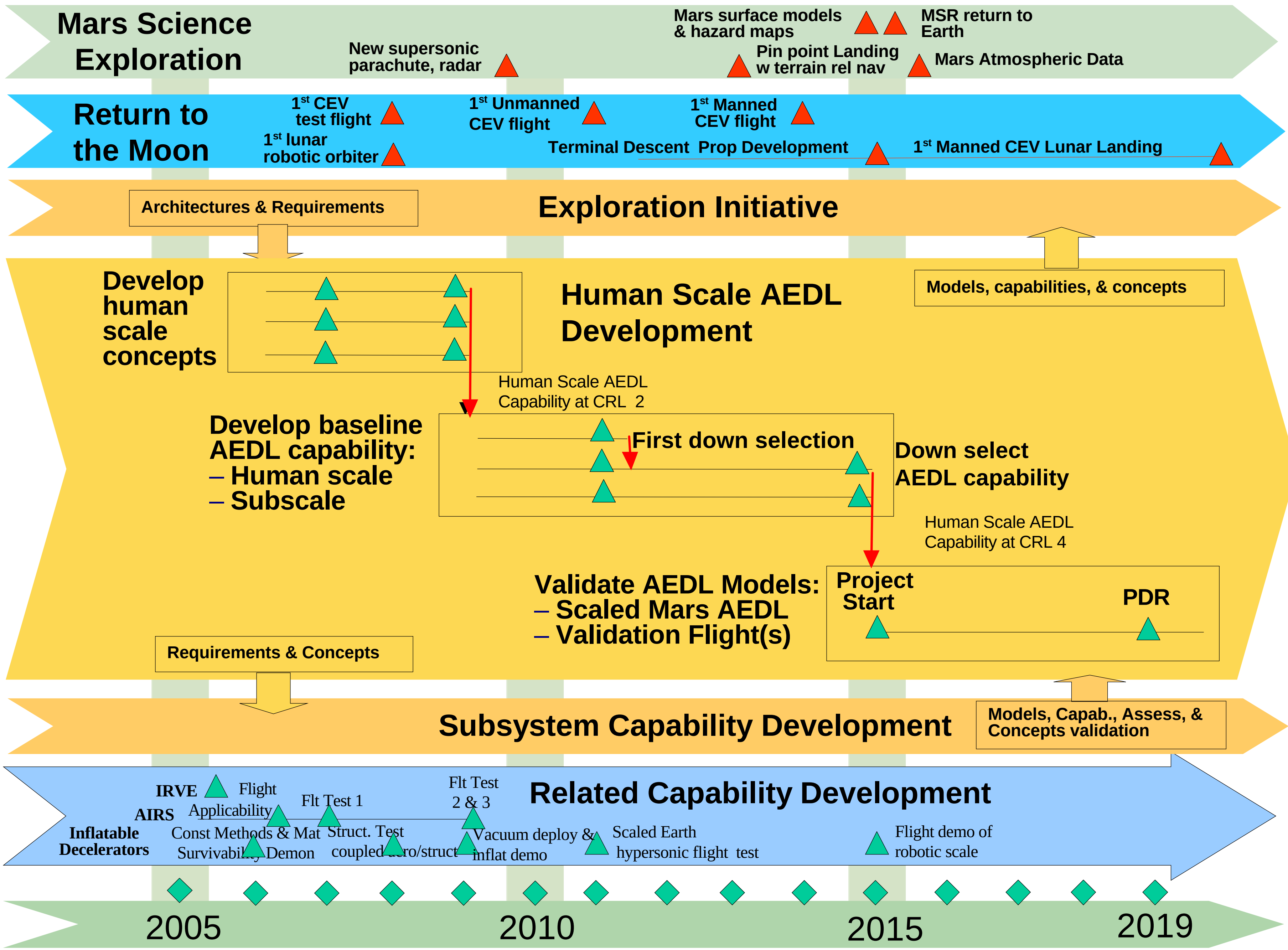
Options for Hypersonic Decelerators

Options for Supersonic Decelerators

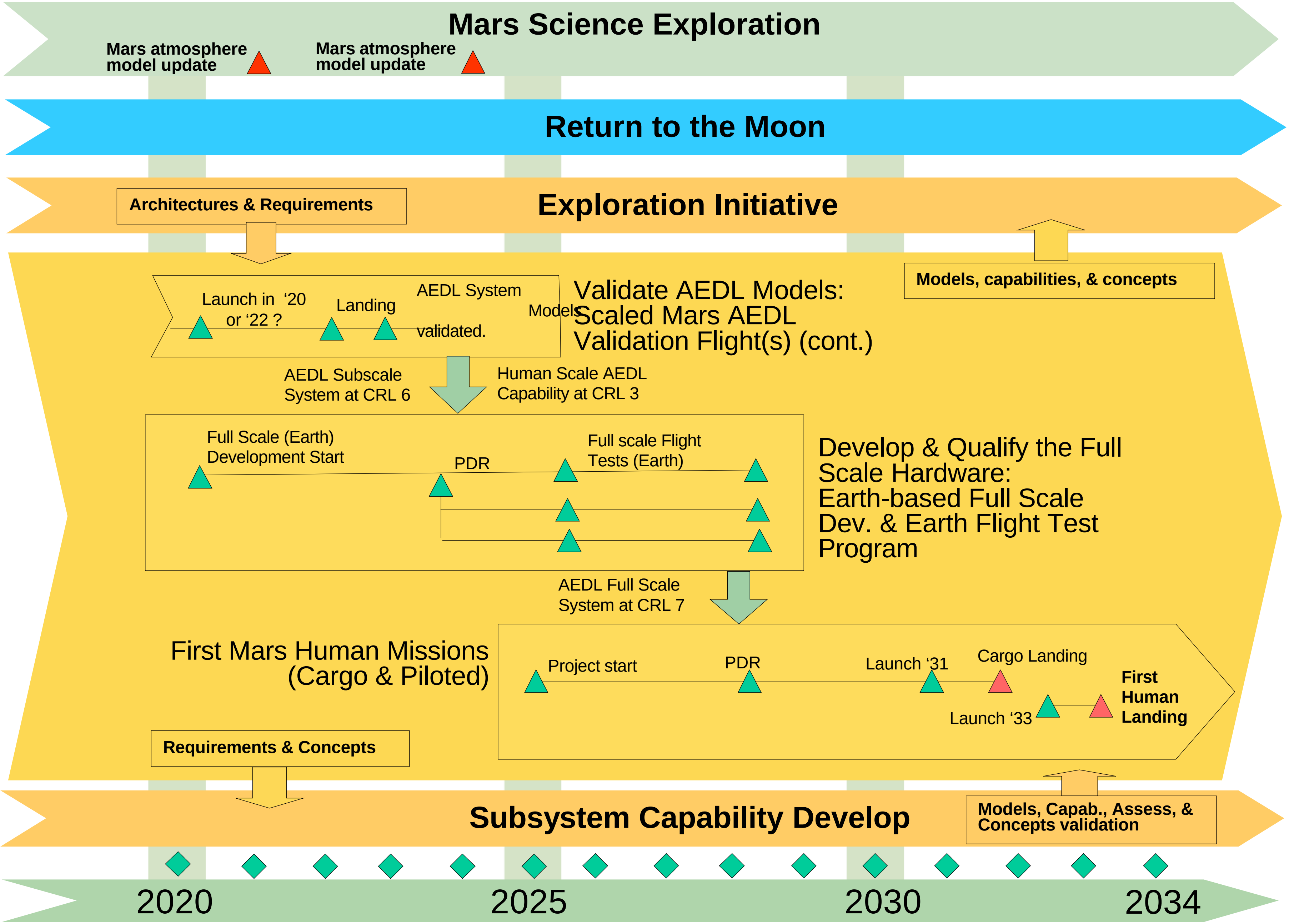
Options for Subsonic Decelerators

Options for Terminal Descent Systems

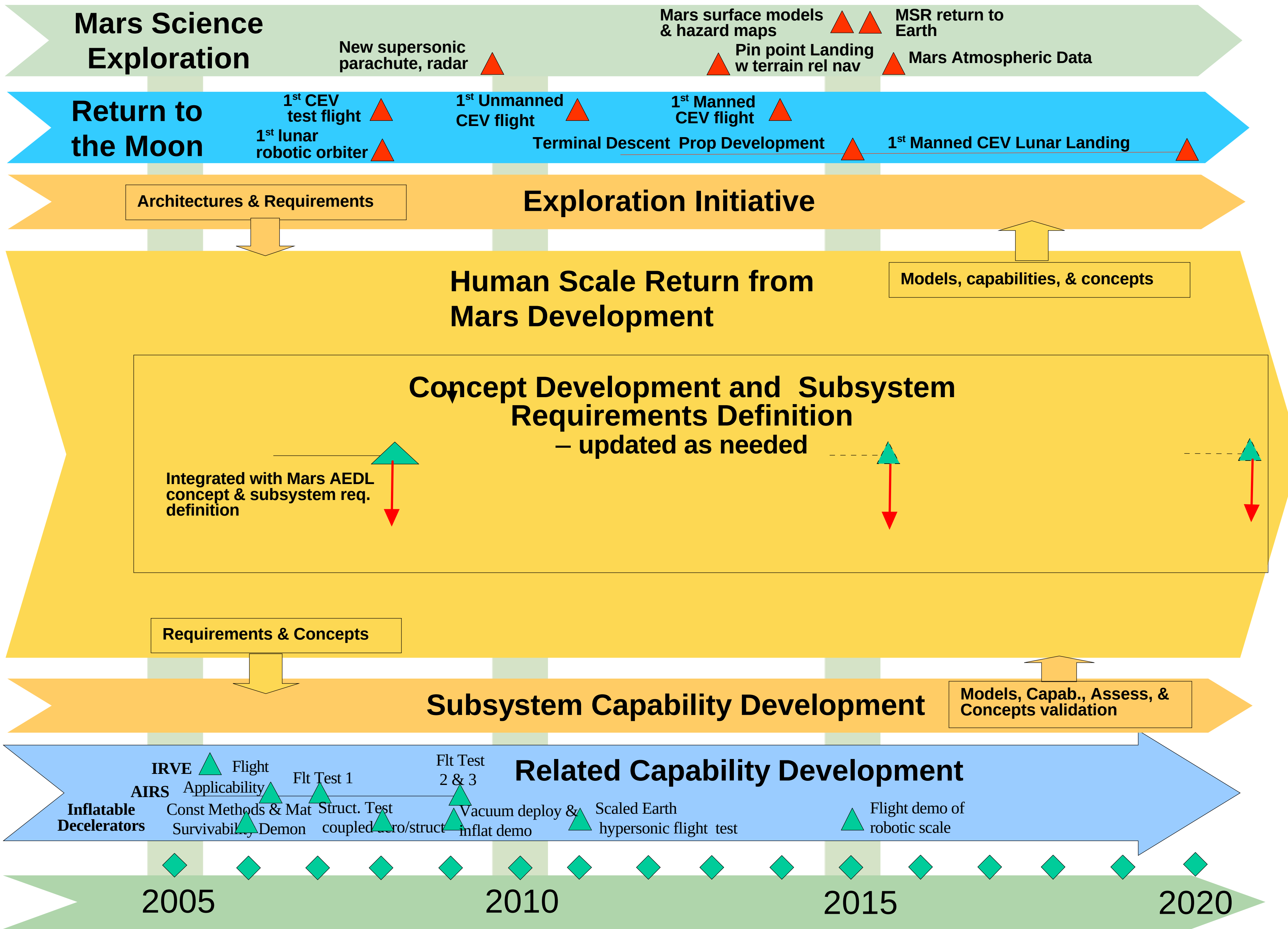
Detailed Mars AEDL Road Map: 2005 - 2020



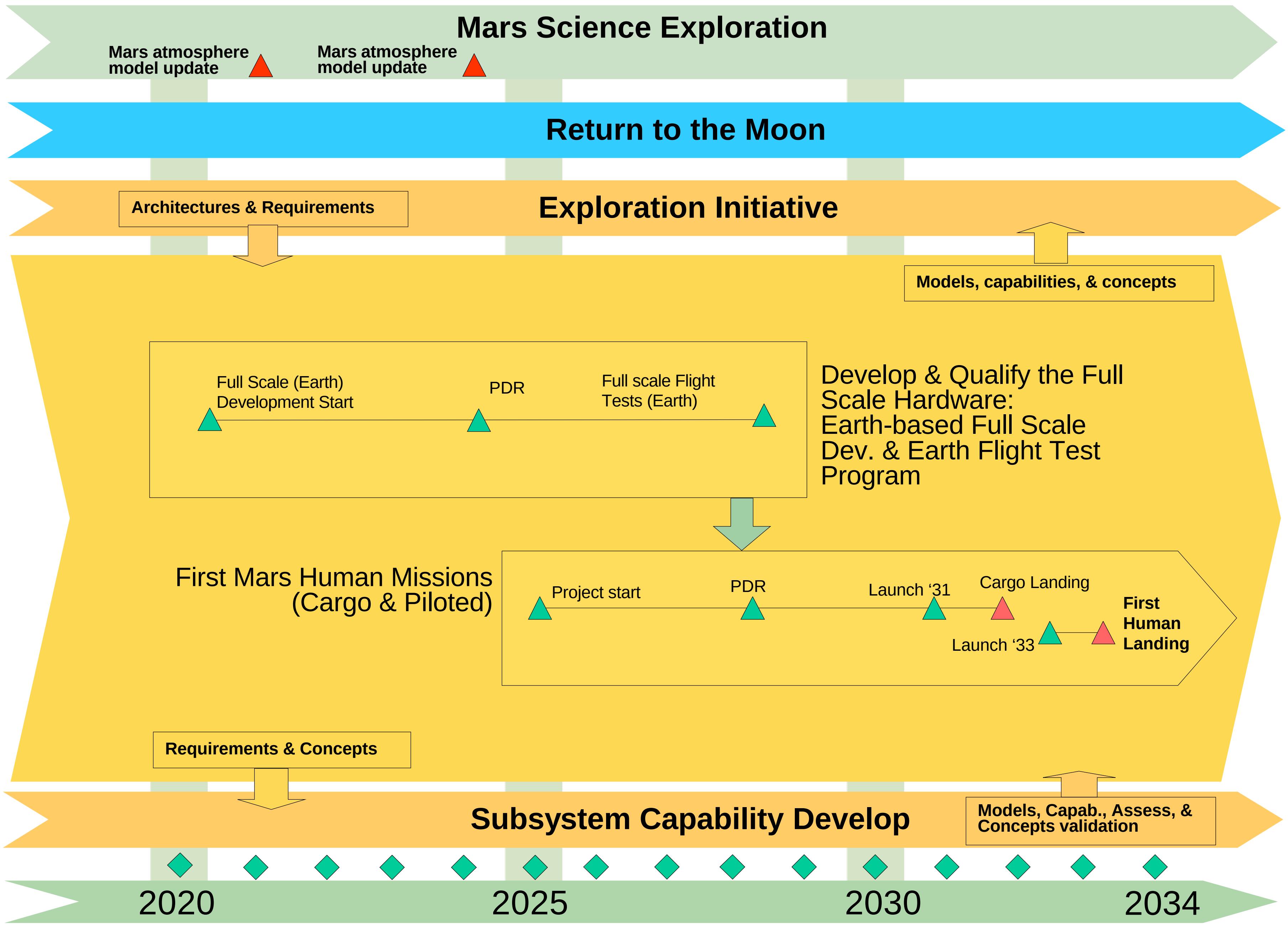
Detailed Mars AEDL Road Map: 2020 - 2034



Detailed Return from Mars Road Map: 2005 - 2020



Detailed Return from Mars Road Map: 2020 - 2034



Maturity Level

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Maturity Level – Capabilities for HPLS Systems

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- Mars AEDL
  - Current Mars EDL capability is not applicable for human scale Mars EDL
    - Current Mars EDL capabilities limit the EDL mass to about 2 Mt. This may be extendable to 4 to 6 Mt, the current EDL capability is simply not applicable for human scale Mars EDL
  - A credible concept for human scale EDL does not exist (TRL 2)
    - Limited assessment of EDL systems has identified candidate EDL aeroshell concepts that may provide the needed capability.
  - Mars Science Exploration missions will develop some capabilities needed for Mars AEDL
    - The entry GN&C algorithms developed for the MSL provide precision entry trajectory control (TRL 5 for rigid aeroshells; 3 for flexible aeroshells)
    - Pin Point Landing capability, supersonic parachutes, Mars environment modeling (TRL 2)
    - Mars Sample Return will provide experience for Earth return from Mars
  - Aerocapture into low energy orbits is feasible and ready for exploitation if needed (TRL 4-5 for rigid aeroshells; 3 for flexible aeroshells)
    - Development of this capability should be integrated with the EDL capability development to minimize overall AEDL risk and cost An existing AEDL modeling, simulation, and human resource capability can be expanded for human scale AEDL capability development (TRL 6 simulation, experience, and human resources; TRL 4 modeling)
    - Extensive system modeling, high fidelity simulation capability, operations experience, and human resources from previous programs, ongoing robotic

Maturity Level – Capabilities for HPLS Systems (Con't)

- **Return from the Moon will be based on the CEV (TRL 6)**
  - The Apollo program demonstrated the use of rigid, blunt body aeroshells from the moon
  - Long duration missions will require reduced aerodynamic loads compared to Apollo which will result in reduced aerodynamic heating rate per unit mass but will increase the total heat input into the system
  - System options need to be assessed to incorporate new capabilities and to integrate with the remainder of the AEDL capabilities
- **Return from Mars will be an extension of the return from the moon (TRL 2 – 3)**
  - Mars return speeds will result in a 40% increase in spacecraft energy at the start of atmospheric flight compared to return from the moon
  - Aerocapture followed by EDL will reduce aerodynamic loads on the flight crew and may reduce the total heat compared to direct entry, but would require a TPS reuse
  - A rigid, blunt body aeroshell is a candidate for return from Mars
  - System options need to be assessed to incorporate new capabilities and to integrate with the reminder of the AEDL capabilities
- **Human rated TPS especially for large systems and inflatable systems is a capability gap that requires capability development. (TRL 5)**
  - Mars science missions will provided only limited assistance in addressing the scalability and manufacturability issues

Metrics for HPLS Systems

Advanced Planning & Integration Office

- Metrics will include the traditional metrics – risk, cost, schedule, and performance – as this effects the AEDL but more importantly as it effects the Exploration Initiative – with more specific metrics to be added later
- Some important non-traditional metrics are:
  - Commonality of systems, subsystems, and components to maximize the benefits of ground test, flight test, and operational flight experience
  - Continuity of resources – skilled people, tools, practices, and facilities across all of the aeroassist efforts

Advanced Planning & Integration Office

1.0 Mission Drivers For Human Landing Systems

Presenter: Harrison H. Schmitt

Team Lead

Optimized Integration of Human Capabilities Into Planetary Landing Systems to Enhance the Probability of Mission Success

Benefits

- Increased probability of human mission success and reduction of human risk
  - Trained, experienced and intuitive qualitative super computer - the brain
    - Integrated with a stereo-optical system of high dynamic range - the eyes
    - Integrated with a potentially highly sensitive manipulation sub-system - the gloved hands
  - Intuitive response to new situations and observations that integrates the full multi-dimensional environment
- Scientific return far greater than for comparable funding of fully automated or robotic missions
- Increased public interest and involvement

Consequences and Requirements of Having Human System Capability

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- Aero-capture into an initial parking orbit
- Large minimum mass at Aero-capture, Entry, Descent and Landing (AEDL)
  - Pre-positioned assets to enable long duration stay
- Increased complexity of systems and of system interaction
- Large support infrastructure on Earth for mission preparation and remote support
- Major capability for human rating testing and validation
- Major research effort to understand space adaptation syndrome and human performance capability after long duration, zero-g flight

Space Flight Heritage

- Apollo technical, test, operational and mission control heritage
- Skylab, ISS, MIR, Space Shuttle human experience
- Shuttle entry technologies, tests and operations
- Post-Apollo paper studies (“DRMs” etc.)
- Mars Robotic Program
  - Martian physical and environmental parameters and variations
    - Currently better than pre-Apollo understanding for the Moon
  - Operational experience with spacecraft at Mars distances
  - Core of experienced, deep space engineers and controllers for work ahead

Missing from Our Space Flight Heritage

- Adequate, scientifically credible understanding of space adaptation syndrome and adaptation countermeasures beyond that currently available
  - Need broad, coordinated research protocol on human system
  - Need large "n" of pairs of "field" physician test subjects
  - Need NASA-NIH partnership for world class research
  - Need focus on long-term operations in space
  - Need an "occupational medicine" perspective
- Operational understanding of human performance after prolonged adaptation to the space environment and when under deceleration loads
  - **Need to take advantage of all flight opportunities prior to CDR**
    - Long duration flight and Earth entry environments
  - **Need to coordinate use of Earth-based research facilities**
  - Need research protocol for performance investigations
  - Need data mining and analysis of existing records
  - Need review of privacy assumptions to broaden research base
  - Need performance compensation strategies as required

Missing from Our Space Flight Heritage (See Backup Slide)

Advanced Planning & Integration Office

- Operational experience with providing "mission control" functions with long delay in communications
  - Solar flares
  - Training and mission simulations
  - "Another set of eyes" during AEDLSA (aero-capture, entry, descent, landing, surface and ascent) operations
- Essential mission control functions will be required in spacecraft in transit and at Mars
  - Crew and new systems can provide functions in real-time
  - Two landers will enable an orbital mission control function
    - Crew will land as separate teams (increased mission return and re-adaptation)
    - Nominally two landings
    - Lower lander mass
    - Mission success redundancy

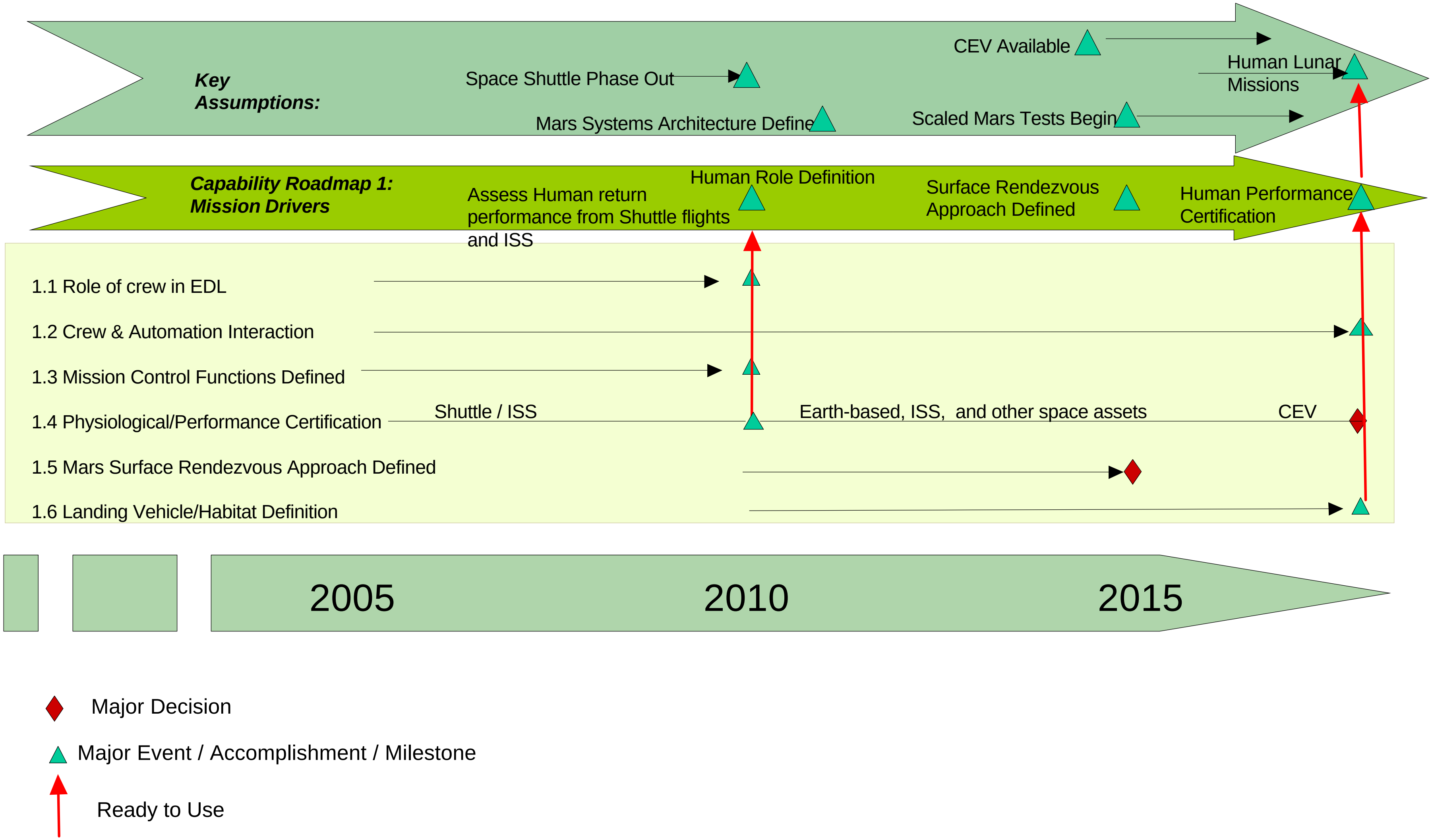
1.0 Mission Drivers For Human Landing Systems - Topics To Be Covered

Advanced Planning & Integration Office

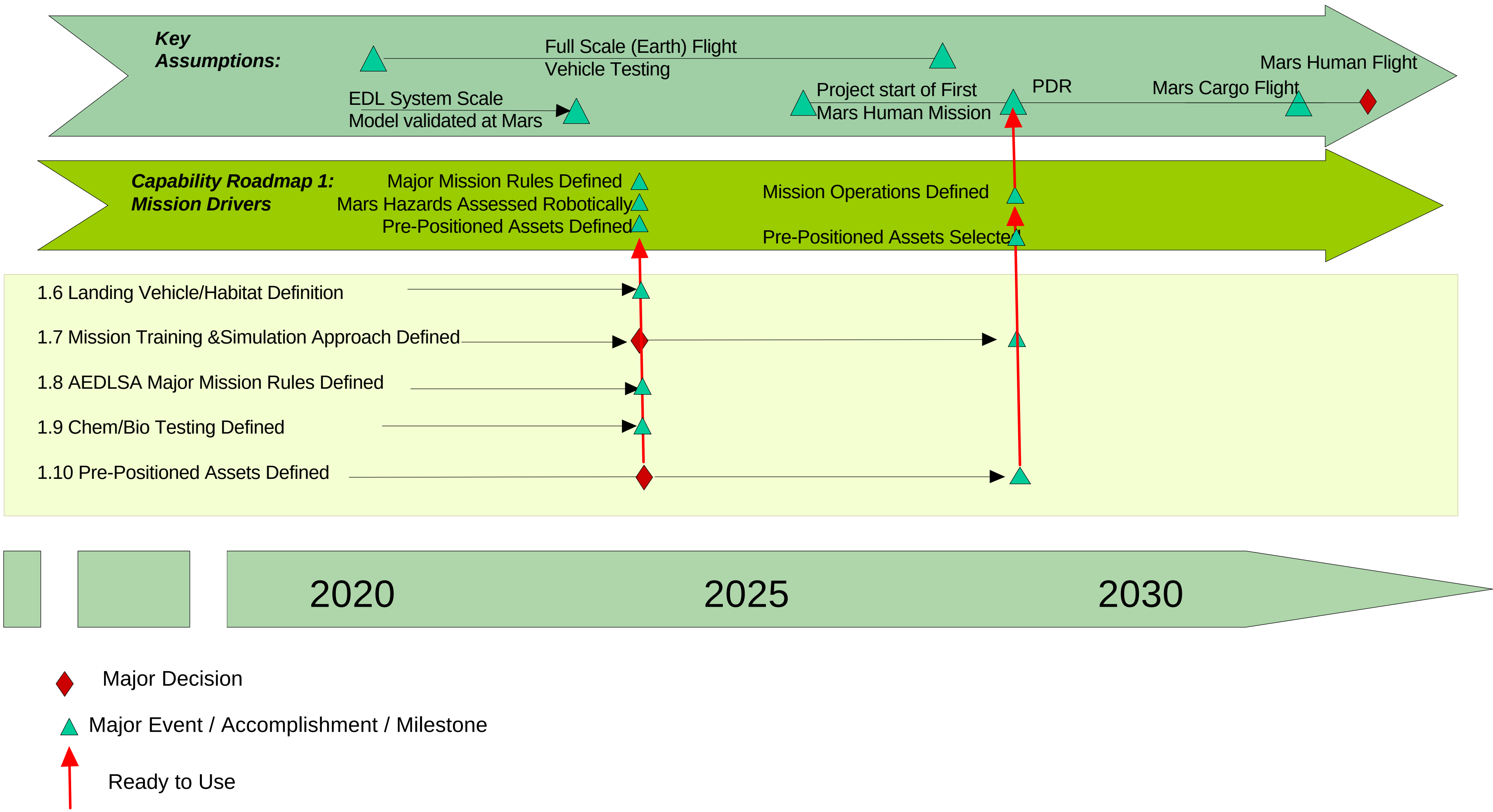
- 1.1 Role of Crew in AEDL and Ascent Operations
- 1.2 Crew and Automated Systems Interactions
- 1.3 Major Mission Control Functions Defined
- 1.4 Physiological and Performance Certification
- 1.5 Mars Surface Rendezvous Requirements
- 1.6 Landing Vehicle Habitat Definition
- 1.7 In-flight Training and Mission Simulation Needs
- 1.8 Major Mission Rules for AEDL, Surface and Ascent Operations
- 1.9 Chemical and Biological Testing Requirements
- 1.10 Pre-Positioned Assets for EDL Trajectory Control, Terrain-relative Navigation and Site Selection
- 1.11 Crosscutting Capabilities
- 1.12 Summary of Major Mission Drivers

Charts in Backup Section

1.0 Mission Drivers For Human Landing Systems



1.0 Mission Drivers For Human Landing Systems



1.1 Role Of Crew In AEDL And Ascent Operations

- Real-time judgment and potential for manual back-up and override
  - Relative to cargo missions, crew capabilities lower overall risk to mission success
    - Need preservation of capabilities under deceleration loads
- Real-time situational awareness for systems evaluation and re-configuration
  - GN&C and sensor data monitoring
  - Spacecraft sub-systems and displays design
  - Landing point re-designation
  - Hazard avoidance enhancement
  - Orbital rendezvous back-up

1.3 Major Mission Control Functions - Can be Evaluated by Lunar Missions

Advanced Planning & Integration Office

Necessary On-board Mission Control Functions in Blue

- All mission phases
  - In-flight training and simulations (shared)
  - Spacecraft systems monitoring
  - Distributed control systems evaluation (shared)
  - Solar particle event monitoring
- AEDLSA (aero-capture, entry, descent, landing, surface, and ascent)
  - Operations support
  - Trajectory monitoring (additional vote)
  - Landing / orbital crew communications
  - Distributed and shared decision protocol
- Surface
  - Exploration consultation
  - Scientific / technical analysis and synthesis (shared)

1.3.2 Orbital Mission Control Rationale

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- Human flight vastly increases complexity of systems for AEDLSA (aero-capture, entry, descent, landing, surface & ascent)
  - Extremely high demand for mission success on each crewed flight, including pin-point landing and abort-to-land requirements
    - Without orbital crew involvement, recovery from off-nominal and unanticipated events may be difficult (comm delays prevent real-time assistance from Earth support teams)
    - Requires multiple redundancy in systems and GN&C
    - Orbital Mission Control provides independent source and analysis of nav data
      - Possible alternative source of nav data (active optical and/or radar tracking
      - Independent source of "votes" on optimum configurations of redundant and back-up systems and GN&C
      - Alternative and independent comm and nav systems if planned precursor system degraded (Deployable sub-satellites or choice of orbit)

1.3.3 Entry, Descent And Ascent Trajectory Monitoring - Can be Evaluated by Lunar Missions (See Backup Slides)

Advanced Planning & Integration Office

- During EDL&A, active crew will need assistance due to possible distractions and possible deceleration load performance issues
  - "Extra set of minds" and computational systems in real-time reduces risk of unforeseen events
    - Reminders to landing crew of deferred or missed tasks (without deceleration load stress)
  - Real-time risk assessment and mitigation assistance
    - Interactions to provide compensation for possible deceleration load effects on landing crew
    - Optimal display design for situational awareness

1.4 Physiological And Performance Certification

- Physiological adaptation and re-adaptation after zero-g
- Deceleration load performance compensation after adaptation to transit environment

Timely Resolution Of These Issues Will be Enhanced by A Performance Test Protocol That Takes Advantage of Shuttle Availability, ISS Access, CEV, and Other Earth and Space-based opportunities

1.4.1 Needed Human Capabilities At Mars

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CAPABILITY	NEEDED
Physical performance of critical AEDLSA functions	Characterization of space adaptation syndrome for each crew member Analysis of deceleration load performance Countermeasures / training Performance decrement compensation Entry deceleration load minimization
Full performance of critical AEDLSA functions	Operational testing & validation Crew skill selection, training & procedures development In-flight training & simulations Surface and transit science & engineering
Full performance of orbital mission control functions	Sensor & ops integration Crew skill selection, training & procedures development In-flight training & simulations

1.4.3 Physiological Issues

- Develop understanding of space adaptation syndrome and necessary countermeasures (individual SAS / CM models for flight crew)
  - Space-based and pre & post flight human / animal research
  - Define countermeasure and exercise protocols
- Establish physiological basis for space occupational medicine (mitigate SAS and normal health challenges)
- Define systems for radiation prediction and protection
- Define protocol & time for re-adaptation to Mars gravity
- Mars surface hazard and risk assessment
- Define re-adaptation protocol for Earth gravity

1.4.4 Performance Issues - (See Backup Slides)

Advanced Planning & Integration Office

- Understand/model crew's individual sub-clinical impacts of space adaptation on deceleration load performance
  - Counter long-duration cardiovascular, musculoskeletal and performance de-conditioning
  - Fatigue / stress / spacecraft environment
  - <u>Perceptual disorientation at g-transitions</u>
  - <u>Sensori-motor errors at g-transitions</u>
- Human AEDL&A role enhancement (after 9 months zero g)
  - Optimized interfaces, displays & controls for use in both zero-g and various deceleration g-levels
  - Training to compensate for any disorientation at g-transition
  - Operations development
    - Distributed control, decision making, & risk management protocols
    - Procedures, checklists, cue cards, emergency procedures
  - Lunar performance evaluation by crews exposed to long duration ISS flight

1.5 Mars Surface Rendezvous - Can be Evaluated by Lunar Missions

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- Pre-deployed assets with auto- or tele-operated rovers for Mars surface rendezvous
  - Include extended stay habitat, consumables and propellant production demonstration and/or production plant
- If “pin point” landing not achieved, assets can be used later
  - Rovers can be operated from Earth as sample and data collectors
- Rendezvous with second landing (two lander scenario)

1.7 In-flight Training And Mission Simulation Needs - 2024 / 2028

Advanced Planning & Integration Office

- Emergency responses
- Mars orbit insertion
- AEDLA
- Surface activities / emergencies
- Nominal and off-nominal ascent
- Earth return

1.7.1 AEDL&A* Training And Simulations

Advanced Planning & Integration Office

- Final AEDL&A training and simulations in transit and Mars orbit will be self-contained
  - Spacecraft are trainers and simulators
  - Earth uploads, evaluation and recommendations

- Ascent training and simulations will be between surface and orbital spacecraft
  - Earth uploads, evaluation and recommendations

1.11 Crosscutting Capabilities - (See Backup Slide)

Advanced Planning & Integration Office

CAPABILITY

- 1.1 ROLE OF CREW IN EDL
- 1.2 CREW AND AUTOMATED SYSTEMS INTERACTIONS
- 1.3 MISSION CONTROL FUNCTIONS
- 1.4 PHYSIOLOGICAL / G LOAD PERFORMANCE ISSUES
- 1.5 MARS SURFACE RENDEZVOUS
- 1.6 IN-FLIGHT TRAINING & SIMS
- 1.7 MISSION RULES
- 1.8 LANDING VEHICLE HABITAT
- 1.9. POST-LANDING BIO/CHEM TESTING
- 1.10 PRECURSORS & PRE-DEPLOYED ASSETS FOR EDL

CROSSCUT

- 1.1 EARTH-MARS TRANSIT COUNTER-MEASURES
- 1.2 MISSION ARCHITECTURE DESIGN / GN&C DEVELOPMENT
- 1.3 DITTO FOR 1.2
- 1.4 SAS RESEARCH
- 1.5 MISSION ARCHITECTURE DESIGN
- 1.6 DITTO FOR 1.2
- 1.7 DITTO FOR 1.2
- 1.8 MISSION ARCHITECTURE DESIGN
- 1.9 PRECURSOR RESULTS
- 1.10 ATMOSPHERIC MODELING AND FORECASTING

RED: ISS / SHUTTLE / CEV VALIDATION

GREEN: LUNAR VALIDATION

1.12 Summary Of Major Drivers

- <u>Main Driver: Maximize for mission success</u>
  - Maximizes mission safety
  - Leads to use of human planetary landing systems
  - Leads to having two landers
    - Gives mission redundancy
    - Reduces lander mass
    - Enables orbital mission control
      - **Highly elliptical, operationally phased or site-synchronous mars orbit**
      - **Operational flexibility and alternatives**
      - **Improved deceleration load performance by crew**
      - **Improved second exploration mission**
      - **Overall crew physiology and psychology**
      - **Solar flare prediction**
    - Increases mission return
  - Leads to pre-deployed nav and comm networks

1.12 Summary Of Major Drivers

- Main Driver: Maximize for mission success
  - Leads to landers having ascent stages
  - Leads to “abort to land” bias in mission rules
    - Requires system and GN&C redundancy and backup options
  - Leads to minimum lander mass
    - Two landers
    - EDL deceleration trades
    - Mars surface rendezvous for extended stay
      - **Requires “Pin-point (tbd)” landing**
  - Requires In-flight training and simulation
    - Spacecraft also are trainers and simulators
    - Primary function of Earth-based personnel is mission support
  - Requires analysis of and compensation for deceleration load performance

Back-Up Slides

Missing from Our Space Flight Heritage

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- Stream-lined management system
  - "Tough, competent and disciplined" management required for deep space missions
- Steady flow of young engineers and technicians
  - Mobilized academic community and revitalize elementary and secondary education
- Adequate industrial base
  - Mobilize and sustain necessary industrial base, particularly sub-contractor base and entrepreneurs
- Necessary test and validation facilities
  - Create applicable research and technology base (NACA)

1.2 Crew And Automated Systems Interactions Defined - Can be tested on Lunar missions

Advanced Planning & Integration Office

- Robotic definition of operational environment
- EDL and ascent interaction
  - Automated systems provide performance efficiency depending on situation & workload
  - Humans provide real-time monitoring, intuition and evaluation of systems performance
    - Provides expertise and judgment to handle unforeseen events
    - Manual reconfiguration or back-up of automated operations (override per NASA HRRSS NPR 8705.24)
  - Definition of levels of automation and back-up automation (NASA MSIS STD-3000)
- Integration and standardization of systems, procedures and crew centered displays between mission phases
- Post-landing, surface rendezvous interaction
  - Human tele-operation of rovers for rendezvous with pre-positioned assets

1.3.4 Surface Exploration Consultation - Can be tested on Lunar missions

- Orbiting mission control can provide support to surface crew
  - Near-real time EVA planning and systems and physiological monitoring
  - Near-real time data synthesis and archived data retrieval
  - "Mapping" support
- Training and preparation for second exploration mission

1.3.4 Major Mission Control Functions - Earth

- System, physiological and trajectory trends monitoring, evaluation and modification
- Outbound science planning, analysis and integration in to mission plan
- EDLSA training and simulation planning, upload and evaluation
- Mission planning recommendations and updates
- Mars data analysis, synthesis and integration into exploration planning
- Data analysis, synthesis and integration into sample analysis during return
- REL* training and simulation planning, upload and evaluation

***REL: Return, Earth Entry And Landing**

1.4.5 NASA Requirements And Standards

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- HUMAN-RATING REQUIREMENTS FOR SPACE SYSTEMS (NPR 8705.2A)
  - Defines requirements required for human-rating certification for all space systems involving humans to insure human safety and health
- MAN-SYSTEMS INTEGRATION STANDARDS (NASA-STD-3000)
  - A single, comprehensive document defining all generic requirements for space facilities and related equipment which directly interface with crewmembers.
  - Provides specific user information to ensure proper integration of human-system interface requirements with those of other aerospace disciplines.

1.6 Landing Vehicle / Habitat Definition
2015 / 2024

Advanced Planning & Integration Office

- Definition of structure and EDLSA and ECS systems
- Necessary stay-time before rendezvous with assets for extended stay
- Zenith radiation protection
- Hazard and risk assessment analytical capability (if required)
- Tele-robotic operation of pre-deployed rovers by landed crew
- Habitat / ascent systems / pressure suit repair capability
- Ascent simulation capability

1.6.1 Mission Training And Simulation Schedule

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- Mars orbit insertion
  - ~Once every two weeks outbound, increasing to every other day two weeks prior to to MOI
- Entry, descent and landing
  - ~ Twice per week outbound, increasing to every other day two weeks prior to EDL
- Surface and ascent
  - ~Once per week outbound and on surface, increasing to every other day for a two weeks prior to ascent
- TEI and Earth Return
  - ~Once per month outbound, in Mars orbit, and in bound, increasing to every day for two weeks prior to Earth return
- Earth orbit entry or entry and landing
  - ~Twice per month outbound, twice per week inbound to earth, increasing to every other day for EOE or EL two weeks prior to EOE or EL

1.8 Major Mission Rules For AEDLSA Operations - 2024 / 2028

Advanced Planning & Integration Office

- Mission success enhances mission safety
- Transit, aero-capture and orbital mission command rests with mission commander
- EDLSA mission command rests with orbital mission control director (Kraft precedent)
- EDLSA spacecraft command rests with lander commander (Apollo precedent)
- EDL&A design and operations will be biased toward “abort to land”
  - Ascent option post-landing available for “x” days
- Exploration decisions rest with exploration director (~Apollo 17 LMP and Shuttle MS precedents)
  - Subject to override by spacecraft commander
- Surface hazards/risks evaluation joint responsibility of lander commander and Earth-based mission director

1.9 Chemical And Biological Testing Requirements 2024

- Precursor information may make this a non-issue
- Tele-operated soil and atmosphere sampling system (lander and/or rover robotic arm)
- Exterior, tele-operated testing system
- If hazard exists, protective cover suits may be required
  - Also, air / dust lock for decontamination

1.10 Pre-positioned Assets For EDL Trajectory Control, Terrain-relative Navigation And Site Selection 2024 / 2028

- Mars positioning satellite network or phasing method
- "VOR-DME" beacon on pre-deployed surface assets
- Accurate modeling of descent atmospheric parameters & EDL trajectory (optimum mass & minimum mission risk)
- Accurate knowledge of any significant mass anomalies near descent and ascent trajectories

1.11.1 Cross-cutting Sub-capabilities

		Mission Driver / Capability									
		Role of Crew in EDL	Crew and Automated Systems Interactions	Mission Control	Training	Rules	Pre-positioned Assets	Physiological / Mental Performance	Surface Habitat	Planetary Hazards	Surface Rendezvous
Sub-Capabiliites	Override	P	S	P/S	P	P					
	Re-Des / Haz avoidance	P	S	P/S	P	P	S				P
	Abort Decision	P	S	P	P	P					P
	System Re-config	P	P	P/S	P	S					
	Standard Display, Procedures	P	P	P	P			P			
	Tele-operation	P	S	S	P				P		P
	Solar Particle / Radiation	P		P			S		P	P	
	Embedded Systems	P	P	S	P				P		
	Mars Positioning Sat			S			P				S
	Rel Nav			S			P				P
	Envionment / Planet knowledge						P			P	P
	Counter-Measure	P		P	P			P			
	SAS knowledge	P		S	P			P			
	Crew Performance Knowledge	P		S	P			P			
	EVA Suits	P								P	
	Pin-point Landing	S		S	P		P				P
	P=Primary										
	S=Secondary										

Advanced Planning & Integration Office

7.3 Communications & Navigation

Presenter:

Rob Manning

May 04, 2005

7.3 Communications & Navigation

- **In this Capability Road Map (CRM) #7, Communications & Navigation is being considered during Aerocapture, Entry, Descent & Landing (AEDL) only in order to precisely position, track and interact with the spacecraft at its destination (moon, Mars & Earth return) arrival.**

Benefits of Comm. & Nav.

The space communication and navigation capability will fully enable AEDL.

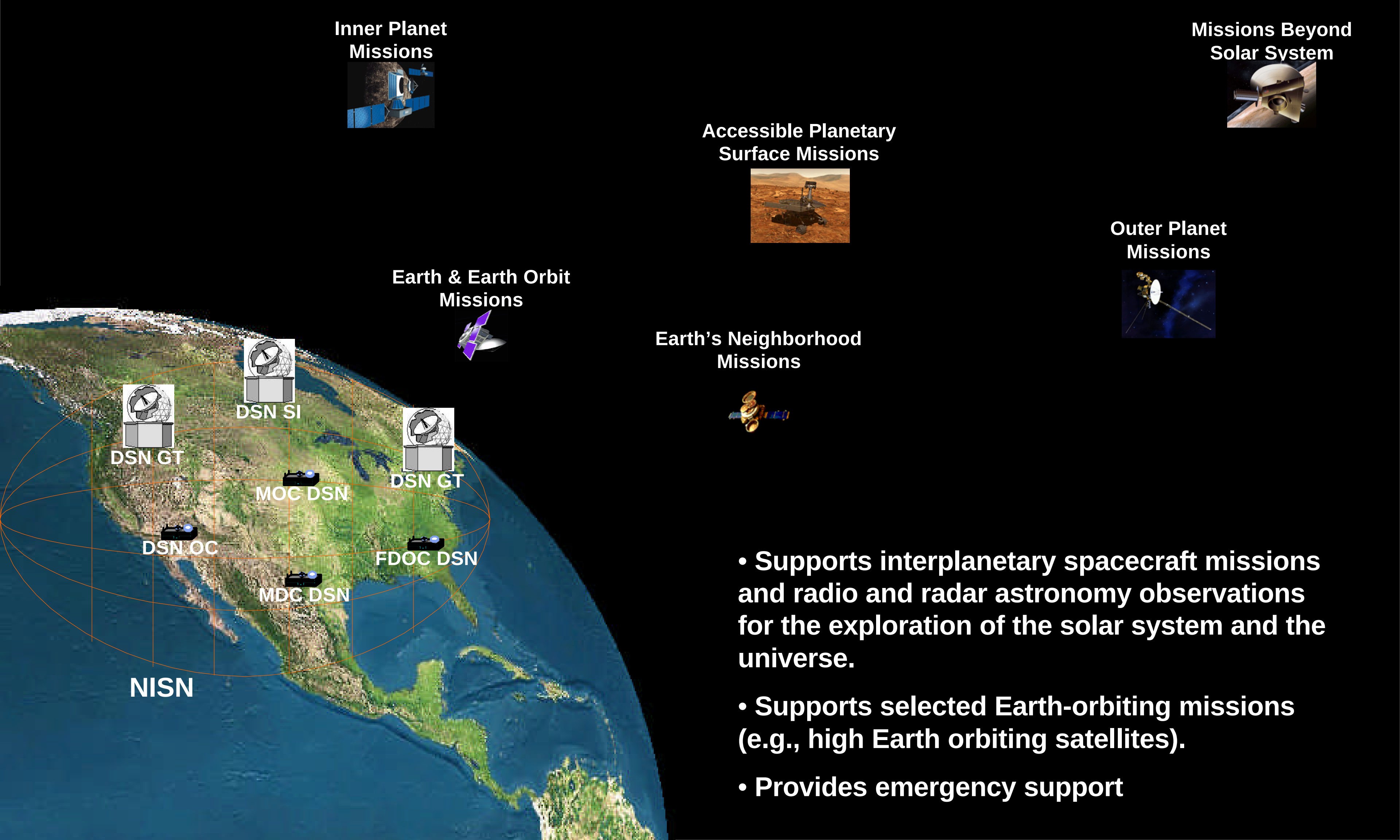
- connectivity to exploration vehicles
- spacecraft position
- transferring mission data
- vehicle telemetry
- voice and commands

Current State of the Art

- **Today NASA Operates Three Communication Networks**
  - **Space Network (SN): A system of Earth relay satellites covering low Earth orbit**
  - **Deep Space Network (DSN): Three global installations with large aperture antennas for communicating with missions operating in Deep Space**
  - **Ground Network (GN): A network of Earth-based ground communications stations primarily used for communicating with satellites in Earth orbit**
- **SN, DSN, and GN have evolved to support NASA's Current Science and Human Space Flight Mission Model**
- **The Future Exploration and Science Mission Set will Require New Communication Capabilities**

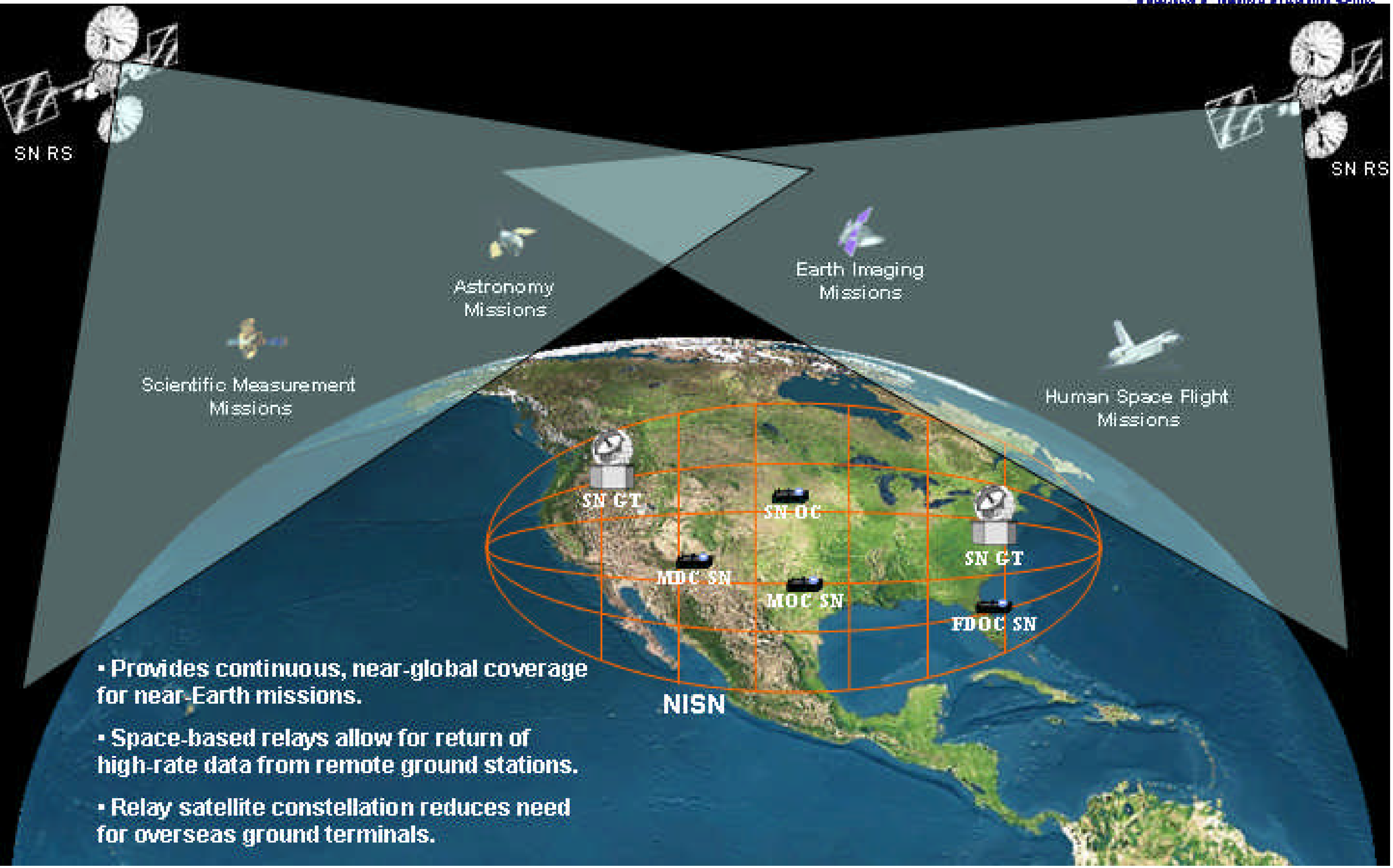
Deep Space Network Today

Advanced Planning & Integration Office



- Supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe.
- Supports selected Earth-orbiting missions (e.g., high Earth orbiting satellites).
- Provides emergency support

Space Network Today

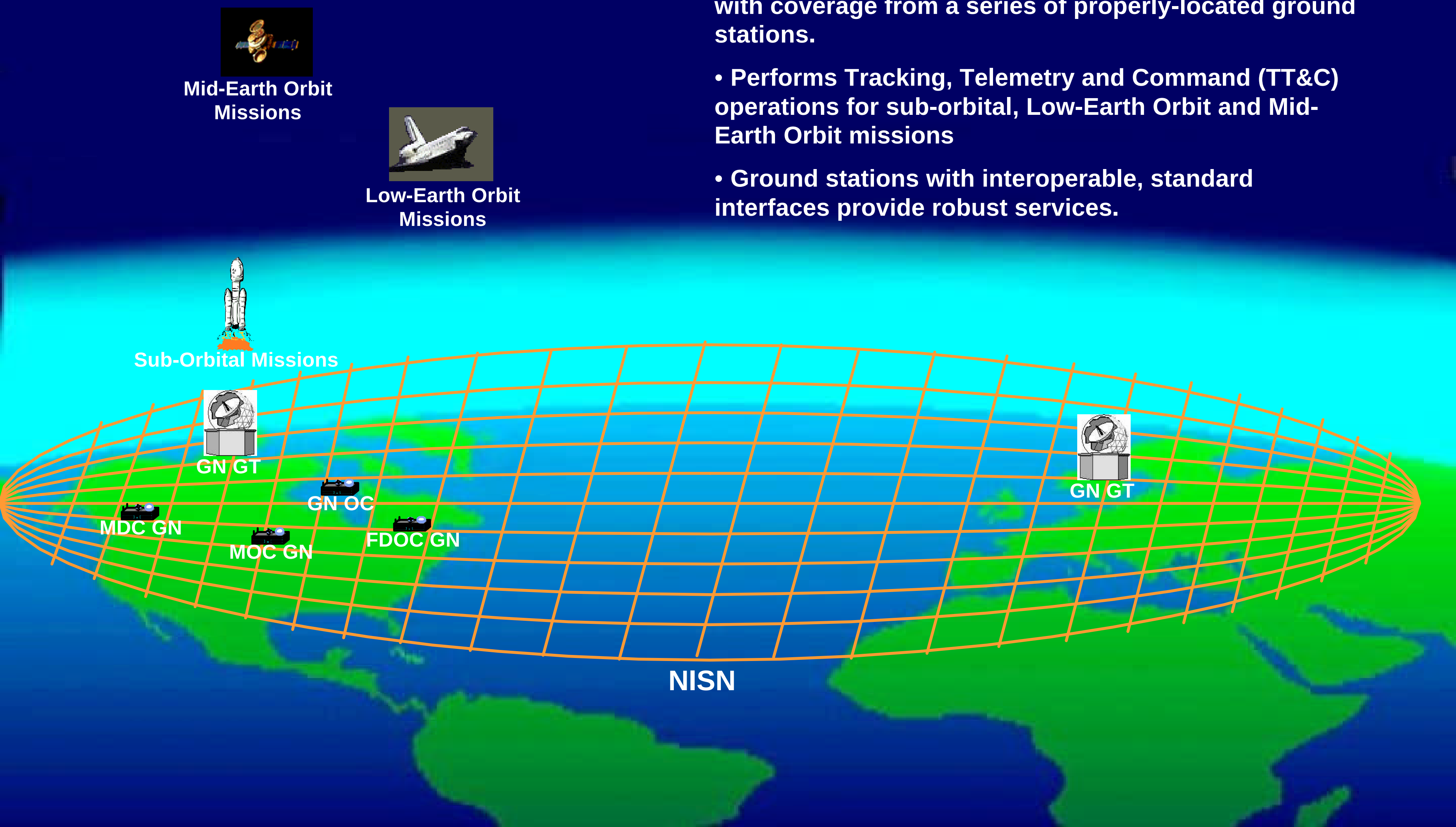


- Provides continuous, near-global coverage for near-Earth missions.
- Space-based relays allow for return of high-rate data from remote ground stations.
- Relay satellite constellation reduces need for overseas ground terminals.

Ground Network Today

Advanced Planning & Integration Office

- Supports Launch and Early Orbit (L&EO) operations with coverage from a series of properly-located ground stations.
- Performs Tracking, Telemetry and Command (TT&C) operations for sub-orbital, Low-Earth Orbit and Mid-Earth Orbit missions
- Ground stations with interoperable, standard interfaces provide robust services.



Current State-of-the-Art for Communication Capability

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- <u>Current Earth-based Network:</u>
  - Communication and tracking services are available for Earth orbiting satellites in any orbit.
    - Up to 300 Mbps in Ku-band for low Earth orbiters
    - Support for TT&C services in any Earth orbit in S-band
    - Ground-based antennas provide communication with satellites in S-, X-, and Ka-bands
  - Communication support is available for launch phase of space flight as well as for communication support for re-entry and landing of vehicles.
    - Example: Space Network currently provides telemetry support to launch vehicles such as Sea-launch during powered flight
    - Example: Space Network provides communication support with Space Shuttle during re-entry including communication through plasma period.
  - Communication support for deep space missions including connections with Mars network orbiting relays and surface robots.

Current State-of-the-Art for AEDL Communication Capability

Advanced Planning & Integration Office

- **Current Lunar network:**
  - Earth-based DSN antennas can currently provide S-band and X-band coverage of the near side of the moon.
  - No capability is in place that allows communication to the back side of the moon

- **Current Mars Network:**
  - EDL communication via direct-to-Earth long haul X (or Ka) Band to the Deep Space Network.
    - < 0.5 bps during EDL plus signal carrier dynamics
  - EDL UHF communication via relay services to one or more of the three Mars orbiters:
    - NASA Relay orbiters: Odyssey, Mars Global Surveyor
    - ESA Relay orbiter: Mars Express
    - 8 k bps during EDL but no data during plasma outage.
  - International use is enabled by common frequency / communication protocols.
  - The orbiters forward for proximity communications with AEDL assets via long haul X-band data relay back to Earth.

Existing Communication Capability Not Adequate for Future Exploration Program

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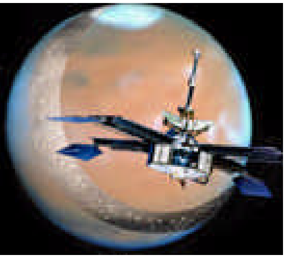
- Moon:
  - No lunar backside capability
  - Limited lunar pole coverage
- Mars:
  - Limited Mars comm data rates and numbers of connections
  - Limited surface coverage
- Possible to include international spacecraft via common (CCSDS) standards for spectrum, protocol, network for Moon & Mars
- Limited precision lunar and Mars navigation capability
- Space-based range capability does not meet rigor required by DoD/NASA concept
- Existing Earth-based relay (TDRSS) will suffer attrition over next few years if not replenished
- Large aperture DSN antennas (26m, 70m, 34m) aging & must be maintained / replaced over next few years

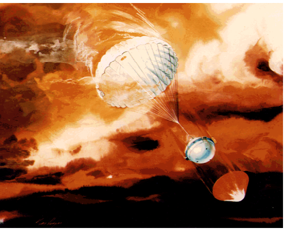
Why is Change Needed?

Integration Office

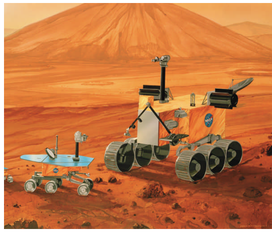
- MRO will obtain high resolution images of only about 1% of Mars surface
  - This data rate limitation unnecessarily constrains the ability to understand the planet
- Future missions desire to do similar remote sensing as now done for the Earth



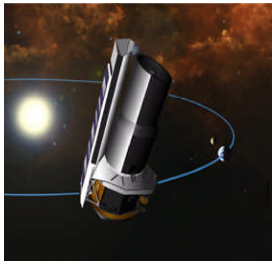
Preliminary solar system reconnaissance via brief flybys. → Detailed Orbital Remote Sensing. (e.g., MRO, JIMO)

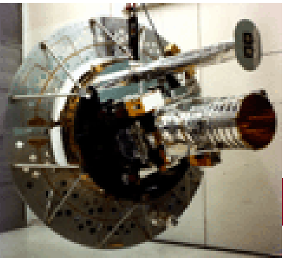


In situ exploration via short-lived probes. → *In situ* exploration via long-lived mobile elements. (e.g., MER, MSL)

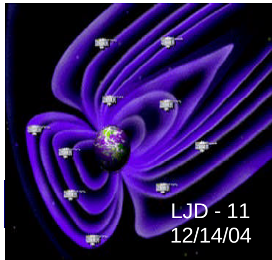


Low-Earth-orbit solar and astrophysical observatories. → Observatories located farther from Earth. (e.g., SIRTF, JWST)

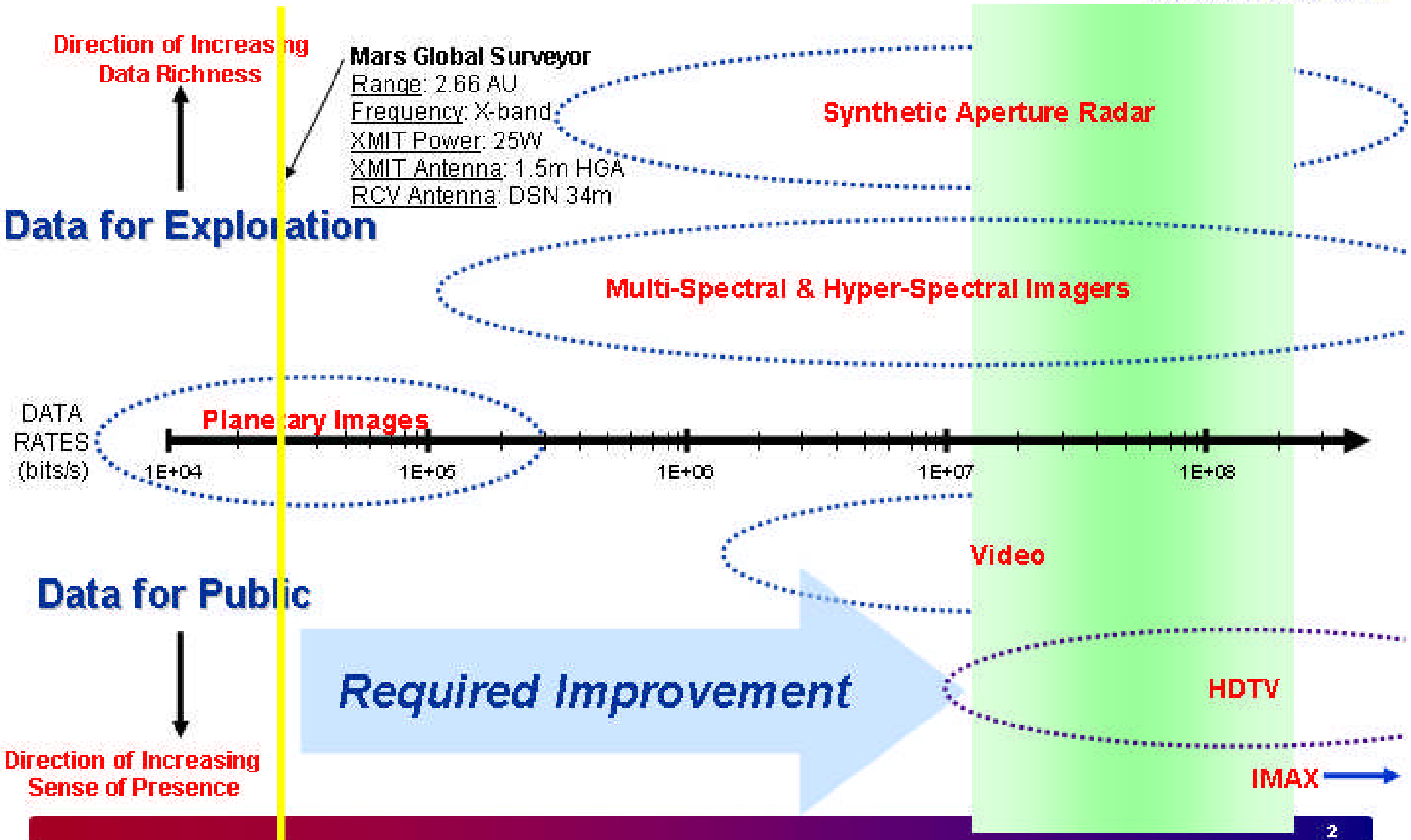




Single, large spacecraft for solar and astrophysical observations. → Constellations of small, low-cost spacecraft. (e.g., MMS, MagCon)



Doing Similar Remote Sensing at Other Planets as We do Today at Earth



A Combined Optical/RF Strategy for the Future of Deep Space Communications

Advanced Planning & Integration Office

The Challenge: Capabilities are needed in deep space communication that will accommodate orders-of-magnitude increase in science data and at least a doubling of the number of supported spacecraft over the next 30 years

- The present DSN architecture is not extensible to meet future needs in a reliable and cost-effective manner
- NASA must develop a comprehensive strategy for deep space communications that meets the forthcoming dramatic increase in mission needs in a reliable and cost effective manner
  - Optical communication, which will take at least another decade to mature and two to be operational, has development risk and may not be appropriate for all missions or mission phases
  - Radio communication will remain the backbone of deep space communications at least the next two decades

The Current DSN Will Not Meet Future Needs

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- Even the largest DSN antennas (70m) do not come close to meeting the needs of NASA's future mission set
- Maintenance of the 40-year-old 70m antennas is very expensive (continual software/hardware patches; parts difficult to obtain)
  - NRAO shut down its 25-year-old 43m telescope due to high O&M costs
- A solution is needed soon since old antennas can be prone to catastrophic failure (i.e, metal fatigue)
  - When the large DSN antennas were built, they were 64m in diameter and had a 30% duty cycle
  - After Voyager passed Saturn, the 64m were remade into 70m: added 1M pounds/70m antenna and now have an 80% duty cycle.

NRAO's 30-year old 90m Antenna in its Ultimately Relaxed State:
Higher duty cycle → Metal fatigue

Assumed Requirements (cont'd)

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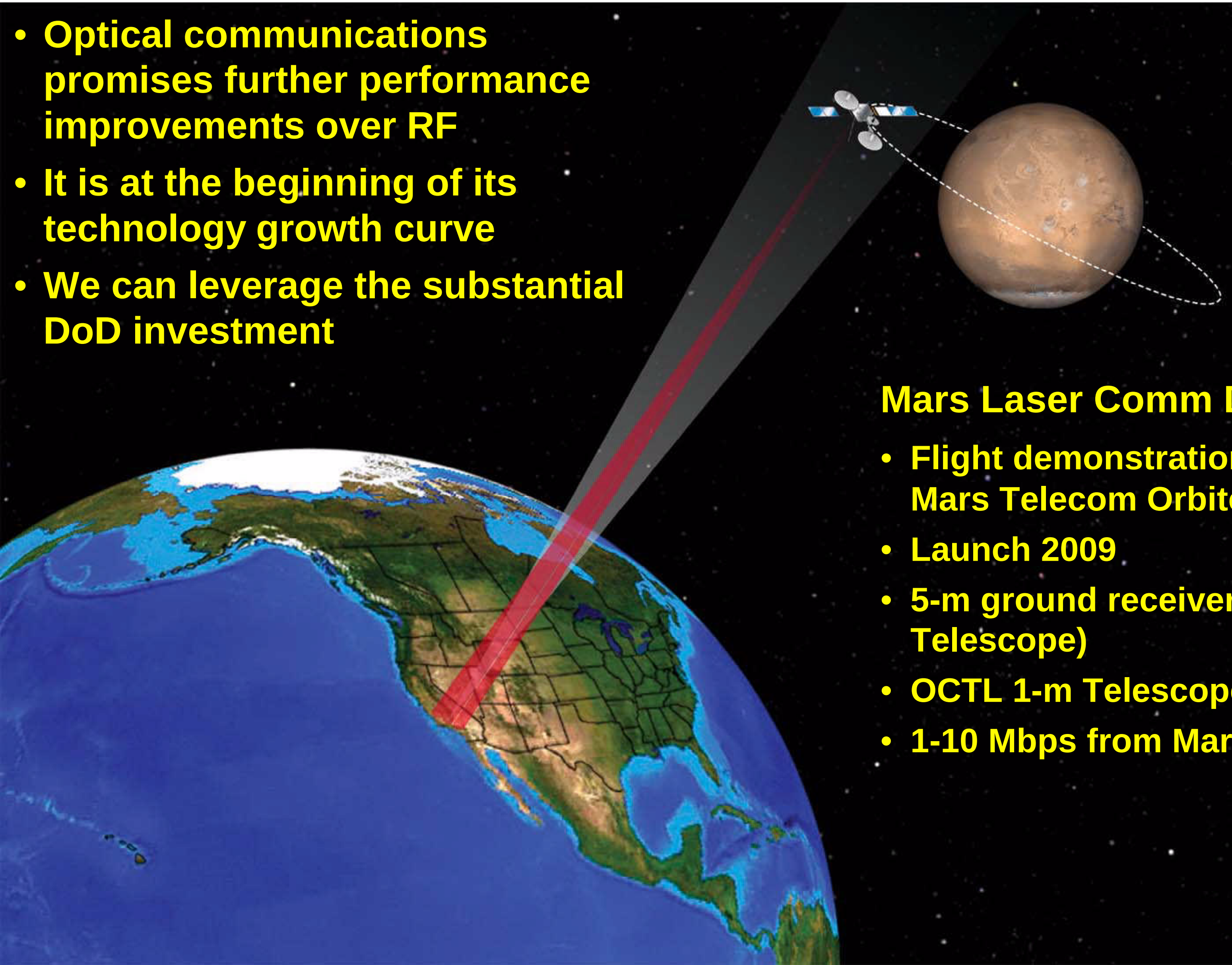
- Human missions to the Moon
  - Continuous communication capability for vehicles and crew
  - Communications for critical flight events over the backside of the Moon
  - Human surface operations on the back side of the Moon South Pole region requiring voice and data transport services between elements as well as to and from Earth
- Human missions to Mars
  - Continuous connectivity supporting Human missions
  - Communication supporting operations on the Martian surface including communication between units on the surface and connections to and from Earth
  - Connectivity to vehicles during critical events
  - Connectivity to vehicles and probes on the Martian surface
  - High data rate instruments operating on the Martian surface and in orbit around Mars

Assumed Data Rate Scenario

- Data rates are major drivers
- Must be developed from assumed activities at destinations
- Developed set of characteristic data rates for typical data types (i.e. HDTV, Hyper-spectral imaging, Audio, etc)
- Apply data rates to activities
- Provides threshold data rates

Optical Communications

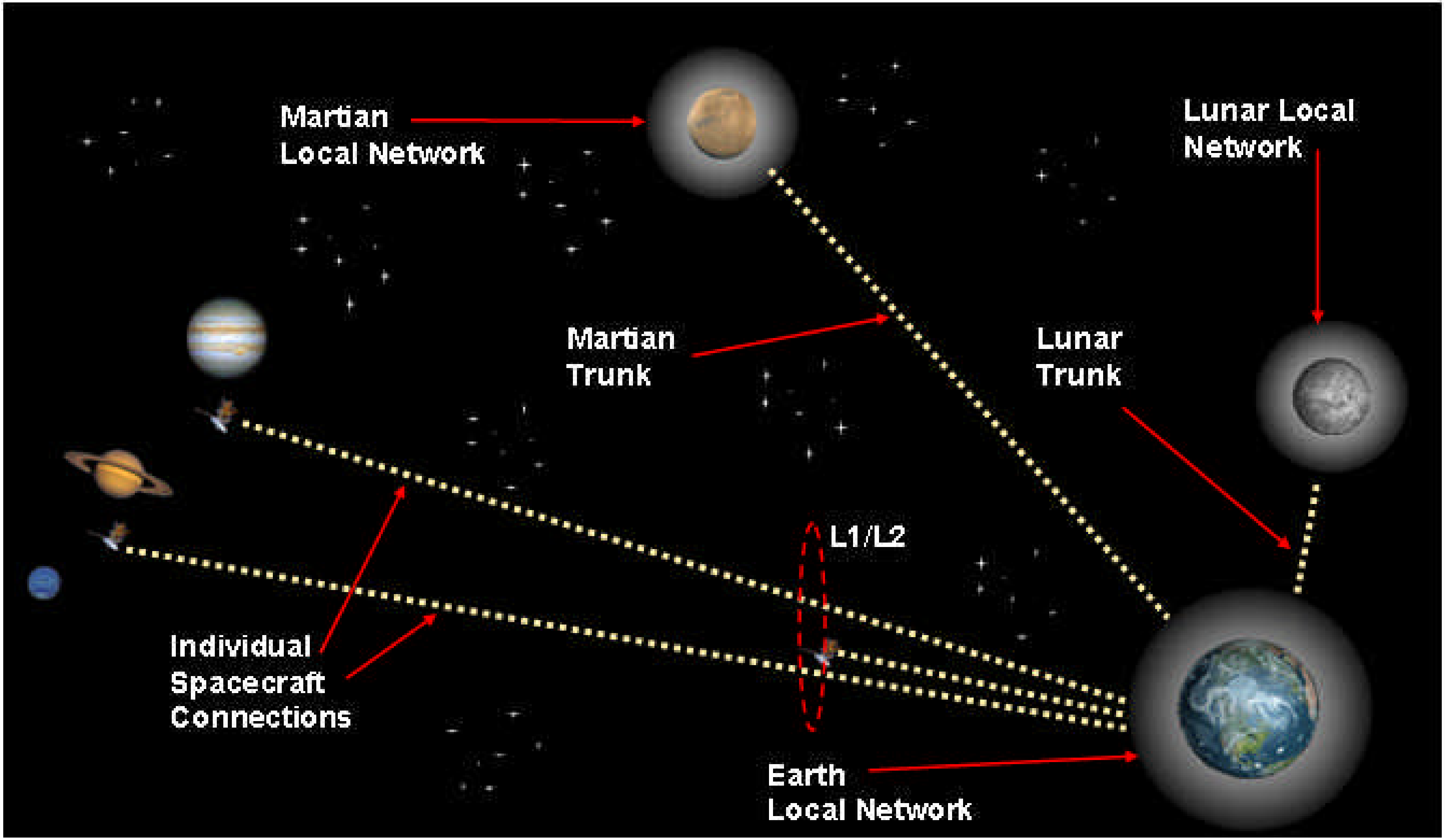
- Optical communications promises further performance improvements over RF
- It is at the beginning of its technology growth curve
- We can leverage the substantial DoD investment



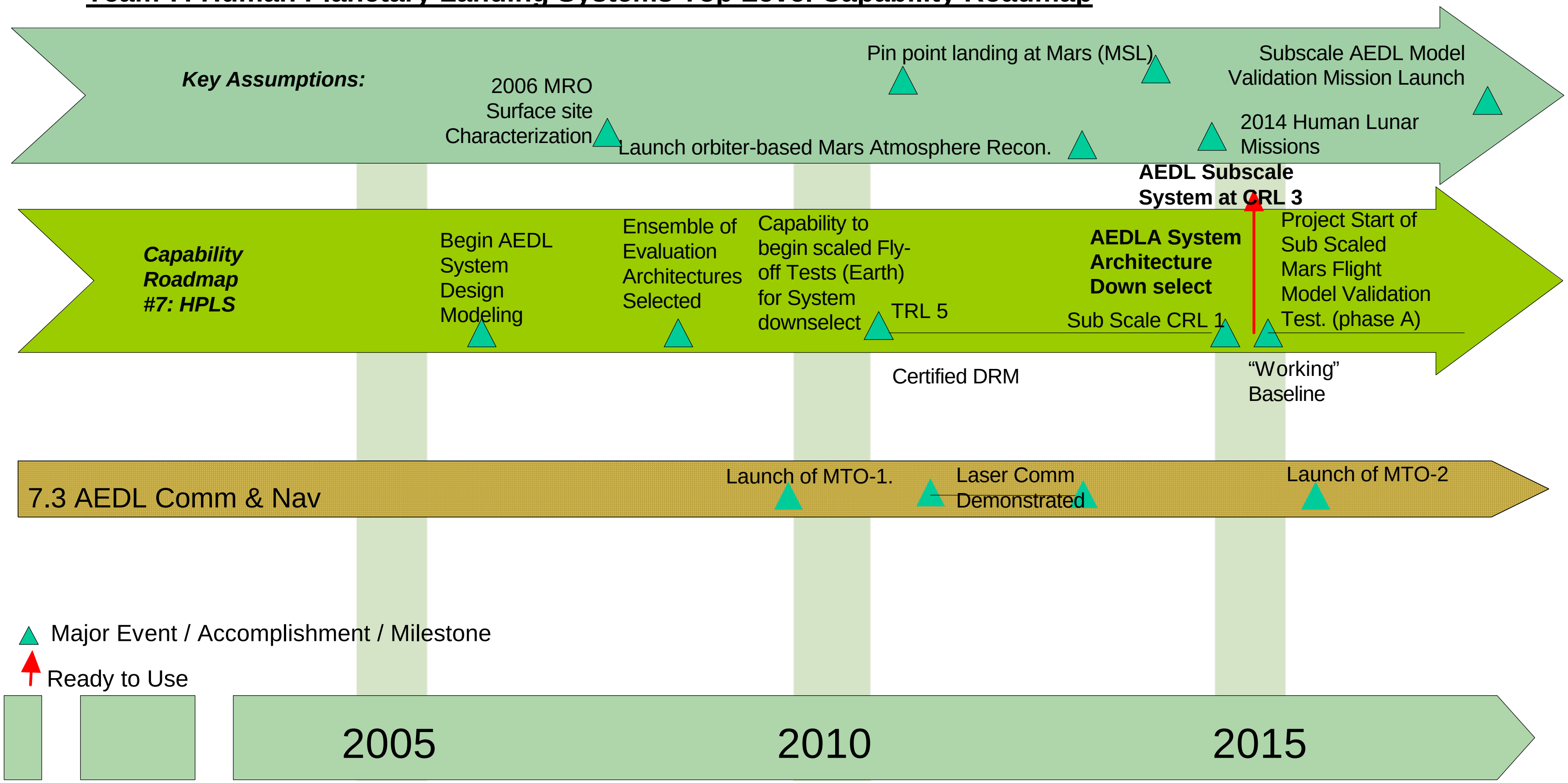
Mars Laser Comm Demo (MLCD)

- Flight demonstration terminal on Mars Telecom Orbiter (MTO)
- Launch 2009
- 5-m ground receiver (Palomar Telescope)
- OCTL 1-m Telescope for uplink
- 1-10 Mbps from Mars

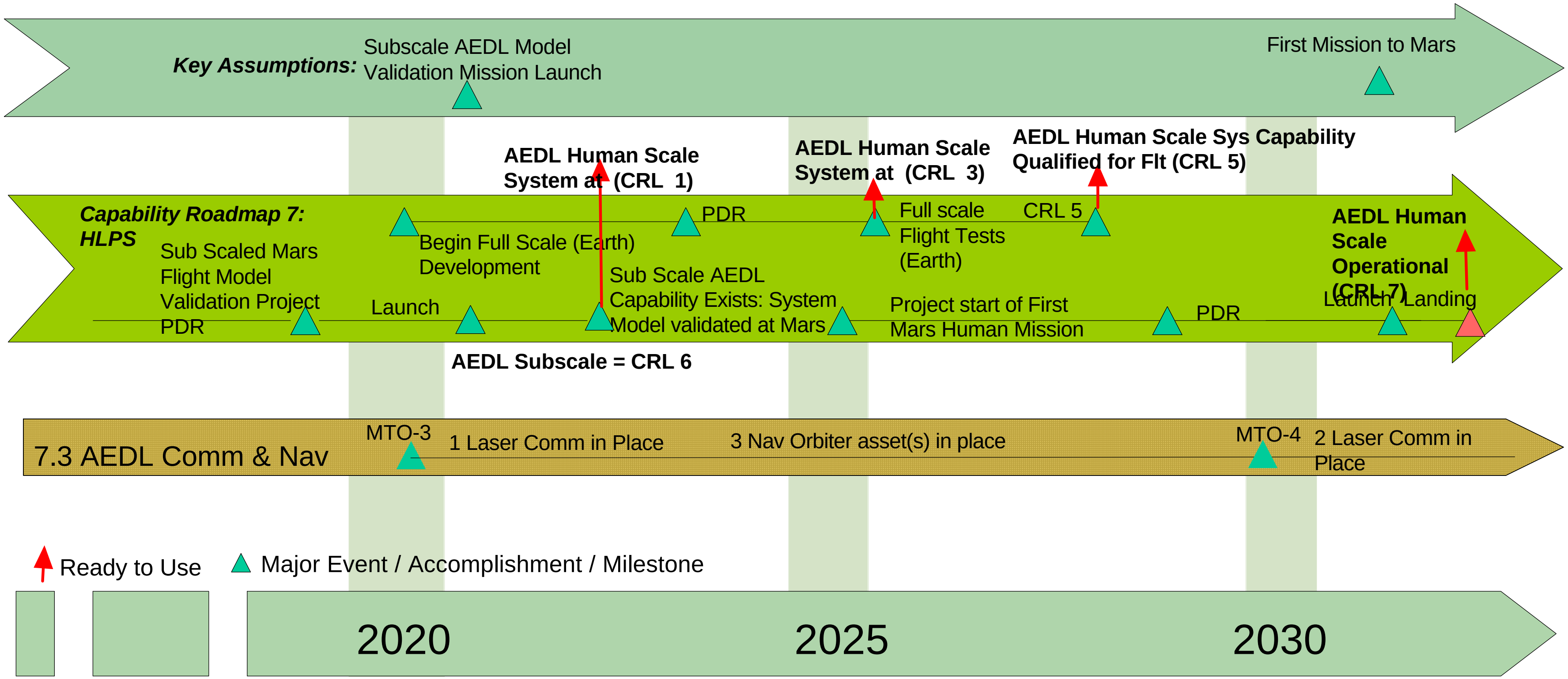
Top Level Communication Architecture ~2030



Team 7: Human Planetary Landing Systems Top Level Capability Roadmap

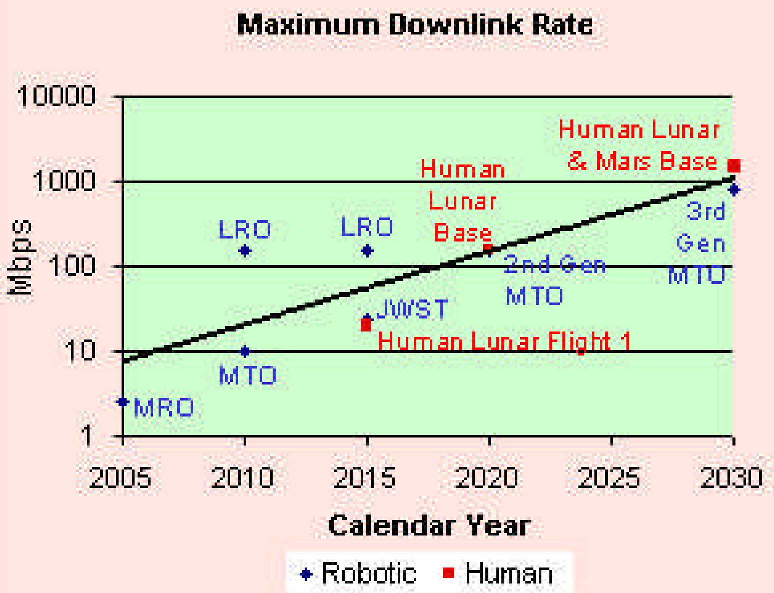


Team 7: Human Planetary Landing Systems Top Level Capability Roadmap



Data Readiness

Data Throughput



- Mars robotic and lunar human missions drive maximum data rates up by almost 3 orders of magnitude over next 25 years – probably an underestimate.

Some Key Technology Areas

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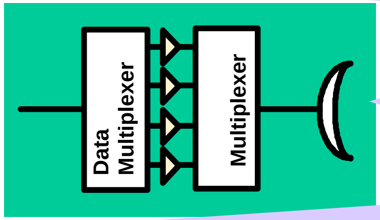

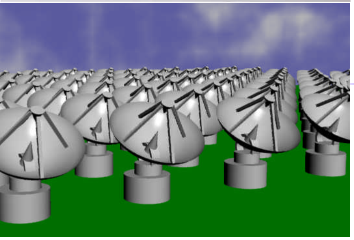

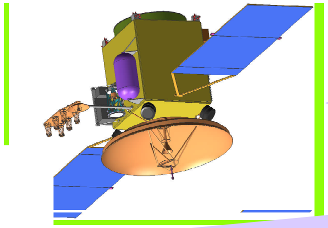

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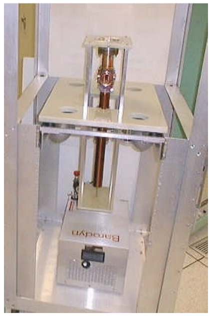

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

- Ka-band communications
  - 4x performance gain and increased bandwidth
- High power spacecraft comm
  - Take advantage of Project Promethius
- Large arrays of small antennas
  - Earth infrastructure of the future
- Optical communications
  - New infrastructure for high bandwidth
- Error-correcting codes
  - Protect data sent through deep space
- Data compression
  - Use links efficiently
- Ultra-stable clocks (including spaceborne)
  - Perform precision navigation
- Communications standards
  - Guarantee quality & interagency cross-support

Figures of Merit

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FOM	Description
Visibility	Assets must have at least 1 visible relay back to Earth at all times (human missions). 10-degree minimum elevation angle
Orbit Stability	Measure of effort to maintain relay orbits: Delta-V for 5-yr period
Failure Tolerance	Percent visibility with 1 relay lost → % of data volume with 1 loss
Navigation Utility	Accuracy measured by Geometric Dilution of Precision; impact of spatial distribution of navigation data source errors
Mission Evolvability	Ability to modify assets by inserting technology * modifying design to meet changing exploration / science goals. Five criteria: programmability, pre-planned product improvement, open architecture, planned technology insertion, planned utilization
Adaptability	Ability to change operations in response to circumstance/environment change. Two criteria: programmability, operational flexibility
Link Capacity	Combination of aggregate data rate, data volume and latency
Scalability	Ability to expand capacity beyond initial deployment. 8 criteria, as ability to: add relays, add transponders, add frequencies, reuse spectrum, increase efficiency, increase locations served, increase data rates, improve other growth features
Sustainability	Cost to replace relay(s) to maintain a constellation for 5 years
User Burden	Effort required by users to use comm services provided. User burden is standardized, so this FOM is used to penalize options that fail to meet the standard or to reward options that reduce user burden

Comm & Nav. Integration

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- **CRM #7 Human Planetary Landing Systems is working closely with CRM # 5 Telecommunications & Navigation**

- **CRM #7 is relying on work by others to provide Nav & Comm. Capability to AEDL**

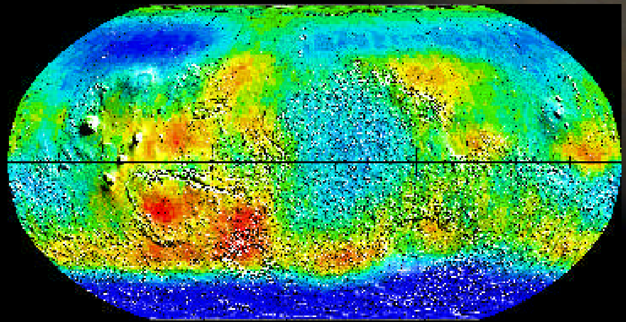
Charts Credits: Les Deutsch, Jet Propulsion Lab
Robert Spearing, Michael Regan & CRM #5 Comm. & Nav. Team Members

Aerocapture, Entry, Descent and Landing (AEDL) Human Planetary Landing Systems
Section 10, AEDL Analysis, Test and Validation Infrastructure

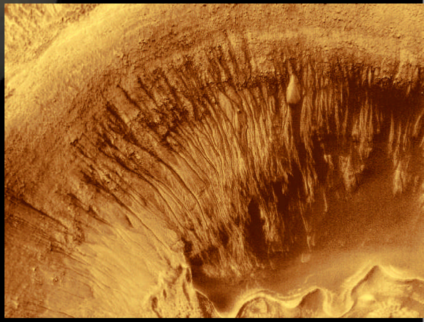
Presented by J. O. Arnold for the

APIO Human Planetary Landing System Study Team

Principal Contributors: J. Arnold, N. Cheatwood, D. Powell, A. Wolf, C. Guensey,
T. Rivellini, E. Venkatapathy, T. Beard, B. Beutter, B. Laub, J. Hartman, H. Goldstein
B. Wilcockson, M. Wright, P. R. Manning, R. Mueller, H. Schmitt and B. Hollis



May 4, 2005



Words of Wisdom

"Test as you fly, fly as you test[1]"

"Train as you fly, fly as you Train[2]"

"If you are not ready, do not fly[1]"

"Mars Exploration program strategy must account for a reasonable number of failures and be robust against their happening[1]"

"Programs have the responsibility to ensure that projects provide data/information for the health of future projects, e.g. flight instrumentation to understand failures and performance[1]"

[1] Tom Young/Mars Program Independent Assessment Team (MPIAT)

[2] Harrison Schmitt, Apollo Astronaut

"No ground facility can simultaneously duplicate the altitude, velocity and scale of human flight vehicles/systems[3]"

"You told the boss (1st president Bush) what it cost ($400 B) to do the human Mars mission and it cost you the program, plus there was no congressional support[4]"

"A sustained Mars Program must sustain public interest[4]"

"I wish I had come to the NASA Ames and Langley Research Centers earlier[5]"

"One strike, and you are out[1]"

[3] Dean R. Chapman/NASA Ames/Stanford

[4] Hans Mark

[5] Tony Spear, Mars Pathfinder Project Manager

Outline

- Listing of critical capabilities (knowledge, procedures, training, facilities) and metrics for validating that they are mission ready
- Examples of critical capabilities and validation metrics: ground test and simulations
- Flight testing to prove capabilities are mission ready
- Issues and recommendations

Capabilities

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Knowledge Facilities*	Metrics*** Model/codes	Ground
10.1 Systems Engineering 1-6	Physics based/cost	- Intercenter teams*,+ Industry + Academia
10.2 G,N & Control (flexibles) 1-5	Real time code	- Simulation
10.3 Aerodynamics 1-5	Aero databases;	- Wind tunnels: (Hyper/
10.3.1 Aeroelasticity for flexibles	Thermo-chemical noneq CFD codes; Coupled CFD/Finite Element Analysis	super/trans/sub sonic with (forced oscillation) - Ballistic range. Quiet tunnels - Low density tunnels**
10.3.2 Aero + Propulsion 1-5 (retro and reaction control system)	Real-Gas Aero + Propulsion CFD; Ground effects	- Wind tunnel with . combined propulsion

.

* Red colored text: critical issue under threat e.g., potential termination, demolition/ closure / mothballing

**Blue colored text: special issue or no capability

*** Metrics: 1. (code to code or model to model fly-offs), 2. (comparison to ground test) 3. pre/post flight test comparisons, 4. (bi-annual peer review) and 5. Proficiency of existing corps as established from flight test and NRC evaluation of education programs for the next generation of explorers, and 6. Capability to replicate previous "landmark" decisions

Capabilities (cont.)

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Knowledge Facilities* | Model/codes Metrics*** | Ground

10.4 Aerothermodynamics

Real-gas/non equ. - Wind tunnels 1-5
CFD: Coupled convective - Shock Tubes
and radiative heating: - Shock Tunnels
Ionized flow, transition - Ballistic range
to turbulence models; - Rarefied flow tunnels
turbulence models; - Quiet tunnels
afterbody heating;
rarefied flow/transitional
codes

10.5 Human Rated Thermal 1-5
Protection Systems (TPS)
Ablators,flexibles;multifunctional
(TPS+ space radiation
+micrometorite shields)

Materials specifications; - Arc Jets
flow/materials coupling - Combined (conv.
(convection/radiation/ +radiation +
unsteady); scalability (e.g unsteady flow)
gaps bonds; seals, e.g. - Materials labs
body flaps to fuselage;
manufacturability - TPS pilot plants with autoclaves
- Full scale TPS manufacture,
environments(shake, vac, bake, etc)
test capability

Capabilities (cont.)

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Knowledge Facilities* Metrics*** Model/codes Ground

10.6 Engineering Flight 1-5 Sensors

Press, Temp, heat (rad/convect); TPS recession sensors; accelerometers; gyros strain; flutter sensors, flush air data system

- Arc jets
- Wind Tunnels
- Instrument labs

10.7 Terminal descent/land 1-5
10.7.1 Propulsion w/toxics
10.7.2 Aerodynamic decelerators
10.7.3 Hazard avoidance
10.7.4 Touchdown

Engineering models based on physics-based codes and extensive tests for combined effects incl. dynamics with correct gravity effects, etc.; Real time hazard recog-, inition, terminal GN & C lidar and radar

- Large wind tunnel (NFAC)
- Large Prop. Test (White Sands)
- Large Cold Soak/start GRC (Plum Brook)/AEDC
- Helicopter / balloon air drop/ sounding rockets
- China Lake (Rocket sled
- Large Enviromental Test Facility facility (shake, bake, etc.)
- 7'X9' Aero/propulsion tunnel (ARC)

Capabilities (concluded)

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Knowledge Metrics***	Model/codes	Ground Facilities/data source	
10.8 Engineering Model of AEDL Planetary Environment 10.8.1 Atmospheric predictions (structure {Press, Temp.), turbulence, winds) and surface properties (dust, toxicity, strength, slopes, terrain, hazards)	Real time updatable models based on robotic missions: rock distribution models; 30 cm imagery; digitial elevation maps; mesoscale wind models; global circulation models; global dust transport models	- Simulators (ARC) - Mars atm. sim. lab - Odyssey (atm/rocks) - TBD future atm. orbiter.	1-5
10.8.2 Pico/nano satellites and probes to provide just-in-time update information	Pico/nano satellite and atmospheric probes to update models	- None additional for pico/nano sats./probes	
10.9 Astronaut AEDL performance at Mars g-profiles, etc. Human-machine-robotic interface	Human perf. engineering models based on extensive testing.	- China Lake Type rocket sled (with tailored g - profiles) - High performance aircraft - ARC Vertical Motion Simulator - ARC Bed rest facility - ARC Future Flight Central - ARC Vestibular Research Facility	1-5

Outline

- Listing of critical capabilities (knowledge, procedures, training, facilities) and metrics for validating that they are mission ready
- **Examples of critical capabilities and validation metrics: ground test and simulations**
- Flight testing to prove capabilities are mission ready
- Issues and recommendations

Wind Tunnels: Apollo era vs. 2005

Government (NASA and military)

Year	Transonic	Supersonic	Hypersonic
1965	24	31	40
2005	10	9	7

1965 Government: NASA, Arnold Engineering Development Center, Wright Aeronautical Laboratory, Naval Ordnance Laboratory, Sandia National Laboratories, Ballistic Research Laboratory, David Taylor Model Basin

2005 Government: NASA, Arnold Engineering Development Center, Sandia National Laboratories

Large subsonic tunnels ARC 40'x80' & 30'x60' at LaRC 1965 vs 40x80x120 (NFAC) 2005 (may be needed for parachute tests)

Commercial

Year	Transonic	Supersonic	Hypersonic
1965	10	15	14
2005	7	7	6

1965 Commercial: AVCO, Boeing Aircraft, Cornell Aeronautical Laboratory, Convair, Douglas Aircraft, Fluidyne, General Dynamics, Grumman Aircraft, Lockheed Aviation, Ling-Temco-Vought, McDonnell Aircraft, North American Aviation, Republic Aviation, United Aircraft

2005 Commercial: Aero-Systems Engineering, GASL, Boeing, Lockheed-Martin, Veridian-CUBRC

Quiet tunnels - new capability developed in the 1980/1990's

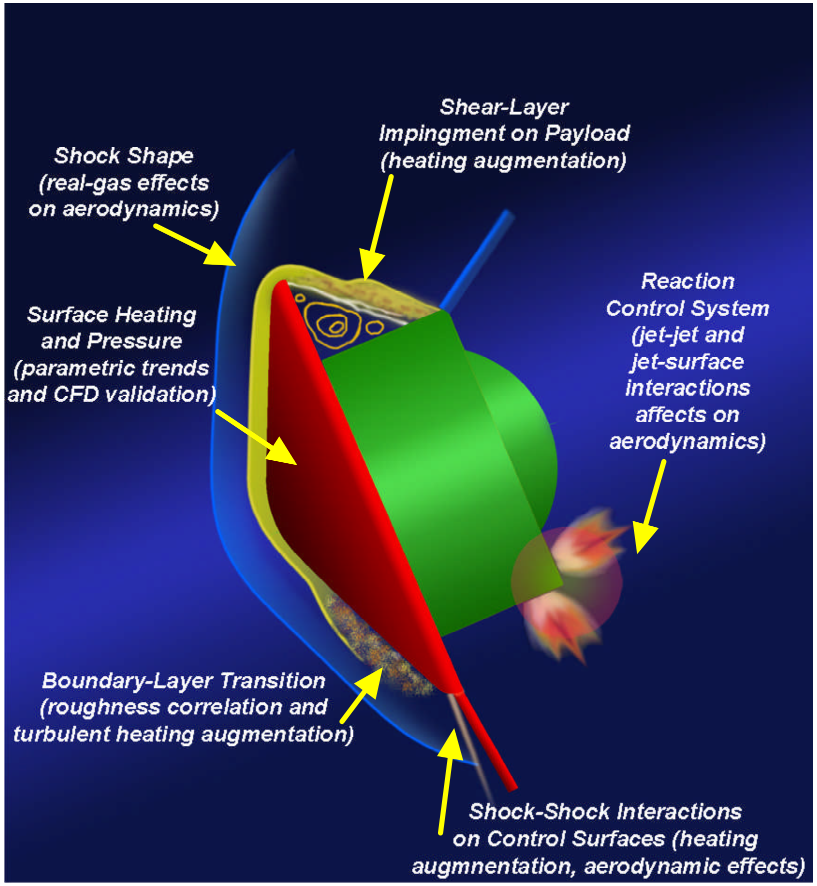
* Does not include propulsion, arc-jet, or ballistic range facilities

** source for 1965 data: High-Speed Wind Tunnel Testing, Alan Pope and Kennith Goin, Wiley & Sons, 1965

Hypersonic Aero/ Aerothermodynamics Wind Tunnel Testing

Advanced Planning & Integration Office

Aerodynamic and Aerothermodynamic phenomena produced in wind tunnel tests

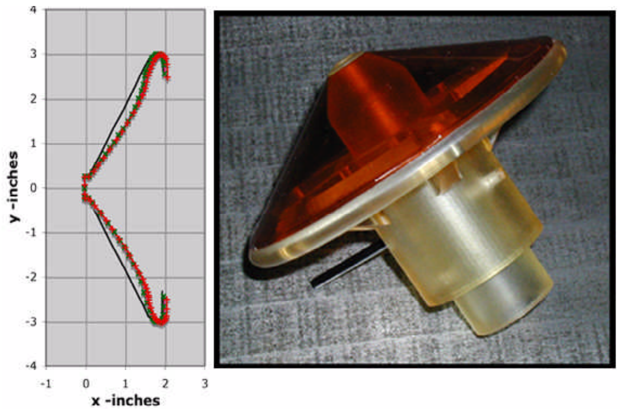


Results of Hypersonic Wind Tunnel Testing:

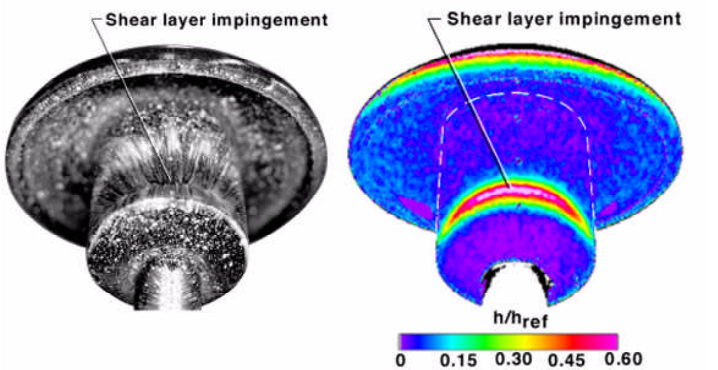
- Aerodynamic forces and moments
- Control surface effectiveness
- Surface pressure distributions
- Laminar and turbulent convective heating distributions
- Boundary-layer and shear-layer transition correlations
- Reaction control system (RCS) jet effectiveness and interactions
- Mach number, Reynolds number, shock-density ratio (real-gas simulation) effects
- Configuration parametric effects
- CFD validation/verification data

Recent Hypersonic W.T. tests

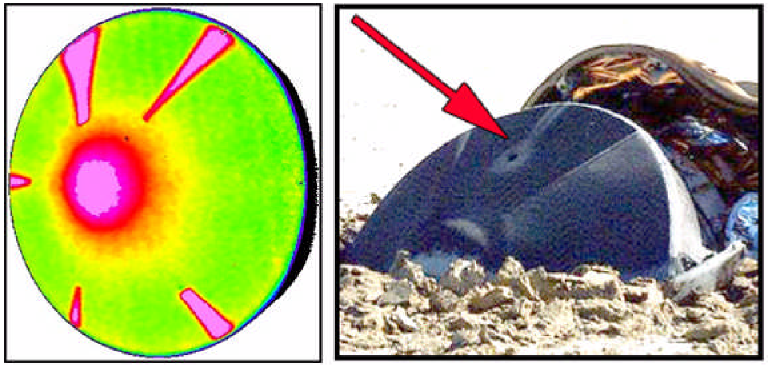
Attached ballute aeroelasticity



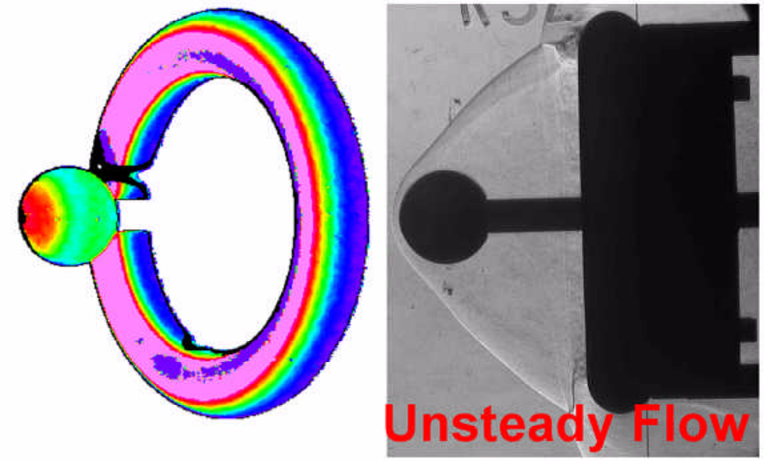
Wake shear layer payload impingement



Heat-shield cavity boundary-layer transition



Trailing ballute heating and flow-field

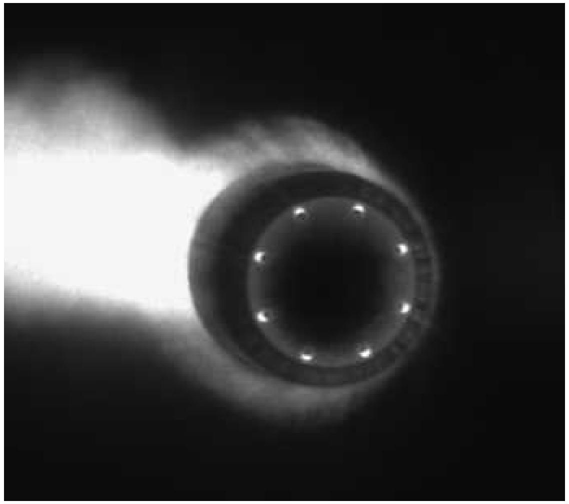


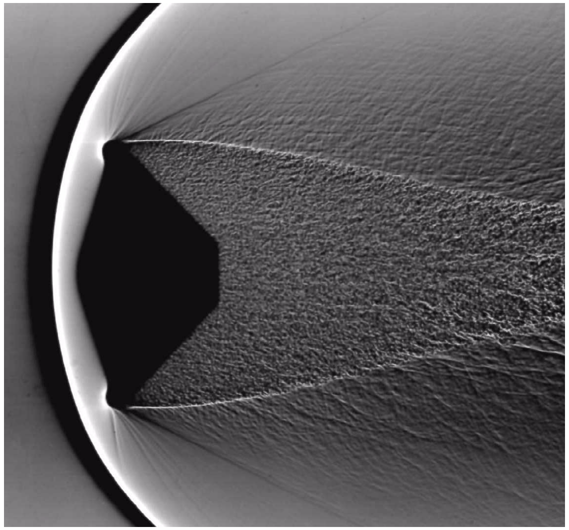
Real gas ballistic range testing

Ballistic Range: Any Test Gas

- Aerodynamic forces and moments in free flight, no sting effects and true real gas effects
- Afterbody flow simulations without sting effects
- Laminar and turbulent convective heating distributions
- Transition to turbulent flow in real gas, on real surfaces in a quiet environment
- Mach number, Reynolds number, shock-density ratio true real gas
- CFD validation/verification data

- **Disadvantage: Small scale models**





Aerodynamics: Example Metrics

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- Every US entry vehicle flown at Mars has used the basic Viking shape, but we do not fully understand its aerodynamic performance. Lack of understanding is disturbing.

  - Lack of adequate engineering flight data clouds this issue

- The Shuttle Orbiter pitching moment was mis-predicted despite thousands of hours of wind tunnel testing and early CFD. With today's CFD and wind tunnel testing can we predict aerodynamic performance for an new shape?

- Grand Aerodynamics Challenge: Choose a likely new shape (based on systems engineering) for a human rigid and flexible Mars aeroshells.

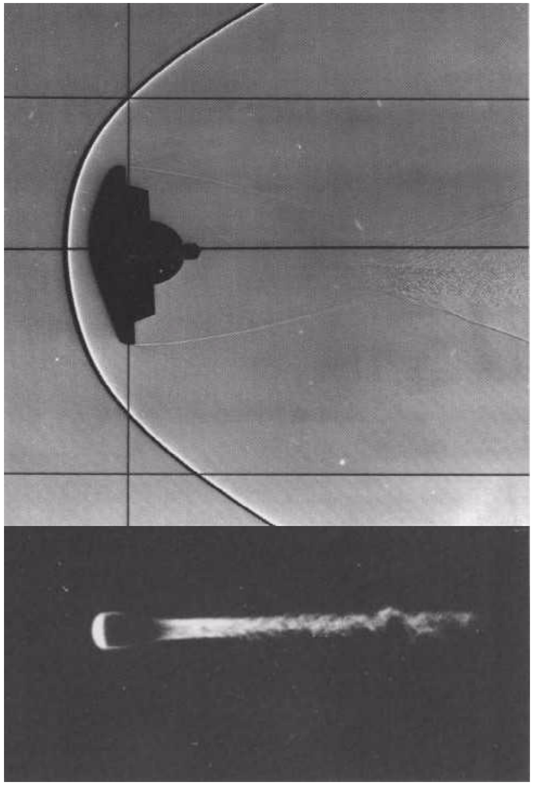
  - With no cross-talk, multiple groups(NASA, academia and industry) predict aerodynamics with emphasis on pitching moment, trim angle of attack and dynamics of the flexible, deformable aeroshell for air and Mars atmosphere.
  - Measure aerodynamics in wind tunnels and ballistic ranges.
  - Conduct balloon/rocket hyper/super/trans/subsonic flight test with a properly instrumented, scaled flight vehicle.
  - Grade teams against pre-determined numerical score

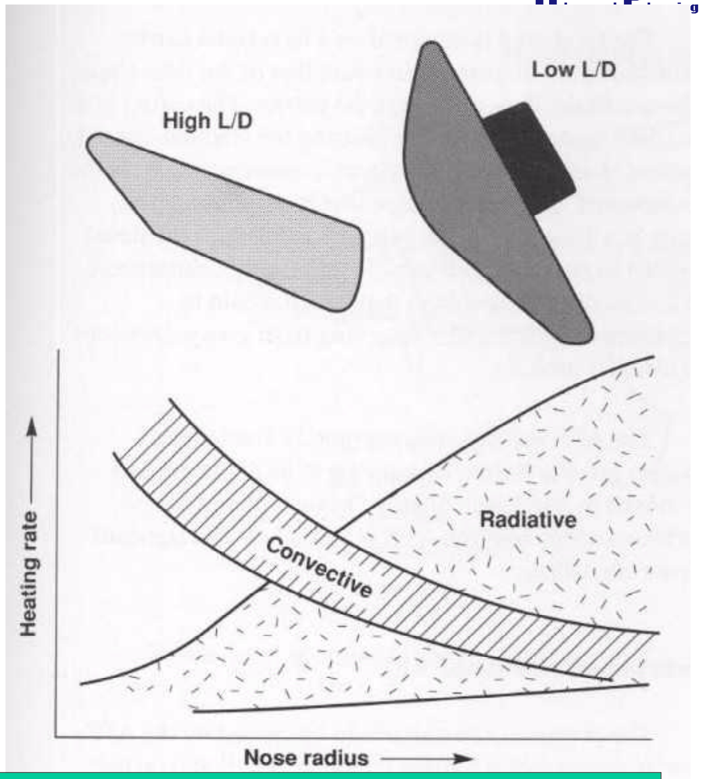
- Properly instrument MSL for 2011 flight. Review Viking aero data base. Examine post-flight data. Grade same teams against pre-determined numerical score.

- Successful efforts on the two prior bullets could make a significant start to validate that our capability is ready for human-critical project development.

Aerothermodynamics

Bow shock layer heating





Apollo peak stagnation point heating

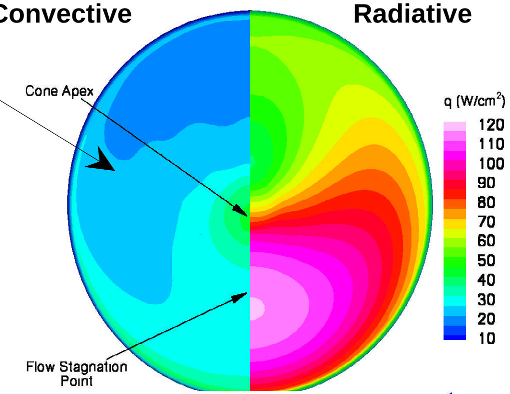
Vel, km/sec	q_c, W/cm^2	q_r, W/cm^2
8.7	39	0.0
11.2	185	336
12.5	241	1283

Radiative heating is an issue for large, blunt bodies at higher velocities for Mars and Earth entry as is the need to develop coupled radiative/convective codes.

Key Aerothermal Gaps

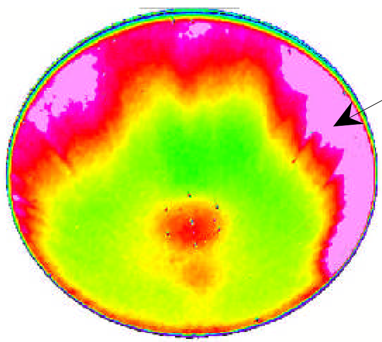
Titan Aerocapture Peak Heating

Convective Radiative



Shock Layer Radiation

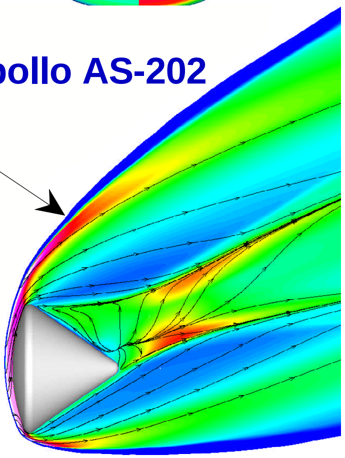
Transition in Mach 6 Tunnel



Transition to Turbulence

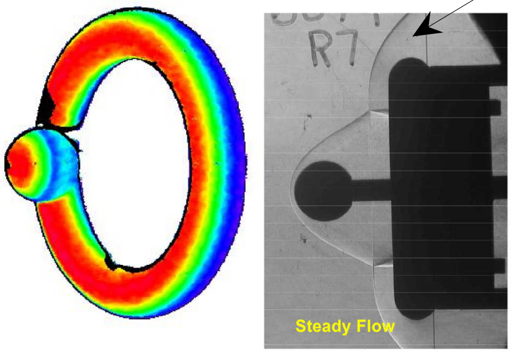
Coupling between radiation/TPS/fluids

Apollo AS-202



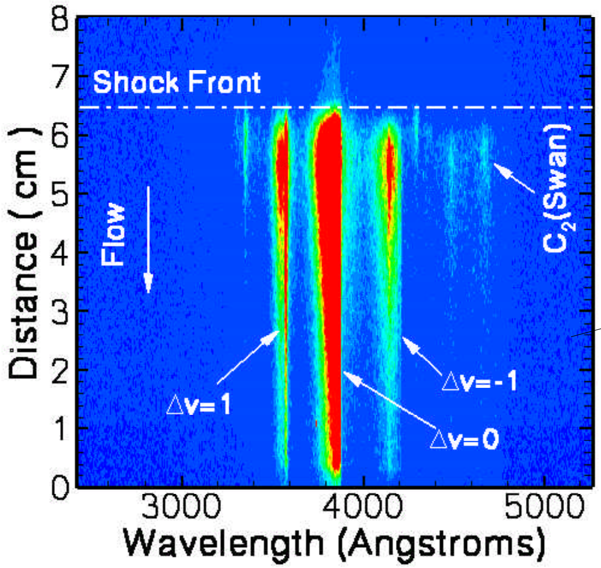
Non-continuum flows and aeroelastic effects for low b entry systems

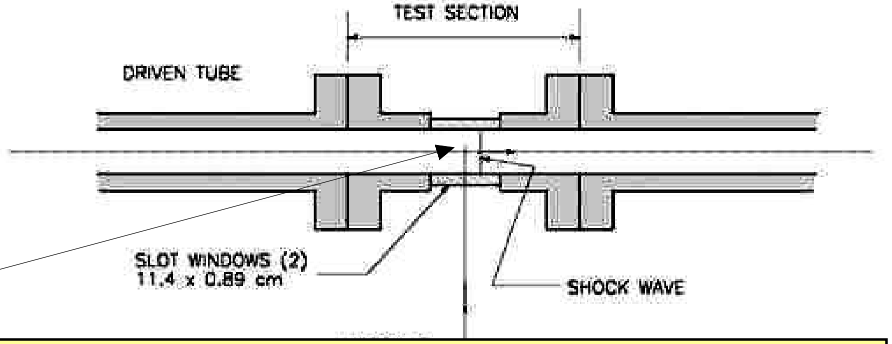
Trailing Ballute Test

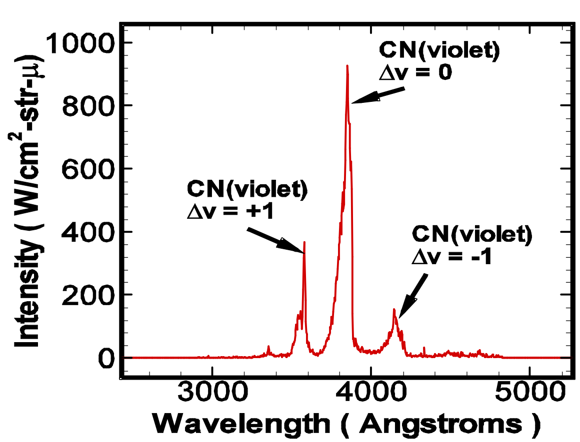


➢ **Gaps are addressed via:**
- Mission-specific uncertainty analysis to rank importance
- Ground testing *tailored* to reduce key uncertainties
- Model development based on test results
- Model validation with flight instrumentation

Shock Tube Radiation Physics for Huygens Titan Entry







Results of Shock Tube Testing

- Provides nominal 1-Dimensional flow with actual rarefied flow gas kinetics, chemical reactions and radiative properties that occur for flight system at given free stream conditions
- Electric Arc Shock Tube (EAST) can simulate Mars, Earth, Outer Planet and Titan atmospheric gases over all velocity ranges of interest.
- Provides rate constants for basic gas processes and properties needed for real-gas CFD codes

Ablative Thermal Protection System

Advanced Planning & Integration Office

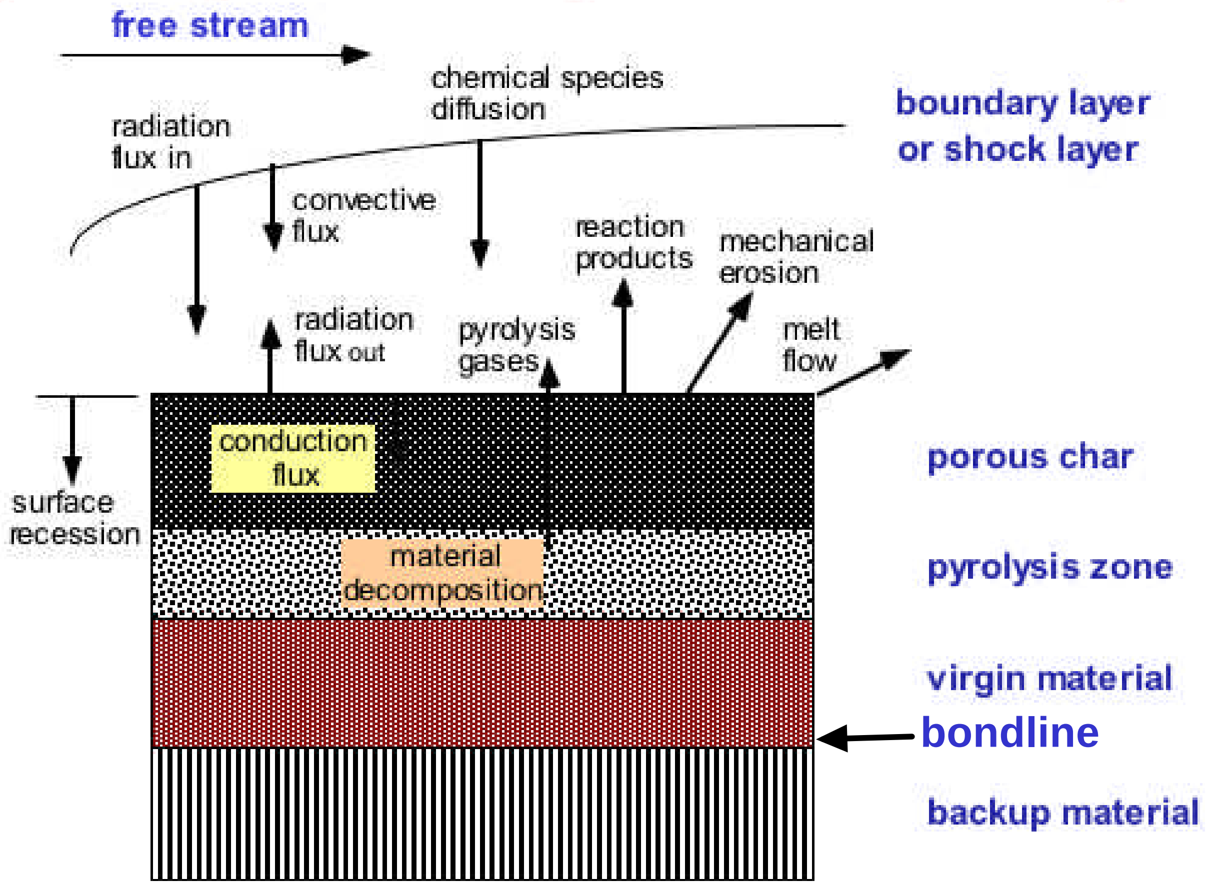
Energy management through material consumption

<u>Given: Vehicle environment</u>
<u>Max. bondline temperature</u>
<u>R & D provides:</u>

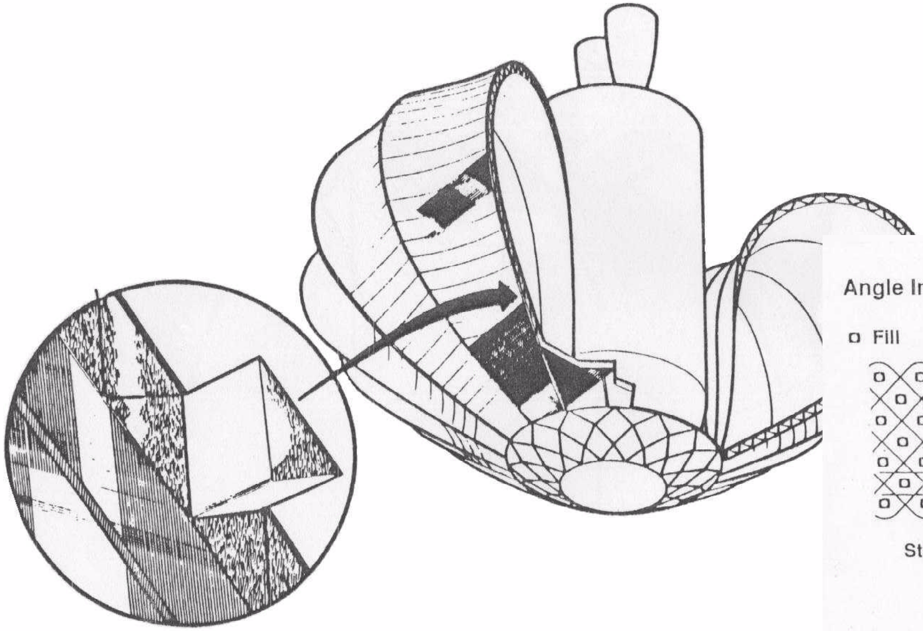
- Materials Specification
- Materials response models
- Scalability
- Manufacturability.

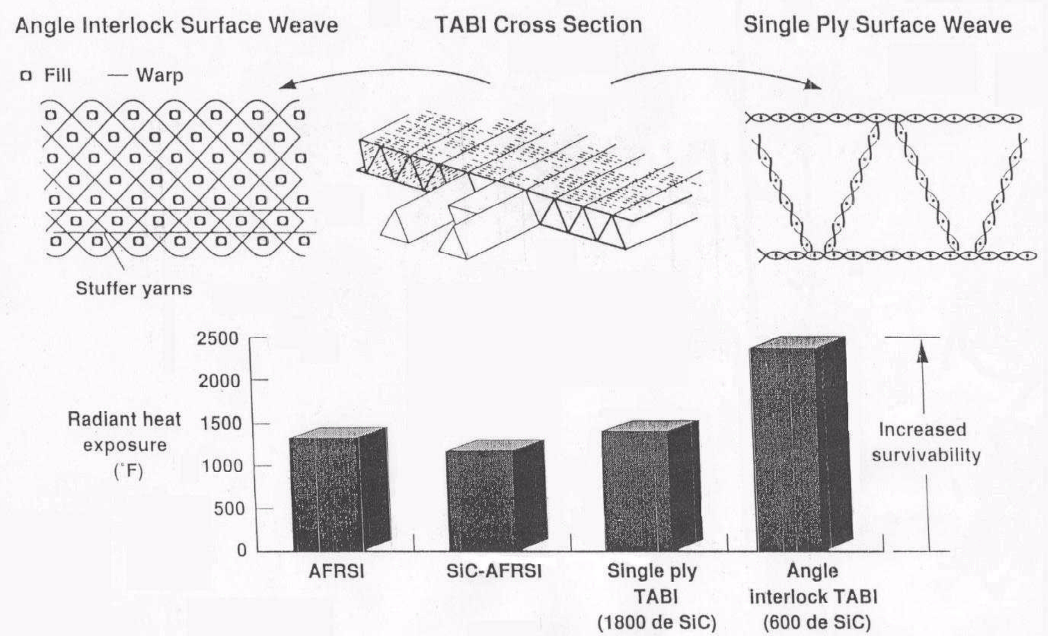
<u>Gaps</u>

- Apollo ablator no longer available
- Extremely small No. of researchers available



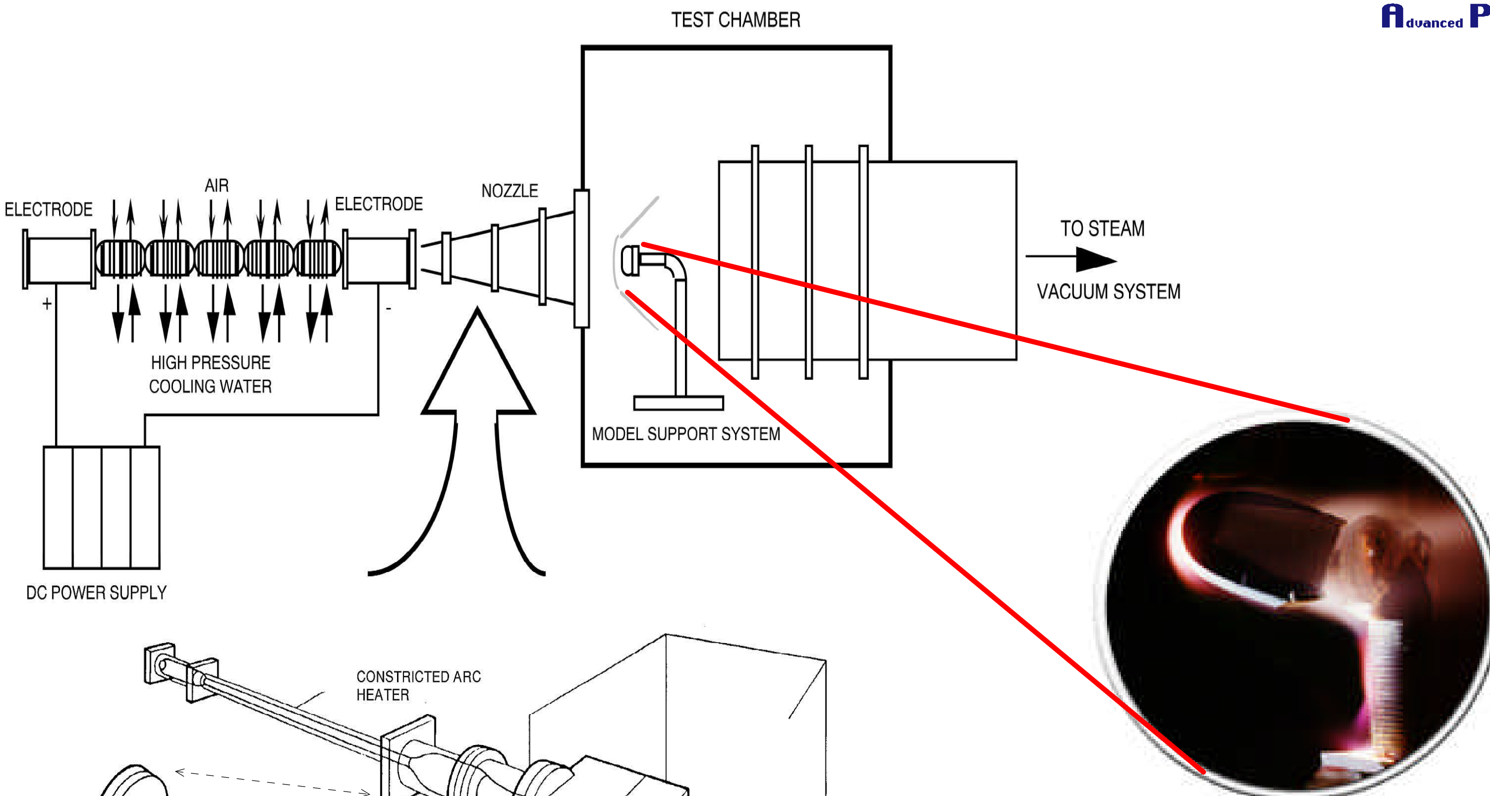
Ballute Thermal Protection System
using Tailorable, Advanced Blanket Insulation (TABI)

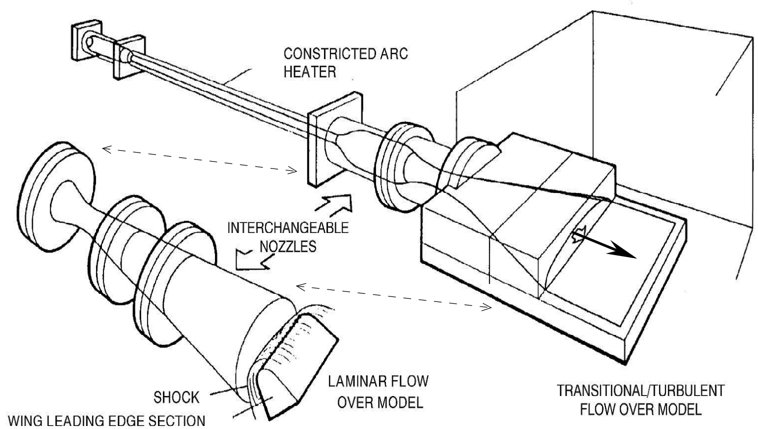




Aeroacoustic survival of flexible TPS after 600 sec at 170 dB (after exposure to radiant heat cycle)

Arc Jet and Test article





Arc Jet Simulation: Missions

"In the 1960's hundreds of arc jets were operational - this is the remainder" J. Hartman (ARC)

Advanced Planning & Integration Office

Mission / Gov. Facility	SOMD (Shuttle)	Capsule LEO/Lunar Return	Mars (Viking, Pathfinder, MER)	Mars (Human and cargo)	Venus (Pioneer Venus)	Gas Giants (Galileo, Jupiter Multi-Probe)	Human Mars Return
Heat rate, W/cm^2	20 – 80 (convective)	20 – 350 (convective / combined)	25 – 150 (convective)	Up to approx. 400 for Triconic* (combined)	6,000 – 12,000 (combined)	35,000 – 50,000 (combined)	800– 2,000 (combined)
Pressure, atm	**0.02 – 0.05**	**0.02 – 0.5**	**0.05 – 0.25**	**0.05 – 0.25**	**4 – 10**	**5 – 10**	**0.5 - 1**
ARC	●	D	●	D	○	○	D
JSC	●	D	●	D	○	○	D
AEDC	○	○	○	○	D	○	○
CIRA	◉	◉	◉	○	○	○	○

- ● **Capable of full range with existing facilities**
- D **Capable of partial range with existing facilities**
- ○ **Gap identified: Capability not available**
- ◉ **Potential exists but not demonstrated**

*For Triconic. Much larger for Blunt Ellipseld

Combined = radiative + convective. This is a gap for human missions at both Mars and Earth Return

Langley Drop Research Facility -- to test large landing test articles

Advanced Planning & Integration Office

- **Rigorous Landing Test Program Will be Required and Includes tests such as:**
  - **Landing dynamics**
  - **Control system validation**
  - **Pilot training**
  - **Payload egress and deployments**
  - **Emergency procedures**
  - **Simulated ascent vehicle launches**

- ***The gantry built for testing the Apollo lander (Langley's IDRF) is the ONLY existing facility capable of testing future human landers (lunar or Mars).***

- **Little modification or upgrading required to test these systems**
  - **Up to 60,000 kg landers currently envisioned in the reference missions.**
  - **60,000 kg in 1/6 gravity →22,000 lbs**
  - **IDRF could handle up to 60,000 lb**
  - **Customization for vehicle and test specific needs will be required**

Full-Scale Impact Dynamics Research Facility

Advanced Planning & Integration Office

Point of Contact:
Karen E. Jackson, Ph.D.
US Army Research Laboratory
Vehicle Technology Directorate
M/S 495, 12 West Bush Road
NASA Langley Research Center
Hampton, VA 23681-2199
ph: (757) 864-4147
fax: (757) 864-8547

- **Quick Facts**
  - **Length: ~ 400 ft**
  - **Width: ~ 280 ft (at bottom), (100 ft top)**
  - **Height: ~ 240 ft**
- **Originally built for:**
  - **30,000 pound lander, 28 ft/sec (limited by the bridge)**
  - **Bridge upgrade to 60,000 lb ($250k) stopped when facility was closed.**
  - **Each A frame is rated to 100,000 pound load.**
- **Currently "Closed"**
  - **Primarily means no maintenance being done**
  - **$200,000 averaged yearly maintenance cost**
- **Slated for Demolition**
  - **NASA LaRC's Structures and Materials branch has determined that the facility should be demolished.**
  - **It is a National Historic Landmark**
    - **In Sept 04 NASA submitted public notice of demolition intention**
    - **Public hearings being held to approve the demolition plan**
  - **Raytheon has been discussing take-over plans**

- **THIS IS A MUST-HAVE FACILITY FOR HUMAN SURFACE MISSIONS!**

LaRC Full-Scale Impact Dynamics Research Facility

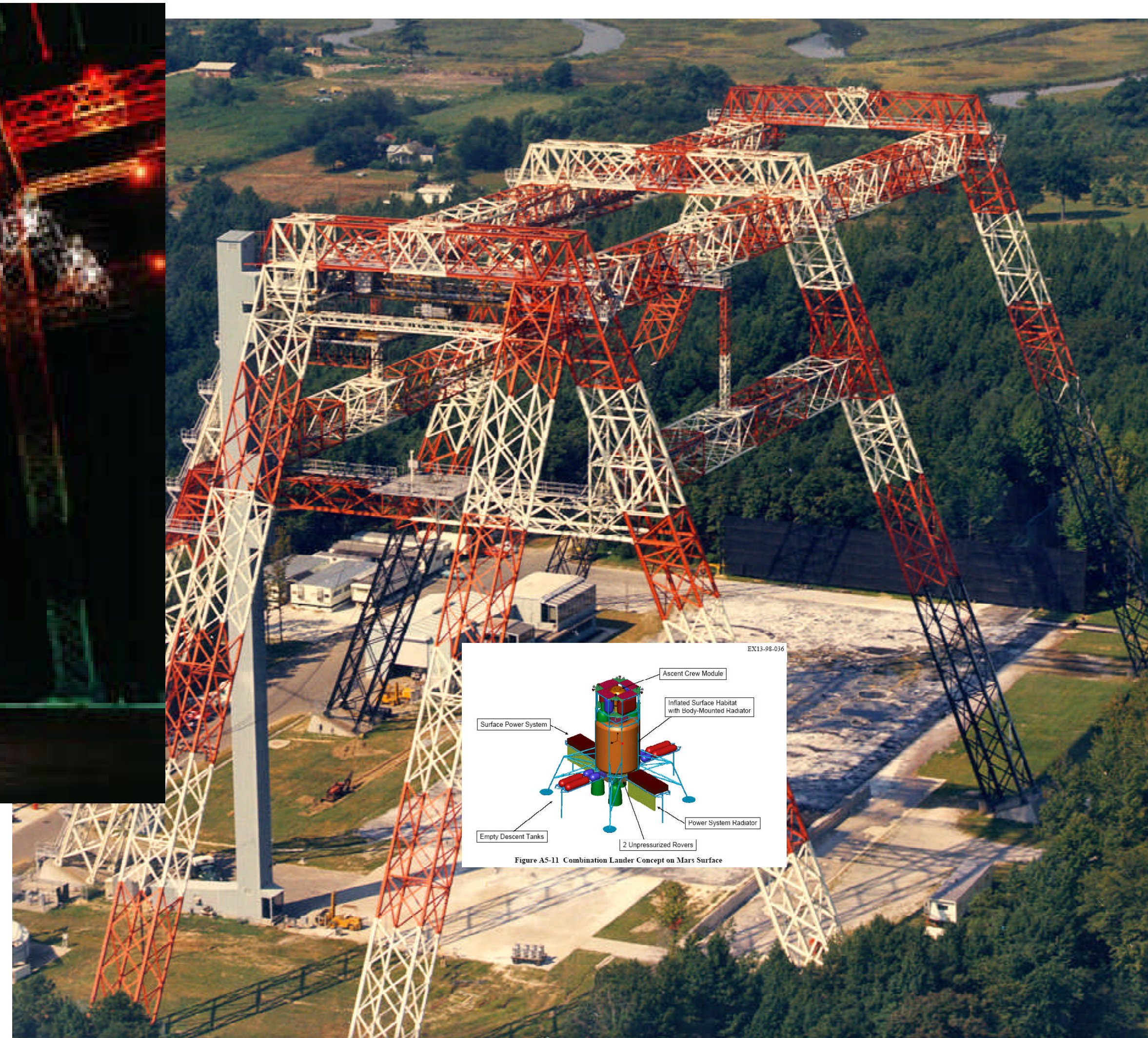


Figure A5-11 Combination Lander Concept on Mars Surface

Outline

Advanced Planning & Integration Office

- Listing of critical capabilities (knowledge, procedures, training, facilities) and metrics for validating that they are mission ready
- Examples of critical capabilities and validation metrics: ground test and simulations
- **Flight testing to prove capabilities are mission ready**
- Issues and recommendations

Flight Tests 2008 - 2015

Advanced Planning & Integration Office

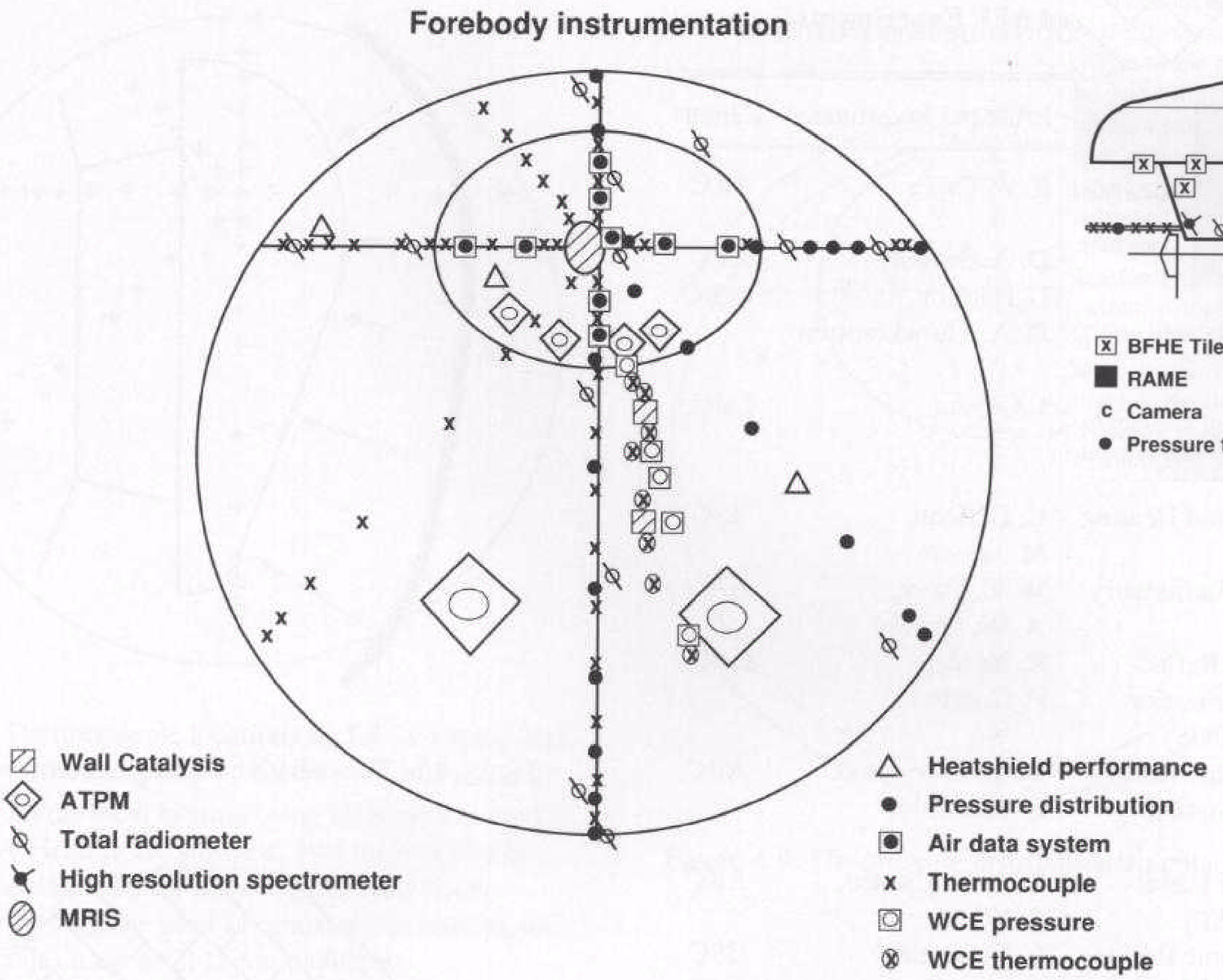
Class flights	Validates	No.
Earth, suborbital ballon, ballon + rocket, sounding rocket and piggyback out-of-orbit	- Aerodynamics - Toward human rated TPS - Engineering Sensors - Flexible aeroelasticity/control	Eight
Earth, Shuttle/Station	- Test Human AEDL Perf.	3-4
Mars, Instrumented MSL	- Engineering Sensors / G,N&C - Transition to Turbulence (Mars) - Viking aerodynamics	One
Mars, Robotic scale flights to prove aero. capture when possible/ Affordable - still being discussed	- Aerocapture System	One
Earth, instrumented CEV	- GN & C, aero/aerothermal human rated TPS for Earth orbital entry and engineering inst.	Two

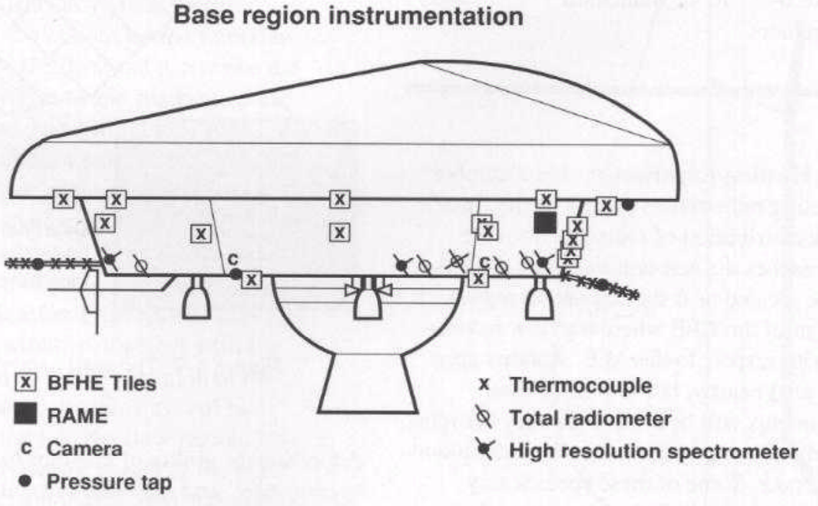
Flight Tests 2015 - 2029

Advanced Planning & Integration Office

Class	Validates	No. flights
Earth, Instrumented Aero. Capture From Lunar return	Aerocapture into Earth orbit for Mars return to orbiting quarantine station	Two
Mars, Small scale (human configuration) A/C + EDL	Aerocapture System EDL System	Two
Earth, full scale	DL, Super/trans/ subsonic and touchdown systems	Five-Seven
Mars, Instrumented Astrobiology Lab	EDL	One
Moon, CEV Spiral 2 accomplished	DL	All

Example of Properly Instrumented Flight Experiment
Aeroassist Flight Experiment (AFE) :
Vehicle Environment, TPS, GN&C, etc.

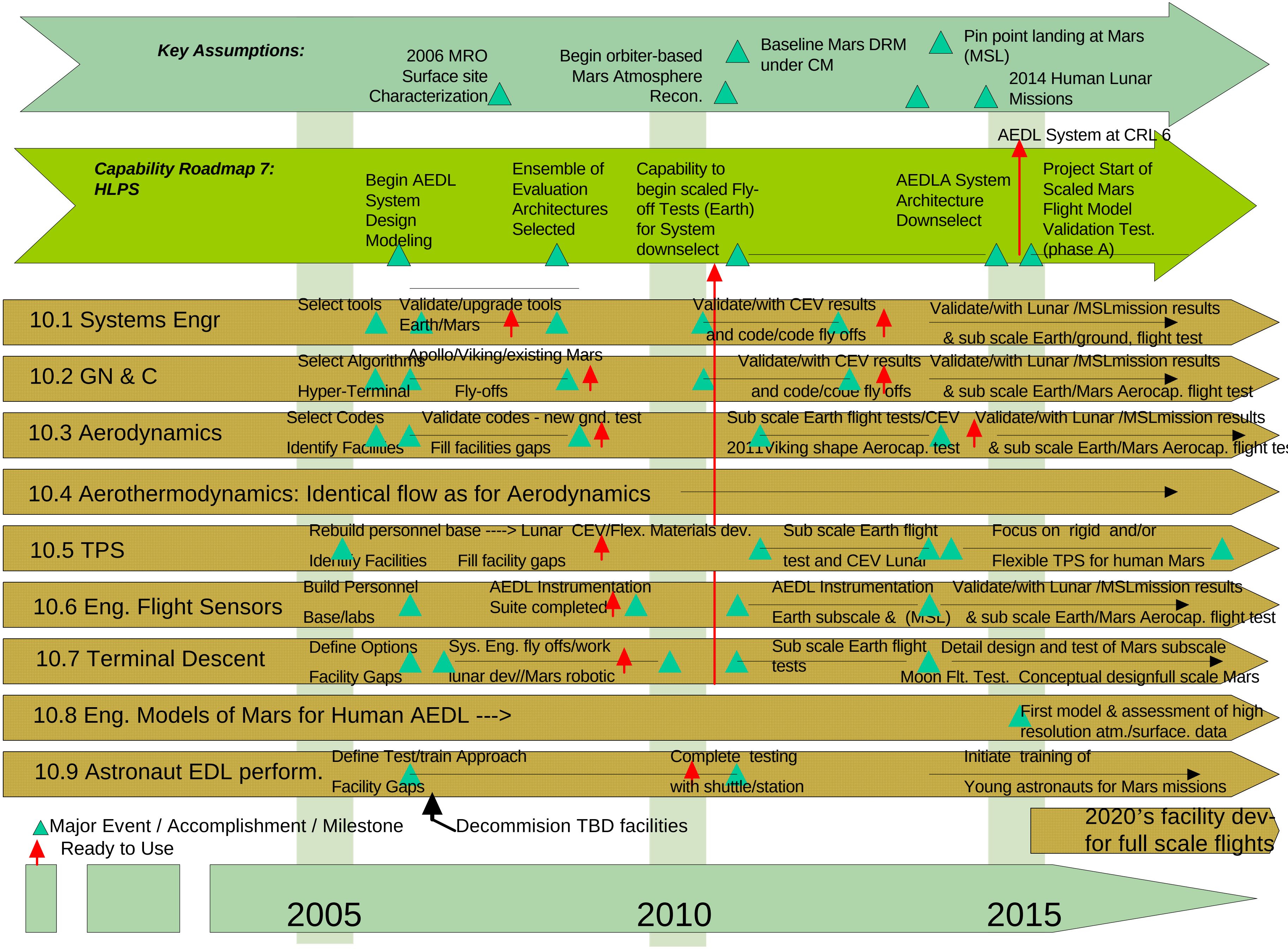




Flight Tests 2020 - 2036

Class	Validates	No. flights
Repeat tests TBD (planned failure and train mission implementers)	Acceptable mission risk	TBD
Mars, Full scale (cargo configuration)	EDL for Mars 1st Crewed Landing	One
First Human Landings	Staggered by 2 years or on same opportunity	Two

Team 7: Human Planetary Landing Systems Section 10.0 Roadmap



Outline

- Listing of critical capabilities (knowledge, procedures, training, facilities) and metrics for validating that they are mission ready
- Examples of critical capabilities and validation metrics: ground test and simulations
- Flight testing to prove capabilities are mission ready
- **Issues and recommendations**

Issues

- Knowledge capture/training across generations of implementers (technologists project/program personnel, leadership, managers, crew {medical, pilot, science: geology, biology, etc.})
- Sustaining/developing facilities, technologies and tools across three decades
- Independent review, analysis and assessment capability
- Early Technical Interchange Meetings (TIMs) and facility review required to ensure that facilities are not closed prematurely and that new facility capabilities are clearly understood during the NASA transformation, e.g. Aerodynamics and Aerothermodynamics CFD validations

Recommendations

Advanced Planning & Integration Office

- Review/adopt the best practices/lessons/program funding approaches learned from the Apollo, Viking, Shuttle, ISS and current Mars program as initiated after Mars '98

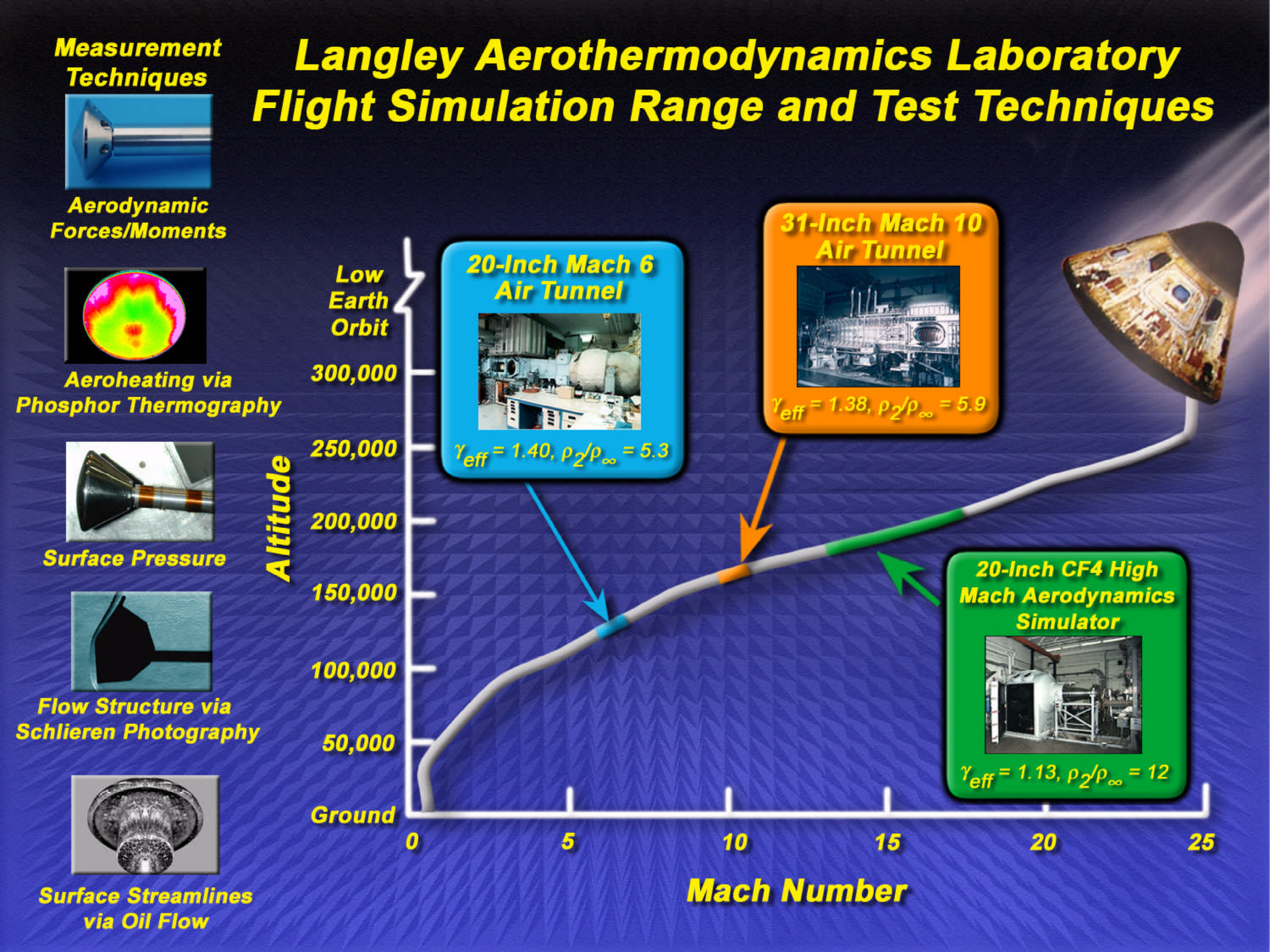
  - Example: in the 60's, 70's and 80's NASA separately (and adequately) funded facilities, technology programs, flight projects and salaries for core compentencies. Flight program/projects only paid facility "occupancy" fees. Technologists were not beholding to projects for funding. Independent, expert opinions were critical for project reviews. New enabling technologies were adopted.

- In the late 80's/early 90's an ad-hoc "Aeroassist Working Group" was formulated by Langley, Ames, JSC and MCFC, later joined by JPL. Industry/Academia have played roles from time-to-time. In the one-NASA spirit, leadership rotates from center to center. This group has been successful in securing funding for its activity.

  -This group should be re-invigorated and expanded to include all aspects of AEDL for both human and robotic missions. Its charter should be to facilitate multi-generational knowledge , tools and facilities necessary for agency missions for the next 3-4 generations. It must include early involvement by academia (next generations) and industry (system builders).

- This expert group should be tasked to conduct TIMs and facilities reviews to understand/advocate for facilities needed by the HPLS for the next 3 decades

Facility Details



Langley Aerothermodynamics Laboratory
Flight Simulation Range and Test Techniques
Measurement Techniques
Aerodynamic Forces/Moments
Aeroheating via Phosphor Thermography
Surface Pressure
Flow Structure via Schlieren Photography
Surface Streamlines via Oil Flow
Altitude
Low Earth Orbit
300,000
250,000
200,000
150,000
100,000
50,000
Ground
0
5
10
15
20
25
Mach Number
20-Inch Mach 6 Air Tunnel
γ_{eff} = 1.40, ρ_2/ρ_∞ = 5.3
31-Inch Mach 10 Air Tunnel
γ_{eff} = 1.38, ρ_2/ρ_∞ = 5.9
20-Inch CF4 High Mach Aerodynamics Simulator
γ_{eff} = 1.13, ρ_2/ρ_∞ = 12

Human-Rated Vehicle Development Program Test Requirements

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Apollo development (1962-1965)

- Estimated 6200+ hours (155 x 40-hour work-weeks or 3 work-years) of wind tunnel testing conducted on Apollo entry and escape configurations.
- Test plan called for use of at least 33 facilities: 22 transonic, supersonic, or hypersonic wind tunnels, 8 high-enthalpy shock tubes or arc jets and 3 free-flight ballistic ranges.
- Ref: Apollo Wind Tunnel Program Report, North American Aviation SID-62-170-5, July 1963).

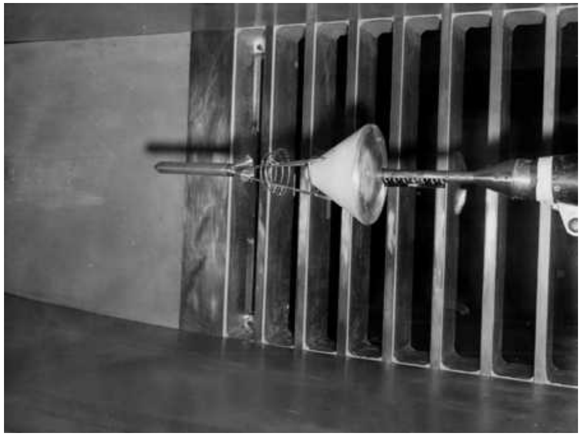
• Space Shuttle (1969 through 1984)

- Shuttle development required over 100,000 hours of wind tunnel testing (2500 x 40-hour work-weeks or 48 work-years) in more than 60 wind tunnels.
- Shuttle was far more complex than Apollo capsule: winged vehicle with external fuel tanks and boosters vs. simple capsule.
- Ref: Romere, P.O, and Brown, S. W., "Documentation and Archiving of the Space Shuttle Wind Tunnel Test Data Base," NASA TM-104806, Jan. 1995.

Sub / Tran / Supersonic Wind Tunnels

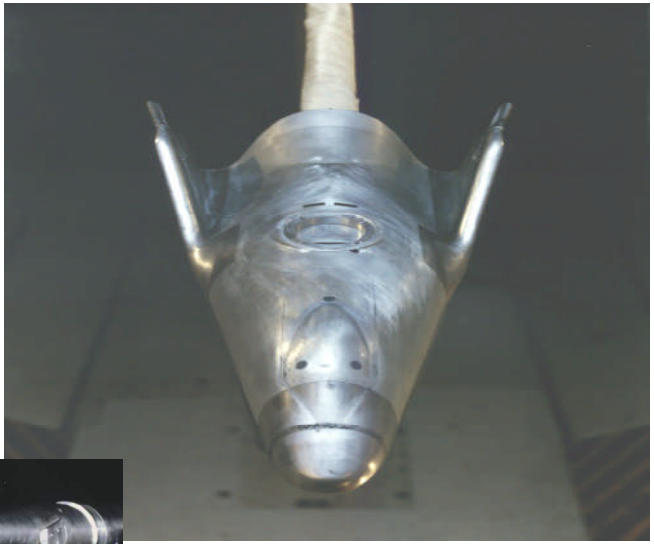
Advanced Planning & Integration Office

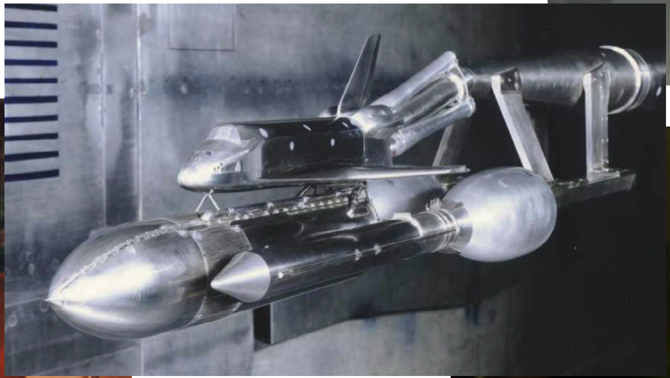
- Robotic exploration programs are more risk tolerant than human-rated programs
- Robotic entry systems are have been simple geometries with no control surfaces
- Every human-rated entry system has been wind-tunnel tested across the speed range
- Many of these tunnels have already vanished
- Remaining tunnels are threatened with closure

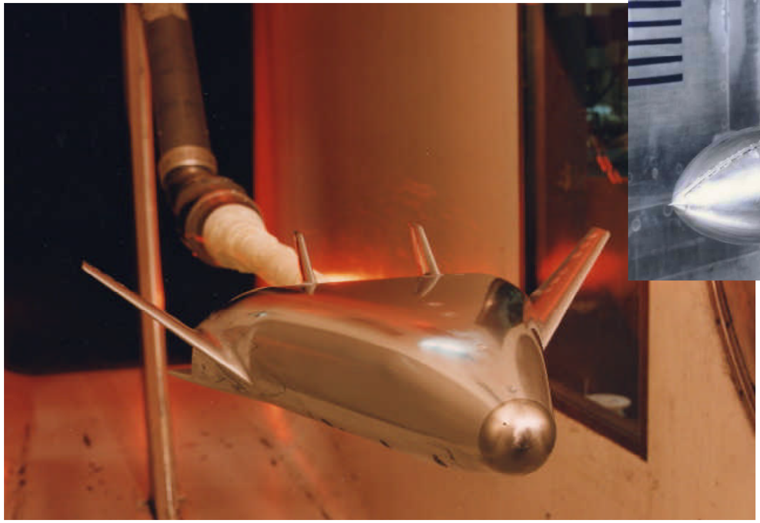


Sub / Tran / Supersonic Wind Tunnel Uses

- Configuration development
- Validation of numerical techniques
- Multi-body interactions (launch stack)
- Reaction Control System (RCS) **interactions with flow field**
- Dynamic stability (forced oscillation)

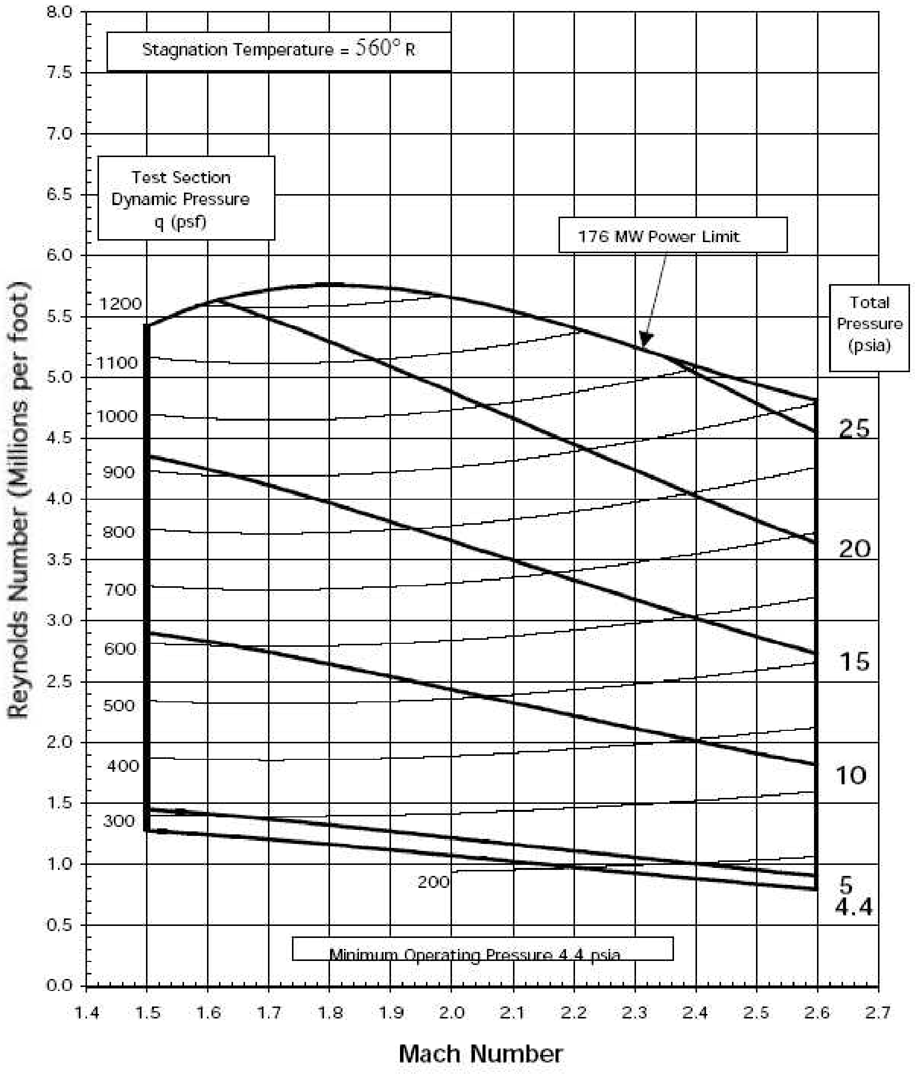


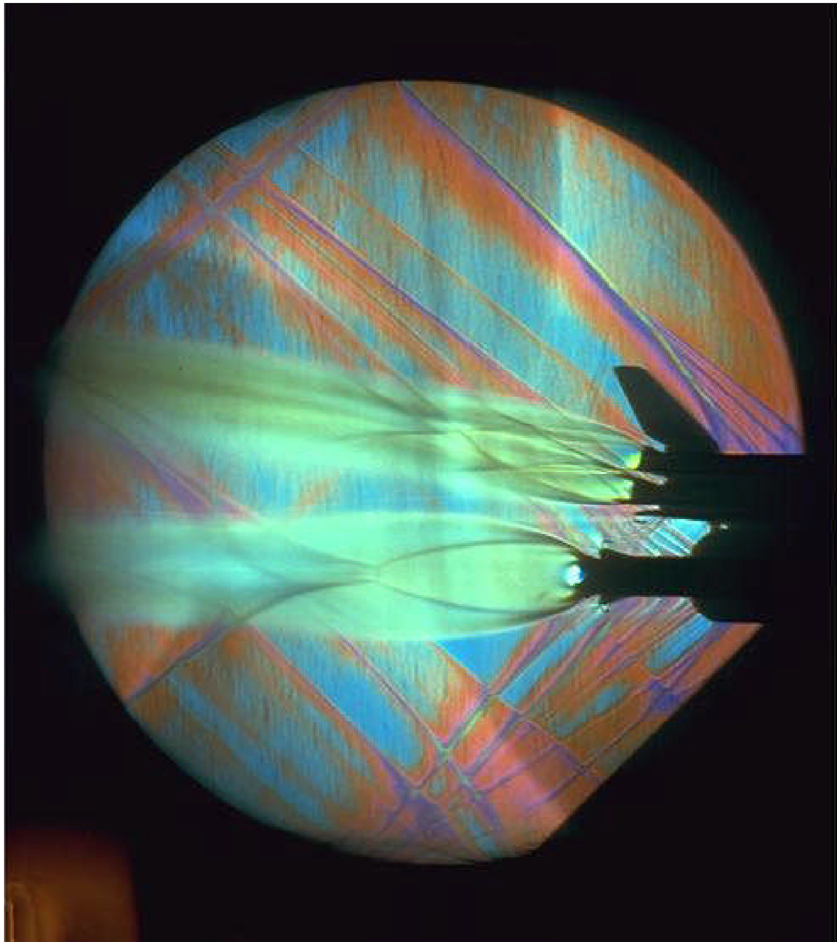




OPERATING CHARACTERISTICS OF THE NASA AMES RESEARCH CENTER 9-BY 7-FOOT SUPERSONIC WIND TUNNEL

Advanced Planning & Integration Office





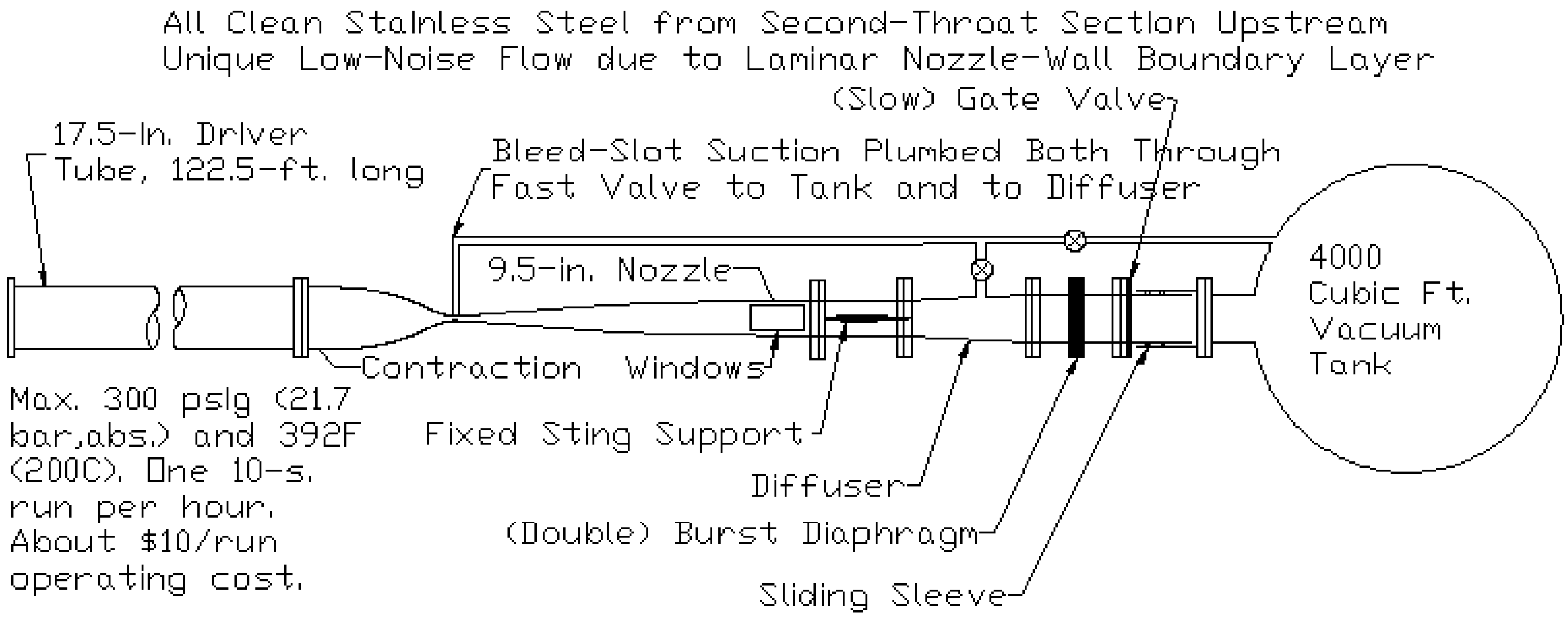
Shuttle exhaust plume - aero interactions

Boeing/AFOSR Mach-6 Quiet Tunnel

- Mach 6 in 9.5-in.-dia. nozzle at $10/shot
- Operates from Re=1E5/ft. to 6E6/ft.
- Quiet flow to about 0.5E6/ft, plans to 3E6/ft
- Usually clean air, could run CO_2

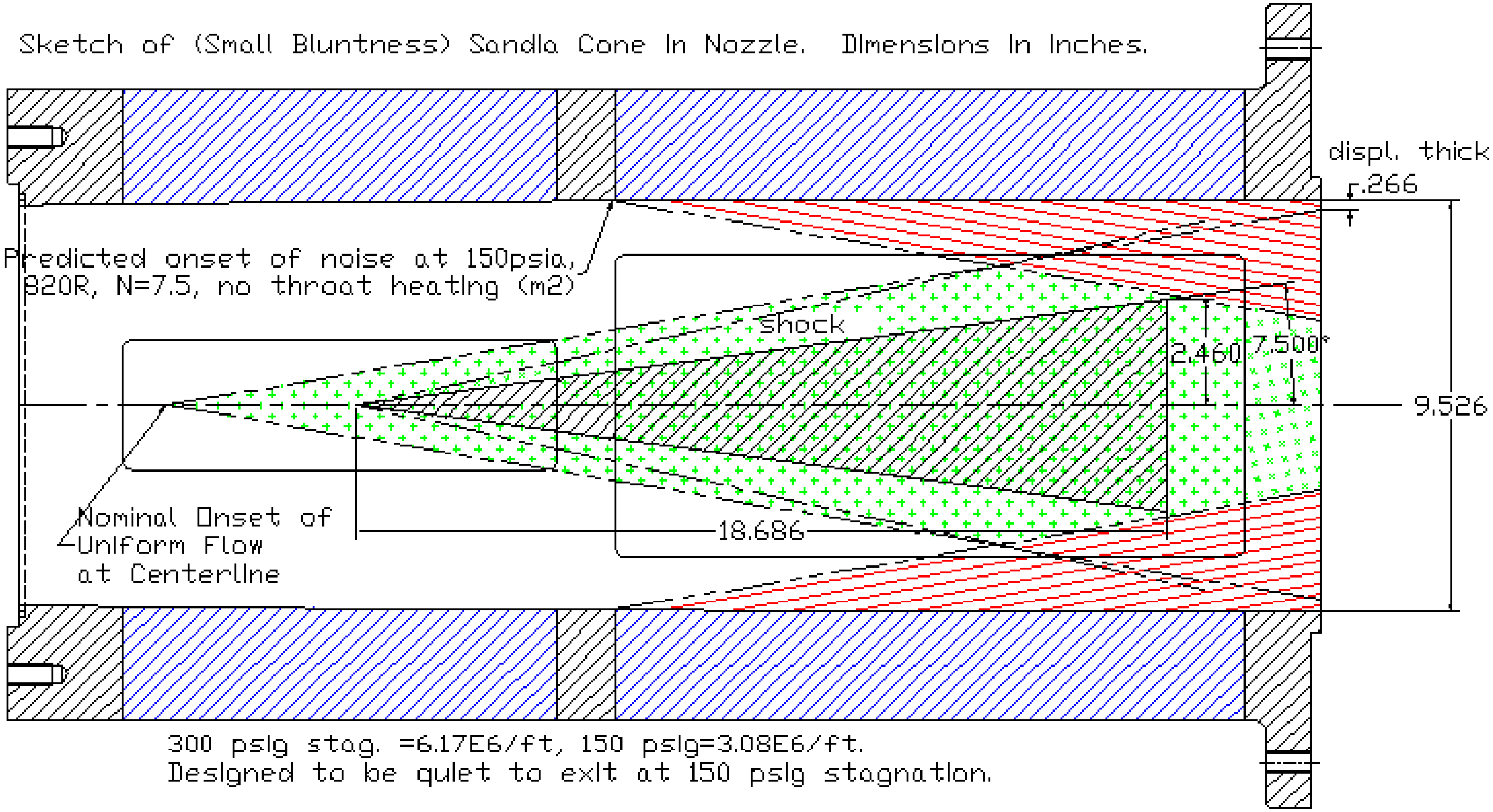
Hot wires (have been calibrated in CO_2), Hot films

Temp. paints, laser differential interferometer, controlled perturbers for stability experiments



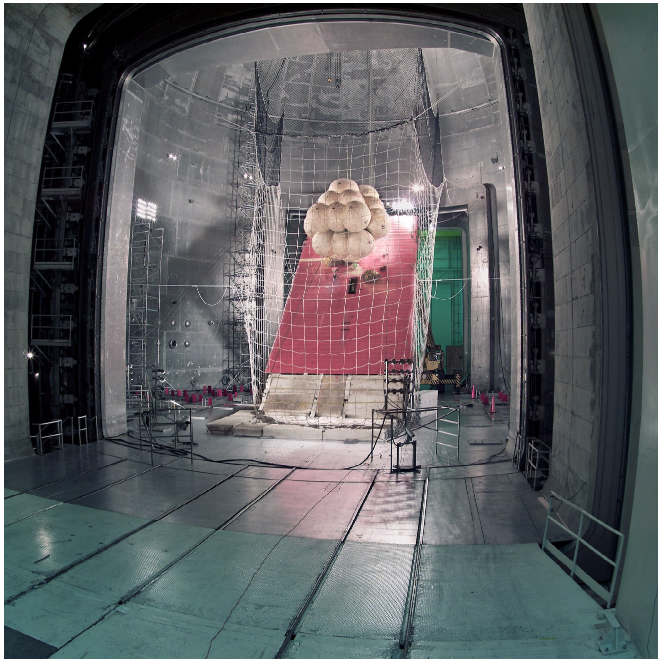
Exit of 9.5-Inch Mach-6 Nozzle

Eight openings for windows (blue), presently one 7x14-inch window and one pair of 5-in.-dia. windows. Auto. traverse in vertical centerplane for wires and pitot probes. Green marks nominal low-noise uniform flow.



GRC Plumbrook Quick Facts

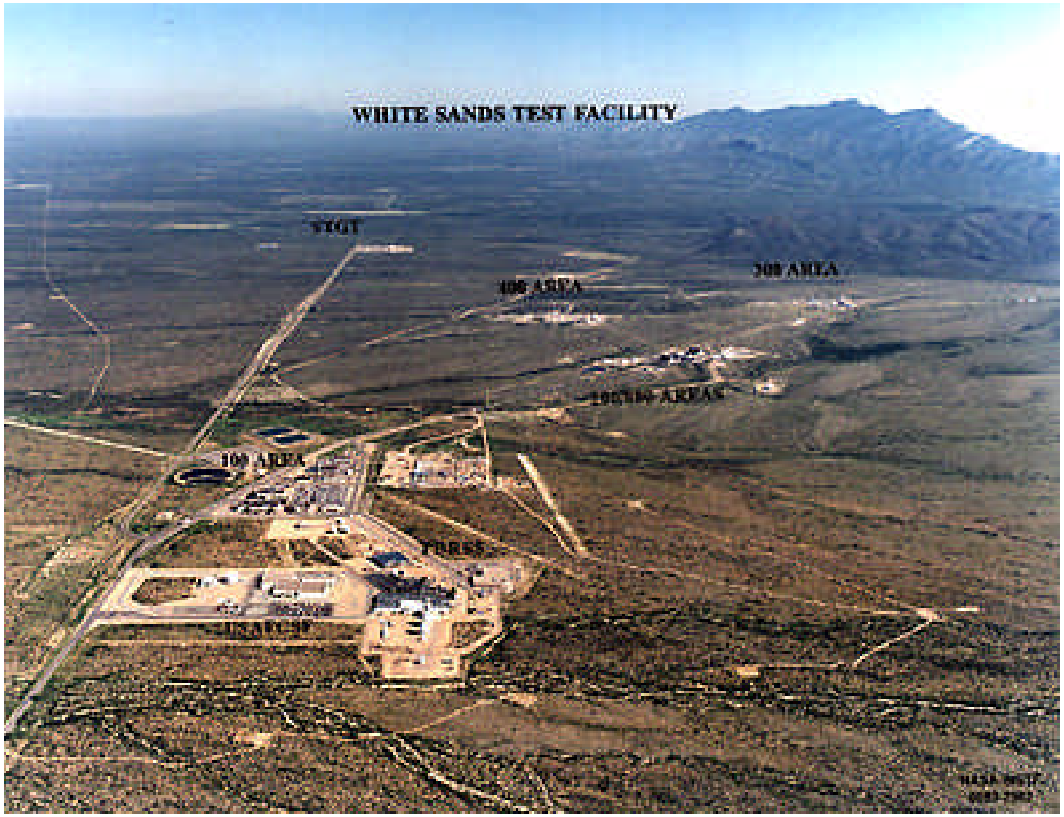
- Overall Functions:
  - **Sustains high vacuum**
  - **Simulates solar radiation (400-kW arc lamp / 4-MW quartz heat lamp array)**
  - **Produces cold environments via cryogenic cold wall (-320 °F)**
  - **Provides a high degree of vibration isolation for sensitive optical tests**
- Test Chamber
  - **100-ft diameter by 120-ft.-tall test area**
  - **Chamber penetrations for power, data acquisition, and high-pressure liquids and gases**



WSTF Overview

Advanced Planning & Integration Office

- Constructed in 1962-64 to support project Apollo
- Component of JSC Houston
- Occupies 28 square miles - SW Corner of WSMR

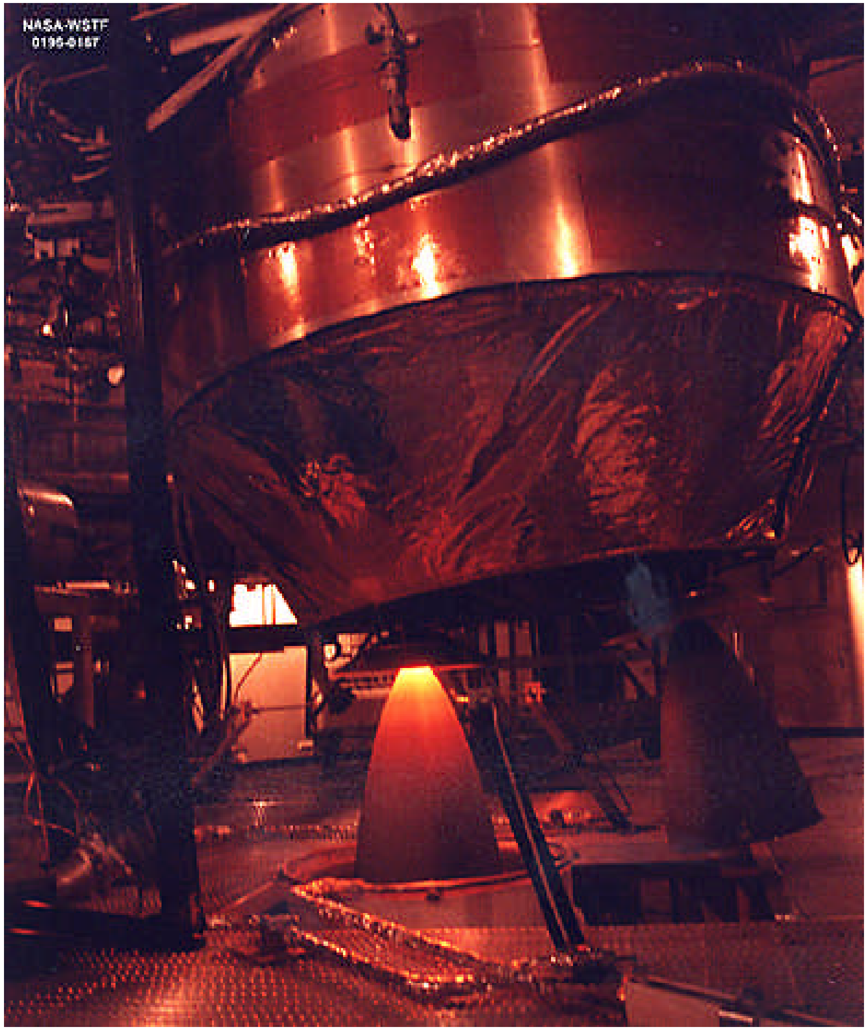


Aerial View Looking North

Unique WSTF Capabilities

- Simulated altitude testing of full-scale integrated hypergolic propulsion systems
- Agency facility for hypervelocity impact testing, including accommodations for hazardous targets
- Capability for all materials testing defined by NASA Standard 6001 (NHB 8060.1C)
- Design and hazards analysis of oxygen and hydrogen systems
- Large-scale explosion testing of hypergolic, cryogenic, and solid propellants
- Component testing in high temp/high flow gaseous oxygen and hydrogen

Full-scale Shuttle OMS pod installation at vacuum test cell TS-403



Cassini - Saturn orbit insertion engine glows during 3 hr. 20 min. continuous firing

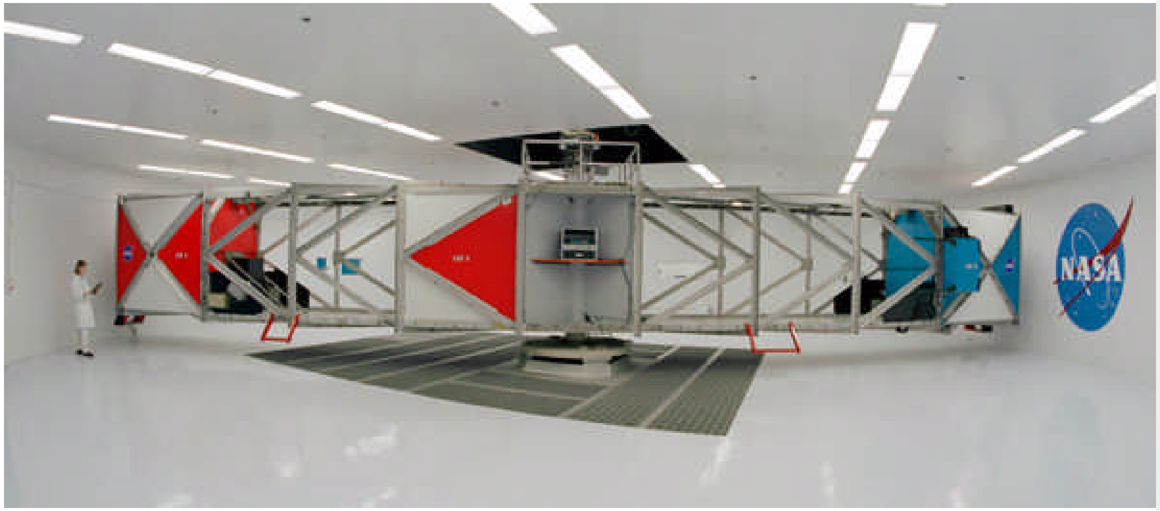
Vestibular Research Facility

The Vestibular Research Facility (VRF) located at NASA Ames Research Center houses approximately 2,000 square feet of laboratory space and 1,000 square feet of office space. The VRF provides a centrifuge and two types of linear sleds for ground-based studies of vestibular function. Support laboratories and office areas complete the facility. Both flight and ground-related science questions may be addressed using either humans or animals as subjects.

30-ft Linear Sled
Vestibular Research Facility

The 30-ft Linear Sled of the Vestibular Research Facility can be used to examine otolith-ocular-perceptual responses humans (the reinterpretation of otolith signals driving both perception and gazer stabilization reflexes is a major component of human adaptation to altered gravity). It consists of a carriage mounted on an ultra smooth horizontal 10-m granite slab. The carriage is supported by low-pressure air bearings that float ~2.5 microns above the granite surface to provide a silent, frictionless linear motion. Artifacts due to mechanical vibration and auditory noise are therefore eliminated. The sled is human-rated and instrumented to deliver visual stimuli in conjunction with the linear-acceleration vestibular stimulus while recording eye movements, arm m

20-G Centrifuge



20-G Centrifuge
Performance limits and specifications:

Radius: 29 ft
Payload: 1,200 lbs
Max G: 20 G (human-rated to 12.5 G)
Max RPM: 50 RPM

The 20-G Centrifuge located at NASA Ames Research Center can be used to evaluate the effects of altered gravity, and G-load transients, and rotational acceleration on humans (in addition to examining G-effects per se, this device can be used to evaluate candidate AG regimes that astronauts may also be exposed to). A cab mounted at the end of the 6.8m-diameter rotating arm contains a modified jet-fighter ejection seat. The centrifuge is human-rated and instrumented to deliver a variety of visual stimuli at a range of possible static g levels (usually up to 3g; capable up to 20g) while recording eye movements, limb movements, and perceptual responses.

Vertical Motion Simulator

Advanced Planning & Integration Office

The Vertical Motion Simulator (*VMS)* , which is located in the Flight and Guidance Simulation Laboratory (SimLab) at *NASA* Ames Research Center, is renowned for its efficient production of high-fidelity, fixed and moving base, real-time, piloted flight simulations of aerospace vehicles. Engineers can customize the system to simulate any aerospace vehicle, whether existing or in the design stage. Existing vehicles that have been simulated include a blimp, helicopters, fighter jets, and the Space Shuttle Orbiter. One aircraft being designed that may be simulated at the *VMS* is a next-generation transport capable of flying in near-earth orbit. Simulations occur with high fidelity; that is, the simulator reproduces flight characteristics with a high degree of accuracy. This entails delivering realistic cues to the astronaut/pilot in real time.

Interchangeable Cab (ICAB) on the VMS Motion Base

Human Planetary Landing System (HPLS) Capability Roadmap

Wrap Up

Rob Manning - NASA Chair

May 4, 2005

Challenges

- **Delivery of large masses and volumes to Mars orbit & surface and safe return of astronauts to Earth.**
  - Large, human-rated Mars systems (hypersonic ->supersonic, subsonic, terminal)
  - Decelerating from supersonic to subsonic speeds before touchdown at Mars
  - Mars thin, variable atmospheric structure, local winds and dust storms
  - Pin point landing & low altitude winds drives need for late position compensation.
- **Using combined Manned and Robotic program, flights, test missions and resources to effectively develop aeroassist vehicles and systems capabilities to reduce risk and cost.**
  - Building on the significant body of previous aerocapture and related work to develop an aerocapture capability.
  - Understanding and modeling the variations in Mars natural environment
  - Building system commonality across robotic and piloted AEDL missions
  - Providing continuity of resources – skilled people, tools, practices, and facilities to accomplish the NASA's HPLS functions
  - Development of aerodynamic and aero-thermodynamic design and verification capabilities including simulation tools, ground and flight measurements
  - Development of light weight human-rated Thermal Protection Systems for large aeroshells
  - Development of light weight human-rated TPS systems
  - Development of new terminal descent and touchdown systems.
- **Accommodating human safety and AEDL-mission interaction.**
  - Safety and resiliency drives size and complexity of the AEDL & Ascent system.
  - Understanding how to best incorporate humans in the loop for AEDL

Summary of Top Level Capability: Key Questions

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- **"When and how does the full scale system and subsystems need to be qualified & Human-rated for flight?"**
  - **Answer: No later than '29. Full scale AEDL Flight Tests can and should be done at Earth (need to get fast turn around between multiple tests).**
- **"Do we need a "Full Scale Validation Flight Test" at Mars?"**
  - **Answer: Not, specifically, but the AEDL community is very uncomfortable with the notion of the very first full scale AEDL being piloted. The full scale unpiloted AEDL advance cargo mission that immediately precedes the human landing could do the trick.**
- **"What kind of precursor AEDL Flight Tests are needed at Mars?""**
  - **Answer: We need to validate our performance & aerodynamic models by flying a scaled (1/10th?) version of the Full Scale Mission by '22.**
- **"When and how do we decide on the AEDL system to fly?"**
  - **Answer: No later than 2015 (earlier is harder). We need to do multi-path full scale flight simulations and subscale / component development testing starting ASAP.**
- **If we find an AEDL for a landing mass of 40 MT, will this same architecture and technology paradigm extend to landing 80 MT? 120 MT? Is there another break point?"**
  - **Answer: We do not know yet.**

More Key Questions

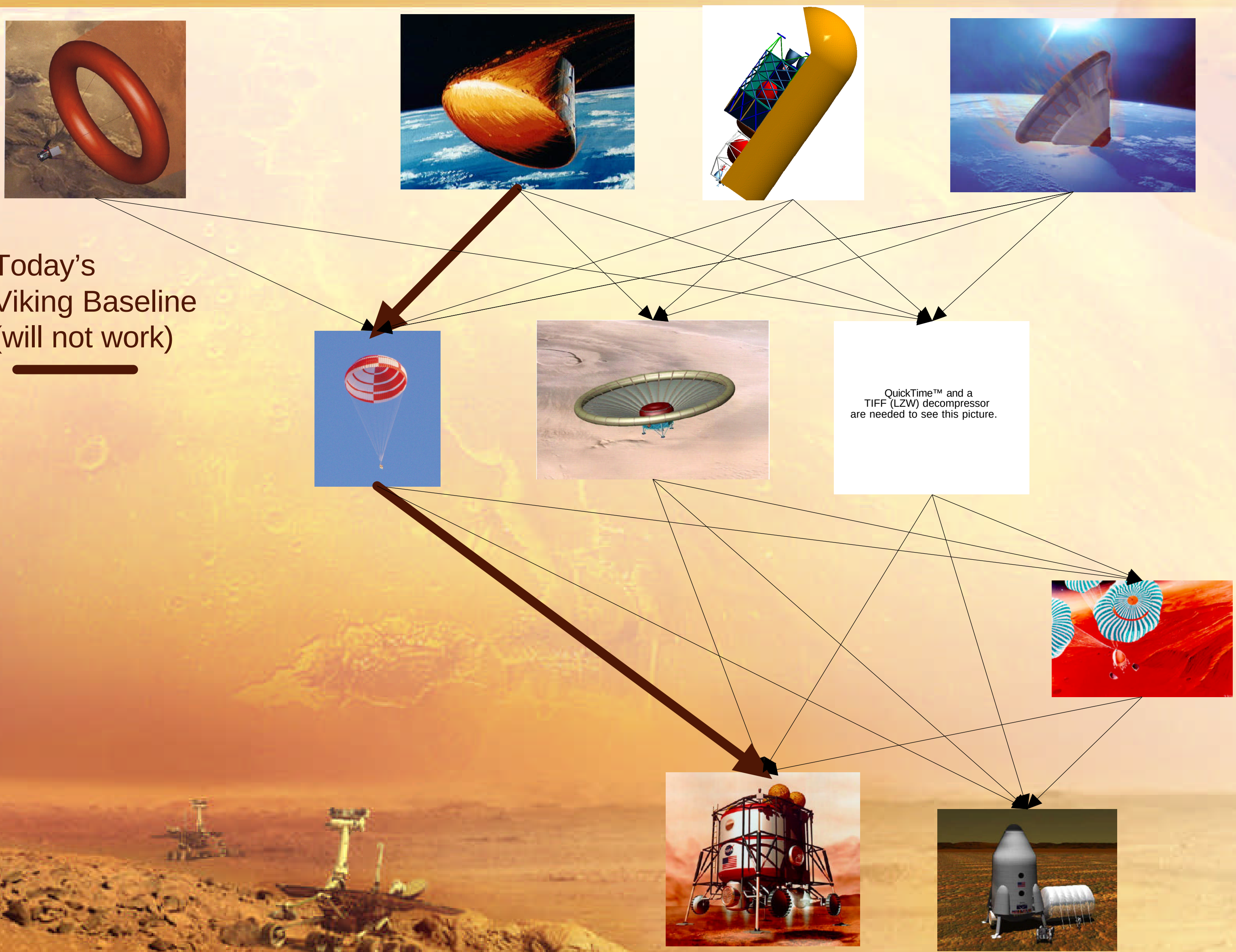
Advanced Planning & Integration Office

- "What Mars Environmental data are missing for AEDL?"
  - Answer: In order to get the system reliability up, we need validated models of the Mars atmosphere. Instrumented robotic landers are essential but insufficient. We need a long-term atmosphere observer mission.
- "What Human Factors data are missing?"
  - Answer: A lot, human physiological and behavioral constraints, yet to be determined, could be key drivers for many decisions including the EDL architecture.
- "What can the CEV & Lunar missions do to advance Mars AEDL?"
  - Answer: These missions could develop and retire risk in Mars terminal descent propulsion systems, aerocapture/entry guidance & aerodynamics, large scale TPS, human-EDL interaction systems, human physiological performance assessment & Earth entry instrumentation.

Which will it be?

Options for Hypersonic Decelerators

Today's Viking Baseline (will not work)



Options for Supersonic Decelerators

Options for Subsonic Decelerators

Options for Terminal Descent Systems

Summary Remarks

- We are a long way from understanding what the Mars AEDL system will look like. Significant near-term work is required to baseline a design for a Human Scale Mars AEDL system.
  - If NASA waits until 2015 to initiate design and development of the Mars AEDL systems and scaled subsystems, it is unlikely that human Mars landings could be flown in the 2030's.
- A near-total absence of data on Human physiological and psychological post-entry deceleration performance forces conservative assumptions on the design of the human-AEDL system.
  - NASA should begin taking performance measurements now before the shuttle & ISS retires.
- A near-total absence of measurements that validate the variation of the Mars atmosphere forces very conservative or prohibitive design requirements on the AEDL system to get human-rated reliability.
  - NASA should initiate a program to acquire the data on the variations so that these systems can be built.
  - NASA should ensure that robotic EDL and surface assets have adequate atmosphere, aerothermal and aerodynamic instrumentation.
- The US AEDL community and infrastructure is small and aging.
  - NASA needs to grow and invigorate this field to enable the HPLS capability.
- Despite its small numbers, the technical capabilities developed by the historic manned and on-going robotic EDL community may be exploited to begin design and detailed assessment of human scale AEDL systems.

Forward Work

Advanced Planning & Integration Office

Work to go:

- **2nd NRC Review will address 4 additional questions:**
  - **Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?**
  - **Do the capability roadmaps articulate a clear sense of priorities among various elements?**
  - **Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?**
  - **Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?**

THE NATIONAL ACADEMIES / NATIONAL RESEARCH COUNCIL

NASA Capability Roadmap Review

Panel E: Robotic Access and Human Planetary Landing Systems

FIRST/ONLY PANEL MEETING
May 4, 2005

AGENDA

Meeting Location
National Academies Keck Center
Room 101
500 Fifth St, NW
Washington, DC 20001
Tel.: 202-334-3827 (Liz Albrigo)
Fax: 202-334-2482 (ASEB Office)
Here's a proposed agenda for the NRC presentation.

WEDNESDAY MAY 4, 2005

7:30 am *Continental breakfast available in Room 101*

Open Session

8:00 am	Welcome & Discussion of Review Process	Robert Tolson, Panel E Chair, and Karen Harwell, CRM Staff Lead
8:15 am	General Capability Roadmap Background from NASA	Rob Mueller, NASA APIO
8:45 am	Introduction for Human Planetary Landing Sys. Roadmap	Rob Manning, JPL
9:30 am	Mission Drivers for Human Landing Sys.	Harrison Schmitt, Ret. Astronaut
10:15am	Break	
10:30 am	AEDL Systems Engineering	Claude Graves, NASA JSC
11:15 am	AEDL Communications and Navigation Support	Rob Manning, JPL
11:45	*Lunch in Room 204*	
12:15 pm	Hypersonic Systems	Raj Venkatapathy, NASA ARC

NASA Capability Roadmap Review— Panel Meeting: May 4, 2005

1:00 pm	Supersonic-subsonic Decelerators	Juan Cruz, NASA LaRC
1:45 pm	Terminal Descent & Landing Systems	Aron Wolf, JPL
2:30 pm	*Break*	
2:45 pm	A-priori In-situ Mars Observations	Rob Manning , JPL
3:00 pm	AEDL Analysis, Test and Validation Infrastructure	Jim Arnold, NASA ARC
3:45 pm	Wrap Up	Rob Manning, NASA JPL
4:00 pm	Open Discussion / Q&A with NRC Panel	Robert Tolson, Chair
4:45 pm	*Break*	

Closed Session
(Committee Members and NRC Staff Only)

4:45 pm	Panel discussion of key issues	NRC Panel

Open Session

5:30 pm	Discussion of key issues with NASA	NRC Panel
6:00 pm	*Adjourn*	

NASA Capability Roadmap Review— Panel Meeting: May 4, 2005

List of NRC attendees May 4 in DC

1. Rob Manning - JPL (Co-Chair)
2. Harrison Schmitt - Apollo Consult. (Co-Chair)
3. Claude Graves - JSC (Deputy-Chair)
4. Ray Silvestri - JSC
5. Raj Venkatapathy - ARC
6. Jim Arnold -ARC
7. Brent Beutter –ARC
8. Tina Beard - ARC
9. Mike Wright - ARC
10. Juan Cruz - LaRC
11. Dick Powell - LaRC
12. Neil Cheatwood - LaRC
13. Aron Wolf - JPL
14. Rob Mueller - KSC
15. Mark Adler - JPL
16. Bobby Braun - Ga. Tech Consultant
17. Jim Mascierelli - Ball
18. Michelle Munk – MSFC
19. Cmdr Butch Wilmore – JSC
20. Rita Willcoxon – APIO/KSC
21. Doug Craig – NASA HQ
22. Barbara Kreykenbohm – NASA HQ
23. Carl Ruoff – JPL
24. Bonnie James - MSFC

A small number of HPLS committee members have requested that a telecon number be provided.

The following information is for members of the public who attend open sessions of NRC meetings:

This meeting is being held to gather information to help the panel conduct its study. This panel will examine the information and material obtained during this meeting, in an effort to inform its work. Although opinions may be stated and lively discussion may ensue, no conclusions are being drawn at this time and no recommendations will be made. In fact, the panel will deliberate thoroughly before writing its draft report. Moreover, once the draft report is written, it must go through a rigorous review by experts who are anonymous to the panel, and the panel then must respond to this review with appropriate revisions that adequately satisfy the Academy's Report Review committee and the chair of the NRC before it is considered an NRC report. Therefore, observers who draw conclusions about the panel's work based on today's discussions will be doing so prematurely.

Furthermore, individual panel members often engage in discussion and questioning for the specific purpose of probing an issue and sharpening an argument. The comments of any given panel member may not necessarily reflect the position he or she may actually hold on the subject under discussion, to say nothing of that person's future position as it may evolve in the course of the project. Any inference about an individual's position regarding findings or recommendations in the final report is therefore also premature.

Advanced Planning & Integration Office

Capability 6.0 Terminal Descent

Presenter:

Aron Wolf

Contributors: Carl Guernsey, Tom Rivellini, Ken Mease, Harrison Schmitt

Capability 6.0 Terminal Descent

- System or Systems required for:
  - 6.1 Guidance and navigation to a safe landing at the required target
    - Sensors and algorithms for pinpoint landing (within required distance from target)
    - Sensors and algorithms for hazard avoidance
  - 6.2 Propulsion to decelerate the lander from initial descent velocity to touchdown
    - Meet requirements to land a ~60MT vehicle
  - 6.3 Touchdown systems to protect from terrain hazards at touchdown and integrate all of the other elements of the EDL system and the mission payloads.
    - Provide surface access for astronauts, payload elements
    - Provide stability over a range of terrain slopes and hazards
    - Maximum impact loads not exceeding allowable levels

Requirements /Assumptions for Terminal Descent

- For human missions, need redundant / backup systems
  - Fail-safe design, multiple-string (dual? triple?) for system components essential to safe landing, where possible
    - "Launch vehicle-like" reliability for EDL
  - More redundancy / less tolerance for mission risk than Apollo's "three nines" (human risk), "two nines" (mission risk)
    - Abort scenarios are probably fewer and more difficult
    - Human Mars missions won't be done in rapid succession like Apollo
    - Commitment of resources is greater than Apollo
    - Human risk = mission risk to a greater degree than Apollo

Capability 6.1 Guidance and Navigation

Click to add subtitle

Benefits of 6.1 Guidance and Navigation

- Land within desired distance of the target
  - Essential to take advantage of any prepositioned resources
- Assure safety of crew and vehicle during landing
  - Essential for mission success

Current State of the Art for 6.1 Guidance and Navigation

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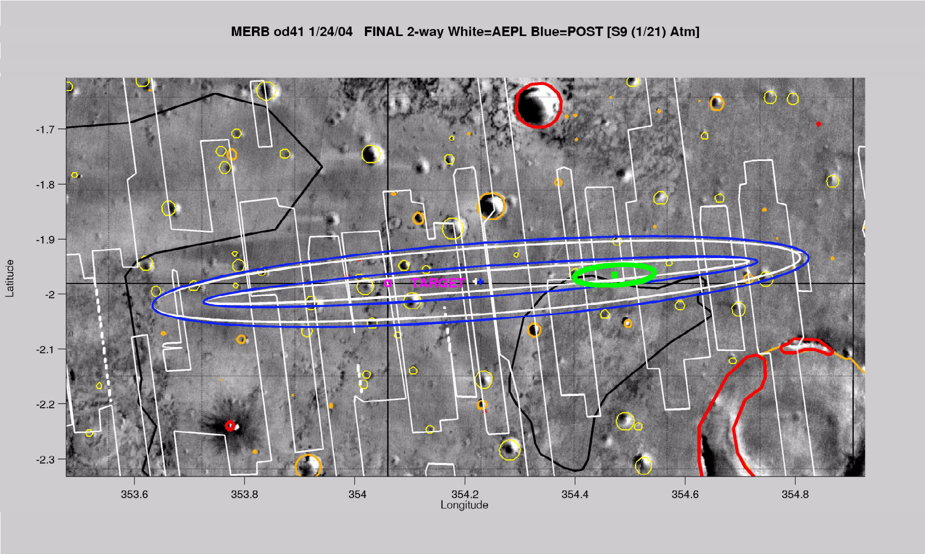
- **Apollo: Pinpoint landing (at body with no atmosphere), guided powered descent and "eyeball" hazard avoidance**
- **MER (2003): Ground-based navigation with unguided, ballistic entry, landing within ~40 km of desired target (3-**s)



- MSL (2009): Ground-based navigation with guided entry, landing within ~10 km of desired target (3-s)

Requirements /Assumptions for Guidance and Navigation

Advanced Planning & Integration Office

- **Need both Pinpoint Landing and Hazard Avoidance**
  - **"Hazard avoidance via pinpoint landing" not sufficient - need to actively avoid hazards to cope with aborts (what if you can't land at the selected site?)**
  - **Need fully automated Pinpoint Landing and Hazard Avoidance**
    - **Role of astronaut is to improve reliability of Pinpoint Landing / Hazard Avoidance system**
    - **Need more examination of human performance issues (performance under G-loading,…)**
- Pinpoint Landing and Hazard Avoidance GNC capabilities developed in robotic precursor missions
  - Extra levels of redundancy remain to be developed for human missions after robotic precursors
- Need navigation improvements in approach and EDL (S/C - S/C and/or OPNAV)
- Site elevation and wind requirement are critical design parameters
- Sensors may need to
  - Be able to land in conditions of high atmospheric opacity due to dust (tau = 3 - 5, "Los Angeles on a smoggy day", ~1/2 mi visibility?)
  - Be usable for night landings?
    - Winds are calmest
    - Increased atmospheric density could improve performance of aerodynamic decelerators for night landings

Maturity Level – Technologies for Guidance and Navigation

Advanced Planning & Integration Office

- "Human-rating" drives development beyond robotic precursors
  - Multiple types of sensors for human-rated Pinpoint Landing / Hazard Avoidance? (Cameras, lidar, radar, IR, data fusion)
  - Monitoring from orbital mission control?
  - Crew displays / interface: lots of thought to degree of autonomous operation vs manual override modes

Sub Capability	Integra
Pinpoint landing and hazard avoidance	Integrat pinpoint avoidan steerab

Capability 6.2 Propulsion Systems

Click to add subtitle

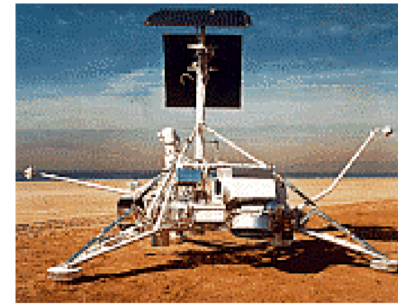
Benefits of 6.2 Terminal Descent Propulsion Systems

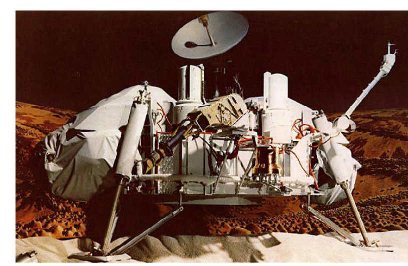
Advanced Planning & Integration Office

- Required to provide controlled deceleration for safe landing (of 30 - 60Mt vehicle)
  - Utility of aerodynamic decelerators is limited due to Mars' thin atmosphere
    - Terminal velocities of ~50 - 150 m/s on these systems require use of propulsive deceleration to near zero
- Controlled touchdown is essential for lander stability after landing
  - Limited vertical velocity component
  - Near zero horizontal velocity component
  - Maintain attitude and attitude rates within acceptable limits

Current State of the Art for 6.2 Terminal Descent Propulsion Systems

- **Terminal descent propulsion systems for soft landers have used**
  - **Solid Rocket Motor (SRM) + Throttled Storable Bipropellants (Surveyor)**
  - **Throttled Storable Bipropellants (Apollo)**
  - **Throttled Storable Monopropellants (Viking)**
- **SRMs have been successfully used for “hard” landers (MPF, MER)**





Requirements /Assumptions for Terminal Descent Propulsion Systems

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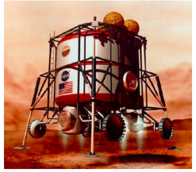
- Landed payload mass of order 30 - 60 Mt and max T/W of 5
- Rapid, deep throttling required
  - 10:1 throttle range
  - 150 millisec throttle response times



- High thrust systems used for initial deceleration may not be optimal for terminal descent
    - If supersonic propulsive system is required, may need two systems (one for initial supersonic deceleration, one for final descent)
    - Limited capability of aerodynamic decelerators at Mars may drive need to thrust while still supersonic (discussed in Section 4)
- Need terminal descent propulsion capability of ~150 m/s • V
  - Separate “braking” • V requirements:
    - ~ 800 m/s on Mars (done with aerodynamic decelerators in missions to date)
    - ~ 1700 m/s on the Moon
- High density, compact systems needed
  - Packaging in aeroshell and crew egress considerations will demand this

Maturity Level – Technologies for Propulsion Systems

- **Significant new propulsion system h/w development needed for Moon and Mars landings**
  - Challenging even for "mature" technologies
    - Industry infrastructure and knowledge base has deteriorated significantly since Apollo era
  - Parallel developments should be considered
    - Apollo example: switched ascent engines in 6 months

Sub Capability	Integr
Throttled	Cavita
Monopropellant	Viking

Capability 6.3 Touchdown Systems

Click to add subtitle

Benefits of the 1.1 Touchdown Systems

- **Primary role of the TD system is to integrate all of the other elements of the EDL system and the mission payloads.**

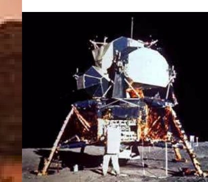
- **A well designed system will minimize the compromises imposed on these other systems while maximizing landing performance.**

- ***TD systems must be designed after all of the other major systems have been identified and defined.***
  - **Eg:**
    - **Aeroshell shape and internal volume constraints**
    - **Parachute technology and deployment schemes**
    - **Separation architecture**
    - **Payload accommodation**

Current State-of-the-Art for Touchdown Systems

- Apollo landed 18,000 kg

- Manned Mars Missions will require 3X this mass:
  - 60,000 kg



Current State-of-the-Art for Touchdown Systems

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Legs

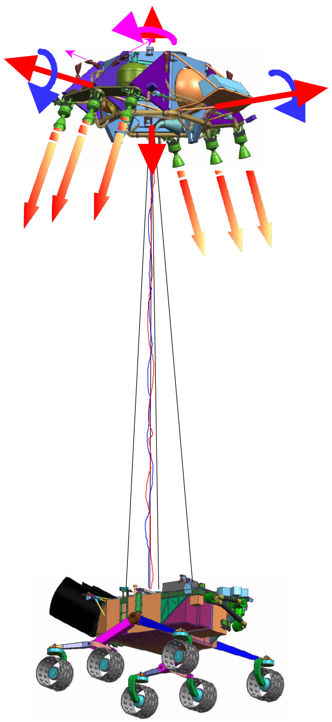
Lunar Surveyor:	7 landings
Apollo Lunar Module:	6 landings
Lunokhod Lander:	2 landings
Viking Lander:	2 landings
Mars Polar Lander:	failed in flight

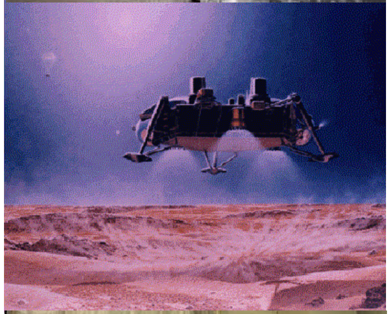
Airbags

Luna Missions:	2 landings
Soviet Mars 96:	failed at launch
Pathfinder & MER:	3 landings
Beagle 2:	failed in flight

Sky Crane System

This is a very new concept being developed for Martian robotic landers
Applicability to manned missions is TBD





Leg technology is the most applicable for large manned and cargo systems.

Leg technology is very scaleable.

Requirements /Assumptions for Touchdown Systems

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– Three categories of Mars landers drive the technology needs
  - Human (+ habitat?)
  - Cargo (+ habitat?)
  - Ascent vehicle
  - Mass: 60,000 kg to the surface, for each category?

– Human factors: peak g's (low, for landing), surface access, visibility (see surface during landing)
  - Near-zero velocity at touchdown

– The "lander" is the system integrator: ***It*** accommodates and separates away all of the EDL and surface stages.
  - Requirements: Launch loads, Cruise interfaces, Payload deployment/egress
  - Components: Heatshield, parachutes, egress systems
  - Form Factor: must fit into Earth launch vehicle as well as Mars entry vehicle

Maturity Level – Capabilities for Touchdown Systems

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– Current state-of-the-art of Landing systems

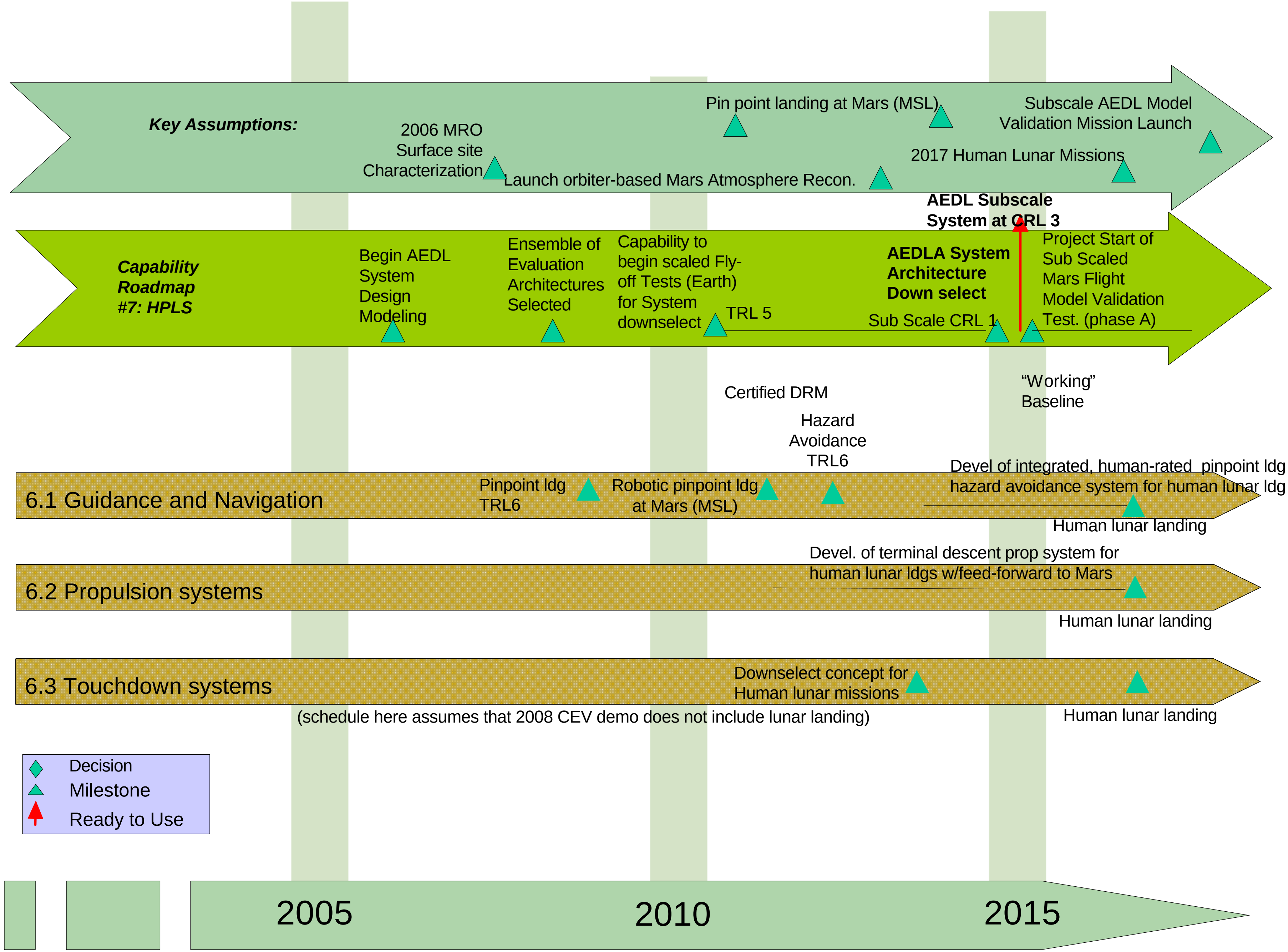
- No major technology gaps identified yet:
- Major technology leaps can only happen as the ***system design*** process matures and generates specific landing system requirements.
- Existing state of the art can accommodate most landing system concepts that have been identified to date.
- Virtually all major technology components fall into the category of enhancing technologies as opposed to enabling.
- Eg: lower mass systems.
- POSSIBLE EXCEPTION:
- The Sky Crane landing system has not been evaluated by human exploration community.
- If deemed applicable, there would be major technology gaps to be filled in.

Good system engineering of known / existing technology is what's needed

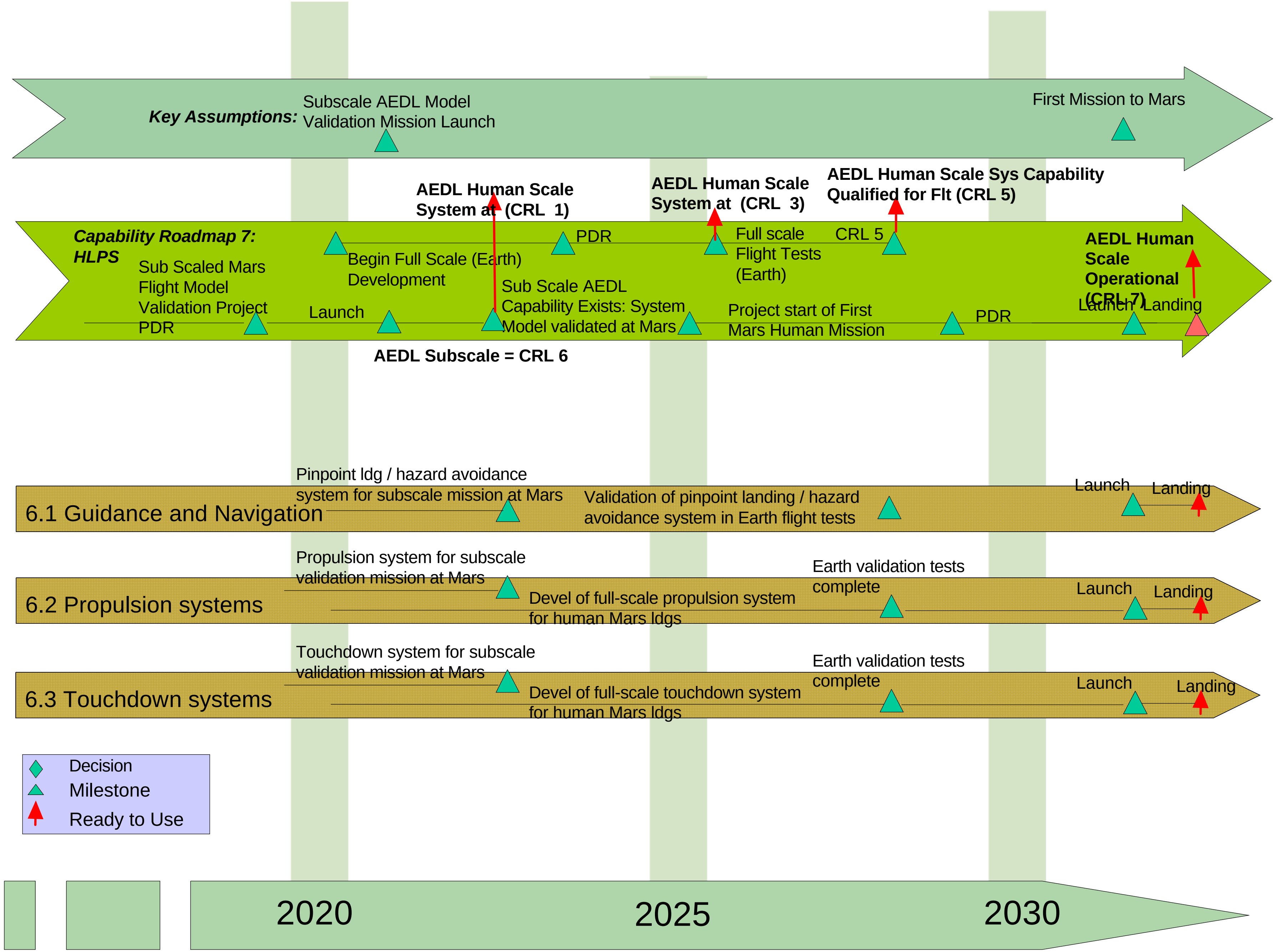
Metrics for Touchdown Systems

– System reliability, robustness, operability (will it work?)

Team 7: Human Planetary Landing Systems - Terminal Descent Capability Roadmap



Team 7: Human Planetary Landing Systems - Terminal Descent Capability Roadmap



5.0 Aerodynamic and Propulsive Decelerator Systems

Presenter: Juan R. Cruz

Sub-Team Lead

Contributing Members

Richard Powell - LaRC, James Masciarelli - Ball Aerospace, Glenn Brown - Vertigo Inc., Al Witkowski - Pioneer Aerospace, Carl Guernsey, JPL

Presentation Outline

Part I - Introduction

- Capability Breakdown Structure
- Decelerator Functions
- Candidate Solutions

Part II - Performance and Technology

- Capability State-of-the-Art
- Performance Needs
- Candidate Configurations

Part III - Possible Technology Roadmaps

- Capability Roadmaps

Capability Breakdown Structure

Advanced Planning & Integration Office

Human Planetary Landing Systems
CRM # 7

Aerodynamic an
Propulsive
Decelerators
5.0

5.1 Supersonic Aerodynamic Decelerators
5.2 Subsonic Aerodynamic Decelerators
5.3 Supersonic Propulsive Decelerators
5.4 Systems Design, Development, Testing, and Qualification

Decelerator Functions

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Decelerators typically provide one or more of the following functions in planetary landing systems:

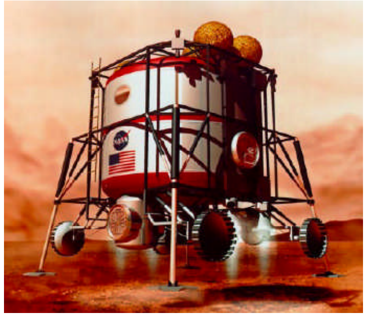
- Deceleration from supersonic to subsonic speed
- Controlled acceleration
- Minimize descent rate
- Provide specified descent rate
- Provide stability (parachute drogue function)
- System deployment (parachute pilot function)
- Provide difference in ballistic coefficient for separation events
- Provide height
- Provide timeline
- Provide specific state (e.g., altitude, location, speed for precision landing)

Aerodynamic and Propulsive Decelerator Capabilities for Mars - Integrated Mission Architecture

Options for Hypersonic Decelerators

Parachutes

Inflatable Decelerators



Propulsion

Options for Supersonic & Subsonic Decelerators

Options for Terminal Descent Systems

5.0 Aerodynamic and Propulsive Decelerator Candidate Solutions

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

	Candidate Mission Scenario	Candidate Solutions
Mars Descent	Mars human and cargo landing	Supersonic parachutes, subsonic parachute clusters Inflatable decelerators Supersonic and subsonic propulsion <u>Combination</u>
Earth Return (Mars)	Human direct entry or landing from orbit	Subsonic parachute cluster Parafoils Lifting body/wings
Earth Return (Lunar)	Human direct entry or landing from orbit	Subsonic parachute cluster Parafoils Lifting body/wings

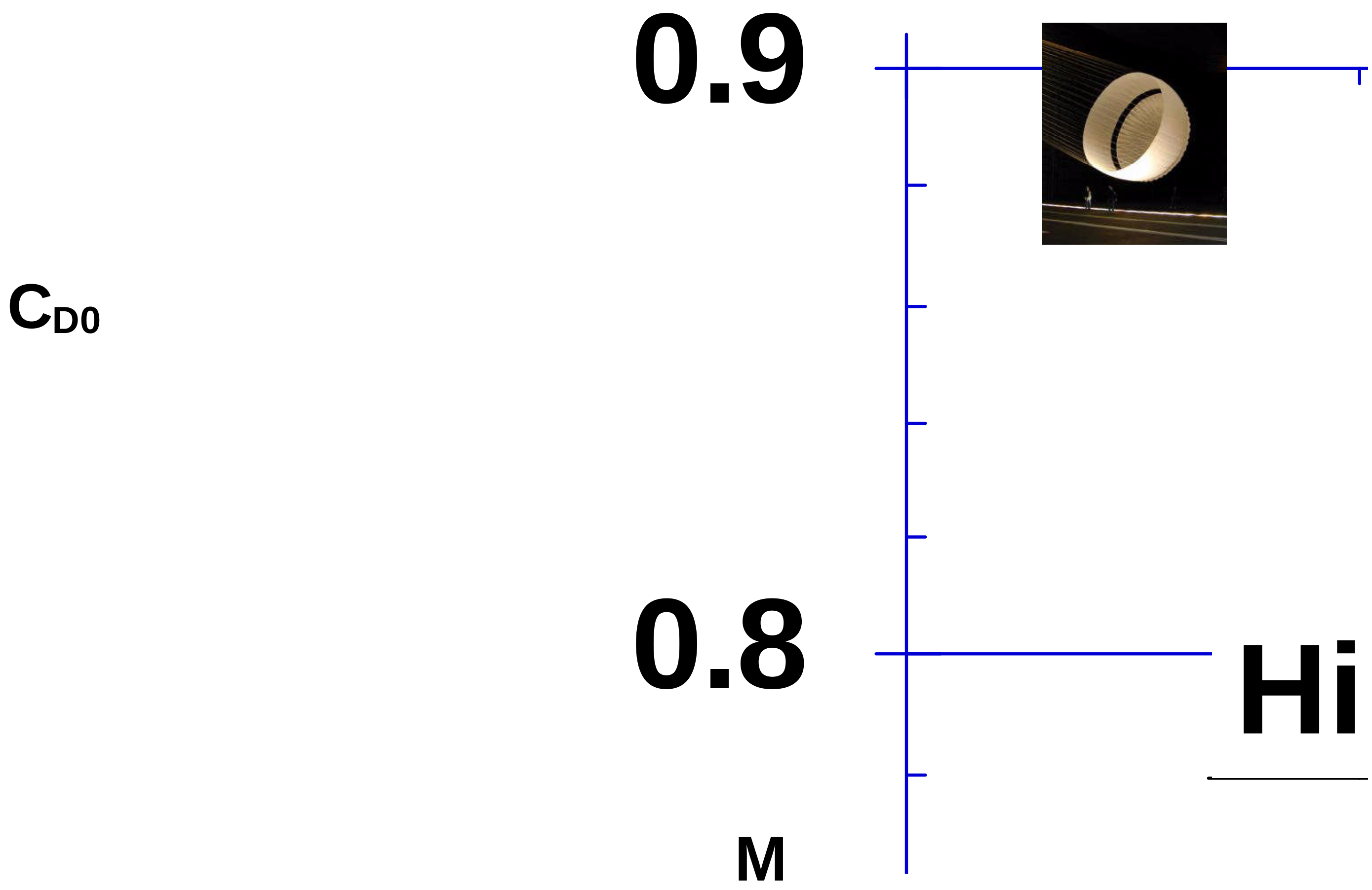
Current Mars Aerodynamic Decelerator Technology Capabilities and Limitations

Advanced Planning & Integration Office

Supersonic Parachutes

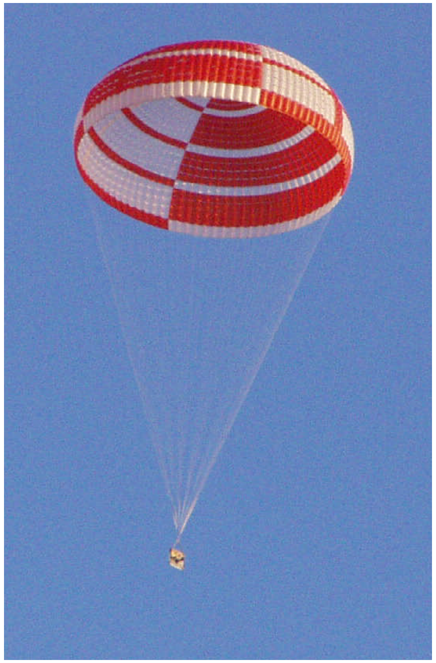
- Disk-Gap-Band (DGB) heritage parachutes
- Deployment at Mach number M • 2.1 (Viking heritage)
- Deployment at dynamic pressure q • 800 Pa (MER heritage)
- Nominal diameter, D_0 • 16.15 m (Viking heritage)
- Maximum drag area, $C_D S$ • 108 m^2 (approximate for Viking parachute with D_0 = 16.15 m at M = 2.1)
- No reefing, clustering, or glide control
- Mortar deployment

Viking DGB Parachute Drag Model

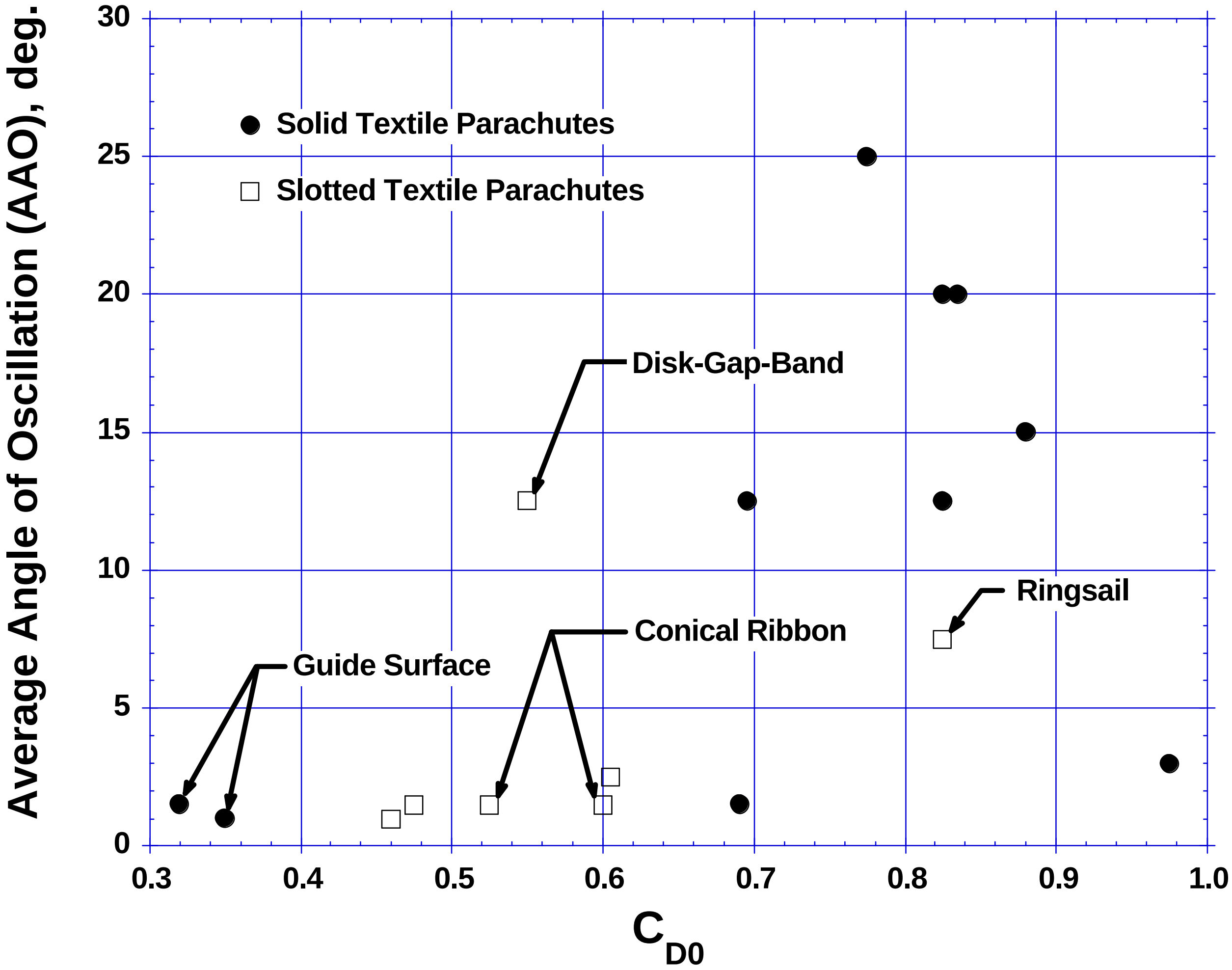


Subsonic Parachutes

- DGB heritage parachutes (see supersonic parachutes)
  - Maximum drag area, C_DS • 139 m^2
- Ringsail heritage parachutes
  - Beagle 2, MTP Subsonic Parachute, extensive Earth-flight experience (e.g.,Mercury, Gemini, Apollo)
  - Deployment at Mach number M • 0.8 (MTP Subsonic Parachute)
  - Nominal diameter, D_0 • 33.5 m (MTP Subsonic Parachute)
  - Maximum drag area, C_DS • 679 m^2
  - Reefing
  - No clustering or glide control



Drag vs Stability Comparison



Inflatable Supersonic Decelerators

- No inflatable supersonic decelerators have been flown in planetary exploration missions
- Several concepts proposed, some tested
- Some concepts show promise

Materials

- Kevlar, Nylon, Polyester (Dacron) are “qualified” materials
- Vectran, Spectra, Technora, Nextel, Zylon now used in some “qualified” applications
- Coated materials (impermeable, ablative) have been used for munitions programs

Current Mars Aerodynamic Decelerator Technology Capabilities and Limitations

Advanced Planning & Integration Office

Analysis Methods

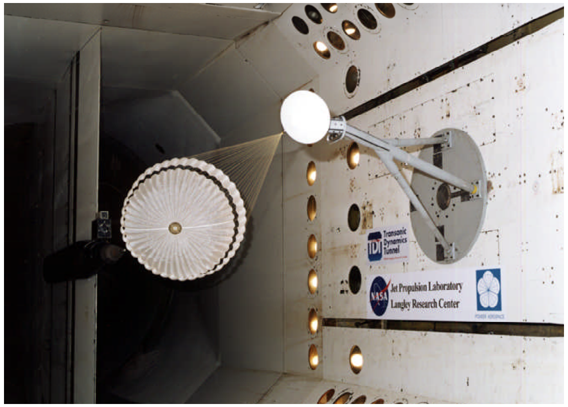
- Current methods have a significant empirical component (need data to calibrate)
- First-principle methods (e.g., Fluid Structures Interaction analyses) are available but validation is lacking
- Scaling of results (physical size and test conditions) possible but poorly understood

Test Methods

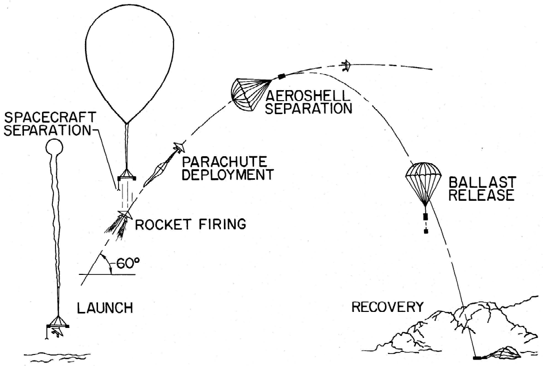
- Need improvements in our ability to adjust results of all testing to other scales and different conditions
- Wind tunnel testing (sub-scale and full-scale)
  - Available facilities at risk of closing
- Low altitude flight testing (subsonic)
- High altitude flight testing (supersonic and subsonic)
  - Sounding rocket
  - Balloon
  - Balloon/Rocket

Current Earth and Mars Aerodynamic Decelerator Technology Capabilities and Limitations

Advanced Planning & Integration Office

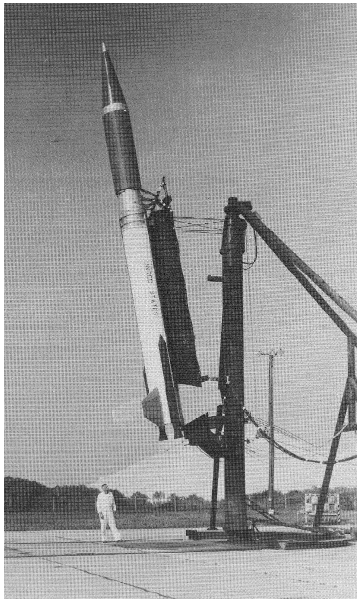


Sub-Scale Wind Tunnel Testing

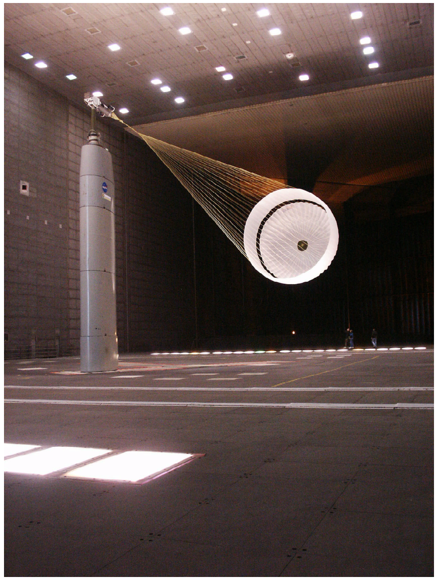


Balloon/Rocket

Full-Scale Flight Testing



Sounding Rocket

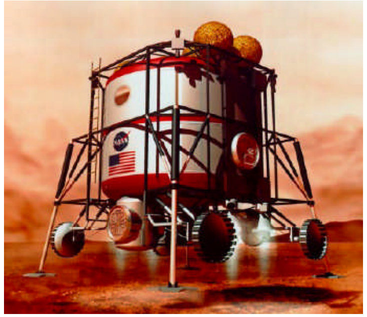


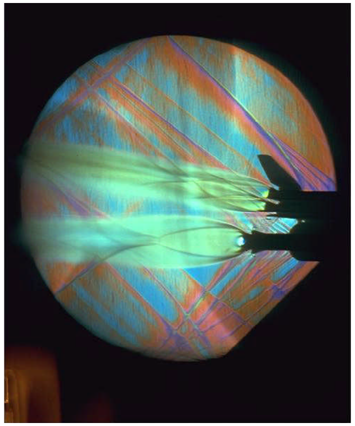
Full-Scale Wind Tunnel Testing

Mars Propulsive Decelerators

Advanced Planning & Integration Office

- Supersonic deceleration at Mars may require a propulsive component
  - An aerodynamic-decelerator only solution may not be realistic (extremely large parachutes)
- Use of retrorockets to decelerate from supersonic to subsonic speeds has issues
  - Initiation of thrusting is likely to require blow-out covers in TPS
    - MER TIRS motor covers are a primitive example
  - Thermal protection must be provided while vehicle is enveloped in high enthalpy recirculating exhaust
  - Plume / freestream interaction will be fundamentally unsteady
    - Freestream Mach number and dynamic pressure change rapidly
    - Rapidly changing aerodynamic forces on aeroshell will require significant control authority, especially in the transonic regime
- Development of modeling capability for this “inverse base flow” problem will be likely require subscale wind tunnel tests and flight testing.





Mars: Performance Needs

Supersonic-to-Subsonic Deceleration

- Larger aero decelerator drag area (C_DS) at supersonic speeds
- Aero decelerator drag area control at supersonic speeds (loads and trajectory)
- Aero decelerator deployment at Mach number > 4
- Propulsive supersonic deceleration

Subsonic Terminal Descent

- Larger aero decelerator drag area (C_DS) at subsonic speeds
- Large propulsive descent system

Pinpoint Landing Capability

- Ability to make parachute glide in a chosen direction
- Propulsive descent system guidance and hazard avoidance

Earth and Mars: Aerodynamic Decelerators Technology Needs

Advanced Planning & Integration Office

Fluid-Structures Interaction Analyses

- Joining of Computational Fluid Mechanics (CFD) with structural Finite Element Methods (FEM)
- Allows for numerical design optimization
- Can yield insight on scaling of test results (physical size and test conditions)
- Can yield values of quantities usually obtained by test (e.g., C_{D0})
- Can yield values of quantities that are difficult to obtain by test (e.g., dynamic aero coefficients - C_{mq})
- Has possibility of reducing testing and qualification costs by decreasing number of tests
- Works with trend of cheaper computing
- In need Verification (are we solving the equations right?) and Validation (are we solving the right equations?) to obtain level of trust suitable for exploration missions
- <u>Must-have technology</u>

Earth and Mars: Aerodynamic Decelerators Technology Needs

Advanced Planning & Integration Office

Scaling

- Ability to scale test results to the system size and test conditions
- May allow for relevant sub-scale testing of systems in flight at supersonic conditions
- Must-have technology for large Mars systems

Testing

- Adequate wind tunnel and flight test (e.g., high-altitude balloons, sounding rockets) capabilities must be retained and in some cases expanded
- Capability to flight test supersonic systems will become a necessity for Mars systems

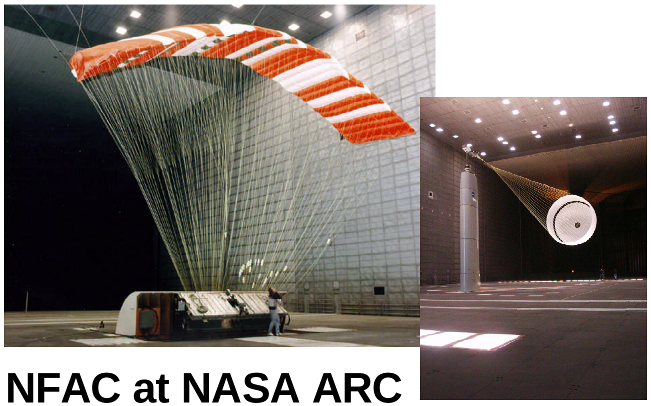
Materials

- Development of new space-qualified materials will have a significant impact on aerodynamic decelerator design (i.e., mass to drag area ratio)
- Materials with high temperature capabilities for parachutes (M > 2.5) and inflatable decelerators will be required

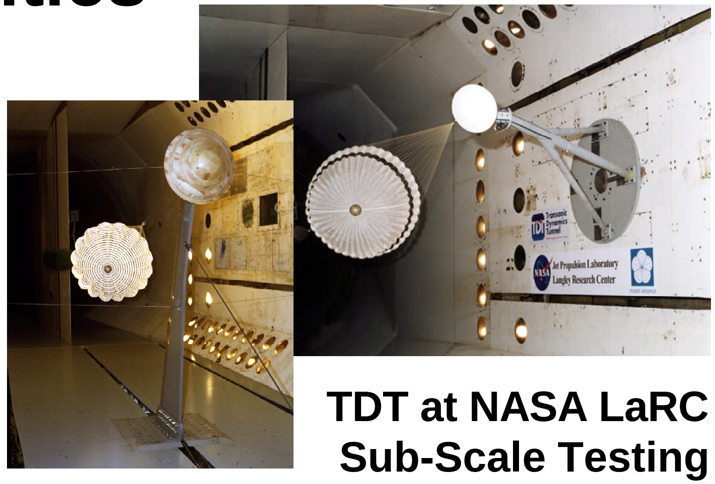
Earth and Mars: Aerodynamic Decelerators Technology Needs

Advanced Planning & Integration Office

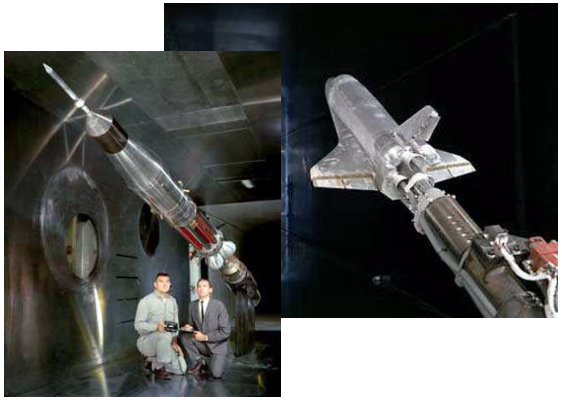
Key Wind Tunnel Testing Facilities



NFAC at NASA ARC
Full- and Sub-Scale Testing
Subsonic



TDT at NASA LaRC
Sub-Scale Testing
Subsonic and Transonic



10’ x 10’ Supersonic at NASA GRC
Sub-Scale Testing Supersonic

Possible Mars Configurations

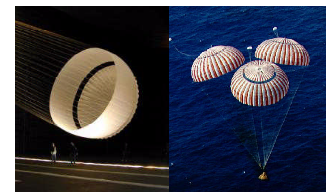
2 Metric Ton Entry Mass Level

Disk-Gap-Band Supersonic Parachute
Ringsail Subsonic Parachute (single canopy)

4 Metric Ton Entry Mass Level

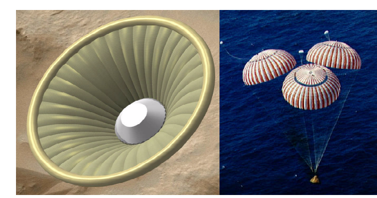
Disk-Gap-Band Supersonic Parachute (reefed)

Ringsail Subsonic Parachute (cluster)



10 Metric Ton Entry Mass Level

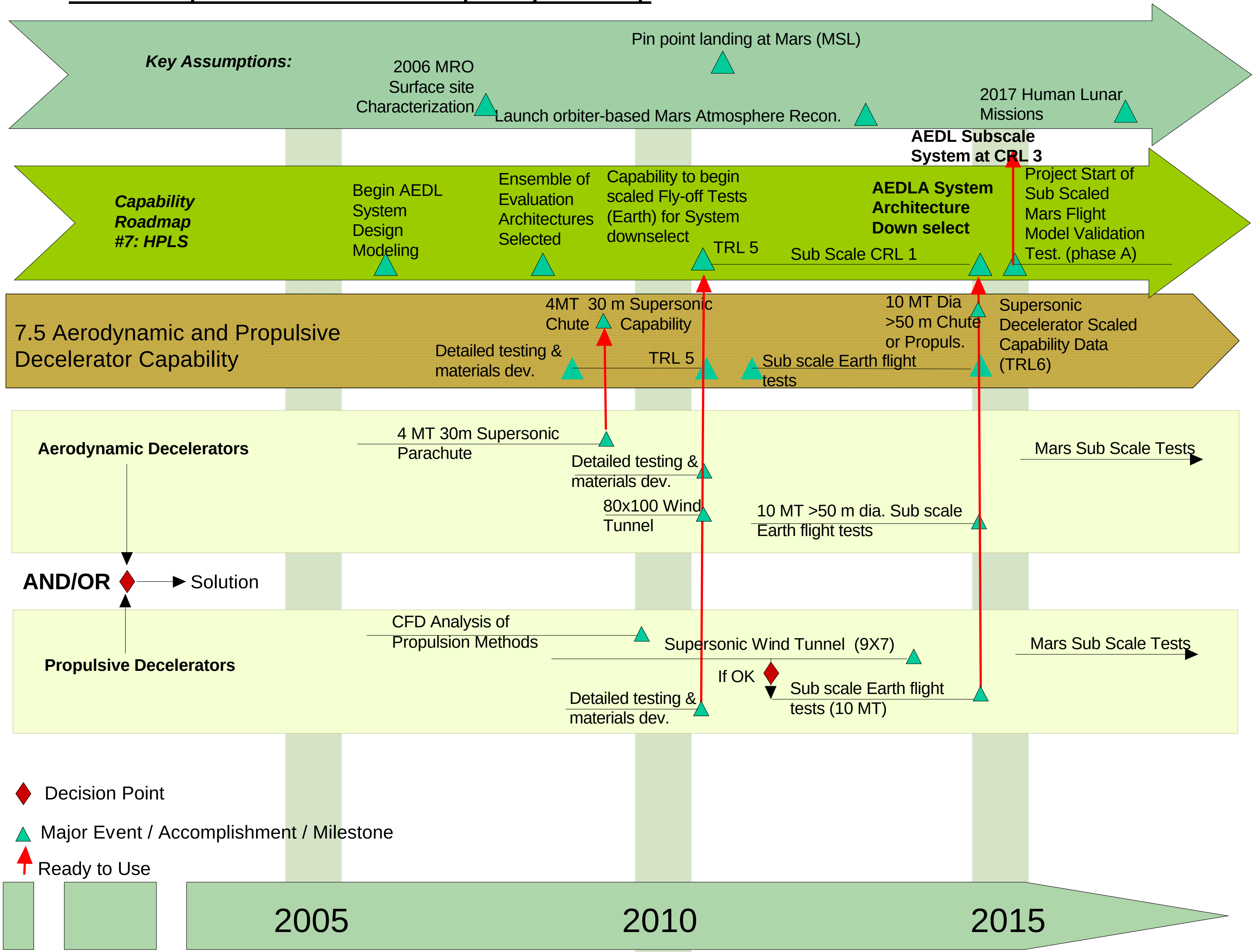
Inflatable Supersonic Decelerator
Ringsail Subsonic Parachute (cluster)



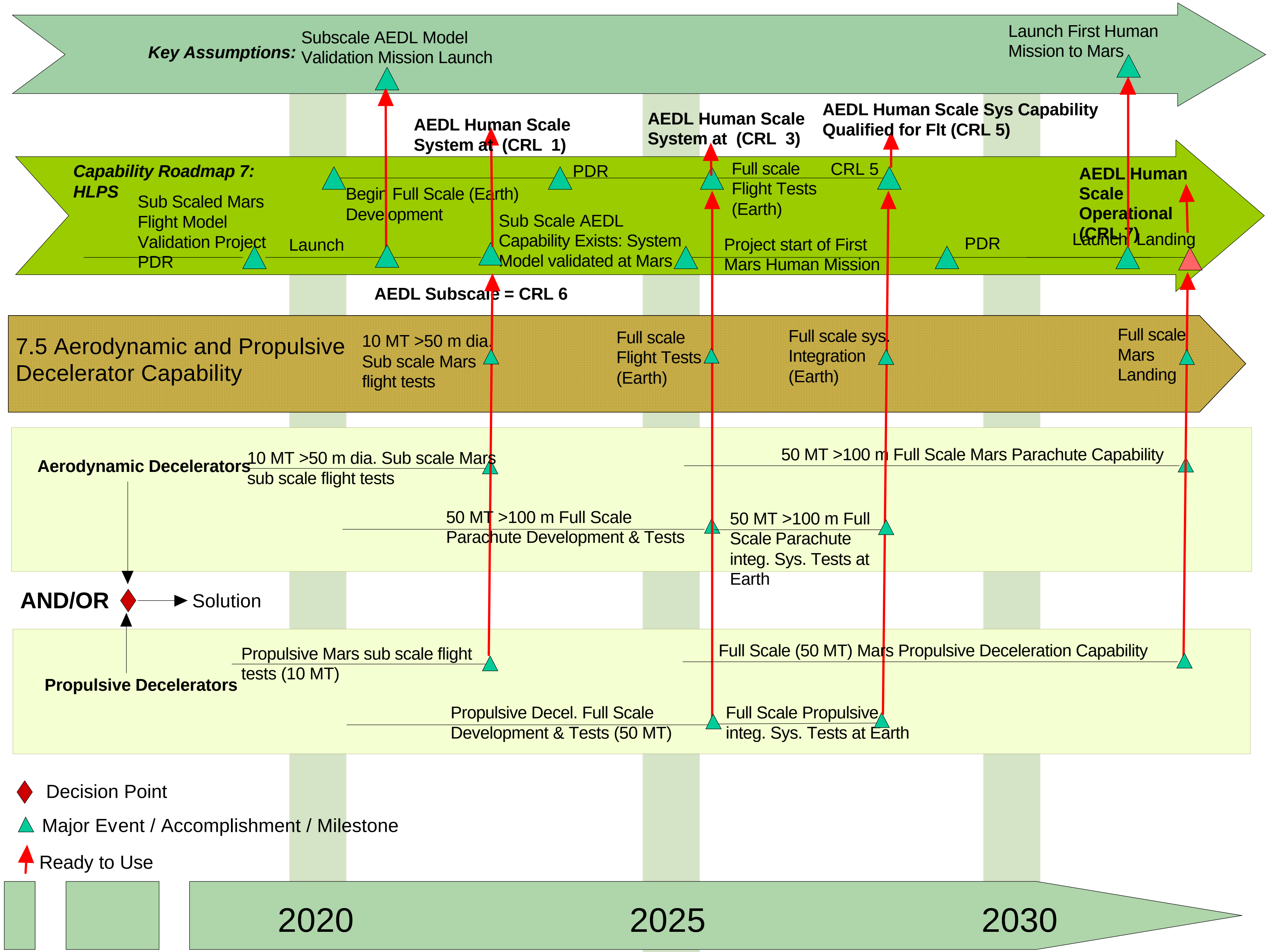
50 Metric Ton Entry Mass Level (Human)

Inflatable Supersonic Decelerator
Ringsail Subsonic Parachute (cluster)
Propulsion Assisted Deceleration

Team 7: Supersonic Decelerators Capability Roadmap



Team 7: Supersonic Decelerators Capability Roadmap



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Backup Material

Symbols and Acronyms

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Symbols

C_{D0}	drag coefficient
C_DS	drag area
C_{mq}	derivative of pitching moment with respect to pitch rate
D_0	nominal diameter
M	Mach number
q	dynamic pressure

Acronyms

AAO	Average Angle of Oscillation
ARC	Ames Research Center
CFD	Computational Fluid Dynamics
DGB	Disk-Gap-Band
FEM	Finite Element Method
FSI	Fluid Structures Interaction
GRC	Glenn Research Center
LaRC	Langley Research Center
MER	Mars Exploration Rover
MT	Metric Ton
MTP	Mars Technology Program
NFAC	National Full-Scale Aerodynamics Complex
TDT	Transonic Dynamics Tunnel
V&V	Verification and Validation
WT	Wind Tunnel

4.0 Hypersonic Systems

Presenter: Ethiraj (Raj) Venkatapathy

Sub-Team Lead

Contributing Members:

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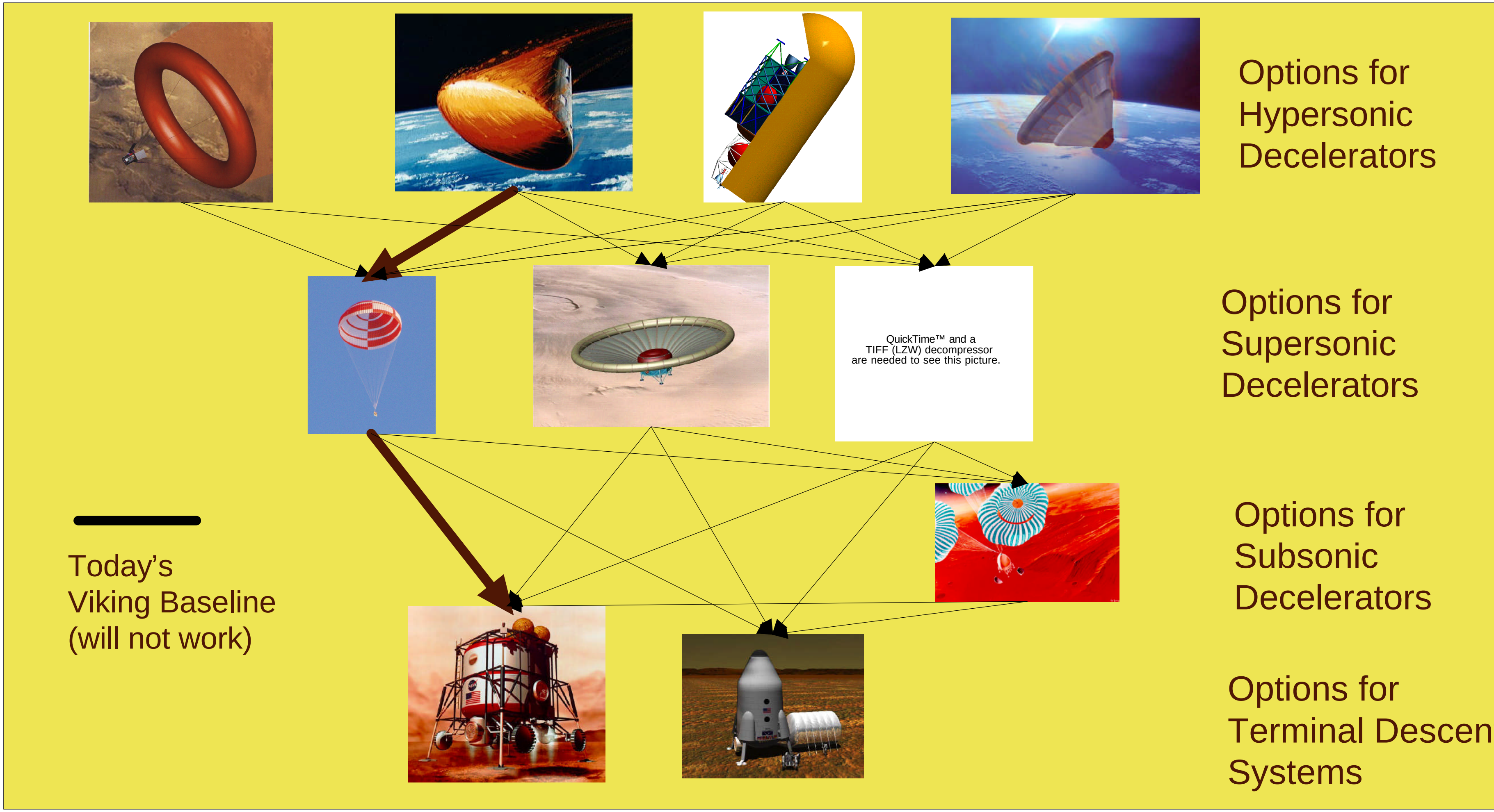
4.0 Hypersonic Systems - Outline

- Capability Description
- Some Initial Thoughts
- Capability State-of-the-Art, Gaps and Requirements
- Capability Roadmap
- Candidate Technologies
- Metrics

Flight Phases

- **Mars Entry:**
  - **Aerocapture & Hypersonic Entry**
- **Earth Return** (**Lunar and Mars**)
  - **Aerocapture & Hypersonic Entry**

Which will it be?



- Hypersonic System has to be synergistic with descent and landing system and minimize the Mars EDL mass.

Hypersonic Systems Capabilities for Integrated Mission Architecture

	Candidate Mission Scenario	Candidate Capabilities
Mars Entry	Mars cargo aerocapture Mars cargo aerocapture followed by Entry Mars human and cargo aerocapture followed by Entry	Rigid Aeroshell Flexible /Deployables <u>Combination</u>
Earth Return (Mars)	Direct Entry Entry with skip-out Aerocapture followed by Entry	<u>Rigid Aeroshell</u> Flexible/ Deployables Combination
Earth Return (Lunar)	Direct Entry Entry with skip-out Aerocapture followed by Entry	<u>Rigid Aeroshell</u> Flexible / Deployables Combination

4.0 Some Initial Thoughts

- Greater need to architect system around the “human system”
  - Need to ensure that hypersonic deceleration do not disable pilots.
- Lack of credible concept for human scale Mars EDL means
  - Candidate hypersonic systems capabilities have to be fully explored and exploited for optimal EDL performance
    - Need to establish both requirements as well as performance and operational limitations for flexible and rigid hypersonic systems, early enough, to impact architecture decision
    - Precision controlled Aerocapture has never been done into any planetary atmosphere but significant body of evidence exist to show this is achievable for capture into a low energy orbit
    - Aerocapture and Entry integration via early system engineering /system analysis studies to help set requirements for hypersonic systems DDT&E
    - Obtaining engineering data from Robotic Mars mission to establish confidence in hypersonic system design and analysis methods for human Mars mission

4.0 Some Initial Thoughts (cont.)

– Large mass and volume system
  - Need improved or new ground test facilities
    - Entry heating conditions at Mars will be expected to be dominated by both convective and radiative heating and Entry and Aerocapture Systems have to be tested and validated for the flight environment
    - Need ground based testing and flight validation
  - Human rating and qualification will be more demanding than robotic missions
    - Reliability of systems such as TPS, Flexible/Deployables for Human missions will require higher level of confidence and demonstrating reliability in the system and sub-systems
  - Establishing the right combination of higher fidelity analysis, ground testing, scaled flight and integrated system testing and full scale component testing for V&V prior to full scale flight
  - Large mass and volume entry required for human Mars missions will be more demanding from manufacturing /scalability/ qualification

Capability Breakdown Structure

Human Planetary Landing Systems CRM # 7

Hypersonic Systems 4.0

4.1 Entry Vehicle configurations (Rigid)

4.2 Deployable / Inflatables (Flexible)

4.3 High-Performance, high reliability TPS for both rigid and flexible

4.5 Aero-thermo-structural Dynamics Design

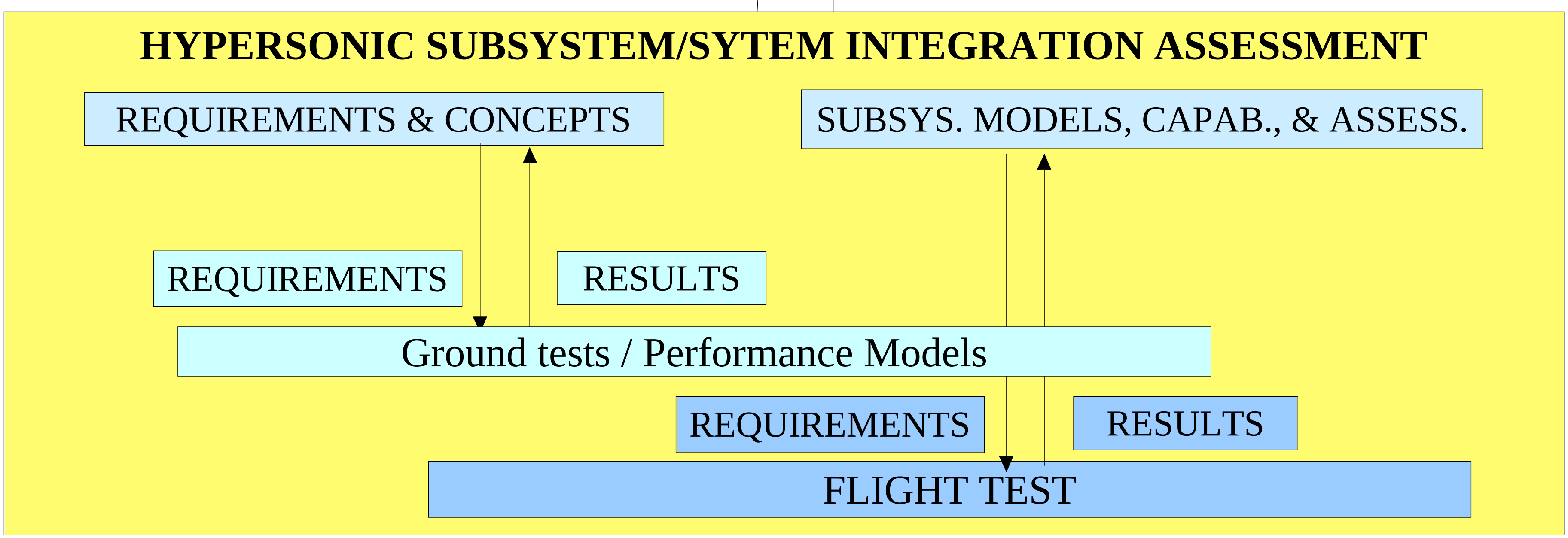
4.4 Aerocapture / Entry GN&C

4.6 Sensors and ISHM

4.7 Ground and Flight Testing

4.8 Aerocapture & Entry System

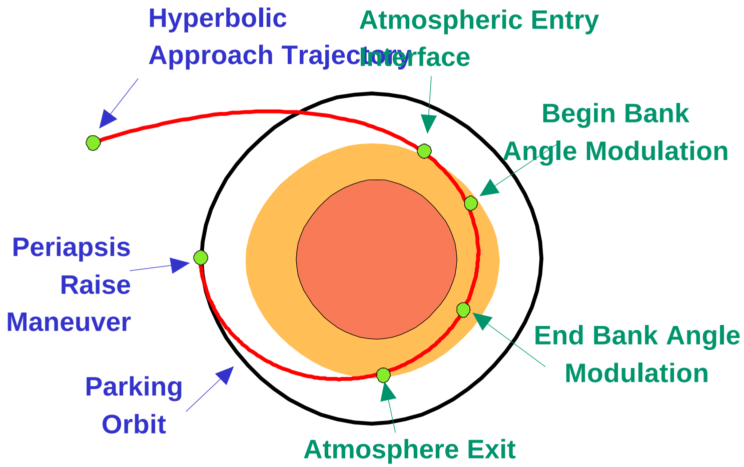
4.0 Hypersonic Capability Development



State-of-the-Art and Gaps

4.0 Current State-of-the-Art & Gaps

- **Precision controlled Aerocapture and Aerocapture/Entry Integration**
  - Never been done into any planetary atmosphere. Significant body of work shows that technology for aerocapture into low energy orbits is ready for program application
  - Aerocapture followed by Entry may require either multiple use ablative TPS and/or multiple aeroshell/TPS systems
- **Aerocapture capability, particularly for aerocapture from up to 13 km/s into high energy orbit may be required for Earth return from Mars.**
- **Aerocapture System architecture capability is required for:**
  - 70 - 100 MT at Mars with arrival speed (6 - 10) km/s



4.0 Current State-of-the-Art & Gaps (Cont.)

- **GN& C for Aerocapture:**
  - **SOA**: Aerocapture GN&C using bank-angle control only is mature (TRL 6) for robotic missions with rigid aeroshells and atmospheric exit velocity <80% escape speed
    - Apollo capsule had human-rated aerocapture-like guidance mode (never flown)
    - Aeroassist Flight Experiment (1990's), Mars 01 Aerocapture Mission, CNES/NASA Mar Premier Orbiter all developed mature aerocapture guidance algorithms
    - Multiple detailed systems analysis for multiple destinations (Titan, Neptune, Venus, Mars) have all demonstrated that guidance algorithms can be developed that provide the required exit conditions
  - **Gap:** Aerocapture guidance algorithms with atmospheric exit velocities > about 90% escape speed are immature and may required direct drag control (e.g. angle of attack modulation)

- **GN& C for Aerocapture (cont.)**
  - Very limited assessment of guidance algorithms and no flight experience for ballutes with very low ballistic coefficients that fly at very high altitudes and low aerodynamic heating rates
    - Determination of vehicle aerodynamics including control interactions required
    - Guidance algorithms developed for rigid aeroshells expected to be applicable for low ballistic coefficient systems but interaction of the guidance with the flexible structure and the control system is a concern that must be addressed
  - Passive angle-of-attack control needs to be assessed for the HPLS systems
    - Addition of direct drag modulation should be considered to increase robustness
  - Natural maturation of approach navigation to support robotic missions is adequate for aerocapture
  - Inertial navigation system during atmospheric flight is sufficiently accurate

4.0 Current State-of-the-Art & Gaps (cont.)

- **GN& C for Entry to decelerator (e.g. parachute) deployment**
  - State of the art
    - Apollo demonstrated precision entry (position error < 10 km)
    - Apollo entry guidance adapted for Mars Science Laboratory (MSL) – proven through high fidelity flight simulations to provide precision entry capability (2-10 km range error at parachute deploy)
    - 3-axis control using reaction control system (thrusters)
    - Navigation is IMU-based until heatshield jettison (2.5 km AGL) – then radar data available
  - Implications for human missions
    - Direct measurement of altitude and altitude rate required
    - Mars relative navigation required
    - Pinpoint landing and deceleration control may required direct drag modulation
    - More detailed information on Mars climate (density and wind profiles) required for vehicle development and evaluation
    - Guidance algorithms developed for rigid aeroshells expected to be applicable to flexible aeroshells with low ballistic coefficient but interaction of the guidance with the flexible structure and the control system must be addressed
    - GN&C for very low ballistic coefficient inflatable aeroshells has not been assessed

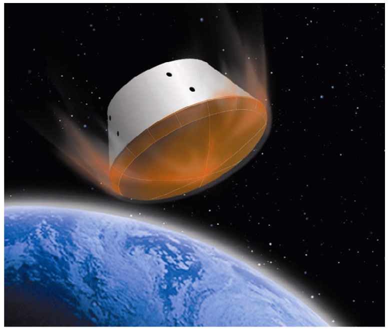
Aerocapture Guidance, Navigation and Control

Capability Objective and Current Capabilities

- **Do a flight experiment to validate aerocapture guidance, navigation and control (GN&C) technology**
- **Aerocapture GN&C is the central technology required to make aerocapture work**
  - The same algorithms and control systems will work at all destinations
  - Any solar system body with an atmosphere can potentially benefit from aerocapture technology. Multiple robotic and human missions in SMD and ESMD are identified as needing or benefitting from aerocapture
  - Aerocapture is a mission critical function. End users want to see a successful flight validation experiment before committing to first use.
- **Aerocapture GN&C is currently at TRL 6**
  - Existing spacecraft avionics, navigation sensors and attitude control systems suffice for aerocapture
  - Specialized guidance algorithms have been extensively evaluated in high fidelity software simulators applying the same methodology used in entry system trajectory analyses

Capability Developed and Metrics

- **Highly robust aerocapture performance**
  - System designed for >99% capture reliability as confirmed by extensive Monte Carlo simulations of the end-to-end system
  - Guidance system will be applicable to all planetary destinations
- **Resource impacts**
  - Specialized guidance algorithm requires < 1000 lines of code
  - 3 axis control with 5 deg/s2 bank angle acceleration
  - Standard aeroshell to provide aerodynamic functionality and environmental protection of payload

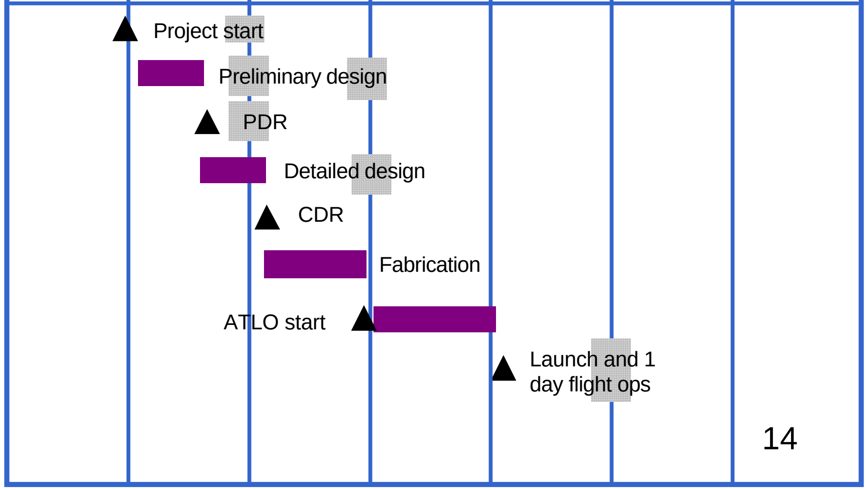


Development Approach

- **Design an appropriate flight test experiment**
  - Leverage mature aeroshell technology using low lift to drag (~0.2) blunt body sphere-cone shapes
  - Studies to date indicate that an Earth orbit mission is sufficient using an aerocapture maneuver to change from a high energy elliptical orbit to near circular orbit
  - An atmospheric delta-V of 1-2 km/s is sufficient to validate the performance of the aerocapture guidance system
- **Employ the algorithms and software developed using the bank angle control**
  - Lift to drag ratio is nominally constant
  - Guidance commands the bank angle of the vehicle in real time to position the lift vector and thereby modulate the trajectory
  - Inertial guidance is used to determine vehicle state in real time
  - Guidance algorithm is highly accomodating of potential uncertainties in atmospheric properties and approach navigation errors
- **Complement the flight test with extensive pre-flight simulations and post-flight data evaluation**
  - NASA has a well established methodology for this based on decades of entry vehicle missions

Schedule

FY	06	07	08	09	10	11	Total
$M	TBD	TBD	TBD	TBD	TBD	TBD	TBD



4.0 Current State-of-the-Art & Gaps (Cont.)

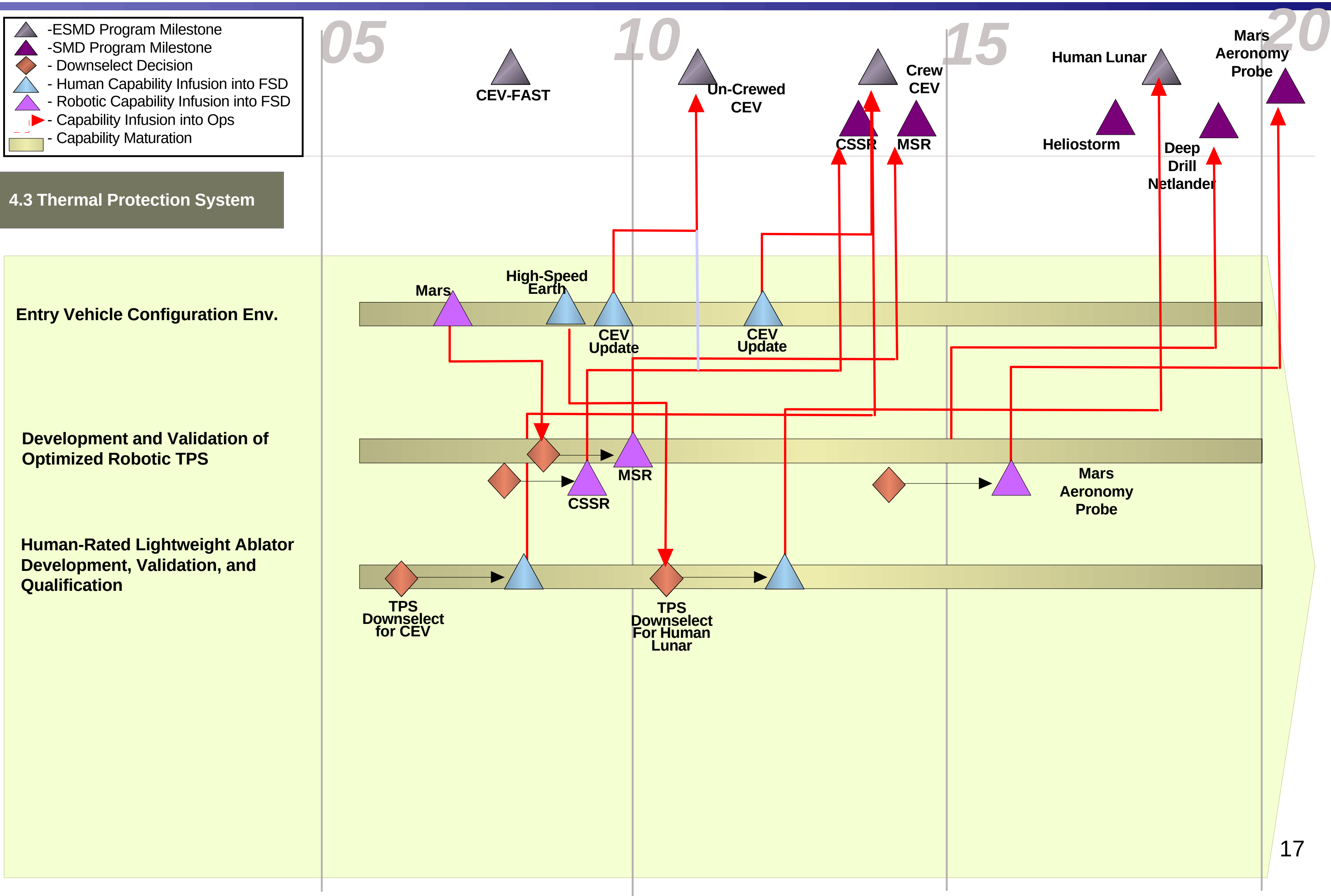
Rigid Aeroshell:

- **Entry Vehicle Configuration - Mars Aerocapture / Entry**
  - **SOA: Viking/Pathfinder/MER/MSL at Mars ; Shuttle at Earth**
  - **Gaps**
    - scalable systems (combination of flexible and rigid) for 50 - 60 MT Mt and large volume (~ 10 m dia., ~40 m long) needed
    - need higher L/D for low G' loads and for precision landing (mid L/D, slender body shapes)
    - precision guided entry will require control authority and potentially movable control surfaces
- **Entry Vehicle Configuration - Mars Return**
  - **SOA: Apollo**
  - **Gaps**
    - Higher entry speed (up to 15 km/s) will require more capable Thermal Protection System
- **Entry Vehicle Configuration - Lunar Return**
  - **SOA: Apollo**
  - **Gaps:**
    - Larger aeroshell for 2 to 4 times the mass of Apollo

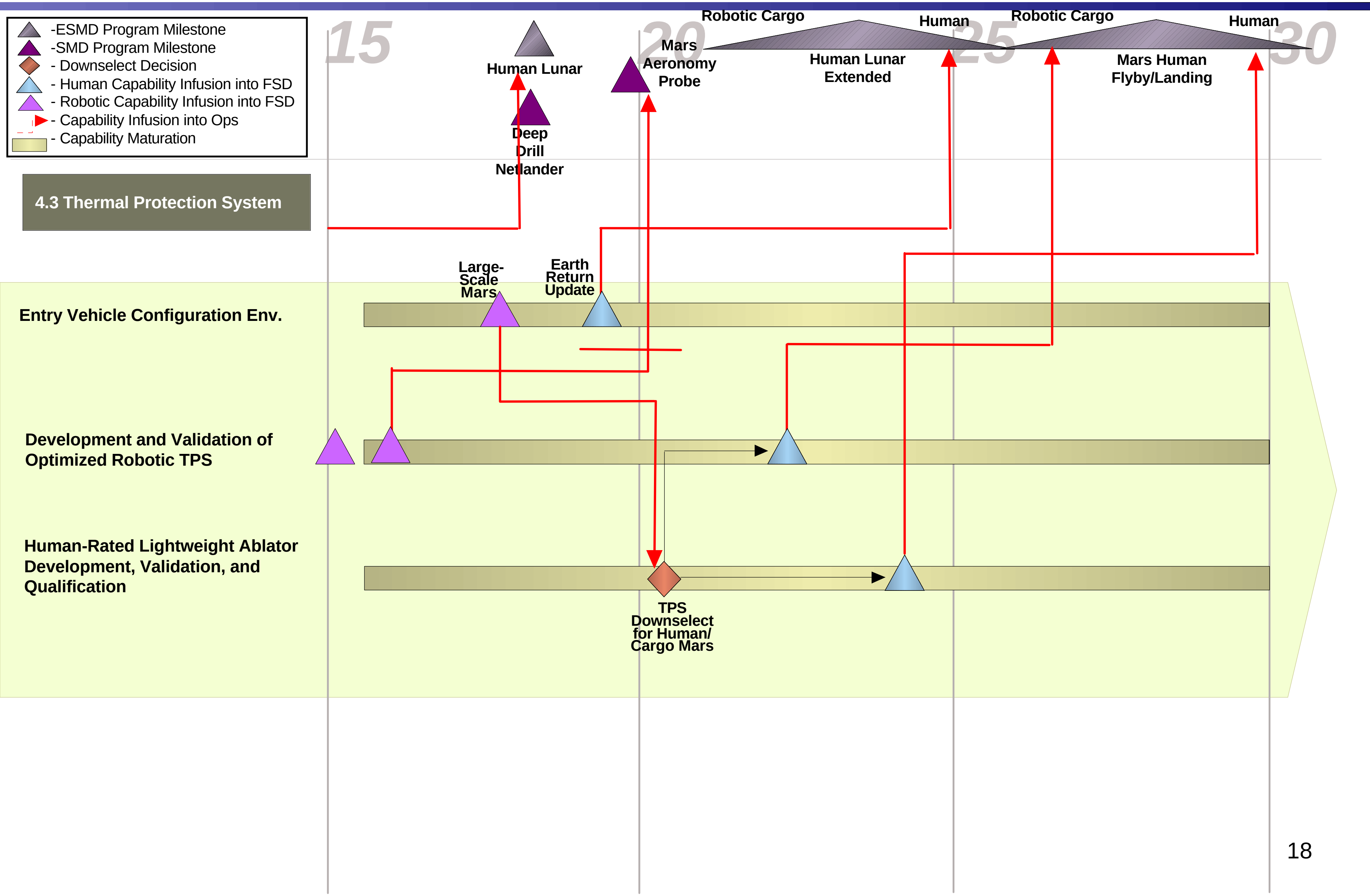
4.0 Current State-of-the-Art and Gaps (Cont.)

- **TPS for Mars**
  - Viking, Pathfinder, MER heritage - Heatshield material is SLA 561-V and backshell TPS is SLA and SIRCA
  - Other higher performance materials for Mars AE exists (TRL 6) but have not been flight qualified
  - A larger suite of TPS materials (more than 2) will be required
  - Human rating of TPS will require relatively more arcjet testing and flight verification of design methods
  - Manufacturability and integration for large volume system need development
- **TPS for Earth Entry (Lunar Return)**
  - Human rated ablative TPS - Apollo TPS does not exist - will require re-establishing manufacturing process and re-qualifying TPS
  - Other capable material will require human rating and establishing manufacturing capability for large scale system
- **TPS for Earth Entry (Mars Return)**
  - Will require more capable TPS compared to Mars Entry or Earth Entry from Moon due to higher entry velocity
- **TPS Development and Qualification for Mars and Earth Entry :**
  - Apollo era combined (convective + radiative) test facilities do not exist
  - Will require reestablishing/upgrading test facilities for TPS development, testing and qualification
  - Current facilities do not test in CO_2 - acceptable for Robotic missions
  - need to establish facility to flight relevance of testing for Mars in air either via analysis and flight data or modification of existing facilities for testing in CO_2

Thermal Protection System Roadmaps - 2005 to 2020



Thermal Protection Systems Roadmaps - 2015 to 2030

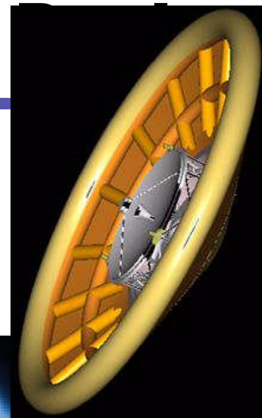


4.0 Current State-of-the-Art and Gaps (cont.)

- **Inflatable aeroshell technologies are in very early stage of development**
  - Moderate to Low ballistic coefficient class
    - Russia designed, developed, and launched an inflatable aeroshell intended to enter the Mars atmosphere and decelerate aerodynamically with penetration of the Mars surface on landing – Launch system failure prevented the system from leaving earth orbit
    - Derivative of this system, Inflatable Reentry and Descent Technology (IRDT) is being flight tested with limited success
  - **Current technology development efforts including the following have proven feasibility of concept**
    - Testing of thin-film material properties in the expected environment
    - Development and testing of material seaming approaches
    - CFD modeling validated with hypersonic wind tunnel testing
    - Trajectory control for use in aerocapture
  - **Key issues still to be addressed**
    - Manufacturing on large scale (B ~ 10) required for human missions
    - Deployment of large system
    - Aeroelastic effects in hypersonic, rarefied flow
    - Trajectory control for precision landing
  - **Efforts to address aeroelasticity, manufacturing of complete system,** applicability assessment for human system and low speed flight test are included in the Exploration Systems Research & Technology (ES&RT) Program.

able Aeroshells

Inflatable Aeroshell



Payoffs

- Reusability
  - Because the host structure does not have to withstand high heating rates, potential for reusability.
- Modularity & In-Space Assembly
  - May be packaged in a small volume and inflated to full size prior to use.
  - Technology has potential for scalablity to a wide range of payload masses for deceleration at Earth and Mars.
- Affordability
  - Attaches to a wide range of payload configurations for logistics delivery.
  - Provides deceleration with a mass equivalent to a propulsion system having a specific impulse greater than 5000 sec.

Description

Objective

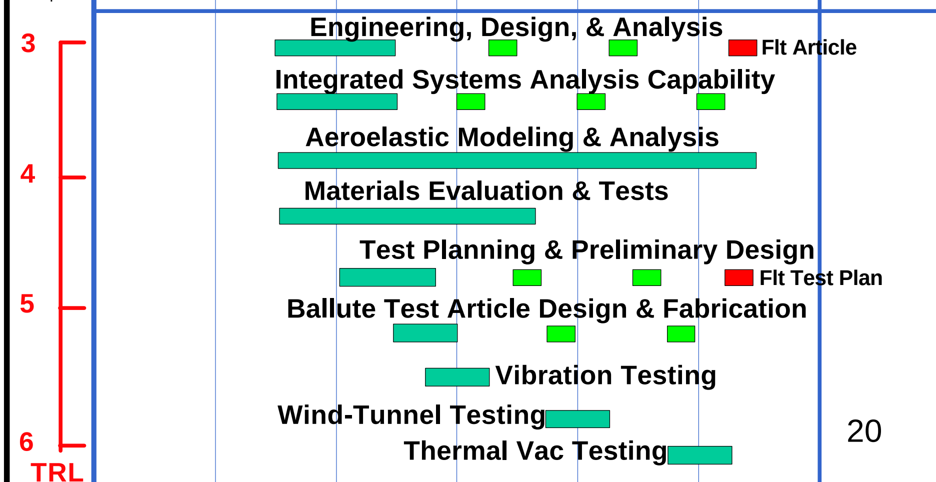
- **Develop ultra lightweight inflatable ballute technology for use in return of humans or cargo from the Moon.**

Approach

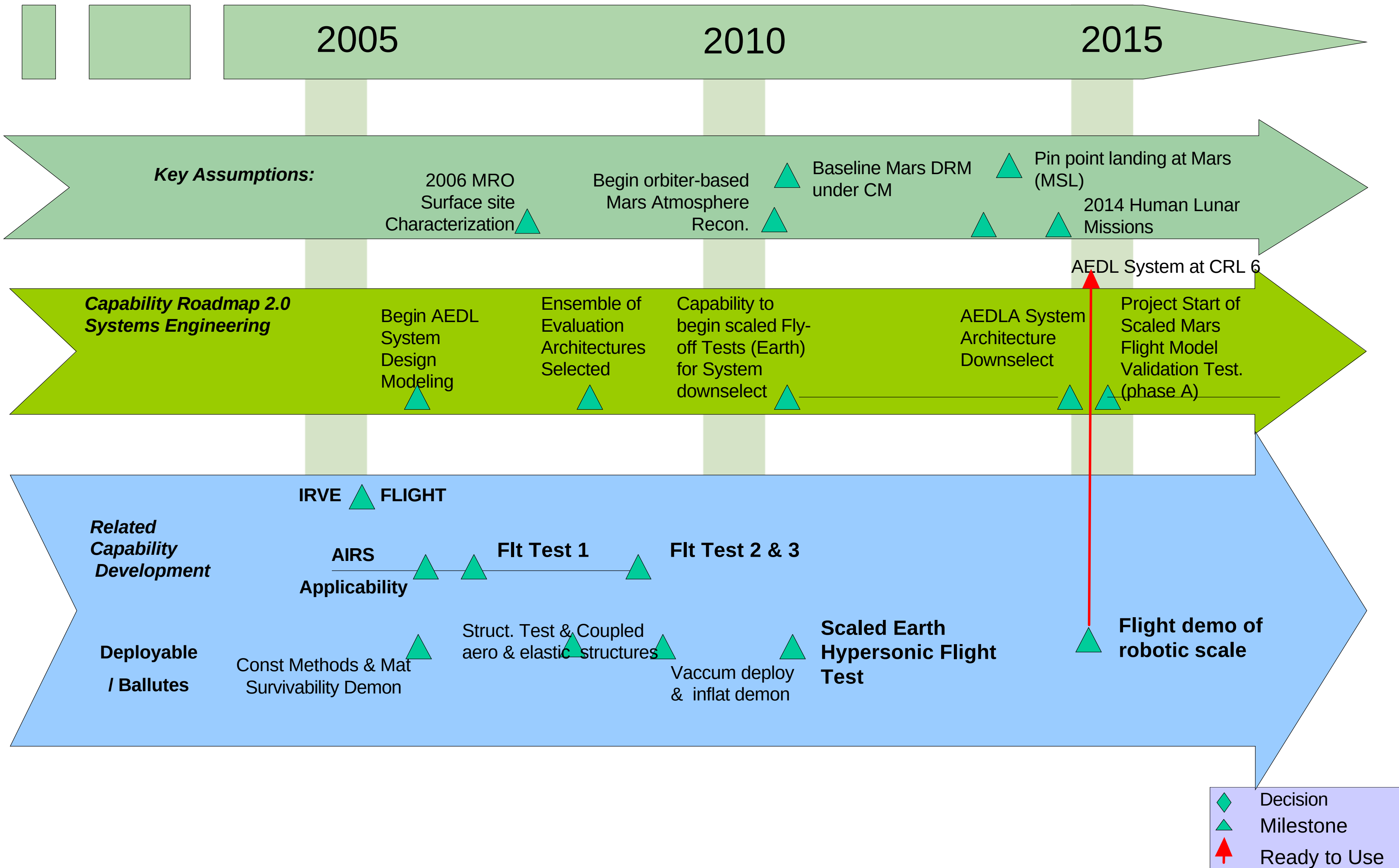
- **Systems analysis to define the lunar return concepts, fully define operational environments, and develop testing requirements;**
- **Integration of computational tools to perform coupled hypersonic aerothermal, nonlinear structural, and thermal analyses;**
- **Materials, seam, and ballute component testing to characterize performance over the entire operational range;**
- **Design and fabrication of subscale (2 to 3-m diameter) thin film ballute system test articles to demonstrate manufacturing processes;**
- **Deployment, strength, and durability testing of the subscale articles at the dynamic pressures expected for a lunar return mission;**
- **Validation of analysis tools with data obtained from subscale tests;**
- **Definition of flight qualification approach for exploration missions.**

Schedule

FY	04	05	06	07	08	09	Total
$M	tbd	tbd	tbd	tbd	tbd	tbd	tbd

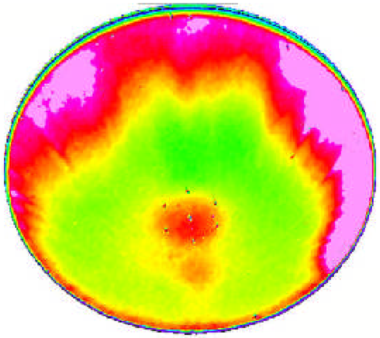


Deployable Aeroshell Roadmap



Key Aerothermal Gaps

Transition in Mach 6 Tunnel



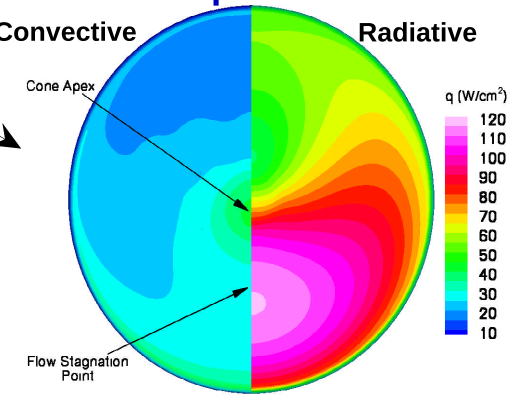
Shock Layer Radiation

Transition to Turbulence

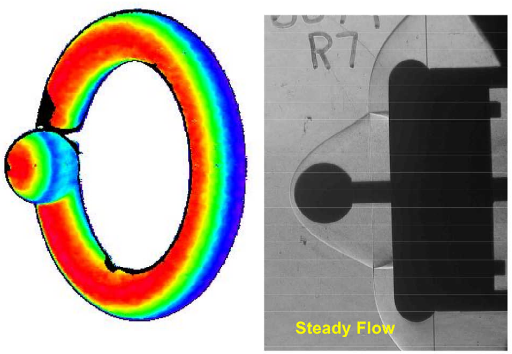
Coupling between radiation/TPS/fluids

Non-continuum flows and aeroelastic effects for low b entry systems

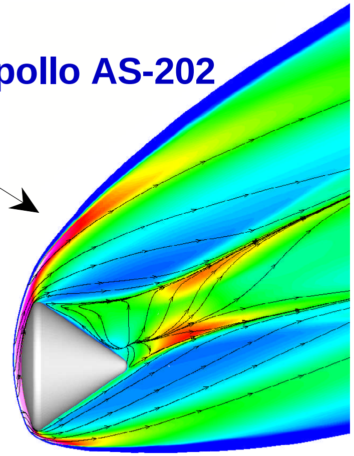
Titan Aerocapture Peak Heating



Trailing Ballute Test



Apollo AS-202



➢ Gaps are addressed via:

- Mission-specific uncertainty analysis to rank importance
- Ground testing *tailored* to reduce key uncertainties
- Model development based on test results
- Model validation with flight instrumentation

Key Aerothermal Gaps

Capability (Metric)

Rating Scale:

- Critical Capability Gap
- Important Capability Gap
- Minor Capability Gap
- \- No Gap or N/A

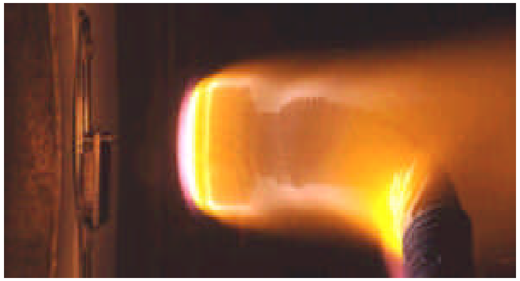
Backup

Development of High Performance/Reliable Human Rated TPS

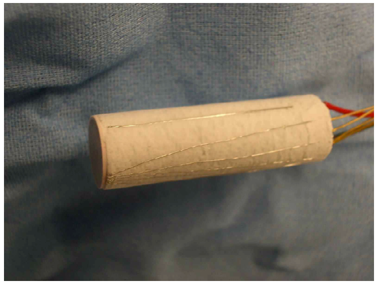
Capability Objective and Current Capabilities

- **Objective: To accurately predict the entry environments for future robotic and human exploration missions, to determine the applicability of existing ablative TPS materials to these missions, and to develop and validate new materials, if none exist.**
- **Goal: To produce multiple human-rated ablative TPS alternatives for application to missions in the various exploration spirals, enabling mass-efficient, robust entry systems. To ensure efficient alternatives are available for robotic exploration, as well.**
- **SOA: In-Space Propulsion Program investments in lightweight ablative TPS for robotic missions have brought some to TRL5+ since 2003;**
  - **Aerothermal Env. / High fidelity TPS response Design methods for large hypersonic systems needs ot be validated with ground and flight data**
  - **flight qualification, validation for specific applications, and human rating are TPS gaps.**

Capability Developed and Metrics



Lightweight Ablator Arcjet Testing



Heat Flux Gauge Ablator Plug

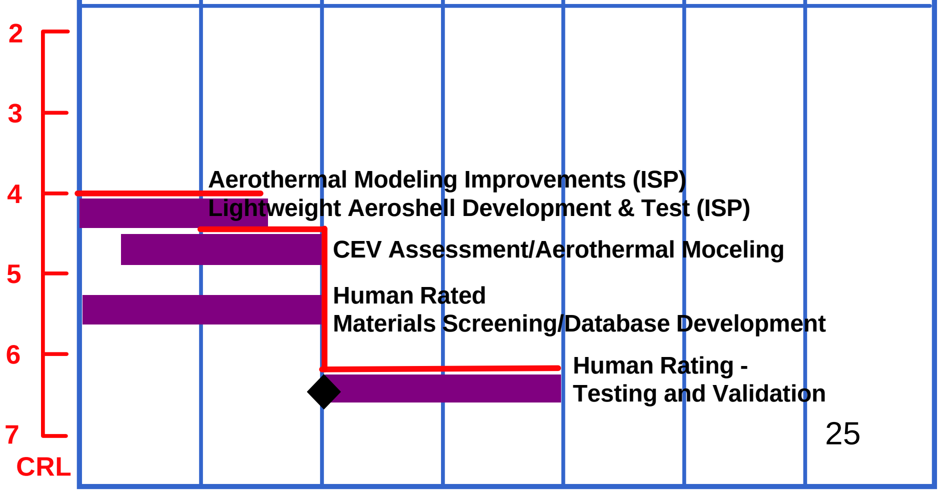
- A suite of light weight TPS to result in aeroshell mass fraction of 10% - 25%
- Scalable to large size
- Capable of withstanding combined (convective+radiative) environment with non-catastropic behavior

Development Approach

- **Define the relevant environments in which the TPS materials must operate, using aerothermal modeling.**
- **Determine the applicability of existing ablative TPS materials, through laboratory characterization, screening test, and model development.**
- **Downselect alternatives and <u>qualify</u> the best candidates for robotic or human mission use.**
  - **Combined environments testing on coupons and sub-components**
  - **Instrumented flight testing to validate models and performance**
  - **Flight testing data from Earth and Mars (robotic) tests and verify design methods**
  - ***Aeroshell system* (structure, adhesive, TPS, and sensors) ground testing and qualification**

Schedule

FY	06	07	08	09	10	11	Total
$M	TBD	TBD	TBD	TBD	TBD	TBD	TBD



Aerocapture/EDL
Thermal Protection System (TPS) Metrics

	Figure of Merit		
Capability (metric)	SOA		Long Term Need
Heat Flux (capability to withstand)	**Space Shuttle: <40 W/cm^2 acreage Mars Robotic: ~100 W/cm^2**		**Approximately 400 W/cm^2 for return from moon, 70 W/cm^2 for Mars arrival, 800 W/cm^2 for return from Mars**
Ablator Density (g/cm^3)	**SLA-561V (Mars): 0.26 g/cm^3**		**Less than ~0.5 g/cm^3 for Mars missions, to keep aeroshell mass fraction <25-30%**
Human Rating of Reusable TPS	**Space Shuttle Tile and Leading edge**		**If true reusability necessary, need system to withstand return from Mars (up to 13 km/s).**
Human Rating of Ablative TPS	**None since Apollo**		**Necessary, if moon/Mars architectures only require 1-2 time reuse**
Manufacturability at large scale (ablatives)	**Mars landers: ~2.65 meter diameter (Viking blunt shape) Earth sample capsules: 1-1.5 meter diameter (blunt shape)**		**Payload-dependent. Estimate <u>slender</u> Mars aeroshell at 5 m dia x 15 m long. Estimate 4.4 m dia for Earth return capsule (blunt shape)**
Aerothermal Environment Prediction Uncertainty	**Varies with destination and geometry. Largest uncertainties are in radiative heating, afterbody flow structure, and transition to turbulence.**		**Must reduce uncertainties to ~20% to enable efficient feed-forward designs. Requires improvements in radiative heating, afterbody flows, turbulence, catalycity, dust interaction, and coupled ablation analyses.**

Aerocapture/EDL
Thermal Protection System (TPS) Gaps (1)

	Gap Identified			
Capability (metric)	Spiral I	Spiral II	Spiral III	Spiral IV/V
Heat Flux (capability to withstand)	**None (if no feed-forward requirement for Spiral II)**	**Need validated ablators at ~400 W/cm^2**	**No additional; Earth return needs from Spiral 2 should be adequate; need to evaluate CO2 vs air effects. MSR EEV may require more capability.**	**Need validated ablators for Earth return from Mars (~600 - 1200 W/cm^2, depending on design).**
Ablator Density (g/cm^3)	**TBD, depending on materials available and mass constraints**	**No additional, depending on materials available and mass constraints**	**No additional**	**Less than ~0.5 g/cm^3 for Mars missions, to keep aeroshell mass fraction <25-30%**
Human Rating of Reusable TPS	**None--use Space Shuttle, if architecture requires reusability**	**No additional**	**No additional**	**If true reusability necessary, need system to withstand return from Mars (up to 13 km/s).**
Human Rating of Ablative TPS	**Need 1-3 materials human-rated, for evaluation and selection**	**Need 1-3 materials human-rated, for evaluation and selection**	**No additional**	**Need 1-3 materials human-rated, for evaluation and selection**

Aerocapture/EDL
Thermal Protection System (TPS) Gaps (2)

	Gap Identified			
Capability (metric)	Spiral I	Spiral II	Spiral III	Spiral IV/V
Manufacturability at large scale (ablatives)	**Demonstration and validation needed on ~4-meter diameter; not done since Apollo**	**No additional**	**Demonstration and validation may be needed, for up to 5- meter-diameter robotic Mars. If Earth return payloads increase substantially above Spiral I, need to address.**	**Payload-dependent. Possible order-of-magnitude increase in mass delivered to Mars, new shape of vehicle.**
Aerothermal Environment Prediction Uncertainty	**None**	**Earth radiative heating tools validated; expertise re-established; coupled ablation models developed and validated**	**Assume growing Mars missions: Mars analyses validated with ground and flight tests; coupling, ablation, catalycity, radiation, turbulence need to be well-understood, to within 30-60%.**	**All tools validated to human qualification levels using data from past instrumented flights. All flowfield parameters predicted within 20%.**

Human Planetary Landing System (HPLS)
Capability Roadmap
NRC Progress Review

Rob Manning - NASA Chair
Dr. Harrison Schmitt - External Chair
Claude Graves - NASA Deputy Chair

May 4, 2005

Agenda

- Capability Roadmap Team
- Capability Description, Scope and Capability Breakdown Structure
- Benefits of the HPLS
- Roadmap Process and Approach
- Current State-of-the-Art, Assumptions and Key Requirements
- Top Level HPLS Roadmap
- Capability Presentations by Leads
  - 1.0 Mission Drivers Requirements
  - 2.0 “AEDL” System Engineering
  - 3.0 Communication & Navigation Systems
  - 4.0 Hypersonic Systems
  - 5.0 Super to Subsonic Decelerator Systems
  - 6.0/7.0/8.0 Terminal Descent and Landing Systems
  - 9.0 A Priori In-Situ Mars Observations
  - 10.0 AEDL Analysis, Test and Validation Infrastructure
- Capability Technical Challenges
- Capability Connection Points to other Roadmaps/Crosswalks
- Summary of Top Level Capability
- Forward Work

Capability Roadmap Team

Advanced Planning & Integration Office

Chairs

NASA Chair: Rob Manning, JPL
External Chair: Dr. Harrison Schmitt , Ret. Apollo 17 Astronaut
NASA Deputy Chair : Claude Graves, JSC

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Capability Description

- Safely deliver human-scale piloted and unpiloted systems to the surface of Moon & Mars.
- Safely deliver human-scale piloted systems to the surface of Earth from a return from Mars & Moon.

Capability Breakdown Structure

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Human Planetary Landing Systems CRM # 7

- AEDL Human Mission Drivers 1.0
- AEDL Systems Engineering 2.0
- AEDL Communication & Navigation 3.0
- Hypersonic Systems 4.0
- Supersonic Decelerators 5.0
- Terminal Descent & Landing 6.0
- A Priori Mars Observations 9.0
- AEDL Analysis & Validation Infrastructure 10.0

Benefits of the HPLS CRM

- This roadmap defines a potentially realizable “master plan” for developing the capability to deliver the first cargo & piloted flights to the surface of Mars by 2032 with a “reasonable” mass starting at LEO.
  - This CRM defines the initial as well as long-term milestones needed achieve that goal.
  - This roadmap was developed by consensus of many (majority) of the AEDL community within and outside of NASA.
  - This roadmap is consistent with the “The Vision for Space Exploration February 2004”
- With the development of aero-assisted Mars landing conceivably, the landed payload mass fraction from LEO is between 5 - 10x.
  - Compare with 70x from LEO for all propulsive landing on Mars.
- However, there is NO known Aerocapture/EDL conceptual design in existence today that has the ability to safely deliver human scale missions to Mars.
  - Significant work remains to determine which “system of systems” will be able to do the job. There are many options and no clear winners.
- This roadmap asserts that in order to achieve the first human scale missions to the surface of Mars (piloted or not) as early as 2032, near term work must begin with little delay.

Roadmap Process and Approach

- Three well attended workshops:
  - Workshop #1: Dec 2004 at JPL & Caltech
  - Workshop #2: Jan 2005 at NASA ARC
  - Workshop #3: Feb 2005 at NASA JSC
- A large fraction of the US EDL community was present.
  30 - 50 attendees from around the US.
- We asked:
  - Can we create an AEDL capability roadmap that provides a clear pathway to the needed capability?
  - Can we establish capability roadmaps that have appropriate connection points to each other?
  - Can technology maturity levels be accurately conveyed and used?
  - What are proper metrics for measuring the advancement of technical maturity?
- We then started at the "end" and worked backward to today.
  - The "end" here was the first Human scale Mars missions in early to mid 2030's.
  - We tried to keep the "critical path" as short as possible, but it still required some movement to the right.
- We then discussed how we intend to retire the risks of this system as expeditiously as possible.
  - First working backwards from a human landing mission in 2032
  - Then defining the full scale system qualification test program (at Earth)
  - Then defining the *scaled* model validation test flights (at Mars)
  - Then defining the methodology to figure out how to *determine* what the full scale mission would look like so that it can be scaled for the model validation test flights.
  - Very quickly we get from 2032 to 2006.

Current State-of-the-Art for HPLS

- So far the largest systems to land safely on Mars were the 2 Viking landers and the 2 MER rovers (<600 kg).
- Today NASA has "working" DESIGNS for robotic vehicles with landed mass up to about 1300 kg. These designs are expected to be realized in 2011.
- Unfortunately the EDL of recent landed missions (MER) is two orders of magnitude smaller than what is needed for human scale systems.
  - The "lightest" of the human scale systems is 45-65 MT.
- Simple scaling of the systems used to land today's robotic systems does not result in physically realizable systems.
- Shuttle provides somewhat of a model (especially for some aspects of human performance, interaction and safety systems), but it falls far far short as a relevant delivery system for Mars.
- Surprisingly, the state of knowledge of human EDL performance is very poor - this may have large consequences on the resulting system and mission designs.

Mars Landing History add moon

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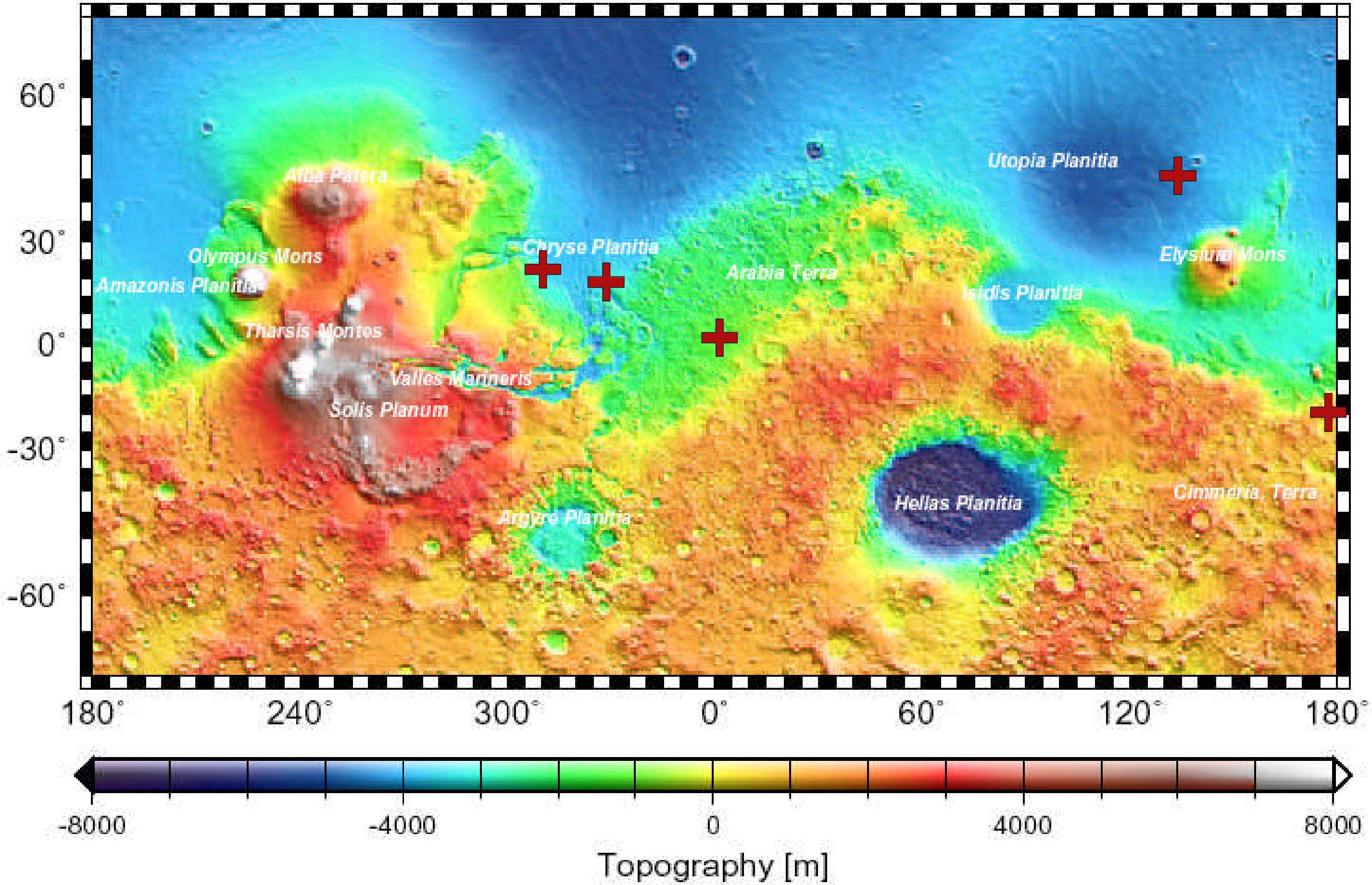
There have only been five successful landings on Mars

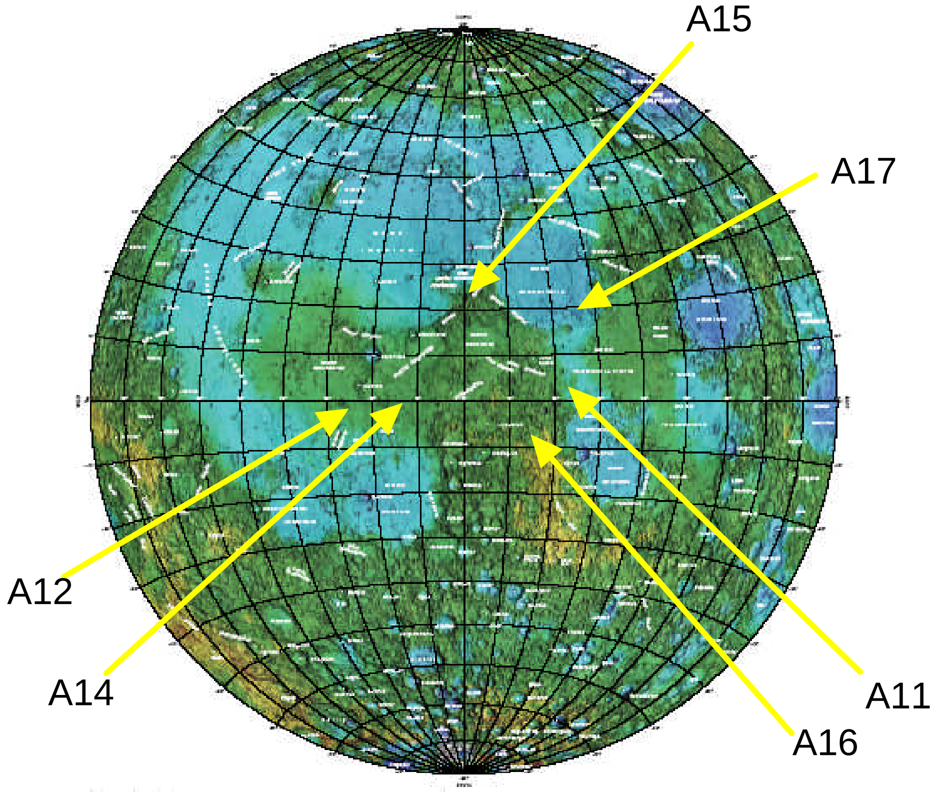
- **2 Viking landing in '76, 1 Mars Pathfinder in '97, 2 MER in '04**
- **There have been at least as many failures**

These systems had touchdown masses < 0.6 MT



Lunar Landing History

- 6 Apollo (US) Lunar landings
- 7 Luna (Russian) Lunar landings
- 5 Surveyor (US) Lunar landings



Near Side

Where are we now with Mars Landers?

We are presently attempting to develop systems that deliver 1-2 MT for Mars Sample Return and for the Mars Precursor Surface missions.

The next step is across an ocean!

- **We will need to develop AEDL systems that can get 30-60 MT down to surface per landing.**

Will these human scale AEDL systems look anything like today's robotic landers?

Probably not.

Moon and Mars Compared

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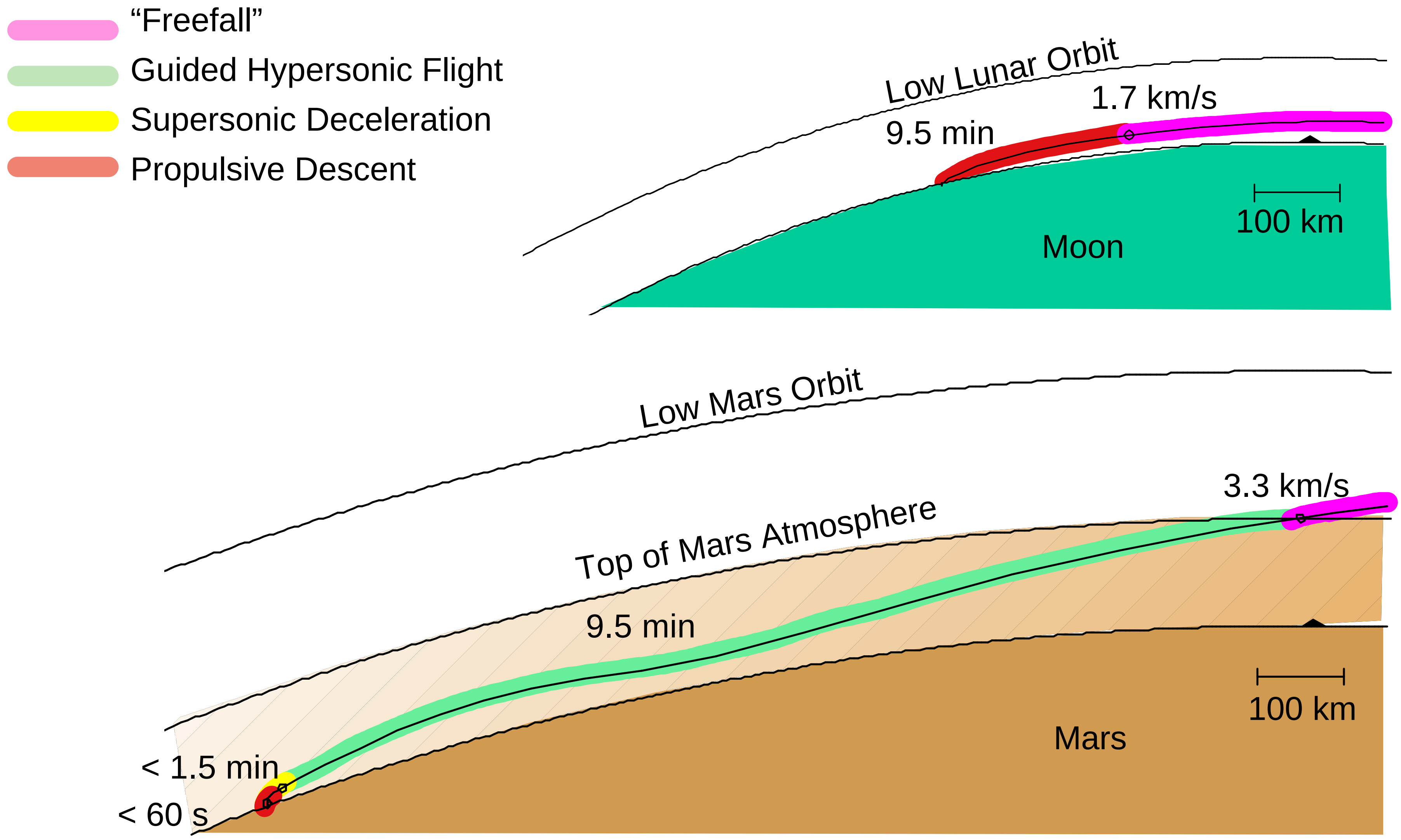
Flight Dynamics Differences:

- Moon: Ballistic "entry" followed by long (11 min) propulsive descent to surface
    - Start terminal descent burn around 18 km at 1.7 km/s
- Why can't we do the same at Mars?
    - Higher entry velocity at Mars by 2x (larger gravity)
    - Atmosphere starts high up (>100 km)
    - Need aero-thermal protection at these speeds
        - prevents melting
        - Results in complex aerodynamics & large forces (this is handy)
        - Likely need to "disrobe" aero-thermal protection < 8 km above ground
    - Natural variations (density & winds) in the atmosphere strongly perturb the system (much worse than the gravity variations at the moon).
        - System needs to muscle through these uncertainties

Human System Flight Dynamics Differences:

- Greater need to "architect system around the "human system"
    - Need to ensure that hypersonic and other decelerators do not disable pilots.
    - Human capabilities reduced by journey to Mars
    - Much faster and more dramatic transformations - challenge to find safe means to enable the pilots to add reliability to the system.

Moon Landing vs Mars Landing (to Scale)



The Mars Atmosphere is a Harsh Mistress

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- Too much atmosphere to land like we do on the Moon
  - Aero-heating, winds, density variations & fuel ruin it.
- Too little atmosphere to land like we do at Earth
  - With 1% of Earth, imagine landing the Shuttle at 100,000 ft.

- But we absolutely need the atmosphere so that we are not forced into unreasonably large masses in LEO.
  - With traditional propulsion and NO aerodynamic assistance from Mars, for every 1 MT on Mars surface we would need 70 MT in LEO !
  - With traditional propulsion and high performance aero-assistance at Mars, for every 1 MT on Mars surface we need only 5-6 MT in LEO.

- That is the promise, but will it work?
  - So far no feasible Human scale AEDL system has been found
  - But there are promising ideas that need assessment and testing.
  - We need a roadmap to guide us to the answers and the systems.

Requirements & DRM Sources for HPLS CRM

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- Fortunately there is a wealth of design framework and reference mission designs to base the AEDL system on.
  - NASA Publication 6107 (Mars Design Reference Mission 1997)
  - DRM 3.0 (update to 6107)
  - JSC Dual Lander Study

- Many common aspect and requirements. E.g.
  - 40-80 MT landing mass
  - Large volume (e.g. return ascent vehicle fuel tanks)
  - Aerocapture from high-speed Mars transfer orbit
  - “Abort to Surface” abort mode (vs Apollo’s “abort to orbit”)
  - High speed direct or aerocapture back into Earth orbit.

Key Assumptions for HPLS CRM

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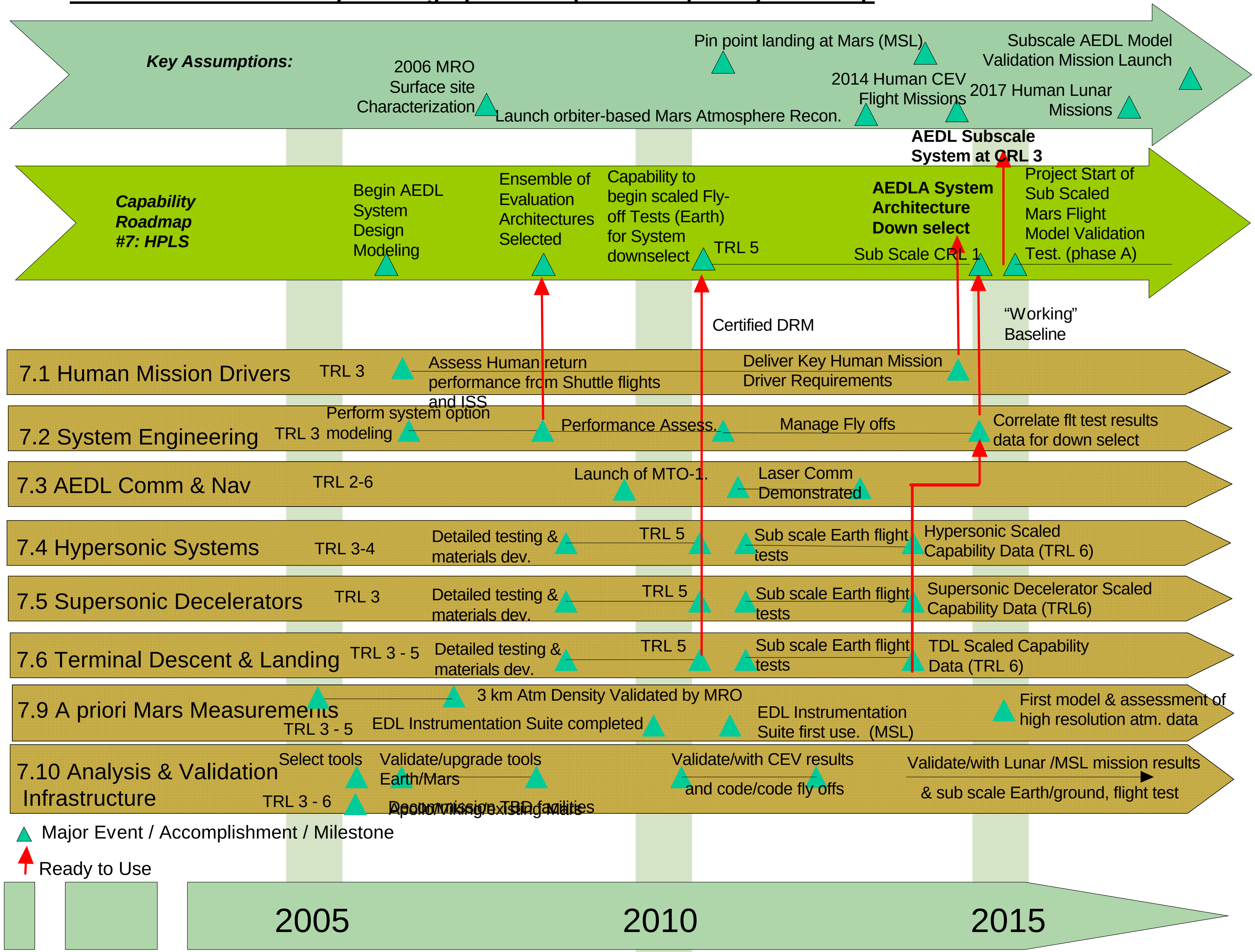
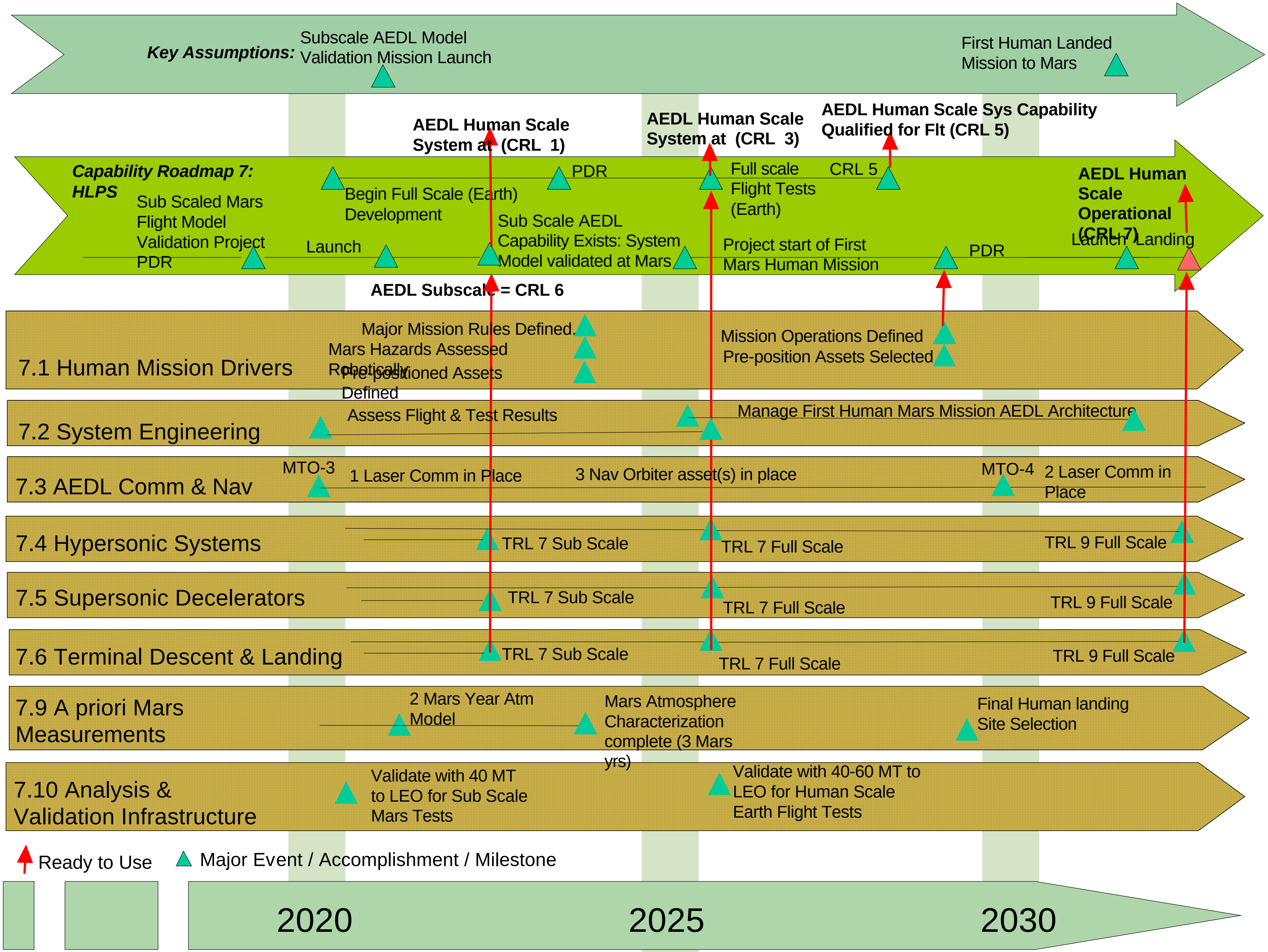
- Ongoing programs will “solve” some problems.
  - Robotic Mars Program:
    - Navigation (GPS-like & terrain relative) system designs (if not assets) to enable pin point landing.
    - Will acquire surface reconnaissance and multi-Mars year atmosphere density & wind monitoring to reduce model uncertainty.
    - Will acquire in-situ atmosphere & aero data to perform model validation of atmosphere and aero-database from robotic landings.
  - CEV/Moon Program:
    - Will develop large (but 1/4 scale) descent engine useful at Mars.
    - May develop large instrumented aeroentry earth return systems useful at Mars.
    - Will develop terminal guidance / human interactive landing & touchdown systems for terminal phase pin point landing.
  - ISS/Shuttle
    - Will begin astronaut post-landed test program to assess post gee crew performance.

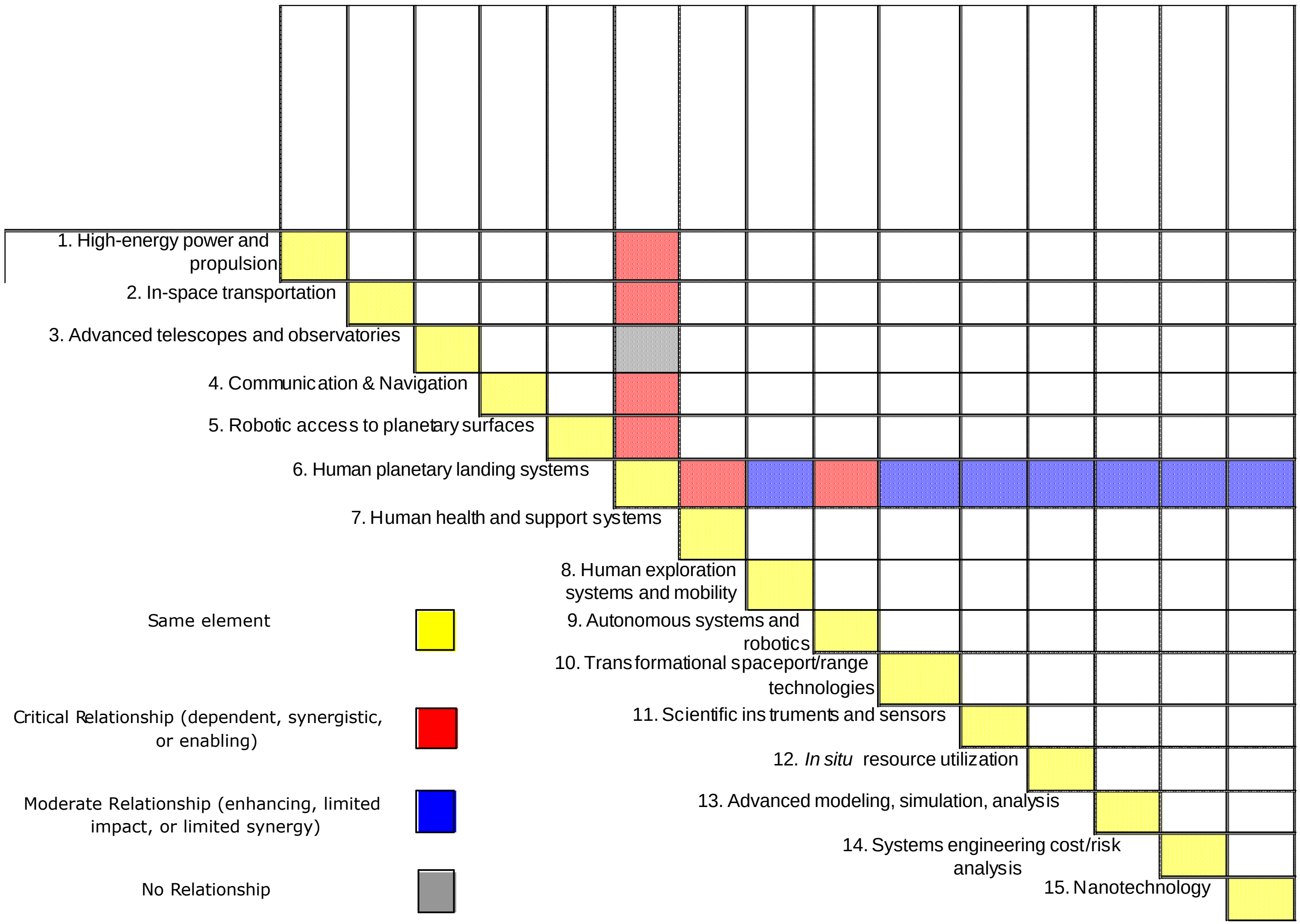
Team 7: Human Planetary Landing Systems Top Level Capability Roadmap



Team 7: Human Planetary Landing Systems Top Level Capability Roadmap



HPLS CRM Crosswalk



Examples of Crosswalk Data

5. Robotic access to planetary surfaces		6. Human planetary landing systems	
Entry: Hypervelocity Transit	⟷	Hypersonic Entry/AeroCapture Aerothermal TPS Systems	Robotic Entry methods may be applied to Human Entry
Descent	⟷	Transonic decelerators	Robotic Descent methods may be applied to Human Descent
Landing	⟷	Terminal Descent Propulsion Touchdown Systems Terrain Relative Sensing	Robotic Landing methods may be applied to Human landing
Observations	⟷	Observations	Orbital reconnaissance requirements for surface site characterization and atmospheric characterization. Precursor surface-mission engineering observational requirements (meteorology, dust characterization, TPS/parachute performance).
Entry, Descent & Landing	⟷	Robotic-human interactions	Human interaction with Robotic systems during EDL
Navigation- Beacons & Orbital Assets	⟷	Communications and Navigation Infrastructure	Common assets can be shared for navigation
Extreme Environment Avionics	⟷	Hypersonic Entry/AeroCapture Aerothermal TPS Systems	Avionics must function in extreme environment of Mars Entry
Planetary Protection	⟷	EDL Systems Engineering, Guidance, Nav & Control Analysis & Rqmnts	Landed mass must adhere to Planetary Protection Rules Robotic methods may be employed in Human landings
Mobility	→	Touchdown Systems	Successful Landing includes deployment of surface asset - robotic methods may be used
Propulsion	⟷	Terminal Descent Propulsion	Robotic propulsion methods may be applicable to Human landing

CRM X SRM Crosswalk (Part 1)

SR-#	Short	Full Name	Chartered Objective	Flow	CRM #7 Human Planetary Landing Systems	Relationship	CRM Communications with SRM
1	Moon	Robotic and Human Lunar Exploration	Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.	⟺		Use common methods for landing on the Moon and on Mars where possible. These common technologies include Terminal descent systems, deep throttling propulsion engines, aerocapture Earth return systems, human systems & instrumentation for data during Earth return.	- Co-Chair (Harrison Schmitt) attended Meeting #2 - Potential invititation to present at Meeting #3 - Reviewing SRM presentations on Docushare
2	Mars	Robotic and Human Exploration of Mars	Exploration of Mars, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration; human expeditions to Mars after acquiring adequate knowledge about the planet using these robotic missions and after successfully demonstrating sustained human exploration missions to the Moon.	⟺		Very Large (30-60 MT) landed masses on Mars will require new Aerocapture, Entry, Descent, Landing and Ascent (AEDLA) technologies/capabilites with long development/test times. Human factors, operations & training must be factored into AEDLA Mars mission planning and human rated design in order to safely land and return human crews from Mars. Aeroassist technologies will dramatically reduce the amount of propellant/mass that is required for human travel to Mars and safe return to Earth.	-Chair (Rob Manning) presented at Meeting #2 -Chair presented at Meeting #3 -Team Member (Bobby Braun) is on SRM Committee - Reviewing SRM presentations on Docushare
3	Solar System	Solar System Exploration	Robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.	NA		Not Applicable	-Reviewing SRM presentations on Docushare
4	Earth-like Planets	Search for Earth-Like Planets	Search for Earth-like planets and habitable environments around other stars using advanced telescopes.	NA		Not Applicable	NA
5	CEV / Constellation	Exploration Transportation System	Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.	⟺		Efficient and feasible CEV/Constellation designs and configurations will require close coordination, systems engineering and packaging of Aerocapture, Entry, Descent, Landing and Ascent (AEDLA) technologies, capabilities and systems. Very Large (30-60 MT) landed masses on Mars will require new AEDLA technologies/capabilites with long development times. Aeroassist technologies will dramatically reduce the amount of propellant/mass that is required for human travel to Mars and safe return to Earth. Large volume & area payload launch fairings will be required. Heavy Lift will be required for full scale earth based testing and actual missions	-Reviewing SRM presentations on Docushare - Chairs presented at Meeting #2
6	Space station	International Space Station	Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures.	⟹		ISS will provide human health and performance data, human factors and interfaces data, training opportunities & test bed, on orbit assembly experience.	-Reviewing SRM presentations on Docushare
7	Shuttle	Space Shuttle	Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the Space Shuttle to a new exploration transportation system.	⟹		Space Shuttle will provide human health and performance data, human factors and interfaces data, training opportunities & test bed, Earth Entry Descent & Landing (EDL) data, Thermal Protection System (TPS) Data & Earth atmospheric conditions data.	-Reviewing SRM presentations on Docushare

	Critical Relationship
	Moderate Relationship
	Minimal or No Relationship

CRM = Capability Road Map

SRM = Strategic Road Map

CRM X SRM Crosswalk (Part 2)

8	Universe	Universe Exploration	Explore the universe to understand its origin, structure, evolution, and destiny.	NA		Not Applicable	NA
9	Earth	Earth Science and Applications from Space	Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.	NA		Not Applicable	NA
10	Sun-Solar System	Sun-Solar System Connection	Explore the Sun-Earth system to understand the Sun and its effects on the Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.	NA		Forecasts of dangerous solar events and on board solar activity monitoring to preserve human health & performance in Aerocapture, Entry Descent & Landing (AEDL)	-Reviewing SRM presentations on Docushare
11	Aero	Aeronautical Technologies	Advance aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.	↔		Direct Entry, Aerocapture, Aerobraking, Guided Hypersonic Flight, Supersonic deceleration, and Aerogravity Assist all require aeronautical technologies/capabilities & test facilities to successfully use the Mars atmosphere.	-Reviewing SRM presentations on Docushare
12	Education	Education	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the nation's scientific and technological capabilities.	↔		Use Aeronautics, Science & Engineering principles to educate, inspire and motivate, which provides a skilled labor force for Human Planetary Landing Systems implementation	-Reviewing SRM presentations on Docushare
13	Nuclear	Nuclear Systems	Utilize nuclear systems for the advancement of space science and exploration.	→		Use of advanced nuclear propulsion systems could reduce the transportation vehicle's arrival velocity at Mars alowing for reduced orbital capture delta velocity (Delta V) requirements	-Reviewing SRM presentations on Docushare
	Cross Cutting		HUMAN PLANETARY LANDING SYSTEMS ARCHITECTURAL ISSUES				

- Critical Relationship
- Moderate Relationship
- Minimal or No Relationship

CRM = Capability Road Map

SRM = Strategic Road Map

SRM X CRM Example Data

Mars

Go Back

Capability	Requirement	Date Required	Investment Start	TRM	Rationale for Capability	SRM Concurrence
Aerocapture, Entry, Descent & Landing (AEDL) Architecture Asessment	Decide what AEDL methods/technologies could work	2008	2006	TBD	Trade studies and research to define an ensemble of Evaluation architectures and AEDLA methods/technologies	
At Earth Sub Scale AEDL Component Development & Architecture Evaluation Testing	Technology development and testing to define & answer questions about AEDL architectures	2015	2009	TBD	Technology options & capabilities must be explored in order to get data for rationale of down selection	
Scaled Mars AEDL Validation Flights	4 MT Landing Capability at Mars: Validate AEDL Models	2022	2015	TBD	Use Robotic Mars program to validate scaleable Mars Human AEDL methods	
Earth Based Full Scale Development Program	Develop & Qualify the Full Scale Hardware	2028	2020	TBD	Use mostly Earth based Sub-Orbital qualification tests to develop the full scale of the hardware	
Prepare & Fly Cargo & Piloted Human Missions to Mars	Fly first Human Missions to Mars > 40 MT AEDL Systems Qualified & Flown	2032	2025		Deliver Cargo & Humans to Mars.	
Validate Mars Surface Models	Mars Odessy and MRO Surface Assessment	2010	2006	TBD	DTM's and Site Hazard Maps for Human Scale Site Selection	
Utilize Mars Robotic Overlap Technology	MSL, MSR, MTO, MSR Data Analysis	2015-2034	2006	TBD	Develop Pin Point Landing Radar, Terrain Relative Navigation, Guidance, Hazard Avoidance Sensors	
Validate Mars Atmosphere Models	Entry, Descent & Landing (EDL) In Situ Measurements & 3 Mars Years Atmosphere Monitiring Mission	2022	2010	TBD	Mars Atmospheric variations and dust characteristics must be understood in order to successfully design high reliability EDL Systems.	
Interaction with Lunar & Earth Return Development	Component Development & Architecture Evaluation Testing	2008-2015	2008	TBD	Use Lunar program and CEV to gain data and test common hardware	
Shuttle & ISS Return Human Physiological Performance Data	Human Performance Data	2006-2015	2006	TBD	Use empirical human performance data to drive designs and enable Human landings on Mars	
Special Test facilities and knowledge	Specialized supersonic and large scale wind tunnels for aerodynamic testing & Other Test Facilities for Terminal Descent Landing	2015	2009	TBD	Test Facilities are required to efficiently develop Aerocapture, Entry, Descent & Landing Hardware on Earth	

Sub Teams

- **Sub Teams will now present charts**

Backup Charts

Technology Readiness Levels (TRL)

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- Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA.

TRL 1 Basic principles observed and reported
TRL 2 Technology concept and/or application formulated
TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4 Component and/or breadboard validation in laboratory environment
TRL 5 Component and/or breadboard validation in relevant environment
TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7 System prototype demonstration in a space environment
TRL 8 Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9 Actual system “flight proven” through successful mission operations

Capability Readiness Levels

Advanced Planning & Integration Office

7 **Capability Operational Readiness**

6 **Integrated Capability Demonstrated in an Operational Environment**

5 **Integrated Capability Demonstrated in a Relevant Environment**

4 **Integrated Capability Demonstrated in a Laboratory Environment**

3 **Sub-Capabilities* Demonstrated in a Relevant Environment**

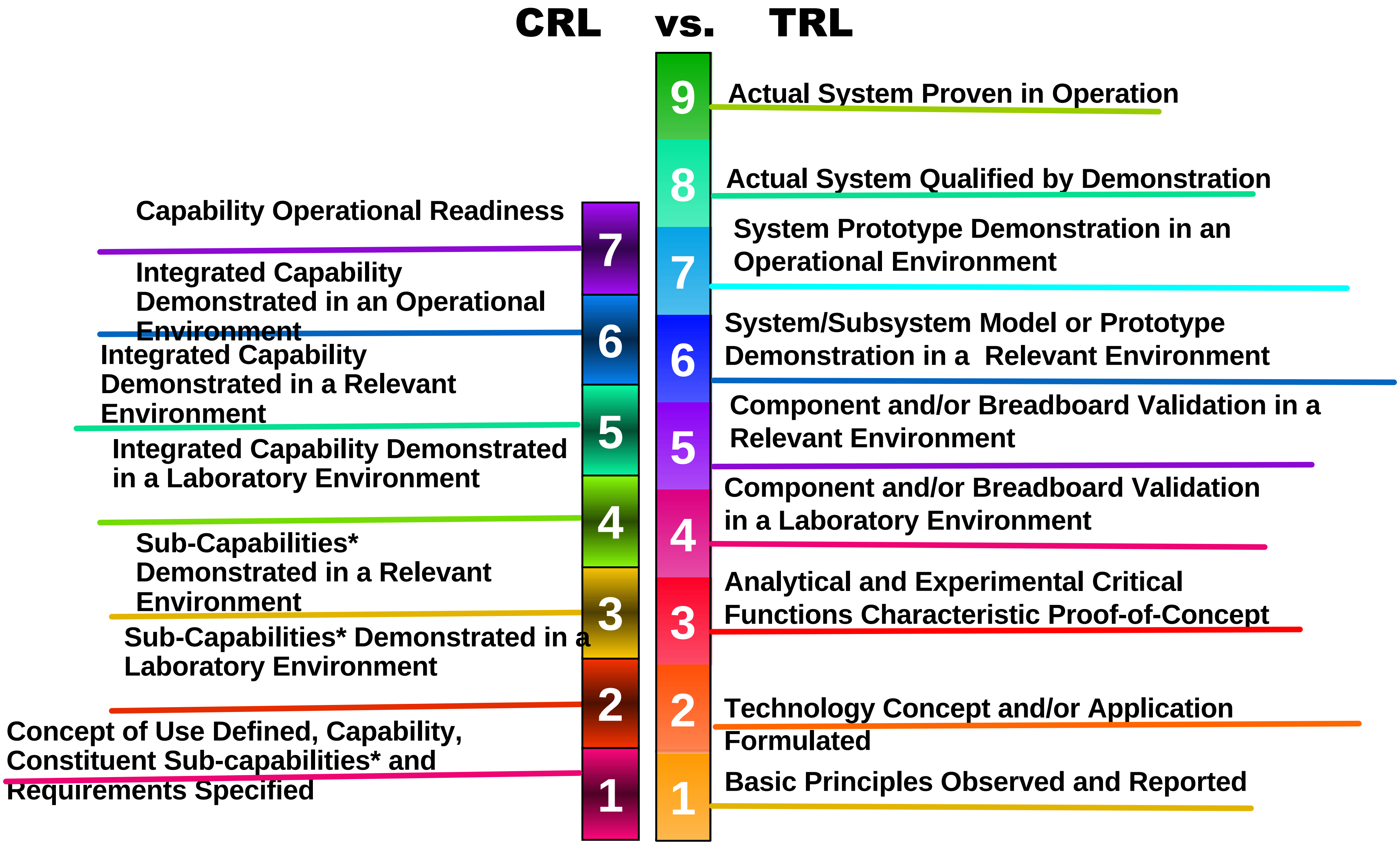
2 **Sub-Capabilities* Demonstrated in a Laboratory Environment**

1 **Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Guidelines for Using CRLs

- A Capability is defined as a set of systems with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.
- The scope of a Capability includes the knowledge or infrastructure (process, procedures, training, facilities) required to provide the Capability.
- A Capability needs to be demonstrated and qualified, just as a technology does, in both laboratory and relevant environments.
  - The infrastructure and knowledge (process, procedures, training, facilities) of the Capability needs to be:
    - Demonstrated and qualified in both laboratory and relevant environments
    - Available in order for the Capability to be considered mission-ready.
- A minimum level of TRL 6 is required to integrate technologies into a Sub-capability.
- Sub-capabilities are required to reach CRL 3 before integration into a full Capability.



A Capability is defined as a <u>set of systems</u> (or system of systems) with associated technologies & knowle that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

1

Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

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3 Sub-Capabilities* Demonstrated in a Relevant Environment

Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

-of appropriate scale

-functionally equivalent flight articles

-major system interactions and interfaces identified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

4 Integrated Capability Demonstrated in a Laboratory Environment

A representative model or prototype of the integrated Capability is tested in an ambient laboratory environment. Performance of the constituent Sub-capabilities is observed in addition to the Capability as an integrated system. Analytical modeling of the integrated Capability is performed.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Levels

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5 Integrated Capability Demonstrated in a Relevant Environment

An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

- -of appropriate scale
- -functionally equivalent flight articles
- -all system interactions and interfaces identified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

6 Integrated Capability Demonstrated in an Operational Environment

The Capability is near or at the completed system stage. The integrated Capability is demonstrated in an operational environment with the intended user organization(s).

- -full scale flight articles
- -demonstrated in the intended operational 'envelope'

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

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7

Capability Operational Readiness

The Capability has been proven to work in its final form under expected operational condition. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

Section 9:
A-Prior Observations

Rob Manning

Agenda

- Capability Description, Benefits, Current State-of-the-Art
- Capability Requirements and Assumptions
- Maturity Level - Capabilities
- Maturity Level - Technologies
- Metrics
- Roadmap for Capability

Capability Breakdown Structure

Human Planetary Landing Systems
CRM # 7

A Priori Observations 9.0

- 9.1 Orbital reconnaissance requirements for surface site characterization.
- 9.2 Orbital reconnaissance requirements for atmospheric characterization
- 9.3 Robotic EDL measurements

A Priori Observations Capability Description

9.1 Orbital Reconnaissance for Lunar and Mars site characterization

- Utilize existing and planned orbital and terrestrial-based surface observations to characterize and develop the surface site landing models & requirements for Lunar & Mars AEDL systems.

9.2 Orbital reconnaissance for Mars atmospheric characterization.

- Utilize existing and planned orbital and terrestrial-based Mars atmosphere observations to characterize and develop the atmosphere models & requirements for Mars AEDL systems. (Earth atmospheric characterization is not required for Lunar and Mars return)

9.3 Robotic EDL measurements

- Utilize existing and planned in-situ EDL reconstruction data to
  - Validate current and future atmosphere models
  - Validate vehicle aerodynamic & aeroheating modeling process
- Develop the in-situ measurement systems (a.k.a. EDL instrumentation) that acquire above reconstruction data.

Benefits

Ultimately the benefits from this roadmap are ones of human safety and AEDL system design efficacy. Specifically:

9.1 Orbital Reconnaissance for Lunar and Mars site characterization

- For Lunar & Mars Landing: Acquisition of site images with <1 m resolution from orbit enables safe site selection and use of imagery for terrain-relative navigation for pin point landing.

9.2 Orbital reconnaissance for Mars atmospheric characterization.

- Characterization of the relevant variation of the Mars atmosphere (over multi-year timescales) will enable the design of a safe Human Scale AEDL system.
  - We do not know if we are under-designing or over-designing our AEDL systems.

9.3 Robotic EDL measurements

- In-situ measurements taken during EDL (and after) will validate the models that are created based on long term atmosphere observations.
- In-situ measurements taken during EDL will validate the processes used to construct AEDL system aero-database and aeroheating models that are created based on long term observations.

State of the Art

9.1 Orbital Reconnaissance for Lunar and Mars site characterization

- Lunar state of the art:
  - 100 - 200 m resolution, global coverage (Clementine).
- Mars state of the art:
  - 100 - 200 m resolution (Viking, MGS, Odyssey, Mar Express)
  - global coverage, small % with 3 m coverage
  - 100 m global topographic elevation data.

9.2 Orbital reconnaissance for Mars atmospheric characterization.

- 2-3 km vertical resolution thermal (density) profiles at 100 km centers at 2 pm local solar time (MGS TES)
- Minimal data on vertical dust distribution and its diurnal, seasonal and long term variability.
- Minimal wind data in 2 - 70 km range (some reconstructed data from 5 landings), however unvalidated Mesoscale wind models exist at 2 sites.

9.3 Robotic EDL measurements

- Partial aero-reconstruction performed for Viking,MPF & MER based on IMU data.
- Aerothermal (TPS) reconstruction performed for Viking and some for MPF.
- No external pressure data.

Assumptions

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- Lunar reconnaissance orbiter before 2014
- Mars reconnaissance orbiter before 2009
  - Acquires 0.3 m resolution imagery of key landing sites.
    - Assume that the first human scale landings on Mars will be at locations that have been well characterized by MRO.
  - 2-3 km vertical resolution thermal (density) atmosphere profiles at 100 km centers.
- Future Mars orbiter mission(s) between 2013-2020 will have characterized the long term variability of the Mars atmosphere to enable detailed design of Human Scale AEDL system.
  - Better than 0.1 km resolution vertical thermal (density) atmosphere profiles at 10 km centers - all times of day.
  - Dust transport measurements between 2 - 100 km.
  - Better than 0.1 km resolution vertical wind profiles at 2 km centers.
- Future Mars landers will be instrumented to measure atmosphere pressure, temp, dynamic pressure, aeroheating.

Technology Maturity Level

9.1 Orbital Reconnaissance for Lunar and Mars site characterization

- Sub meter optical resolution technology is at TRL 6, just need to do it.
- Global assessment at submeter resolution is difficult due to large data volumes - > could take many years at today's communication capabilities.

9.2 Orbital reconnaissance for Mars atmospheric characterization.

- For sub km density, thermal technology is at TRL 4-5.
- For sub km dust profiling, technology is at TRL 1-2.
- For sub km wind profiling, technology is at TRL 1-2.

9.3 Robotic EDL measurements

- Aerothermal measurement technology is at TRL4-6
- Aerodynamic (IMU) measurement technology is at TRL 6
- Pressure / wind measurement technology is at TRL 2-4

Technology Gaps

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9.1 Orbital Reconnaissance for Lunar and Mars site characterization

- If global high resolution optical imagery is required for site selection (not obvious that it is), then higher data volume orbiter data delivery systems are required.

9.2 Orbital reconnaissance for Mars atmospheric characterization.

- Need to develop Doppler (LIDAR-like) limb sounding of dust for dust distribution and large scale wind.
- Other than "spotty" multiple landers (equivalent terrestrial weather balloon measurements), there are few options for higher resolution wind and density measurements.

9.3 Robotic EDL measurements

- Need to develop small pressure/temp transducers for aerosurfaces (thermal & mass challenge).
- Need high rate IMU (inertial measurement) data.

Metrics

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9.1 Orbital Reconnaissance for Lunar and Mars site characterization

- Percent coverage at sub-meter spatial resolution.

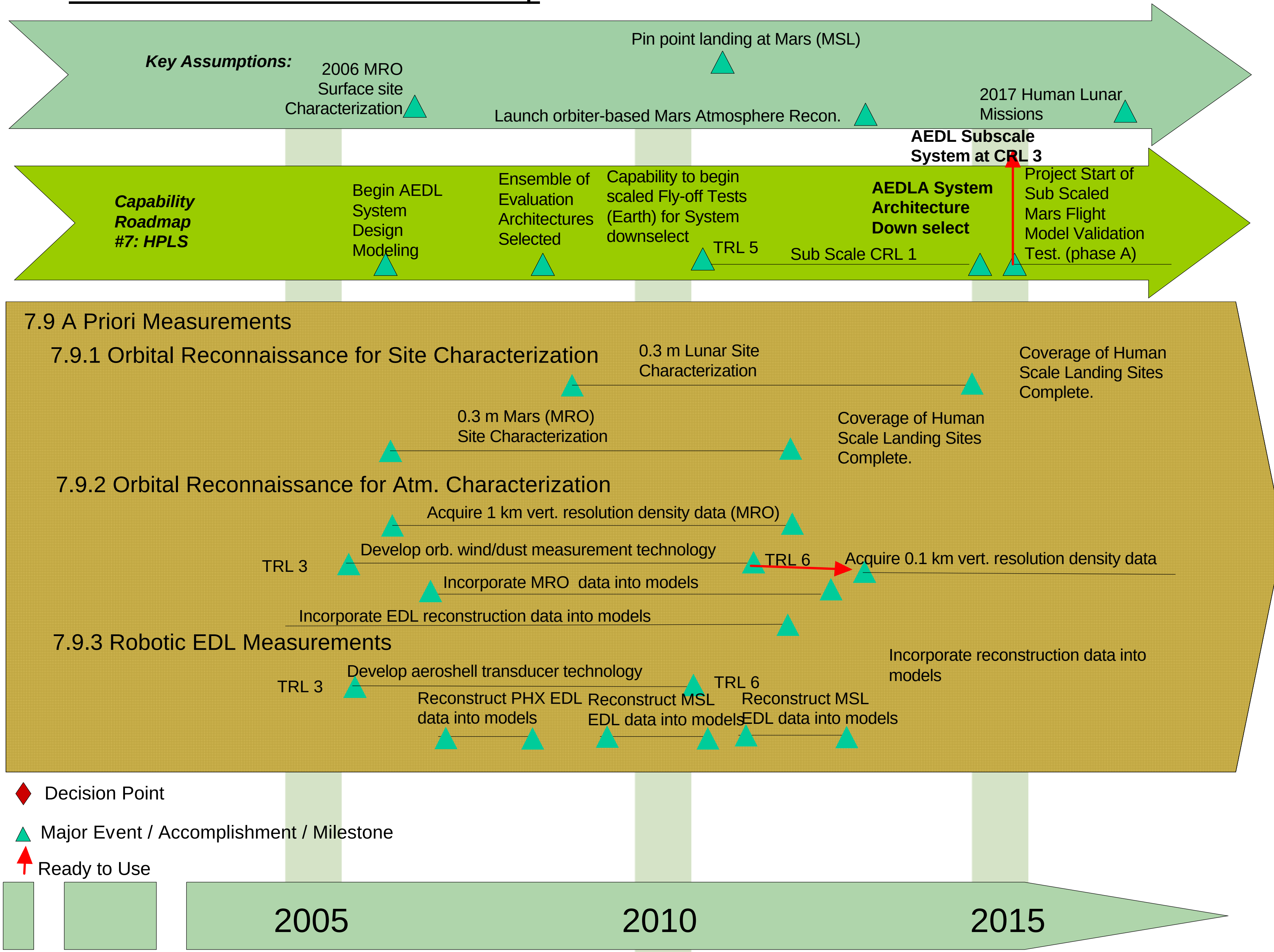
9.2 Orbital reconnaissance for Mars atmospheric characterization.

- The extent that high resolution (sub km) global "mesosphere" atmosphere models have been validated with actual measurements.

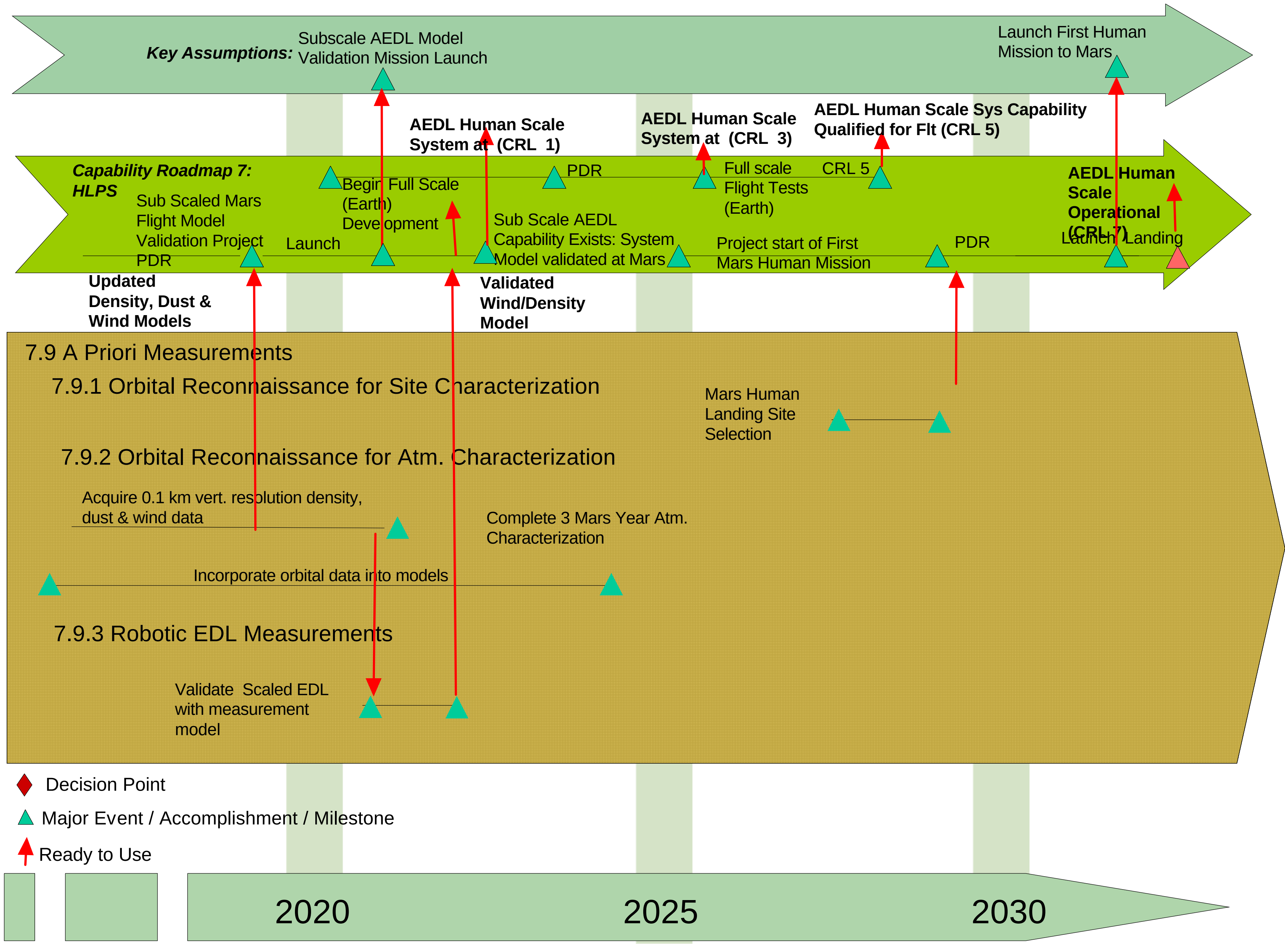
9.3 Robotic EDL measurements

- The extent that an EDL landing's reconstructed atmosphere validates the corresponding atmosphere as measured from orbit.
- The extent that the reconstructed EDL trajectories can be explained by the atmosphere and aerodynamic models.
- The extent that the reconstructed EDL aerothermal profiles can be explained by the atmosphere and EDL trajectories.

Team 7.9: A Priori Measurements Roadmap



Team 7.9: A Priori Measurements Roadmap



A Priori Observation Summary

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- In order to design high reliability Human Scale AEDL systems for Mars, the models of the Mars atmosphere we use today need to be validated with actual data.
  - Measurements of dust, dust storms and its affects on density needs to be understood (especially variance).
  - Measurements winds, wind shears in the range of 2-70 km needs to be gathered.
  - A multi-year global weather observer orbiter is needed.
- Measurements of actual AEDL performance must be made to validate the modeling methodologies used to design today's robotic EDL systems so that these same methodologies may be used to design the Human Scale AEDL systems for Mars.

National Research Council Dialogue to Assess Progress on

NASA's Human Health & Support Systems Capability Roadmap Development

General Background and Introduction

Jan Aikins

March 17, 2005

Contents

- General Background and Introduction of Capability Roadmaps
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

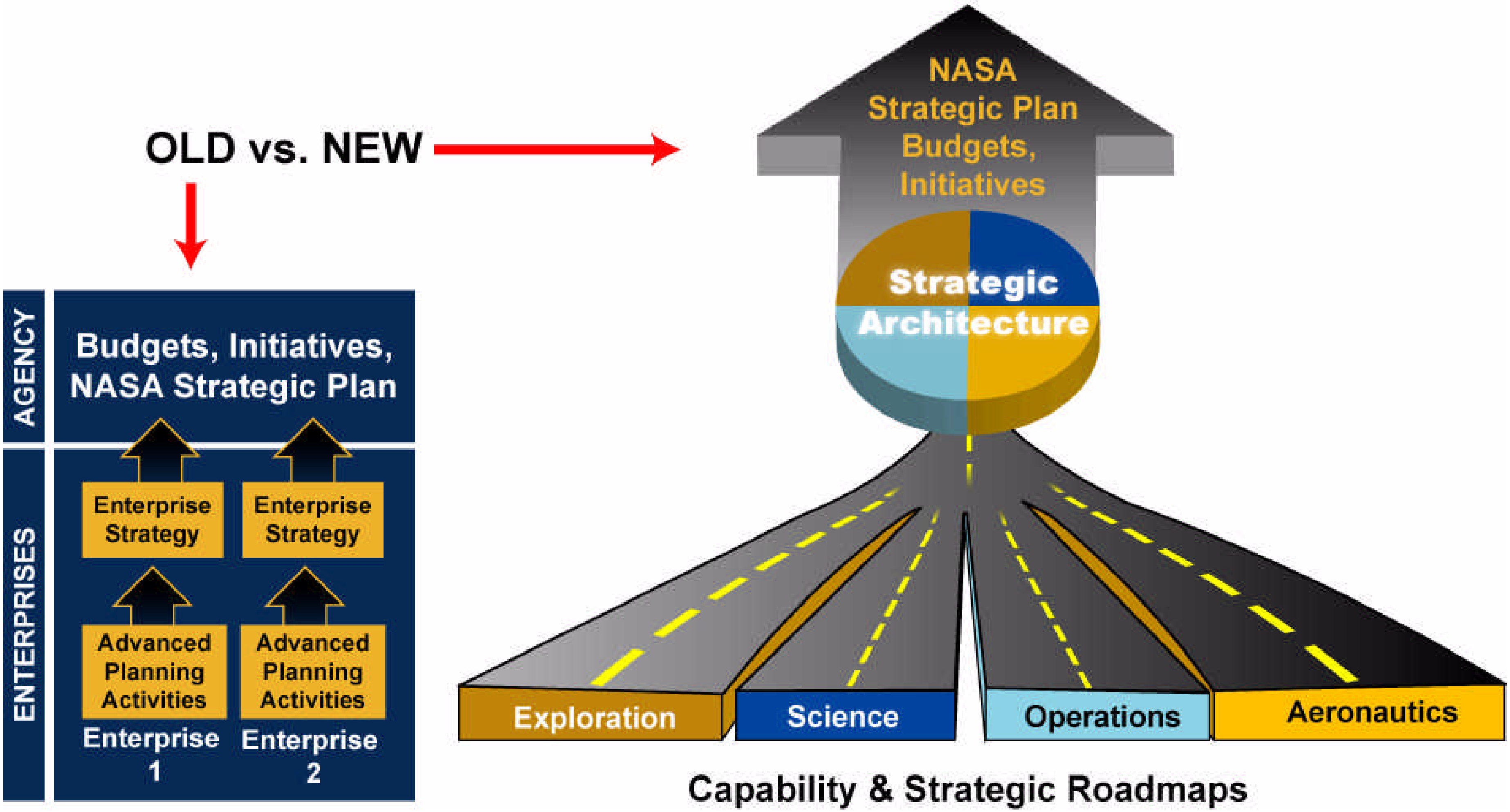
Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	1. Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	6. Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	7. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	8. Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	4. Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	9. Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	5. Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	10. Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

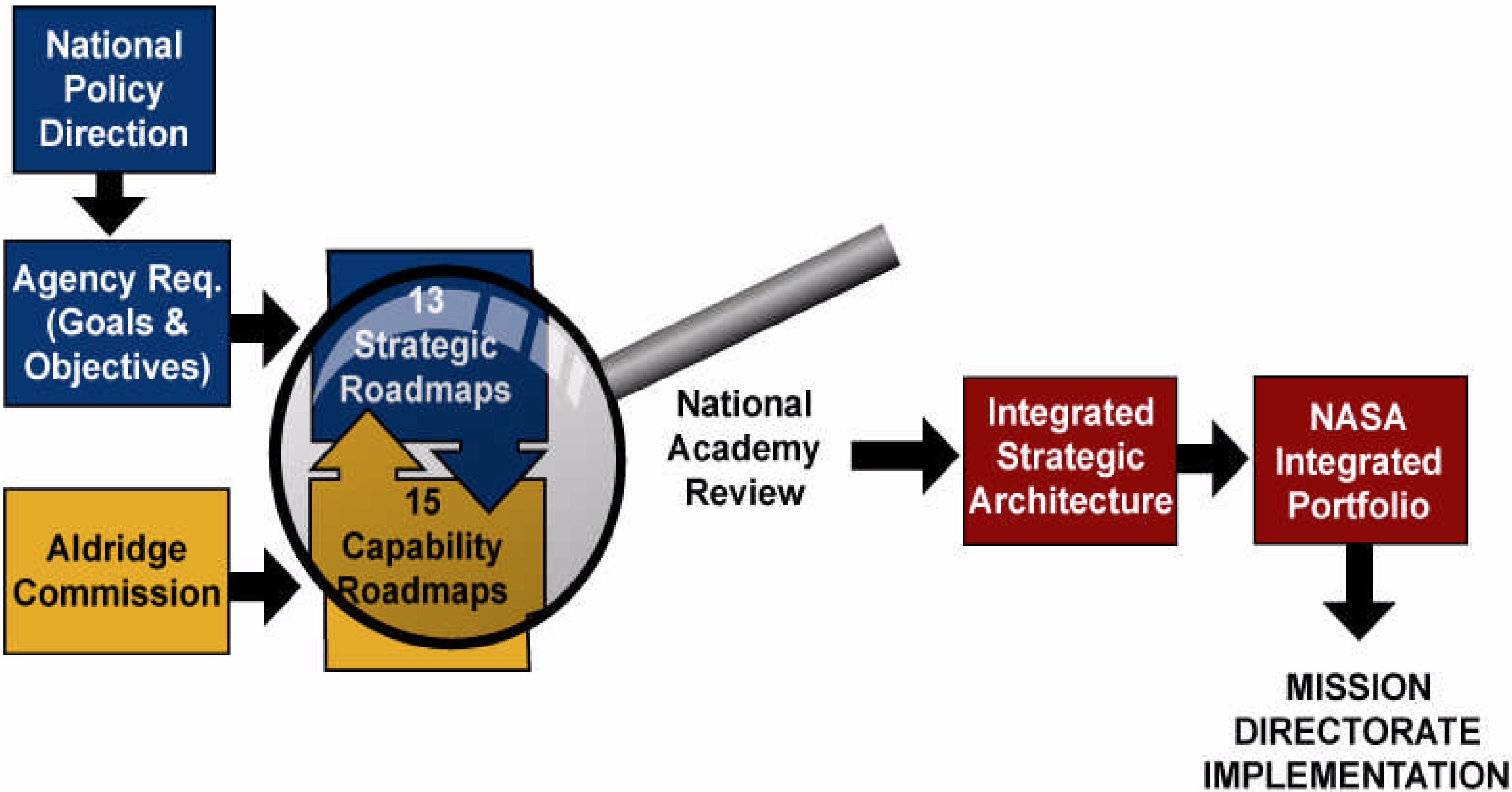
Agency Goals and Objectives

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	3. Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration.	4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	5. Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	11. Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	14. Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems. (SRM 9)	17. Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)
	12. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	15. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)	18. Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)
	13. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	16. Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

Advanced Planning & Integration Office

- NASA Strategic Planning Council (Chair, NASA Administrator)
  – Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  – Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Charles Elachi)
  – Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  – Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  – Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  – Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

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- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

- Broad human and robotic science and exploration goals, priorities, anticipated discoveries
- High-level milestones, options, and decision points
- Implementation approaches, suggested missions

Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

= DoD Participation

Directorate and APIO Coordinators also with each team

Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule

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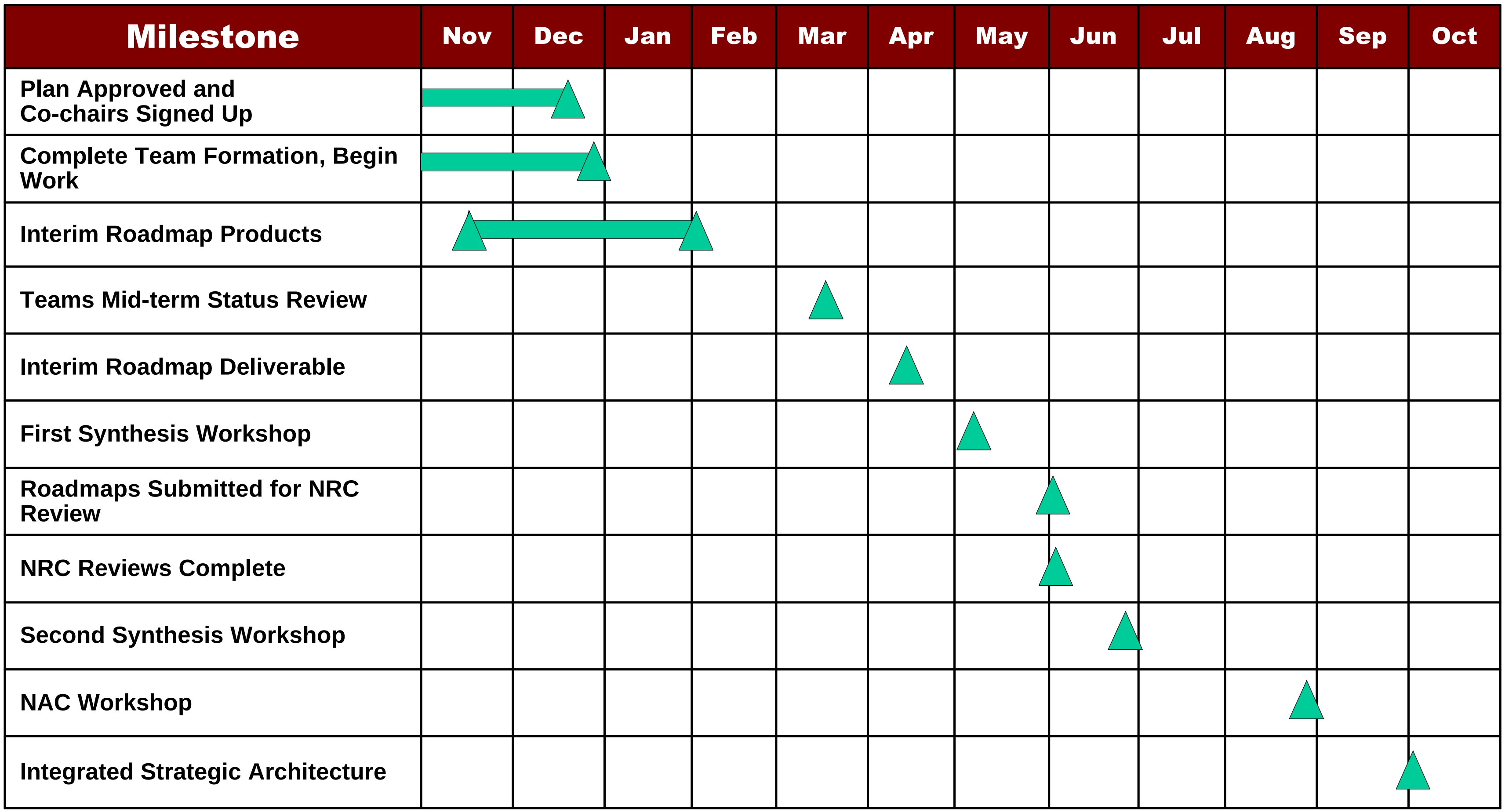

Capability Roadmaps

Advanced Planning & Integration Office

- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**
    - **1/3 Industry**
    - **1/3 NASA & other Government Agencies**
    - **1/3 Academia**
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators also with each team

= DoD Participation

Capability Roadmaps - continued

Advanced Planning & Integration Office

Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

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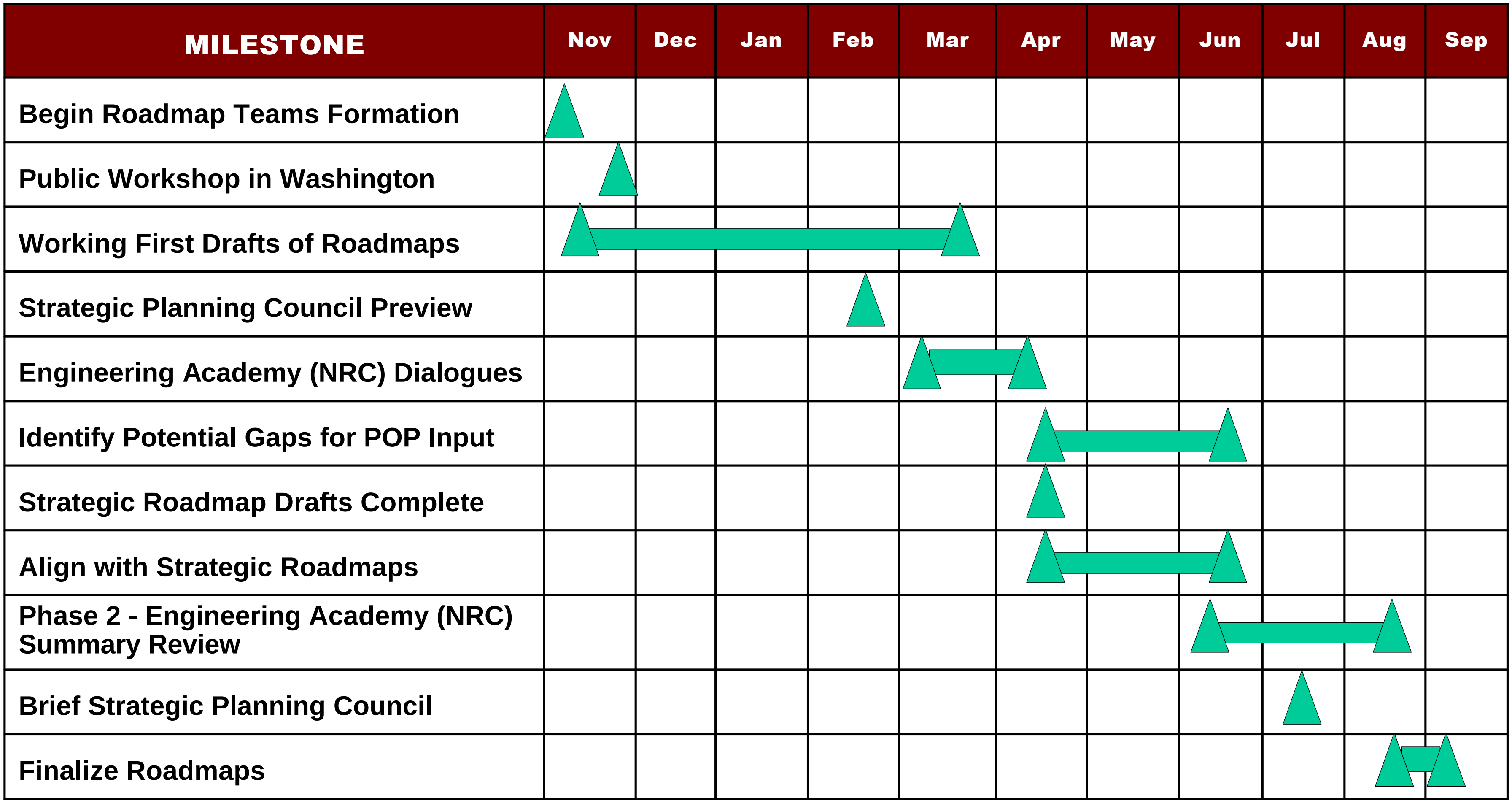

Purpose of NRC Review

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

Back-up charts

Technology Readiness Levels

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9 Actual System Proven in Operation

8 Actual System Qualified by Demonstration

7 System Prototype Demonstration in an Operational Environment

6 System/Subsystem Model or Prototype Demonstration in a Relevant Environment

5 Component and/or Breadboard Validation in a Relevant Environment

4 Component and/or Breadboard Validation in a Laboratory Environment

3 Analytical and Experimental Critical Functions Characteristic Proof-of-Concept

2 Technology Concept and/or Application Formulated

1 Basic Principles Observed and Reported

Capability Readiness Levels

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Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
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A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

Capability Readiness Levels Defined

Advanced Planning & Integration Office

- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  - The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  - A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modelling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  - A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  - An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  - The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).

  -full scale flight articles
  -demonstration in appropriate operational 'envelope'
- **CRL 7: Capability Operational Readiness**
  - The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

Human Health & Support Systems Capability Roadmap Progress Review

Dennis Grounds
Al Boehm

March 17, 2005

Draft Agenda

8:00 a.m.	Welcome & Review Process	Panel Chair & NRC Staff
8:15-8:30 a.m.	Introduction by APIO to CRM	Jan Aikins
8:30-9:00 a.m.	Human Health & Support Systems CRM Overview	Dennis Grounds
9:00 a.m.-10:30 p.m.	Human Health & Performance	Dennis Grounds
10:30 a.m.	Break	
10:45 a.m.-12:15 p.m.	Life Support & Habitation	Dan Barta
12:15-1:00 p.m.	Lunch	
1:00-2:30 p.m.	Extra-Vehicular Activity	Kerri Knotts
2:30-3:30 p.m.	Open Discussion/Q&A with NRC Panel	All
3:30 p.m.	Break/NRC panel meets in closed session	
4:15-5:00 p.m.	NRC panel discussion with NASA	All
5:00 p.m.	Adjourn	

Capability Roadmap Team

Advanced Planning & Integration Office

Co-Chairs
- NASA: Dennis Grounds, JSC
- External: Al Boehm. Retired Hamilton Sundstrand

Team Members

Government
J. Charles, JSC
R. Carrasquillo, MSFC
G. Jahns, ARC
G. Lutz, JSC

Industry
B. Harris
R. Poisson, Ham.Sunstrand

Academia
J. Becker, NSBRI
D. Akins, Univ. Maryland
R. Schlegel, Univ. Oklahoma

NASA Technical Leads
D. Barta, JSC
K. Knotts, JSC

Other/Independent
G. Miller, Lockheed Martin

Coordinators
Directorate: E. Trinh, HQ ESMD; D. Craig, HQ ESMD
APIO: J. Aikins, JPL

Capability Description

- **The Human Health & Support Systems Capability Roadmap focuses on research and technology development and demonstration required to ensure the health, habitation, safety, and effectiveness of crews in and beyond low Earth orbit. It contains three distinct sub-capabilities:**
  - **Human Health and Performance**
  - **Life Support and Habitats**
  - **Extra-Vehicular Activity**

Capability Breakdown Structure

Advanced Planning & Integration Office

Human Health & Support Systems

- **Human Health & Performance**
  - Space Radiation
  - Medical Care
  - Human Health Countermeasures
  - Behavioral Health & Performance
  - Space Human Factors
- **Life Support & Habitats**
  - Life Support Systems
  - Environmental Monitoring & Control
  - Contingency Response Technologies
  - Exploration Habitats
- **Extra-Vehicular Activity**
  - EVA Suits
  - Pressurized Volumes
  - Tools & Aids
  - Ground Support Equipment

Benefits of the Human Health & Support Systems CRM

- The Human Health and Performance area guides the research and countermeasure development to reduce the risks to humans in space flight, as well as define the technology necessary for maintenance of the daily functional requirements of the human system.
  - Space Radiation
  - Medical Care
  - Human Health Countermeasures
  - Behavioral Health & Performance
  - Space Human Factors
- Life Support and Habitation focuses on the research and technology development to sustain the life of the human system during transit and planetary phases of exploration.
  - Life Support Systems (air, thermal, water, food)
  - Environmental Monitoring and Control
  - Contingency Response Technologies
  - Exploration Habitats
- The Extra-Vehicular Activity project develops the technology required to sustain the life of humans outside of the life support systems of the vehicle and surface habitats, as well as the tools required to perform exploration and contingency EVA.
  - EVA suit
  - Pressurized volumes
  - EVA tools
  - Ground support equipment

Roadmap Process and Approach

Advanced Planning & Integration Office

- Input from internal NASA and contractor experts
- Iterative review with Roadmap team members
- Review with NASA Headquarters Exploration Systems Mission Directorate
- Interim NRC review
- Updates based on the NRC review
- Updates based on Strategic Roadmaps
- Final review with NRC
- Final product updated as required during NASA planning phases

Requirements/Assumptions

Advanced Planning & Integration Office

- The following Design Reference Missions were used as guidance in some instances:
  - *Human Exploration of Mars: Artificial-Gravity Nuclear Electric Propulsion Option*
  - *Reference Mission Version 3.0 Addendum to the Human Exploration of Mars*
  - *Mars 98 Reference mission: Reference Mission of the NASA Mars Exploration Study Team*
  - *Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities*
  - *The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities*
- Potential mission timeframes follow the Document: *ESMD-RQ-0019 Preliminary Title: CEV Concept of Operations Effective Date: 1 September 2004*

- Additional requirements/assumptions are detailed within the sub capability charts

Capability Readiness Levels

Advanced Planning & Integration Office

A Capability is defined as a set of systems with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Technology Readiness Levels/ Countermeasure Readiness Levels

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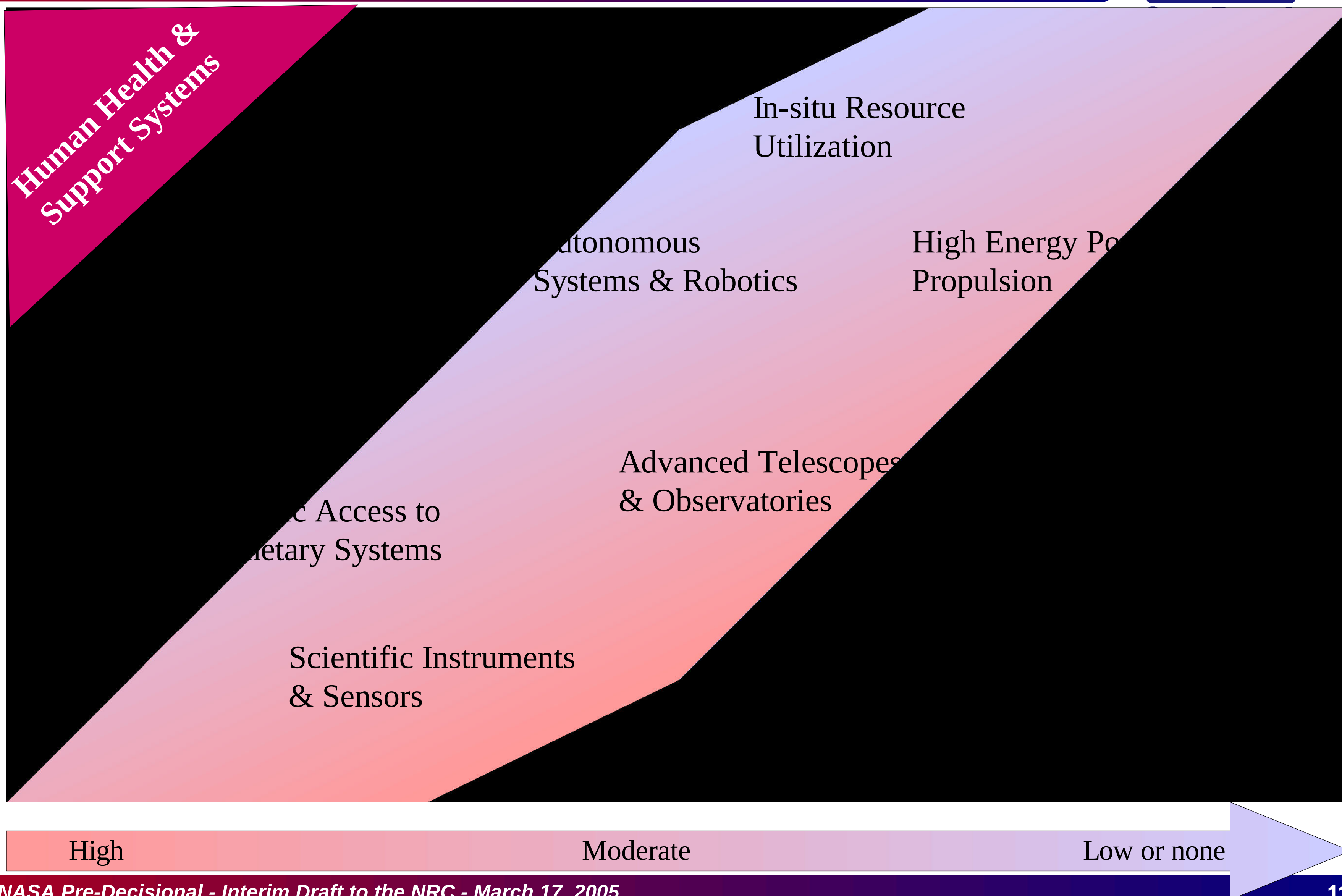
TRL Definition	TRL/CMRL Score	CMRL Definition	CMRL category	
Basic principles observed	1	Phenomenon observed and reported. Problem defined.	Basic research	
Technology concept and/or application formulated	2	Hypothesis formed; preliminary studies to define parameters. Demonstrate feasibility.	Basic research	
Analytical and experimental critical function/proof-of-concept	3	Validated hypothesis. Understanding of scientific processes underlying problem.	Basic research	Research to prove feasibility
Component and/or breadboard validation in lab	**4**	**Formulation of countermeasures concept based on understanding of phenomenon.**	**Countermeasure development**	**Research to prove feasibility**
Component and/or breadboard in relevant environment	**5**	**Proof of concept testing and initial demonstration of feasibility and efficacy.**	**Countermeasure development**	**Research to prove feasibility**
System/subsystem model or prototype demonstration in relevant environment	**6**	**Laboratory/clinical testing of potential countermeasure in subjects to demonstrate efficacy of concept.**	**Countermeasure development**	
Subsystem prototype in a space environment	**7**	**Evaluation with human subjects in controlled laboratory simulating operational space flight environment.**	**Countermeasure development**	**Countermeasure demonstration**
System completed and flight qualified through demonstration	**8**	**Validation with human subjects in actual operational space flight to demonstrate efficacy and operational feasibility.**		**Countermeasure demonstration**
System flight proven through mission operations	**9**	**Countermeasure fully flight-tested and ready for implementation.**	**Countermeasure operations**	

Roadmap Connections/Dependencies



Mars Missions Decisions Related to Human Health & Support Systems

	Mission Factors	Human Health	Life Support	Habitats	EVA
Mission Design	Transit time	✖	✖		
	*Planetary stay	✖	✖	✖	☼
	Precursor Robotic Missions	✖	✖	✖	✖
Objectives	*Location - single outpost/base/ alternate outposts?	☼	✖	✖	✖
	*Surface Mobility/Range	☼	☼	☼	✖
	*ISRU	☼	✖	✖	✖
Key Program Decisions	*Crew Size	✖	✖	✖	
	Artificial Gravity	✖	✖	✖	
	Aerocapture	☼			
	*Robotic Assistants				✖
	Lunar Missions as a testbed	✖	✖	✖	✖
	*ISS as a testbed	✖	☼		

⌧♋●⬧□ 💣□□■

✖ = Critical ☼ = Moderate

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Human Health & Performance

Presenter:

Dennis Grounds

Human Health & Performance

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- Human Health and Performance guides the research and countermeasure development to reduce the risks to humans in space flight, and defines the technology necessary for maintenance of the daily functional requirements of the human system.
  - Space Radiation
  - Medical Care
  - Human Health Countermeasures
  - Behavioral Health & Performance
  - Space Human Factors

Human Health & Performance

Human Health & Performance

Space Radiation
- Measurement Technologies
- Shielding Solutions
- Risk Assessment/ Projection
- Biological Countermeasures

Medical Care
- Medical Devices
- Clinical Capabilities
- Medical Informatics

Human Health Countermeasures
- Artificial Gravity
- Exercise
- Other Physio-logical CM

Behavioral Health & Performance
- Team Cohesion & Productivity
- Psych Health Management
- Performance Readiness
- Individual & Crew Selection

Space Human Factors
- Models & simulations
- Design tools & requirements
- Performance Measurements
- Training & Decision Support Systems

Benefits of Human Health & Performance

Advanced Planning & Integration Office

Reduce Risk

- NASA shall implement a safe , sustained and affordable robotic and human program to explore and extend human presence across the solar system and beyond.

  Level 0 Exploration Requirements for NASA

- For Human Explorers to undertake lengthy research trips on other worlds, they will have to maintain their health in environments that possess higher radiation and lower gravity than Earth that are far from supplies and medical expertise.

  The Vision for Space Exploration

- The successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedules and affordable costs.
- Biomedical risk mitigation – space medicine; remote monitoring, diagnosis and treatment.

Excerpt from "Report of the President's Commission on Implementation of United States Space Exploration Policy," June 2004

Increase Capability

Current State-of-the-Art for Human Health & Performance

Advanced Planning & Integration Office

- Shuttle and International Space Station (ISS) standards and practices
- Terrestrial medical capabilities
- Department of Defense (DoD) standards and practices

Requirements /Assumptions for Human Health & Performance

Advanced Planning & Integration Office

- **Document: ESMD-RQ-0019 Preliminary Title: CEV Concept of Operations**
- **Effective Date: 1 September 2004**

- **The Exploration Systems Mission Directorate recognizes the following major programmatic milestones and associated dates:**
  - **2008: Initial flight test of a Crew Exploration Vehicle (CEV)**
  - **2008: Launch first lunar robotic orbiter**
  - **2009-2010: Robotic mission to lunar surface**
  - **2011: First uncrewed CEV flight**
  - **2014: First crewed CEV flight**
  - **2014-2015: Prometheus 1 demonstration mission**
  - **2015-2020: First human mission to the Moon**

- **Spirals 4 and 5 encompass the capabilities necessary to execute piloted missions to the vicinity of Mars as well as landed missions. The date for humans to reach the Mars vicinity is dependent on the development timeline and discoveries that result from the earlier spirals. However, 2030 is being used as a reference date for extensibility criteria and technology planning.**

- **For planning purposes in this roadmap, target dates were chosen from within the above time spans. These dates will be adjusted as further guidance is given by the Strategic Roadmaps and/or the Directorates.**

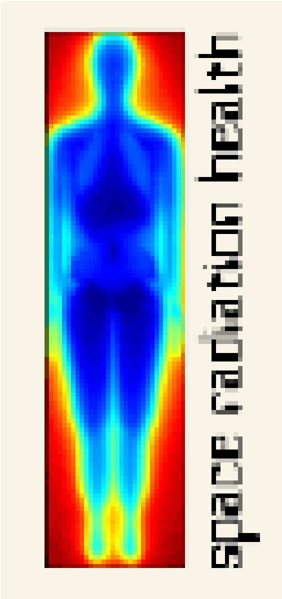
Human Health & Performance

- **Space Radiation**
  - Measurement Technologies
  - Shielding Solutions
  - Risk Assessment/ Projection
  - Biological Countermeasures
- **Medical Care**
  - Medical Devices
  - Clinical Capabilities
  - Medical Informatics
- **Human Health Countermeasures**
  - Artificial Gravity
  - Exercise
  - Other Physio-logical CM
- **Behavioral Health & Performance**
  - Team Cohesion & Productivity
  - Psych Health Management
  - Performance Readiness
  - Individual & Crew Selection
- **Space Human Factors**
  - Models & simulations
  - Design tools & requirements
  - Performance Measurements
  - Training & Decision Support Systems

Space Radiation

Definition

- Space Radiation addresses the risks to human exploration from exposure to space radiation, including ionizing radiation, solar particle events (SPE) and galactic cosmic rays.
  - Possible health risks include cancer, damage to the central nervous system, degenerative tissue disease (cataracts, heart disease, etc.), and acute radiation sickness.
- Components include:
  - Risk assessment/projection
  - Shielding solutions
  - Measurement technologies
  - Biological countermeasures

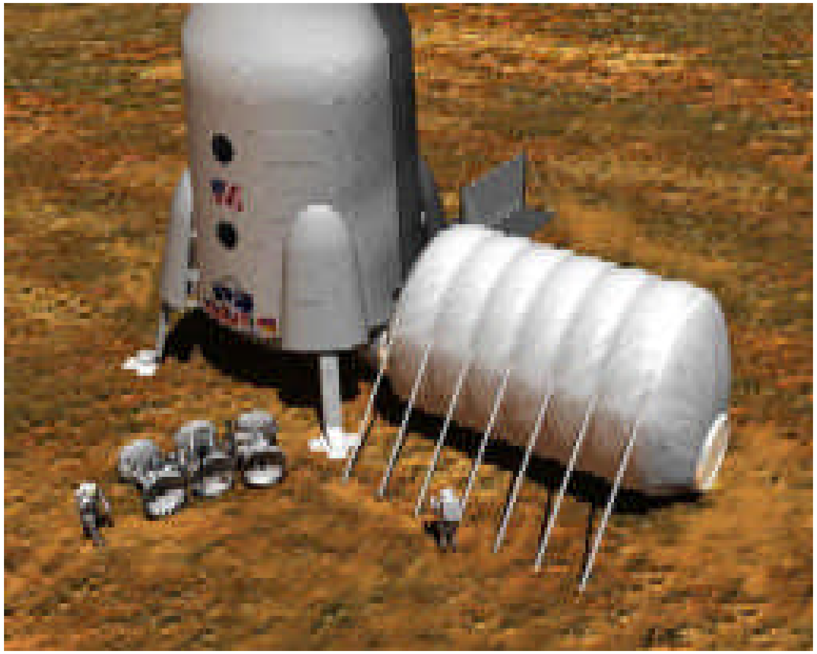


Space Radiation

Advanced Planning & Integration Office

Benefits

- Assure that we can safely live and work in the space radiation environment, anywhere, any time.
- Assure astronauts return to Earth safely, and continue to maintain an acceptable quality of life.

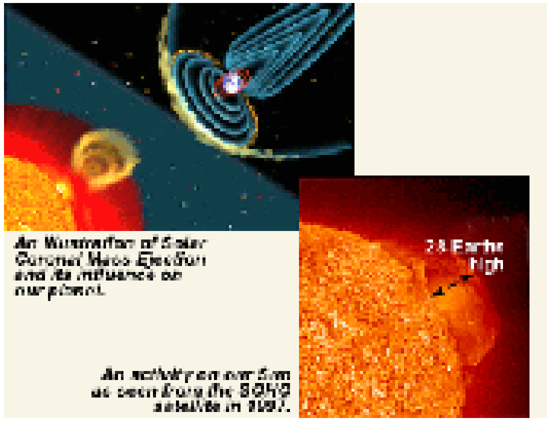


Current State-of-the-Art for Space Radiation

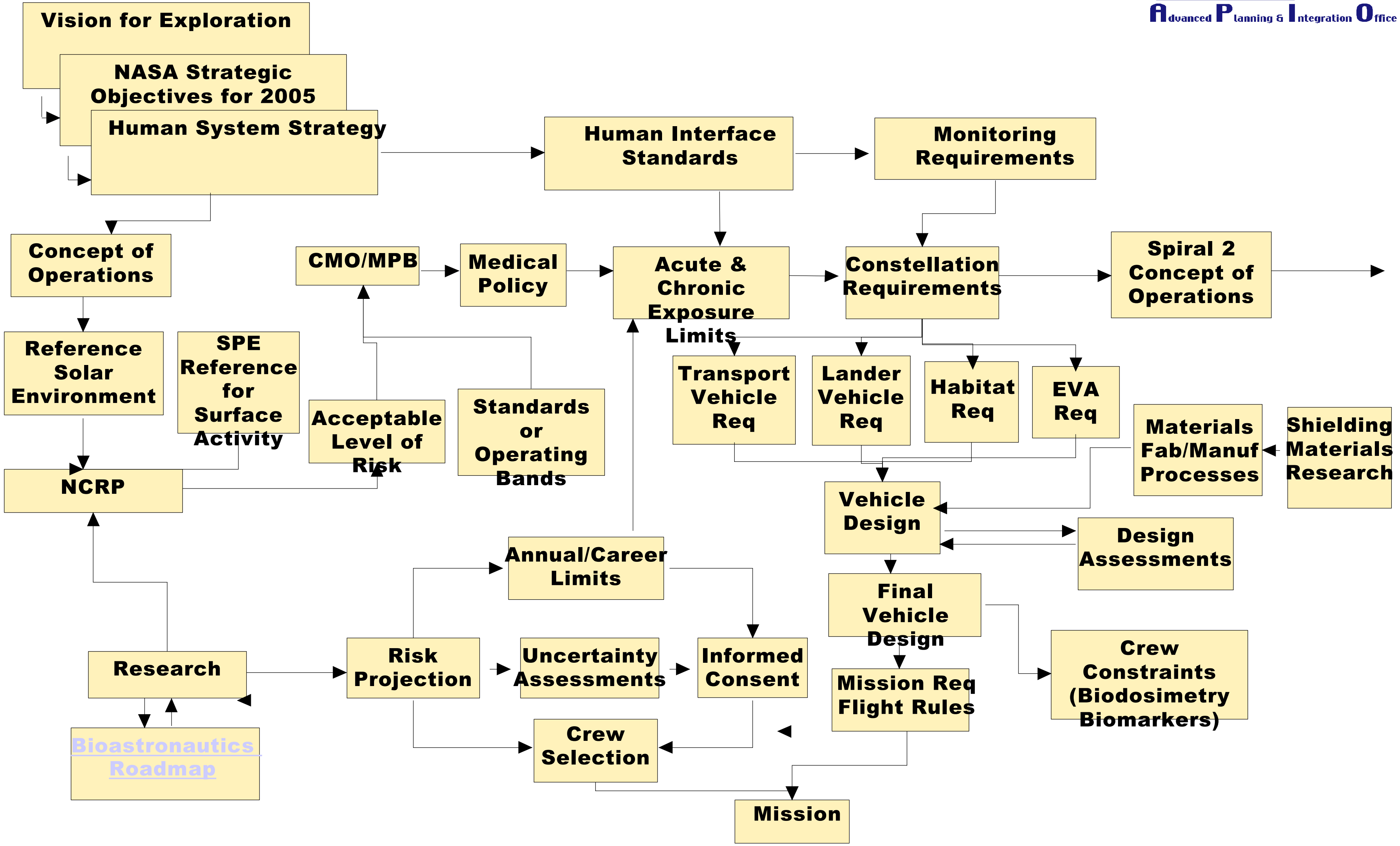
Advanced Planning & Integration Office

State of the Art

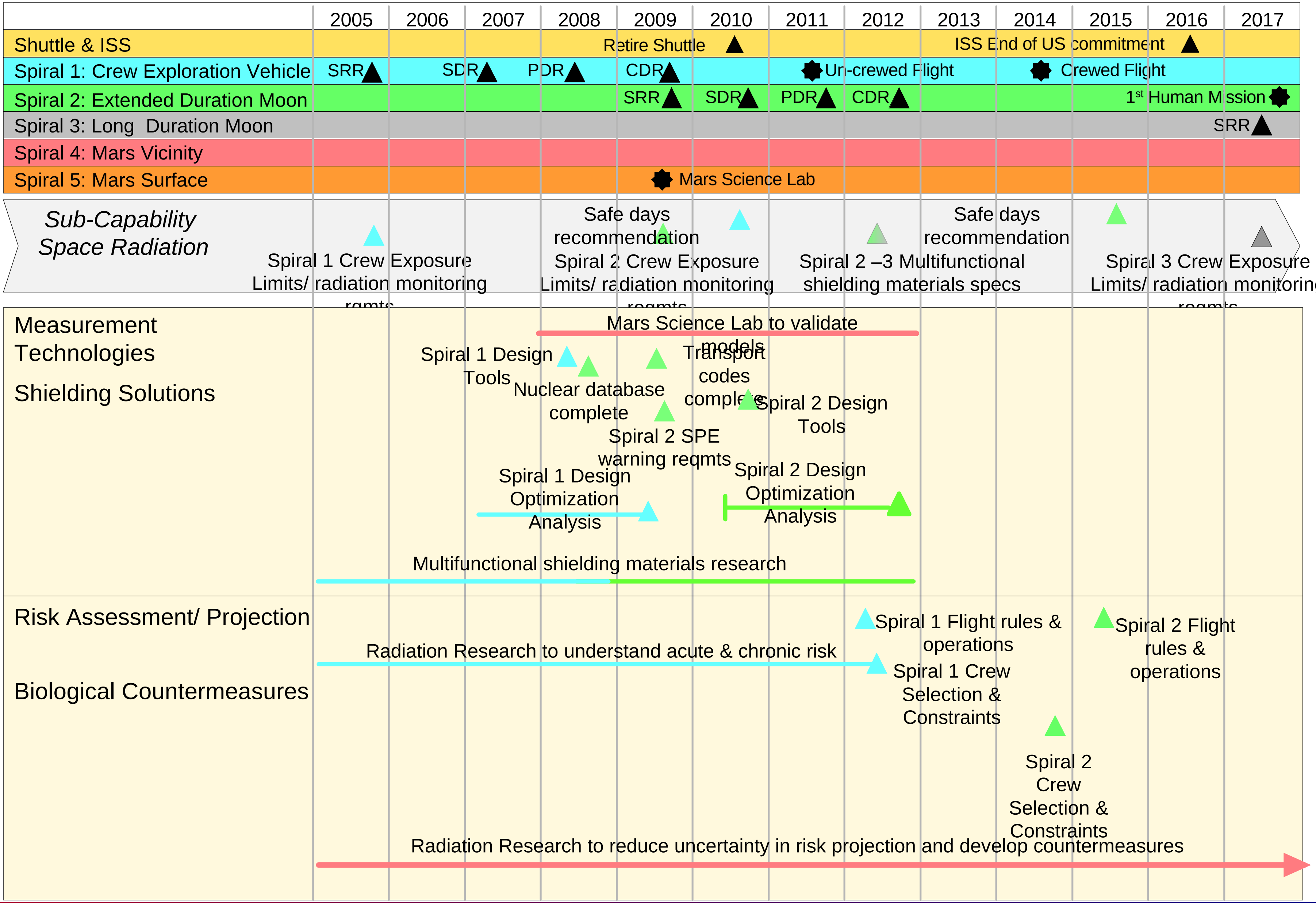
- Shuttle and ISS shielding
  - Not inherently part of the vehicle design; some components added late in development
- Shuttle and ISS monitoring
  - Equipment no longer reliable
  - Lack system integration
  - Require extensive ground analysis
  - SPE early warning uses NOAA space weather satellites with Earth-based analysis and communication
  - No neutron spectrometer
- Low Earth Orbit (LEO) exposure limits
  - Based on LEO environment (different mix of protons and HZE particles)
- LEO risk assessment
  - Based on LEO environment (different mix of protons and HZE particles)
- Space environmental models need to be validated and monitored with in-situ dosimetry



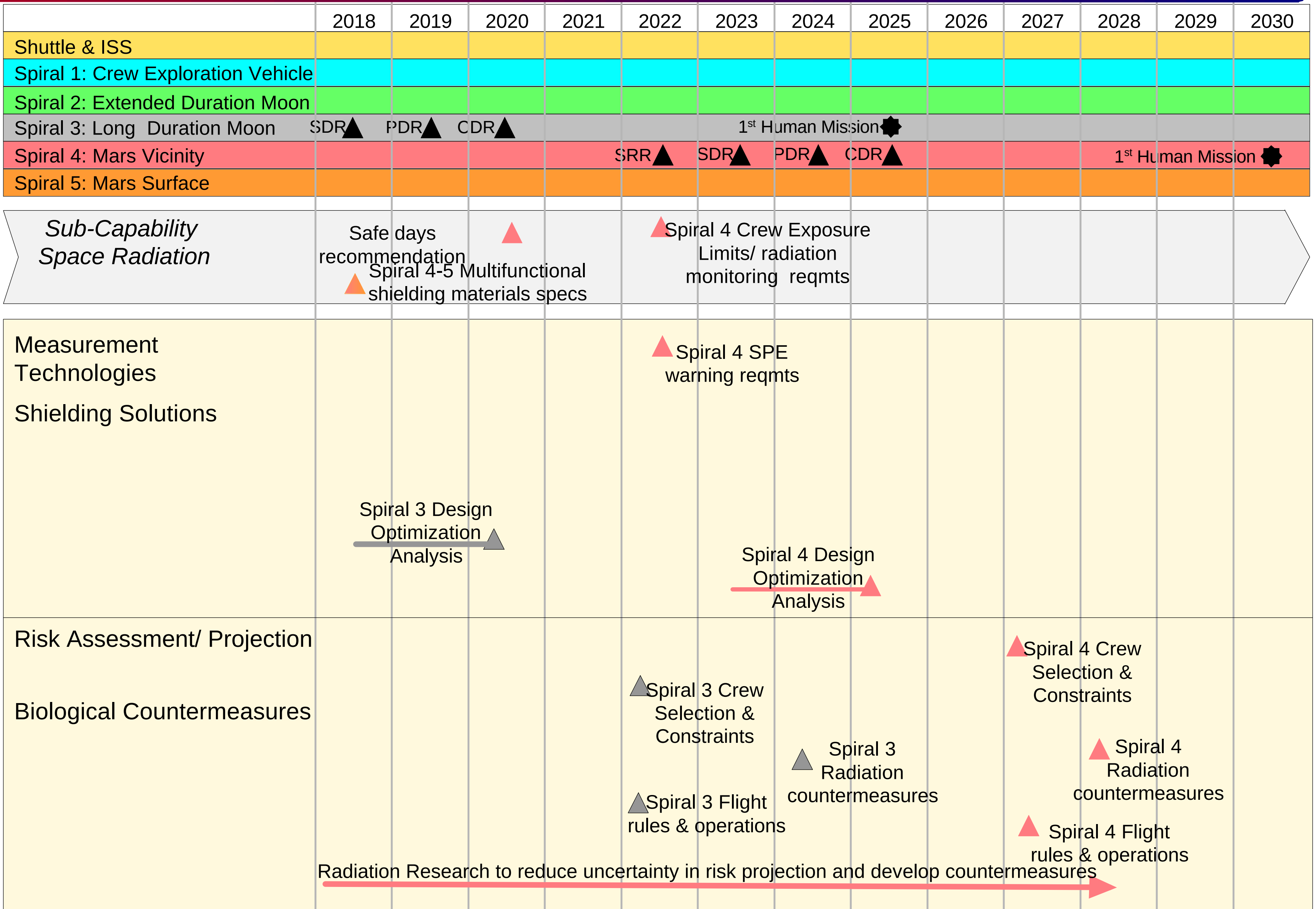
Requirements /Assumptions for Space Radiation



Space Radiation Roadmap



Space Radiation Roadmap



Maturity Level – Capabilities
Space Radiation

Advanced Planning & Integration Office

Integration Approach

Risk

- Ground research (NSRL) to reduce uncertainty in risk projection/Develop biological CM
- Establish human exposure limits per habitable module
- Establish human exposure limits per exploration mission
- Maintain, improve risk assessment models/ Analyze proposed mission architectures
- Develop requirements for habitable volume monitoring/ early warning systems
- Develop operations products (flight rules, crew constraints, training, ground segment support

Shielding

- Develop design assessment tools for vehicle architecture
- Evaluate candidate shielding materials (all habitable volumes) for effectiveness
- Establish criteria for secondary space craft usage (material strength, properties, manufacturability)
- Evaluate candidates for secondary space craft usage (structure)
- Material engineering to optimize application (sandwich, impregnation)
- Deliver candidate shielding tech-nologies to space craft developer

Capability Readiness Level

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Maturity Level – Technologies for Measurement Technologies

Advanced Planning & Integration Office

Gaps	Deliverables	Current TRL/ Need Date
Inability to predict SPEs	Early warning system	1/2020
Reliable Monitoring Instruments covering most significant portions or part of spectrum	Operational radiation dosimetry (multiple instruments) with proven reliability and performance.	5/2011*

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Shielding Solutions

Gaps	Deliverables	Current TRL/ Need Date
Optimized shielding solutions	Requirements for vehicle design/ materials to optimize radiation shielding	3/2012 (moon) 3/2020 (Mars)
Multifunctional Materials	Vehicle Design recommendations (ALARA); Manufacturable materials w/high Radiation protection characteristics for use in vehicle structures	2/2008

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Risk Assessment/Projection

Gaps	Deliverables	Current TRL/ Need Date
Risk prediction tools with $\leq$ 2 - fold uncertainty in prediction	Risk Assessment and Projection tools with 95% Confidence Level	1/2024

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Biological Countermeasures

Gaps	Deliverables	Current TRL/ Need Date
Biological countermeasures	Validated Biological countermeasures for space radiation risks	1/2028

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Space Radiation

- **Number of safe days in space without exceeding career limits at 95% confidence level**

  - **LEO (Spiral 1): three 180-day missions without exceeding career limits at 95% confidence level (Solar Particle Events, Galactic Cosmic Rays, trapped radiation belts)**
  - **MOON (Spirals 2-3): six 30-90 day missions below threshold for acute effects (Solar Particle Events)**
  - **MARS (Spirals 4-n): one 1000-day mission without exceeding career limits at 95% confidence level (Galactic Cosmic Rays, Solar Particle Events)**

Medical Care

Human Health & Performance

Space Radiation
- Measurement Technologies
- Shielding Solutions
- Risk Assessment/ Projection
- Biological Countermeasures

Medical Care
- **Medical Devices**
- **Clinical Capabilities**
- **Medical Informatics**

Human Health Countermeasures
- Artificial Gravity
- Exercise
- Other Physio-logical CM

Behavioral Health & Performance
- Team Cohesion & Productivity
- Psych Health Management
- Performance Readiness
- Individual & Crew Selection

Space Human Factors
- Models & simulations
- Design tools & requirements
- Performance Measurements
- Training & Decision Support Systems

Medical Care

Definition

- Medical Care for exploration missions must provide monitoring, diagnosis and treatment during a mission with little or no real-time support from Earth. It includes identifying, defining and monitoring health risks, establishing medical guidelines, utilizing telemedicine, and developing medical technology for exploration.
  - Medical Devices, e.g., imaging system, surgical instruments, IV fluid generation system, monitoring devices
  - Clinical Capabilities, e.g., crew selection/constraints criteria, pre-mission prevention, on-board procedures, training
  - Medical Informatics, e.g., on-board diagnosis & treatment database

Benefits of Medical Care

Advanced Planning & Integration Office

Benefits

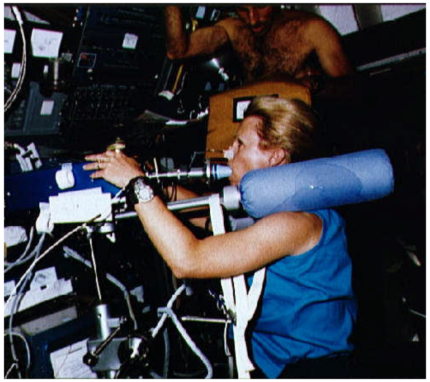
- **Reduce Risk by**
  - Enhancing the prevention of medical events through selection, “vaccines,” training, and medical procedures
  - Identifying and preparing for major trauma and medical events pre-flight
  - Inflight monitoring for early detection of health conditions allowing effective, economical, early treatment
- **Increase Capability by**
  - Providing inflight medical care to ensure mission success, productive crew members and protect crew health
  - Using ISS as a testbed to determine space medical norms
  - Improving Medical Diagnostics and Therapeutics

Current State-of-the-Art Medical Care

Advanced Planning & Integration Office

State of the Art

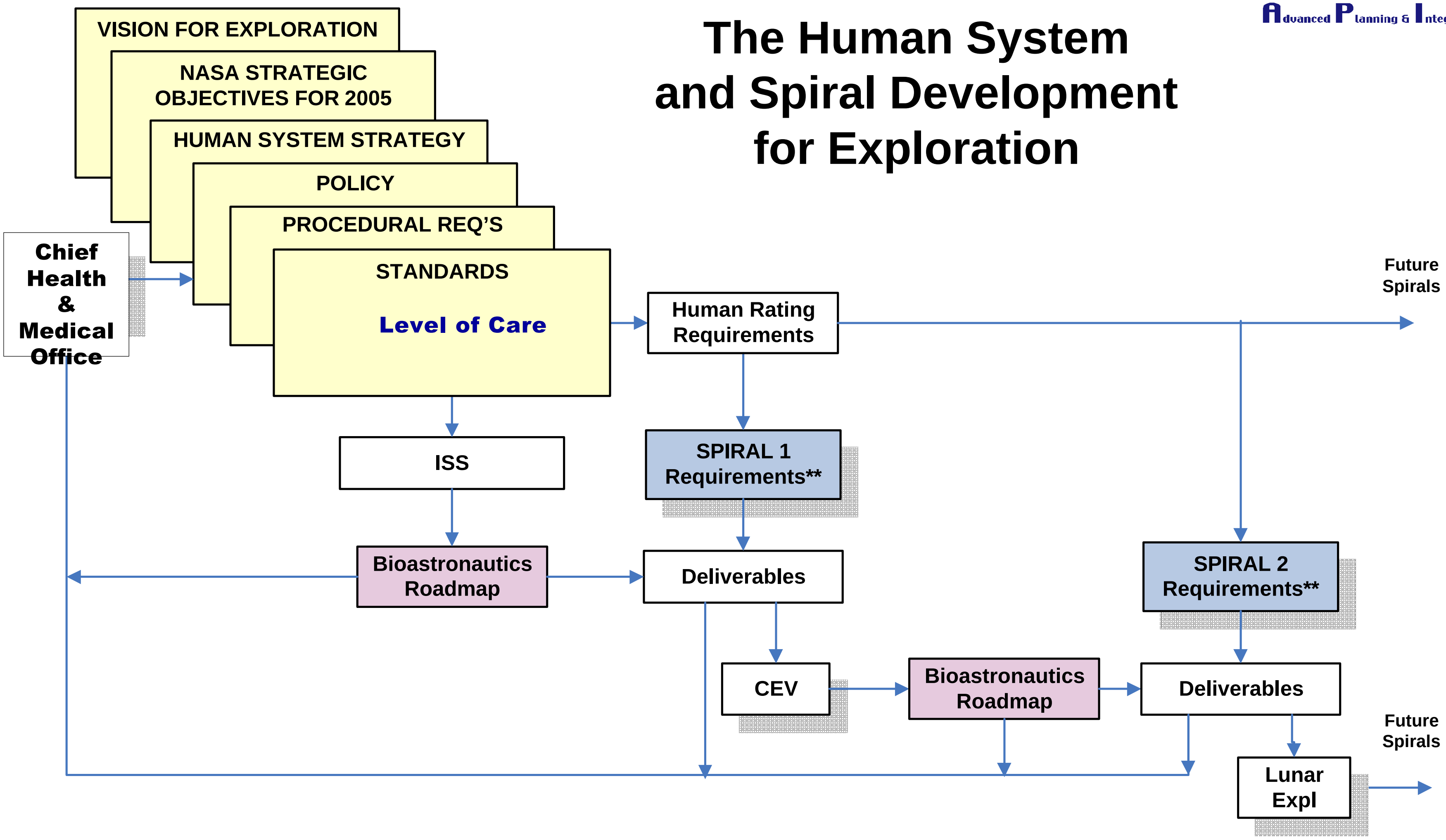
- ISS Crew Health Care System – can provide capability to stabilize and transport crew immediately to Earth
- Terrestrial Medical Technologies – typically not designed to operate in spacecraft closed environment, in microgravity, or in a radiation environment; not designed to minimize mass/volume/power/resources
- DoD telemedicine applications – designed for extreme environments to treat multiple injuries; not constrained to spacecraft resources such as mass, volume, power, interfaces, communication latency; not designed for reduced gravity; has a backup of evacuation to definitive medical care not available for long duration missions
- Shelf life of medical supplies based on terrestrial use – not designed for space radiation environment and the length of a Mars mission



Requirements /Assumptions for Medical Care

Advanced Planning & Integration Office

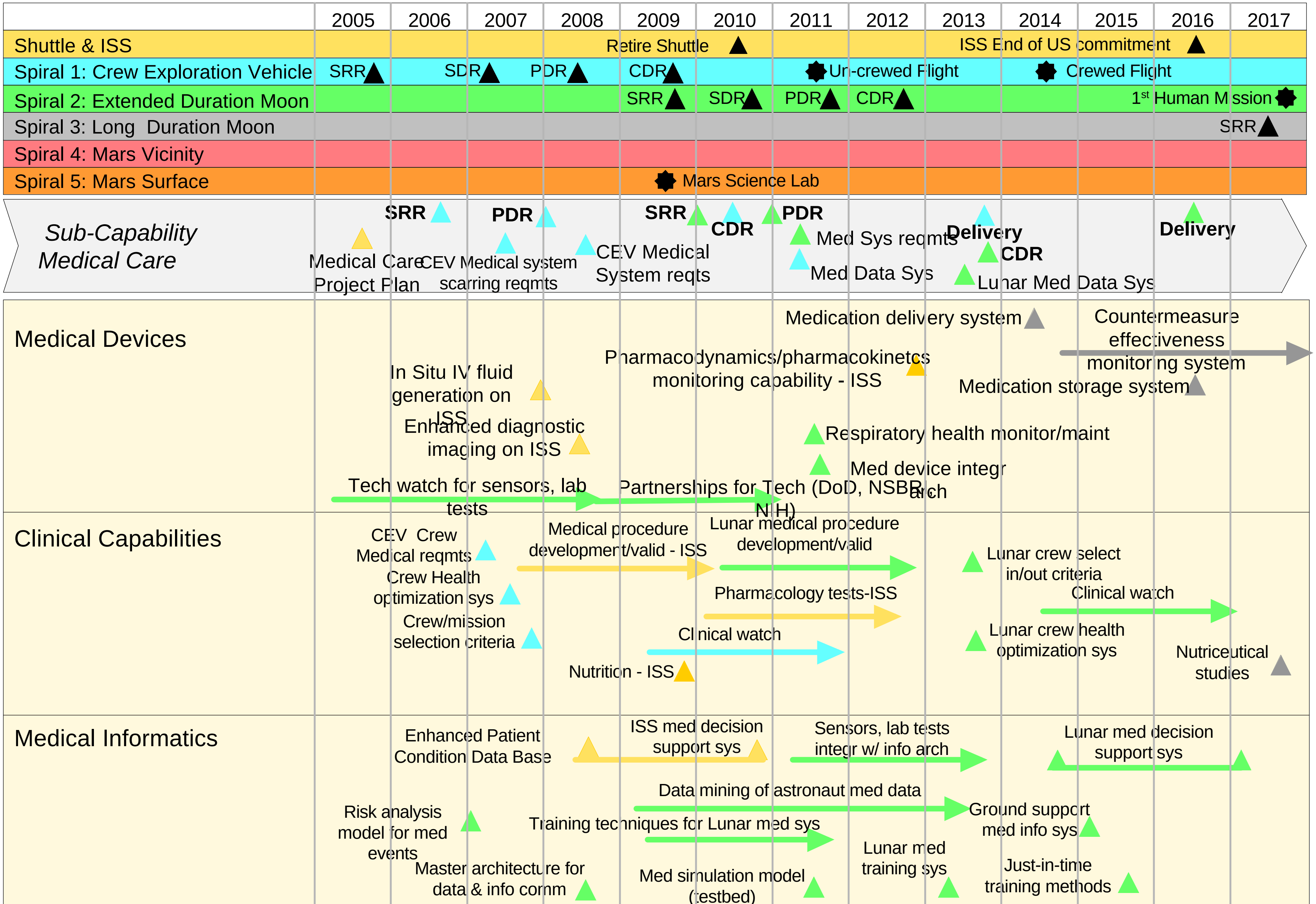
The Human System and Spiral Development for Exploration



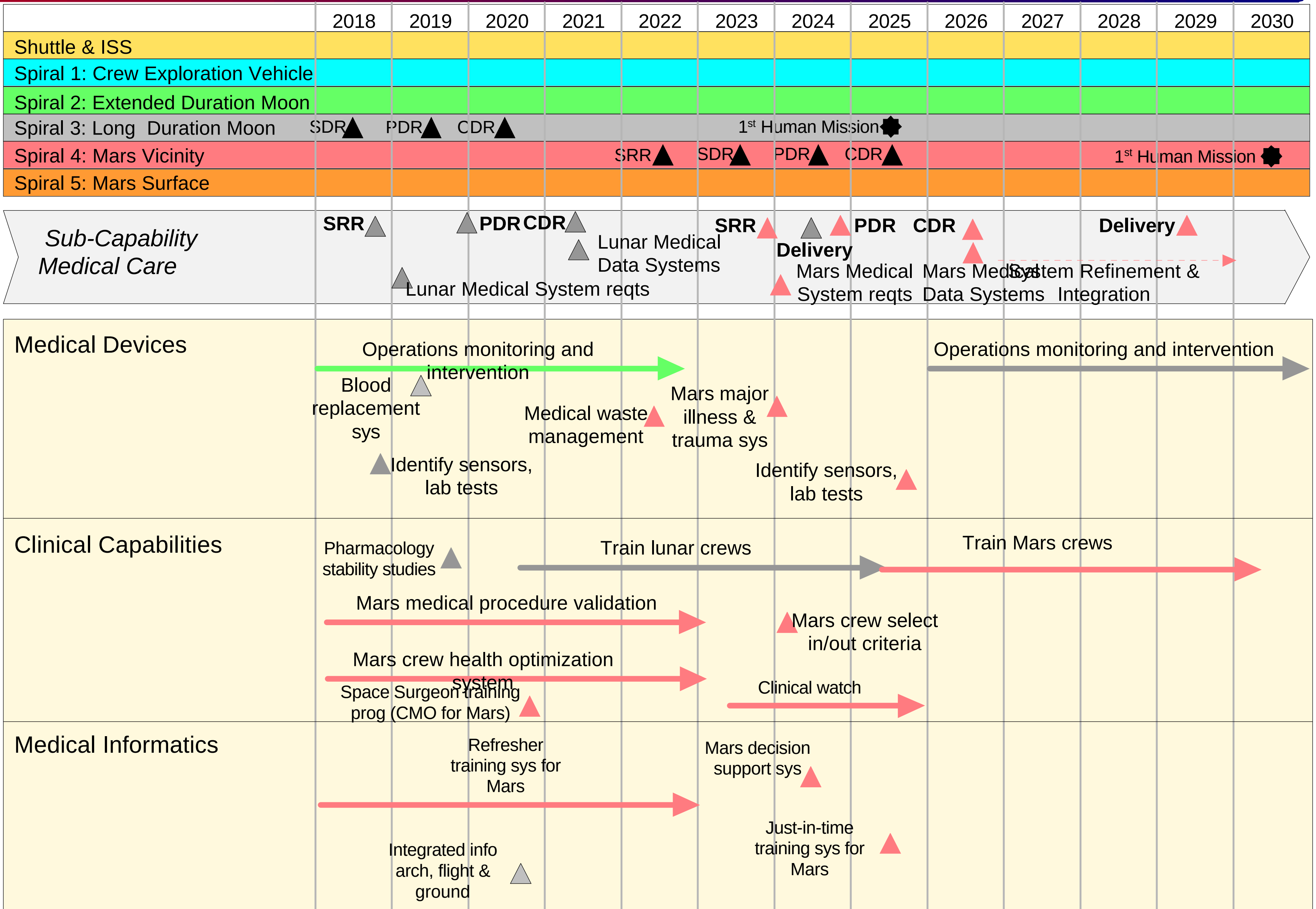
** Includes all program requirements

03/10/05

Medical Care Roadmap



Medical Care Roadmap



Maturity Level – Capabilities Medical Care

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Integration A

NASA unique technology(ies) Identification
- Medical Devices
- Clinical Care
- Informatics

Develop & test prototype systems on ISS, in ground integration facilities, on lunar missions

Continuously evaluate & infuse new technologies until Baseline medical system per spiral

Deliver specifications & technology solutions for system development

Develop ground segment to support flight medical operations

Capability Readiness Level

2 — Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Maturity Level – Technologies for Medical Devices

Advanced Planning & Integration Office

Gaps	Deliverables	Current TRL/ Need Date
IV fluid shelf life	On-board IV fluid generation	4/2016*
Level of care	Appropriate surgical instruments Heart, lung monitoring devices Pharmaceutical delivery system	4/2020 5/2020 2/2020
Limited diagnostic capability	Imaging system Biochemical diagnostic tools	5/2015** 5/2015**

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Clinical Capabilities

Advanced Planning & Integration Office

Gaps	Deliverables	Current TRL/ Need Date
Stabilize & transport to definitive care site	Medical capabilities sufficient for mission concept of ops	6/2015
Pharmacodynamics/ Pharmacokinetics Research	Effective pharmaceuticals/ accurate prescription protocol	3/2016*
Environmental Hazard Knowledge (e.g., dust, radiation, toxicity, chemical properties)	Requirements for robotic precursor missions, including sample return	1/2022
Lack of Partial G procedures	Partial G Procedures	2/2020
Adequate ground and on-board training for increased autonomy	Training materials, methods, certification	2/2015 (moon) 2/2025 (Mars)

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Medical Informatics

Advanced Planning & Integration Office

Gaps	Deliverables	Current TRL/ Need Date
Dependence on ground based support system	Semi- autonomous decision support system	3/2020
Lack of evidence base of medically relevant data.	Searchable, analyzable, structured database of medical information.	4/2010
Multiple system components with individual communications protocols.	Integrated information architecture allowing new devices to be connected in a plug and play fashion.	2/2015
Crewmember providing medical care with limited medical training.	Training system – just-in-time as well as refresher training.	2/2015 (moon) 2/2025 (Mars)
Use of paper-based medical procedures	Automated procedure assistant	4/2015
Reliance on microgravity for testing procedures, etc.	Biomedical models of human systems in microgravity	3/2020

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Medical Care

Advanced Planning & Integration Office

- **Program Goal**:
  - Decrease in mission impacts due to medical and crew performance problems.

*There are several metrics that can be used to assess the progress annually:

- **Annual**:
  - Progression of TRL/CMRL levels of technology components
  - Percent coverage of conditions in the Patient Condition Data Base
  - Match mass, power, volume, redundancy, modularity, resupply constraints to mission profile
  - Few resources spent redesigning (modular design)
  - High usability and integrated testing results
  - Less crew time needed for ground-based training, on-orbit training, and procedure execution
  - High reliability/maintainability (MTBF=Mean Time Between Failures, maintenance time)

Human Health Countermeasures

Advanced Planning & Integration Office

Human Health & Performance

Space Radiation
- Measurement Technologies
- Shielding Solutions
- Risk Assessment/ Projection
- Biological Countermeasures

Medical Care
- Medical Devices
- Clinical Capabilities
- Medical Informatics

Human Health Countermeasures
- **Artificial Gravity**
- **Exercise**
- **Other Physio-logical CM**

Behavioral Health & Performance
- Team Cohesion & Productivity
- Psych Health Management
- Performance Readiness
- Individual & Crew Selection

Space Human Factors
- Models & simulations
- Design tools & requirements
- Performance Measurements
- Training & Decision Support Systems

Human Health Countermeasures

Definition

- Countermeasures mitigate the adverse effects of space flight to ensure that humans can function in a safe and productive manner during transit phases and planetary stays required in exploration missions. Sub-capabilities include:
  - Artificial Gravity, continuous or intermittent
  - Exercise
  - Other Countermeasures to address:
    - Musculoskeletal Alterations (Bone and Muscle)
    - Cardiovascular Alterations
    - Sensory motor and neurological changes (e.g., balance and coordination)
    - Immunology, infection, hematology
    - Environmental Physiology (e.g., Decompression Sickness, toxicity, microbiology)

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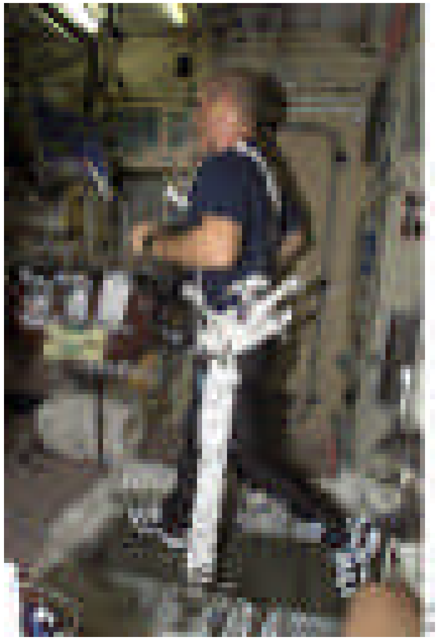


Benefits:

- **Reduce Risk by**
  - **Developing and maintaining permissible exposure limits to the adverse affects of space flight on humans**
- **Increase Capability by**
  - **Providing validated Countermeasure Suites for Moon and Mars to manage or prevent:**
    - **Bone and muscle loss**
    - **Cardiovascular alterations**
    - **Sensory motor problems**
    - **Immunology, infection, and hematology problems**
    - **Environmental physiology conditions**

Current State-of-the-Art for Human Health Countermeasures

Advanced Planning & Integration Office

- Currently used countermeasures have been shown to be effective for flight durations up to 180 days.

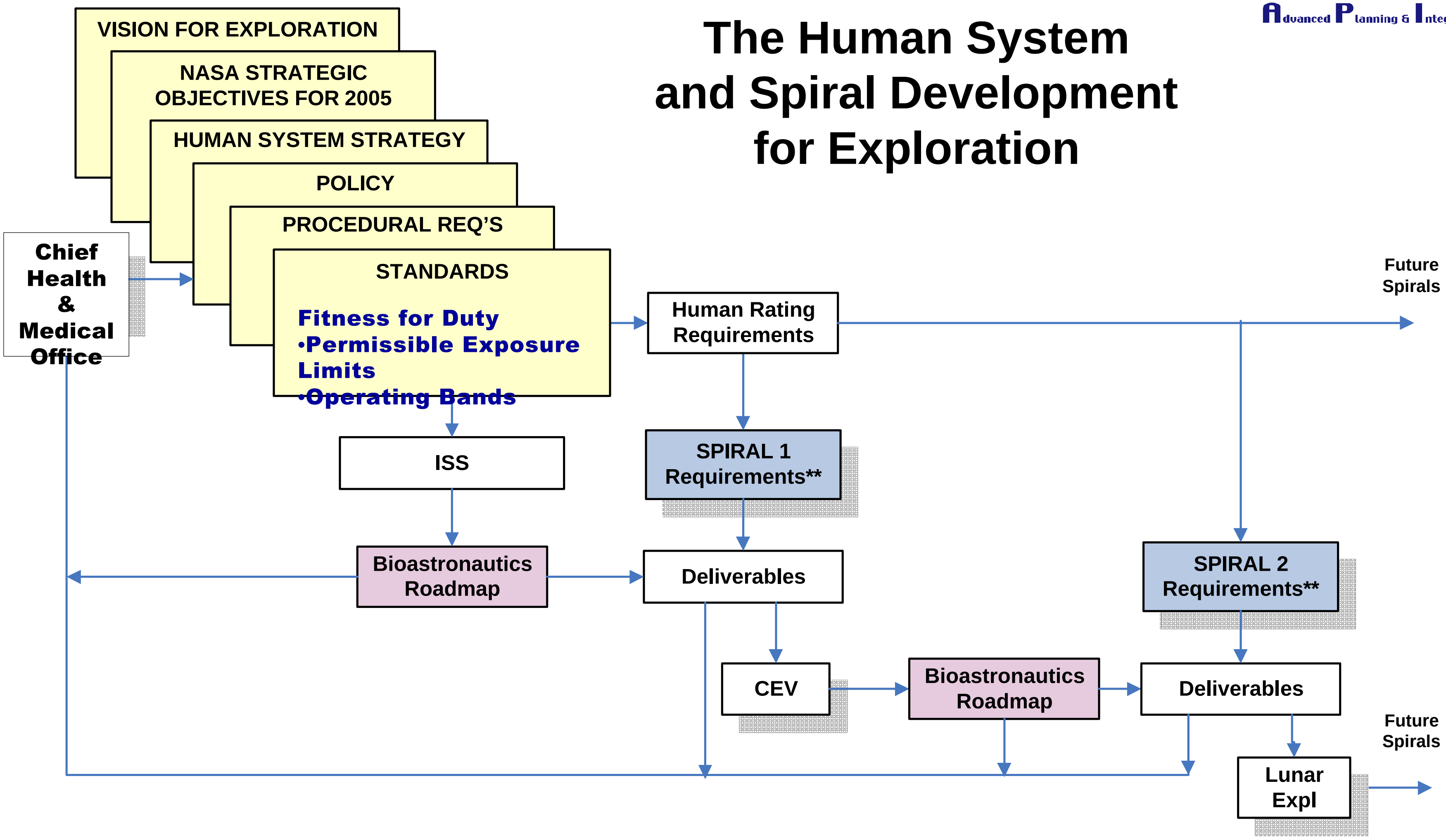
Basic Research → Countermeasure Progression → **On-orbit use**

Development	Evaluation	Validation	Operations
❖Pharmacologics ❖Gaze, Spatial Orientation Protocols ❖Cognitive Tools ❖Immune Regulation ❖Gait Adaptability Training Program ❖Next generation exercise devices	❖ Vibration Plate Protocols ❖ Artificial Gravity ❖ Ultrasound Bone Stimulation ❖ Enhanced nutrition & exercise protocols ❖ Exercise prescriptions evaluation & optimization	❖ Potassium Citrate (kidney stones) ❖ Midodrine (orthostatic intolerance) ❖ Bisphosphonates (Bone Loss) ❖ EVA Pre-Breathe Reduction Protocols (decompression sickness) ❖ Exercise hardware devices and prescriptions validation	❖ Exercise • TVIS • BD-1 • CEVIS • SchRED ❖ Fluid Loading ❖ Re-entry Anti-G suit ❖ Liquid Cooling Garment (LCG) ❖ Recumbent Seat ❖ Promethazine (SMS) ❖ Vitamin D and Caloric Counseling ❖ Acoustics CM Kit ❖ Prebreathe Protocol ❖ Circadian Shifting

Requirements /Assumptions for Human Health Countermeasures

Advanced Planning & Integration Office

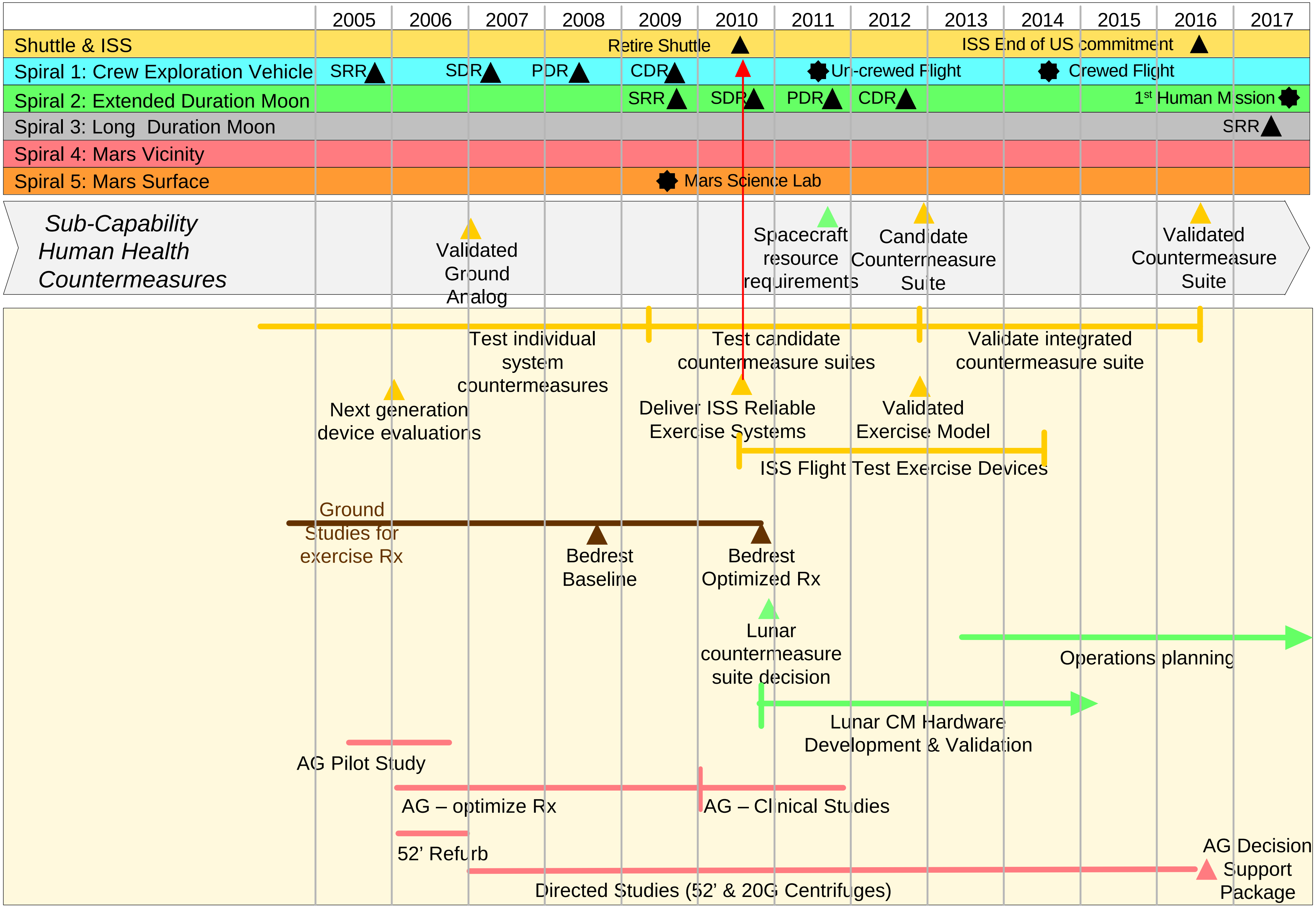
The Human System and Spiral Development for Exploration



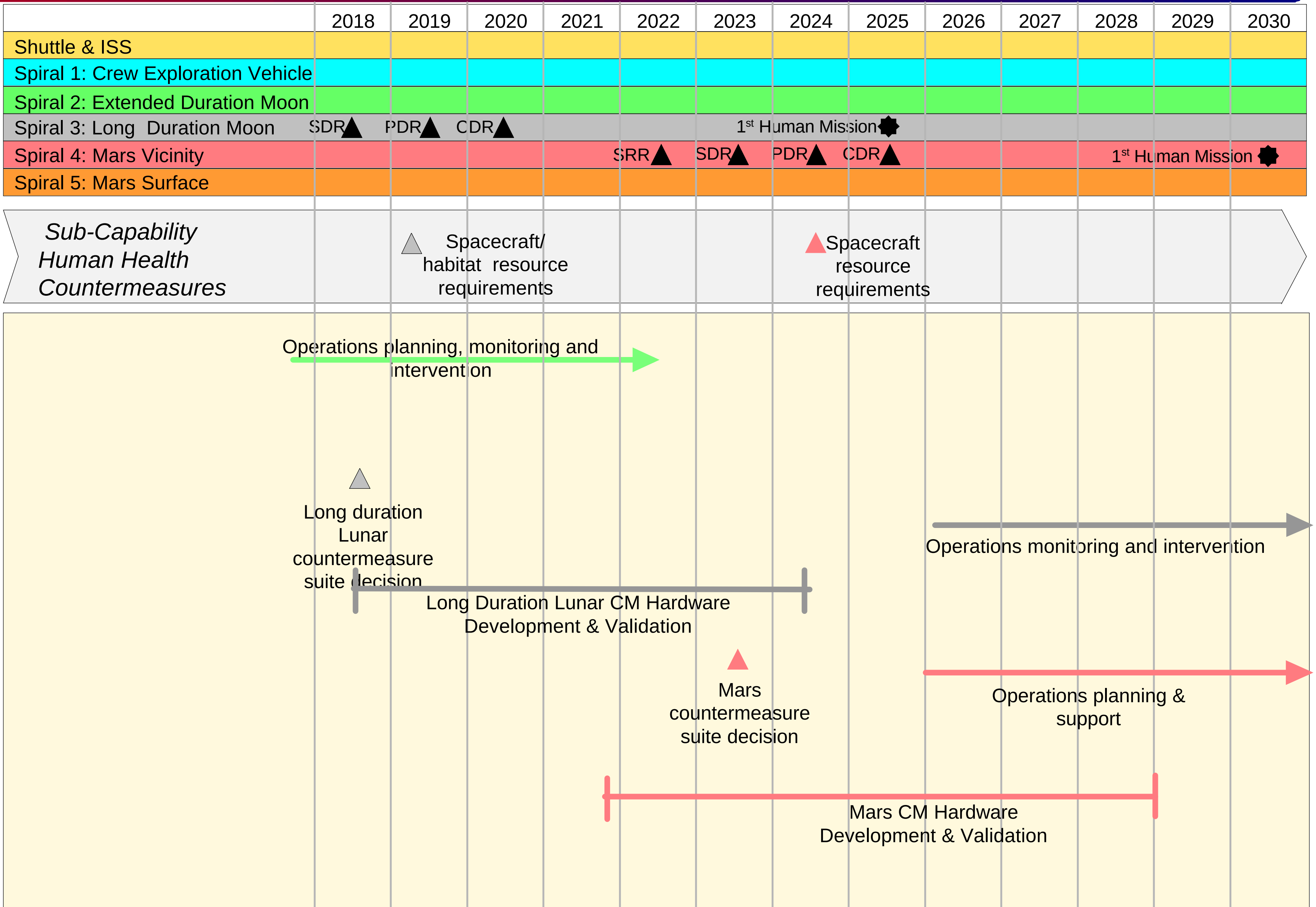
** Includes all program requirements

03/10/05

Human Health Countermeasures Roadmap



Human Health Countermeasures Roadmap



Human Health Countermeasures – Artificial Gravity

Benefits:

- Physiological adaptation in-transit (bone, muscle, cardio, neuro, …)
- Human factors in-transit (spatial orientation, WCS, galley, …)
- Medical equipment/operations (countermeasures, surgery, CPR, …)
- Environmental (particulates, liquids, …)

Risks/Uncertainties:

- Engineering (requirements, design: truss, fluid loops, propulsion…)
- Human factors during spin-up/down
- Physiological adaptation during spin-up/down (neuro, cardio, …)

Human Health Countermeasures – Artificial Gravity

Advanced Planning & Integration Office

Evidence Base to Guide Program Decisions

Transit Vehicle

spin CEV ?

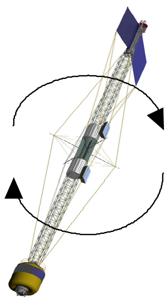
yes → Continuous AG Trade Space

no → Intermittent AG Trade Space

Surface Ops

3/8 g enough ?

no → Intermittent AG Trade Space (exercise req'ts, optimal prescription)



Continuous AG Trade Space

- g, r, ω
- spin up/down req'ts
- human factors

Intermittent AG Trade Space

- g, r, ω, duty cycle
- exercise req'ts
- optimal prescription

Maturity Level – Capabilities for Human Health Countermeasures

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Integration Approach

Exploration Requirements and Medical Standards & Bioastronautics Roadmap

↓

Individual Investigators: Understand scientific basis of problem: Formulate countermeasure concept

↓

Focused research teams: Demonstration of CM efficacy Laboratory/ clinical testing

↓

CM evaluation with human subjects in simulated spaceflight environment

↓

CM validated with human subjects in Actual Spaceflight environment

↓

Countermeasure operational

Capability Readiness Level

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Maturity Level – Technologies for Artificial Gravity

Gaps	Deliverables	Current TRL/ Need Date
Potential ameliorative and/or adverse effects from A/G (spin vehicle)	Decision support from long radius centrifuge research studies	1/2016
Trade Space for Spacecraft Designers (radius, angular velocity,spin down rates)	Decision support from long radius centrifuge research studies	1/2016
Potential ameliorative and/or adverse effects from on-board centrifugation	Decision support from long radius centrifuge research studies Design Options for Short Radius Centrifuge (flight)	1/2016 2/2011
Fitness for duty after spin down	Decision support from long radius centrifuge research studies	1/2016

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Exercise

Gaps	Deliverables	Current TRL/ Need Date
Reliable, instrumented exercise equipment for evaluation on ISS	Robust exercise equipment for validation on ISS	5/2010*
Optimized exercise prescriptions	Optimized & validated exercise prescriptions for use for all phases of exploration missions	5/2012*
Validated exercise equipment requirements for use for all phases of exploration missions	Validated h/w & medical requirements for next generations systems	5/2013 (moon) 1/2023 (Mars)**

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Other Countermeasures

Gaps	Deliverables	Current TRL/ Need Date
Inadequate knowledge of countermeasures for bone, muscle, cardiovascular, and sensory motor	Optimized, validated countermeasure suite	4-5/2016*
Inadequate knowledge of immunology, infection& hematology risks associated with space flight	Definitive knowledge of IIH risk in space flight If risk, then adequate treatment	2/2016*
Inefficient protocols for decompression sickness (probably too conservative)	Safe, effective protocols to prevent DCS Recommendation for cabin pressure	7/2011
Inadequate standards for air contaminants (180 days)	1000 day standards for air contaminants	6/2008
Lack of knowledge of Mars dust chemical composition, toxicity and volatility	Requirement for Mars dust analysis on precursor missions	N/A / SRR for Mars Science Lab

*Utilizes ISS as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Human Health Countermeasures

TRL Definition	TRL/CMRL Score	CMRL Definition	CMRL category	
Basic principles observed	1	Phenomenon observed and reported. Problem defined.	Basic research	
Technology concept and/or application formulated	2	Hypothesis formed; preliminary studies to define parameters. Demonstrate feasibility.	Basic research	
Analytical and experimental critical function/proof-of-concept	3	Validated hypothesis. Understanding of scientific processes underlying problem.	Basic research	Research to prove feasibility
Component and/or breadboard validation in lab	**4**	**Formulation of countermeasures concept based on understanding of phenomenon.**	**Countermeasure development**	**Research to prove feasibility**
Component and/or breadboard in relevant environment	**5**	**Proof of concept testing and initial demonstration of feasibility and efficacy.**	**Countermeasure development**	**Research to prove feasibility**
System/subsystem model or prototype demonstration in relevant environment	**6**	**Laboratory/clinical testing of potential countermeasure in subjects to demonstrate efficacy of concept.**	**Countermeasure development**	
Subsystem prototype in a space environment	**7**	**Evaluation with human subjects in controlled laboratory simulating operational space flight environment.**	**Countermeasure development**	**Countermeasure demonstration**
System completed and flight qualified through demonstration	**8**	**Validation with human subjects in actual operational space flight to demonstrate efficacy and operational feasibility.**		**Countermeasure demonstration**
System flight proven through mission operations	**9**	**Countermeasure fully flight-tested and ready for implementation.**	**Countermeasure operations**	

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Human Health & Performance

Space Radiation
- Measurement Technologies
- Shielding Solutions
- Risk Assessment/ Projection
- Biological Countermeasures

Medical Care
- Medical Devices
- Clinical Capabilities
- Medical Informatics

Human Health Countermeasures
- Artificial Gravity
- Exercise
- Other Physio-logical CM

Behavioral Health & Performance
- **Team Cohesion & Productivity**
- **Psych Health Management**
- **Performance Readiness**
- **Individual & Crew Selection**

Space Human Factors
- Models & simulations
- Design tools & requirements
- Performance Measurements
- Training & Decision Support Systems

Definition

- Behavioral Health & Performance addresses the human performance-related challenges associated with space flight due to isolation, confinement and potential hazards. These challenges are characterized by:
  - Team cohesion and productivity
  - Psychological health management
  - Performance readiness
  - Individual and crew selection

Benefits

- Mitigation of risk of human performance failures through in-flight monitoring and early detection of conditions interfering with behavioral performance and health
- Selection of individuals and crews to match mission requirements and team compatibility
- Performance readiness assessments of individuals and crews
- Mitigation and management of risks related to team cohesion and productivity, individual behavioral health, mission safety and mission success

Current State-of-the-Art for Behavioral Health & Performance

State of the Art

- Anecdotal information from Shuttle, Mir and ISS crews
- Preliminary predictive models for fatigue-related performance deficits based on ground studies
- Dependence on pharmacological aids for sleep management and improvement
- Select-in criteria for astronaut candidate applicants, but no validation with training or performance data
- New select-out criteria and standards developed based on Diagnostic Statistical Manual of Mental Disorders IV; awaiting headquarters approval

Requirements /Assumptions for Behavioral Health & Performance

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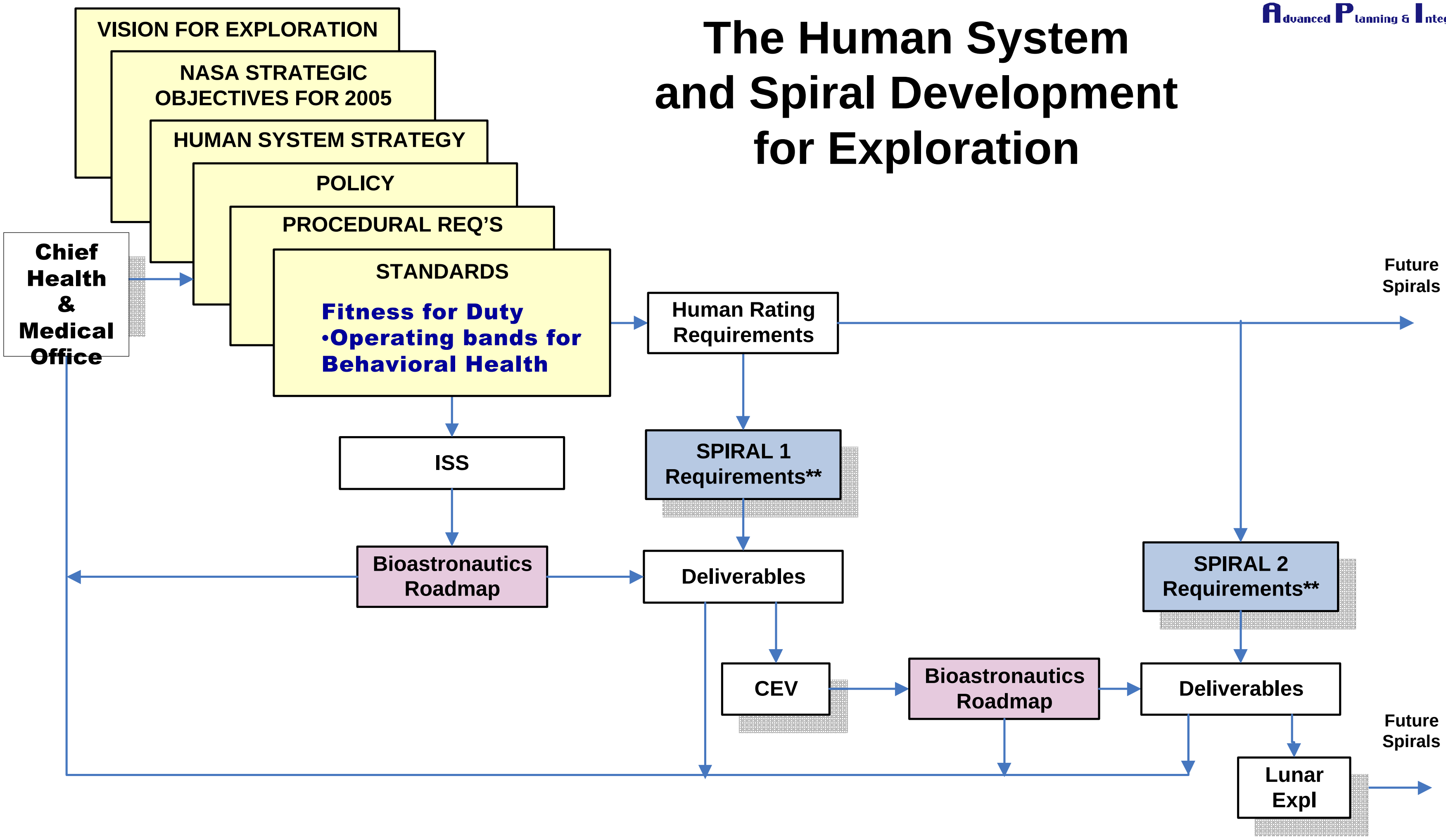
The Human System and Spiral Development for Exploration



** Includes all program requirements

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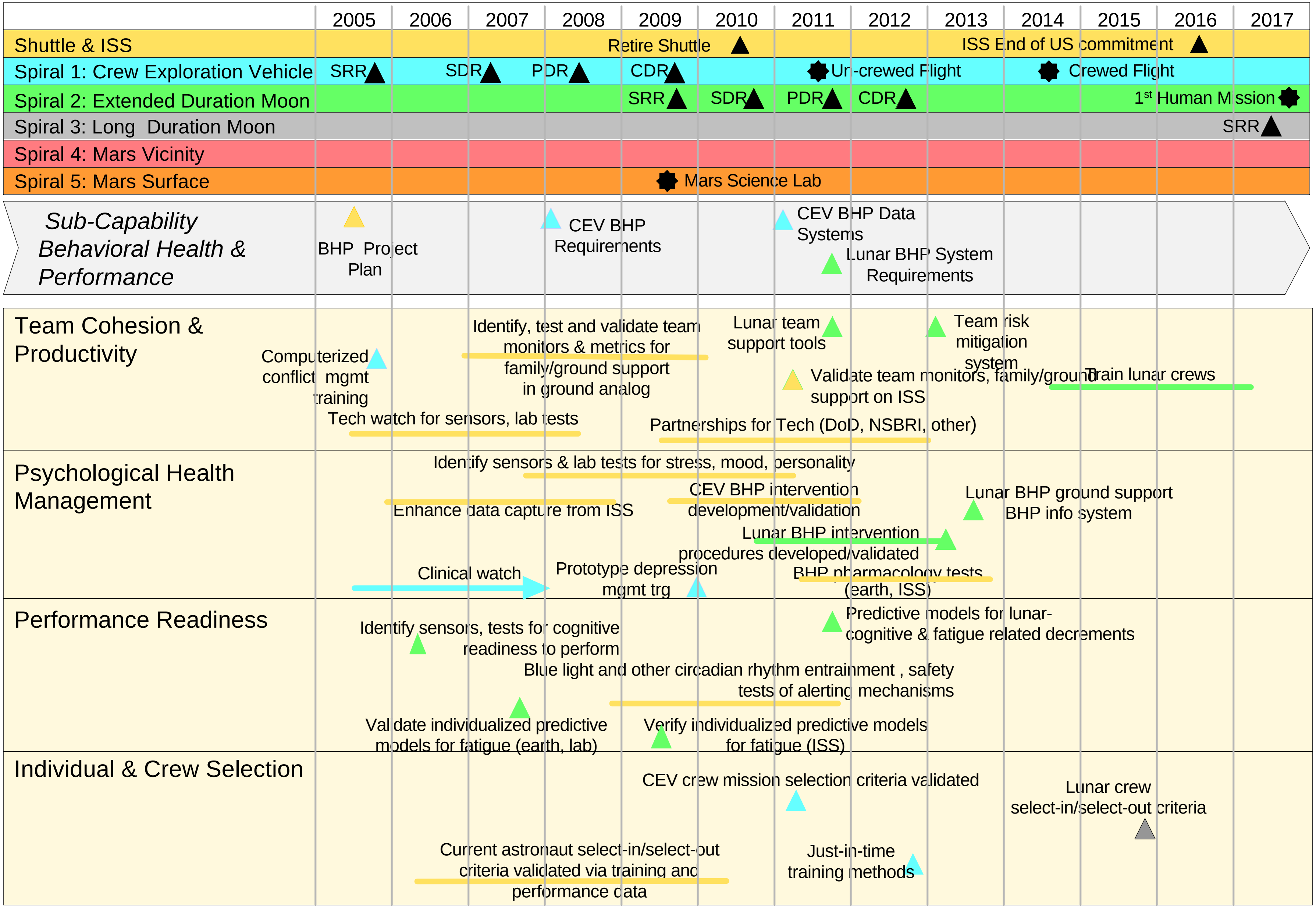
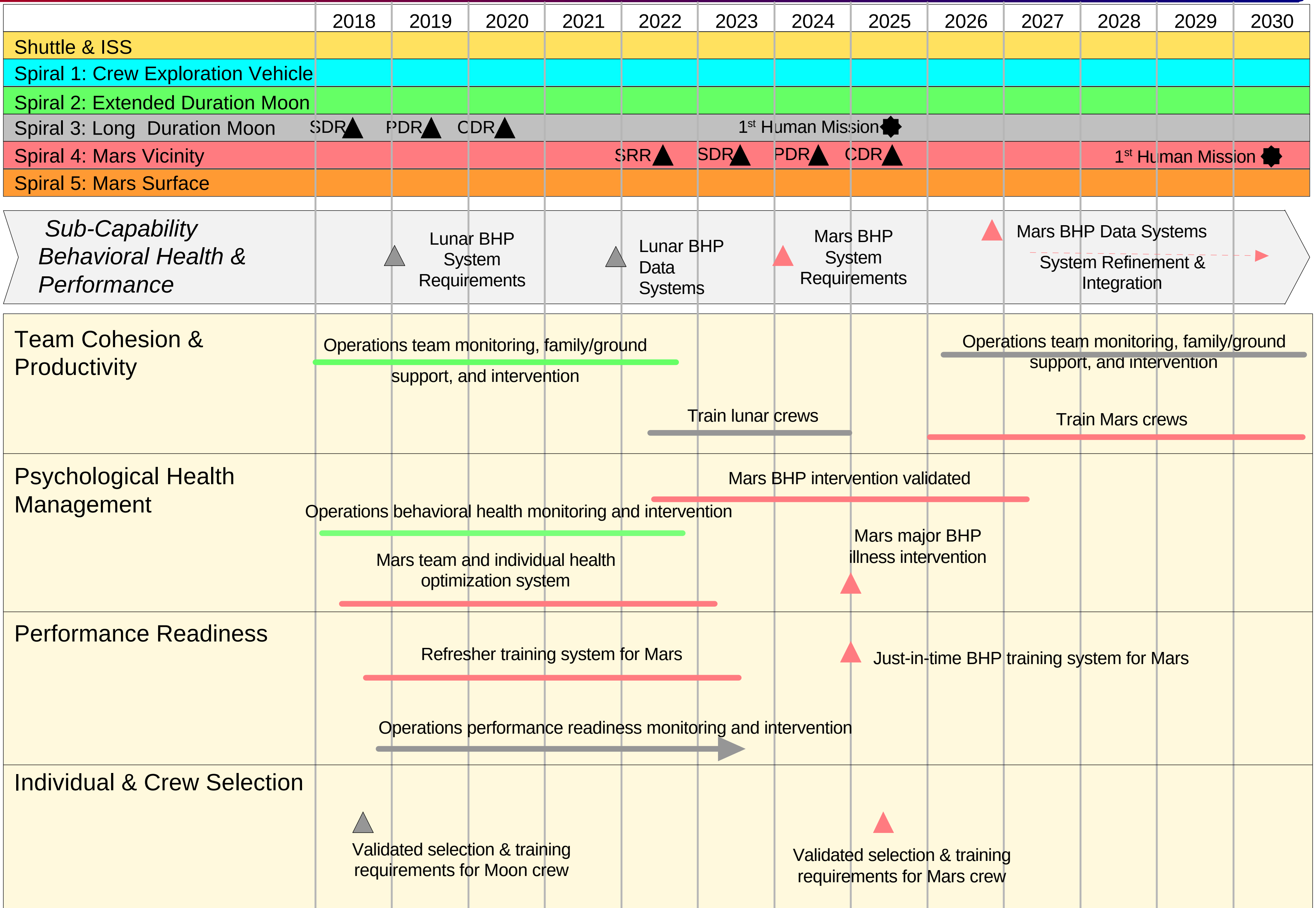
Behavioral Health & Performance Roadmap



Behavioral Health & Performance Roadmap



Maturity Level – Capabilities
Behavioral Health & Performance

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Integration A

- Mission Concept of Operations
- Develop predictive models of individual & team performance
- Validate models
- Develop ground and flight support system
- In-flight monitoring and intervention
- Refine mission operations tools

Capability Readiness Level

1 Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Maturity Level – Technologies for Team Cohesion & Productivity

Advanced Planning & Integration Office

Gaps	Deliverables	Current TRL/ Need Date
Identify standards /operating limits for team cohesion and productivity	Standards, operating limits, guidelines	2009
Sensors, unobtrusive monitoring capabilities	Assessment technologies for team cohesion and productivity	3/2009
Predictive models for team cohesion/productivity*, **	Computer Models, simulations Later refinement for Mars	3/2012 3/2018

*Utilizes ISS as testbed

**Utilizes Moon as testbed

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Psychological Health Management

Gaps	Deliverables	Current TRL/ Need Date
Standards, requirements,operating bands for behavioral health (mood, anxiety)	Standards/requirements/operating bands for mood and anxiety for CEV, lunar, and Mars	2007 (CEV) 2012 (Lunar) 2020 (Mars)
Unobtrusive, ongoing monitoring capabilities	Requirements and validated tech-nologies for unobtrusive monitoring (e.g., optical computer recognition of facial features/ voice analysis; smart clothing or variation thereof) Refinements (lunar, Mars)	2/2008 2014—2025
Biomarker sentinels of mood and anxiety degradation; stress reactions	Biomarkers that are easily obtained and do not require astronaut initiation Refinements for lunar, Mars	2/2012 2014/2022
Just in time training/education for astronaut, ground, flight surgeon	Computerized, modular systems / decision trees Refinements for lunar, Mars	2/2010 2015/2023
Risk mitigation and countermeasures	Tele behavioral health therapy, on-board pharmaceuticals and other countermeasures Refinements for lunar, Mars	2/2012 2015/2025

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Performance Readiness

Advanced Planning & Integration Office

Gaps	Deliverables	Current TRL/ Need Date
Readiness to perform standards/ operating bands/requirements	Standards/requirements/ operating bands for cognitive, sleep and circadian elements	2007
Readiness to perform predictors	Individualized model for sleep-related fatigue Individualized model for cognitive decrements	4/2007 3/2009
Countermeasures for cognitive decrements	Environmental supports (SHF) Pharmaceutical Refresher training Refinements for Mars	3/2012 2020
Risk mitigation for sleep-related fatigue	Pharmaceuticals Rest schedules Developed blue light / other light tools Refinements for Mars	3-5/2009 4/2009 3/2010 2020

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Individual & Crew Selection

Gaps	Deliverables	Current TRL/ Need Date
Requirements for individual select-in for a mission across spirals	Validated requirements -CEV select-in Validated requirements - lunar select-in Validated requirements - Mars select-in	2010 2015 2025
Validation of current select in procedures for astronaut candidacy Revise astronaut candidacy select-in based on validation Lunar Mars	Validated select in procedures for astronaut candidacy Improved select-in procedures	2010 2010 2015 2025
Development of criteria for <u>crew</u> select-in for CEV, Lunar, Mars	System of selecting team members based on group compatibility, productivity and mission scenario	2011 2015 (Lunar) 2025 (Mars)

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Behavioral Health & Performance

Advanced Planning & Integration Office

Program Goal

- Reduction in human error due to lack of readiness to perform, behavioral health dysfunction, imprecise selection, or poor team compatibility / productivity

Annual Metrics

- Progression through TRL levels of technology components
- Percent coverage of the gaps across years
- Validation across lab, earth analog, ISS, and lunar testbeds

Space Human Factors

Advanced Planning & Integration Office

Human Health & Performance

Space Radiation
- Measurement Technologies
- Shielding Solutions
- Risk Assessment/ Projection
- Biological Countermeasures

Medical Care
- Medical Devices
- Clinical Capabilities
- Medical Informatics

Human Health Countermeasures
- Artificial Gravity
- Exercise
- Other Physio- logical CM

Behavioral Health & Performance
- Team Cohesion & Productivity
- Psych Health Management
- Performance Readiness
- Individual & Crew Selection

Space Human Factors
- **Models & simulations**
- **Design tools & requirements**
- **Performance Measurements**
- **Training & Decision Support Systems**

Advanced Planning & Integration Office

Definition

- Space Human Factors addresses the human performance-related challenges associated with space flight due to vehicle and habitat design, tool and task design. Space Human Factors mitigates these challenges through the use of:
  - Models and simulations
  - Design tools and requirements
  - Performance measurements
  - Training and decision support systems

Benefits

- Enhanced human performance through incorporation of human factors into vehicle, task and equipment design
- Increased mission success due to well-designed tasks and matching skills and tools to task requirements
- Expanded Non-intrusive performance measures to enable real-time assessment of readiness
- Utilization of appropriate automation to reduce crew workload
- Improved training and decision support systems for greater crew autonomy to enable missions with large communications lags and blackouts

Current State-of-the-Art for Space Human Factors

Advanced Planning & Integration Office

State of the Art

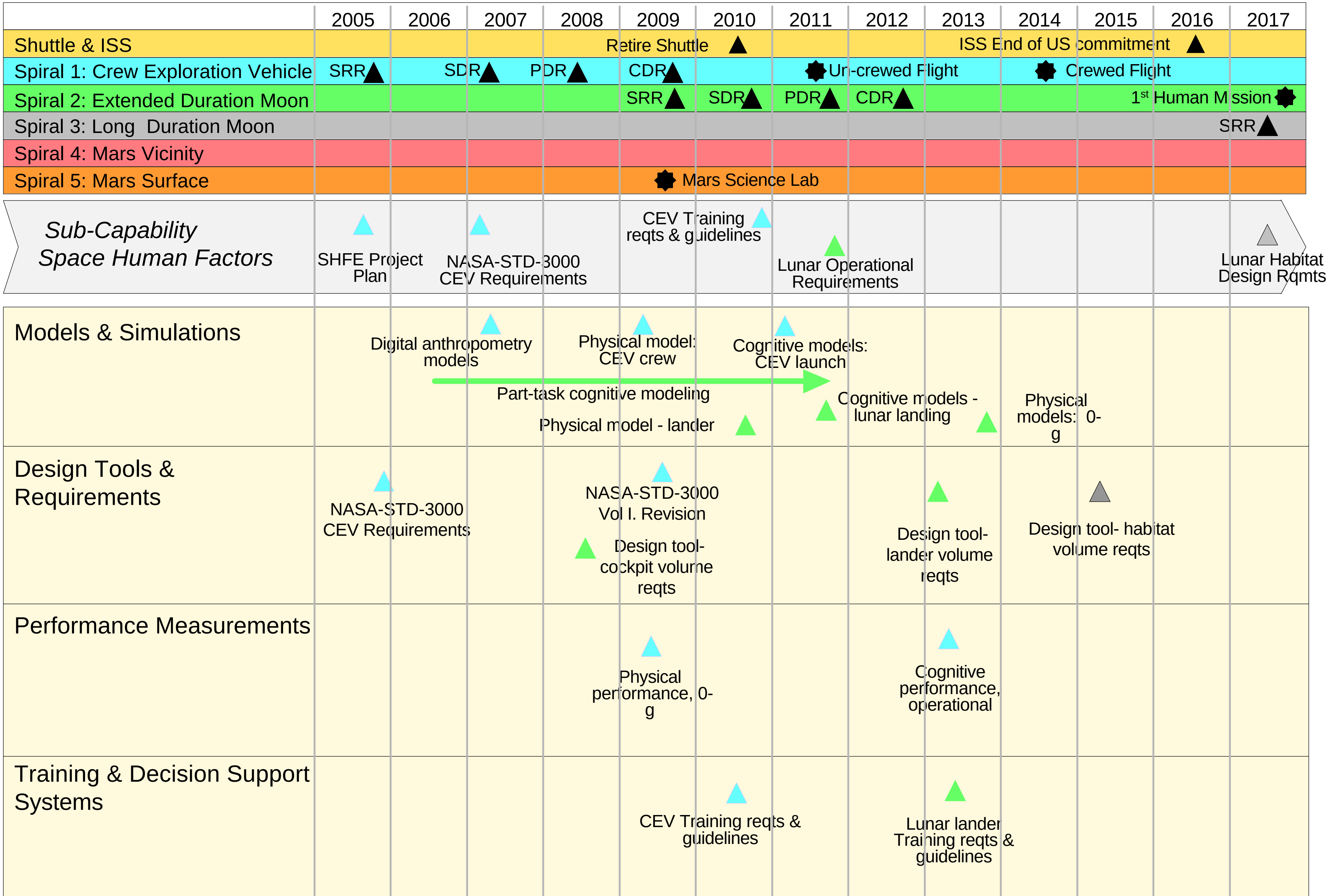
- Anecdotal information from Shuttle, Mir and ISS crews
- Commercial models of 1-g physical performance
- Research models of human cognitive performance
- Commercial CAD design tools do not interface with Human Factors (HF) requirements
- External non-NASA, including DoD, HF knowledge about training, performance measurement, simulations is potentially applicable to some space applications (launch, entry) but not all (microgravity, partial gravity)

Requirements /Assumptions for Space Human Factors

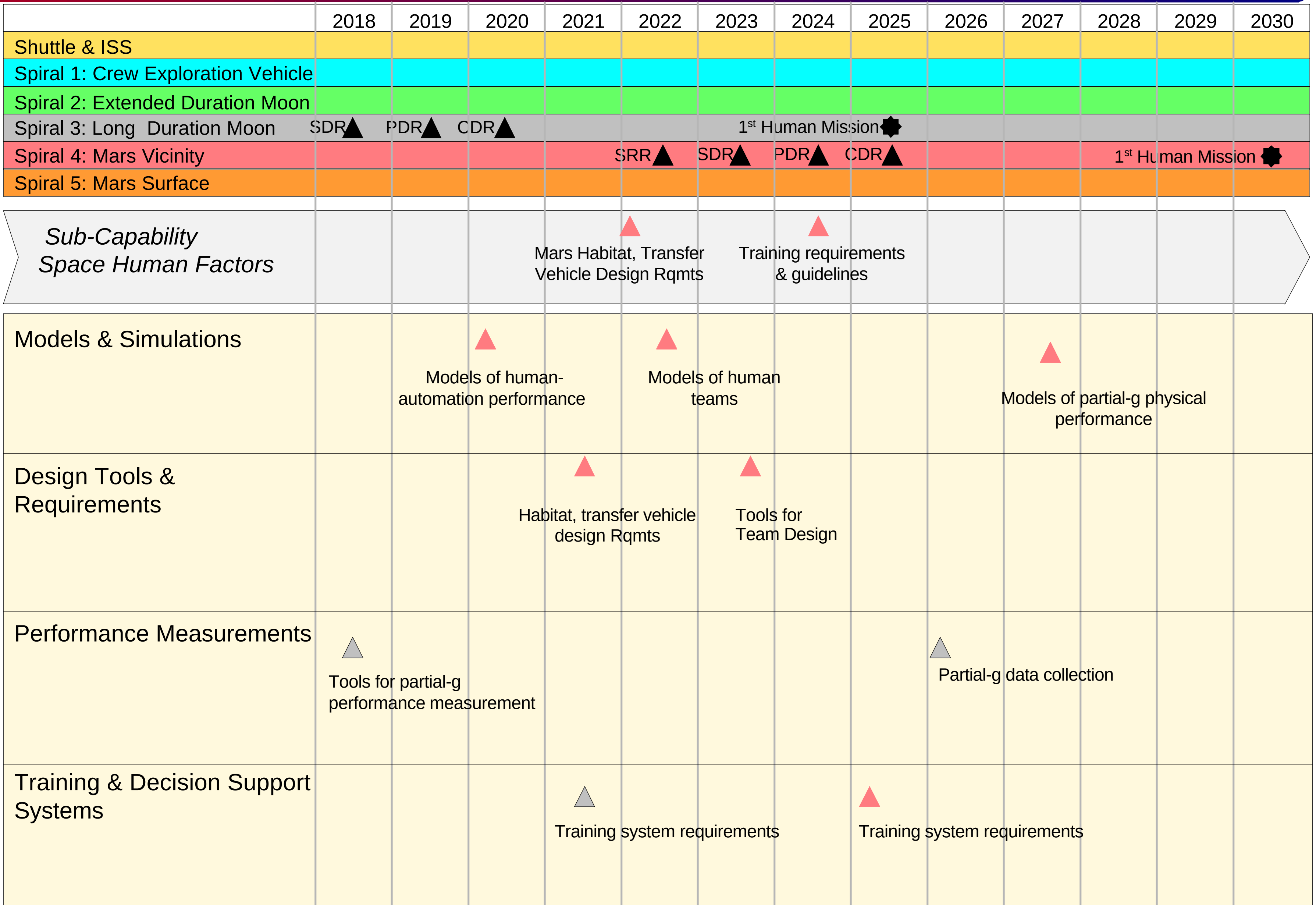
NASA-STD-3000: Human-Systems Integration Standards (HSIS)

- Created by an inter-disciplinary team including NASA, aerospace industry, and academia.
- Agency-wide standard replacing Marshall Space Flight Center and Johnson Space Center Human Factors Standards
- Adopted by the International Standards Organization as ISO 17399:2003
- Includes:
  - Volume: Data for sizing the vehicle
  - Anthropometry & Biomechanics: Data for sizing & operating the vehicle
  - Acceleration Limits: Data for defining the ascent/descent acceleration regimes
  - Radiation: Dose mitigation requirements on a radiation protection system
  - Human/Computer Interaction: Data appropriate to current interface technologies
  - Maintainability/Commonality/Sustainability: Limits to operational overhead
  - EVA: Supporting data appropriate to the top-level EVA requirement for the vehicle
- Document is iterated with supplemental volumes specific to each vehicle or habitat

Space Human Factors Roadmap



Space Human Factors Roadmap



Maturity Level – Capabilities
Space Human Factors

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Integration A...

- Human System Integration Standards
- Research to update contents and fill missing elements
- Evaluate models
- Modify and validate models for NASA applications
- Predict, monitor and assess readiness to perform
- Refine operational tools and capabilities

Capability Readiness Level

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Maturity Level – Technologies for Team Models & Simulations

Gaps	Deliverables	Current TRL/ Need Date
Human size data for input to spacecraft designs	Digital anthropometry models	3/2007
Physical performance models for 0-g (time to perform, strength, fatigue)	Model time to do physical tasks Model strength in different positions	3/2016 3/2016 (end of ISS)
Predictive models of cognitive performance	Part task models – cockpit-type tasks Integrated cognitive models as function of task design, aids	2/2011 2/2017
Predictive models of team performance	Models of human/automation perf. Models of teams of humans	1/2020 1/2022
Physical performance models for partial-g	Model time to do physical tasks Model strength in different positions	2/2027

***Utilizes ISS as testbed**

****Utilizes Moon as testbed**

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Design Tools & Requirements

Gaps	Deliverables	Current TRL/ Need Date
Human-centered design requirements	Updated HSIS standards that are verifiable	5/2009
Volume required for task performance in microgravity	Design tools for cockpit-type volume Design tools for habitable environment: lander Design tools for habitable environment: habitat	3/2011 3/2013 3/2015
Team design requirements & guidelines, including multi-agent teams	Tools for team design Task allocation analysis	8/2023

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Performance Measurements

Gaps	Deliverables	Current TRL/ Need Date
Quantitative performance measurement tools	Validated real-time physical performance measurement tools in zero-g	4/2009
	Validated real-time cognitive performance measurement tools	3/2011
	Validated real-time physical performance measurement tools in partial-g	6/2018

Note: Unless otherwise indicated, assumes Mars mission scenario

Maturity Level – Technologies for Training & Decision Support Systems

Advanced Planning & Integration Office

Gaps	Deliverables	Current TRL/ Need Date
Adaptive skill-based training systems	Gap analysis and trade studies Lunar lander guidelines and requirements	3/2010 3/2015
Decision support systems (DSS) with high reliability	Gap analysis and trade studies Requirements for DSS	8/2021 3/2024

Note: Unless otherwise indicated, assumes Mars mission scenario

Metrics for Space Human Factors

- **Program Goal**
  - Decrease task time
  - Decrease errors, error rate and the effects of errors
  - Decrease engineering design time
  - Increased usability of equipment and procedures

- **Annual**
  - Progression of TRL levels
  - Fewer resources spent redesigning crew systems
  - High usability and integrated testing results
  - Less crew time needed for ground-based training, on-orbit training, procedure execution

Human Health & Performance Summary

Advanced Planning & Integration Office

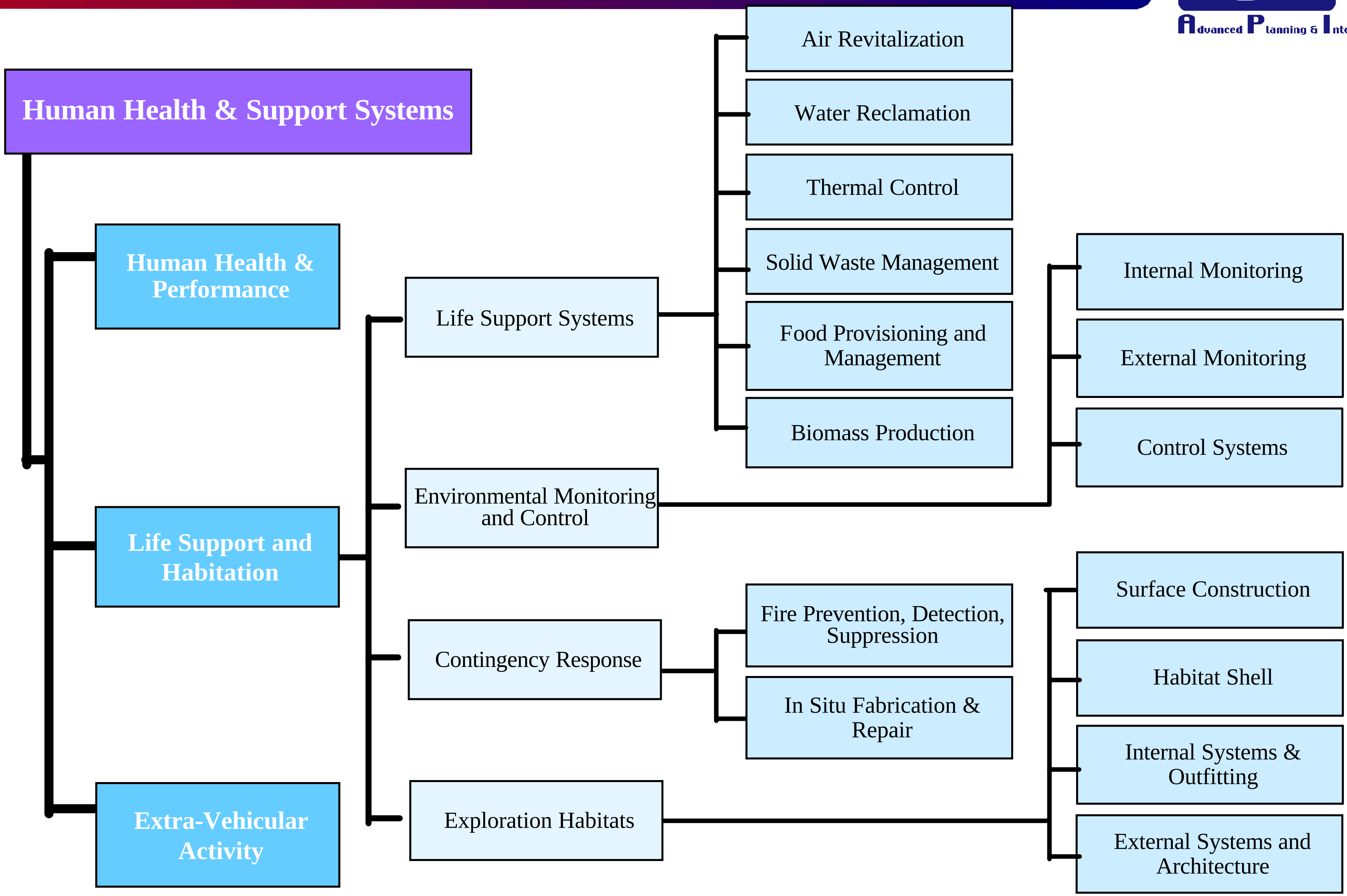
- Optimal radiation shielding solution for spacecraft.
- Adequate warning systems & effective operational protection for Solar Particle Events.
- Validated selection criteria for crewmembers that reduces personal risk & mission risk.
- Validated countermeasure system that limits the deleterious effects of space flight to ensure crew health and performance, and provides the means by which observed deficits can be remedied.
- Medical diagnostic capability to monitor all aspects of health, including predicted adaptation, and the means by which observed deficits can be remedied.
- Optimized medical system to diagnose and treat the widest range of potential heath problems during all mission phases.
- The best possible prediction of risk (including lifetime) to the crew from radiation exposure.
- A system to support normal psychological adaptation to long duration space flight, and the means by which observed deficits can be remedied.
- Accurate predictors of crew task performance during all mission phases.
- Human Factors Engineering that prevents human error and maximizes successful performance.

Life Support and Habitation

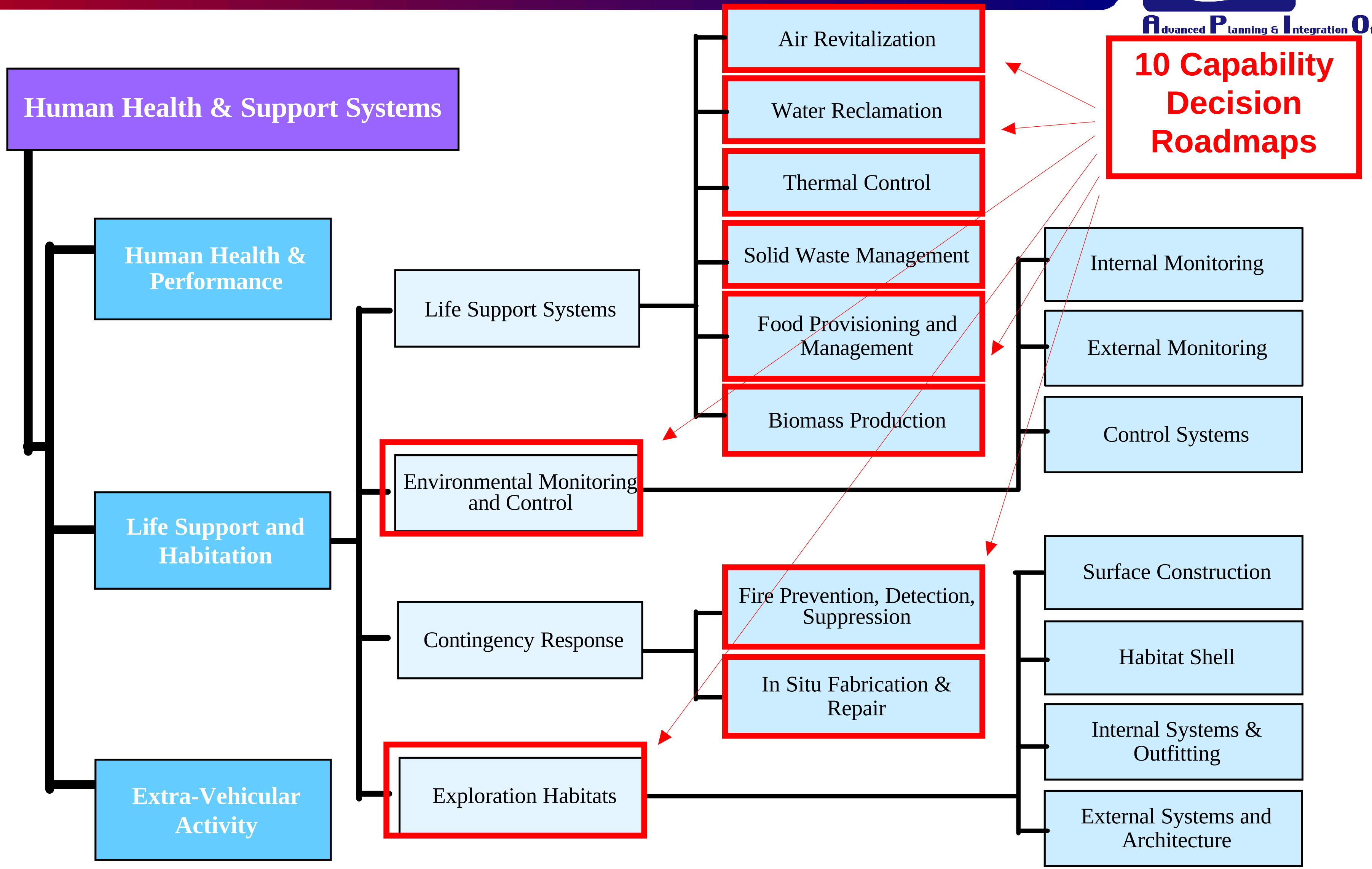
Presenter:

Daniel J. Barta

Life Support and Habitation Capability Breakdown Structure



Life Support and Habitation Roadmaps to be Presented

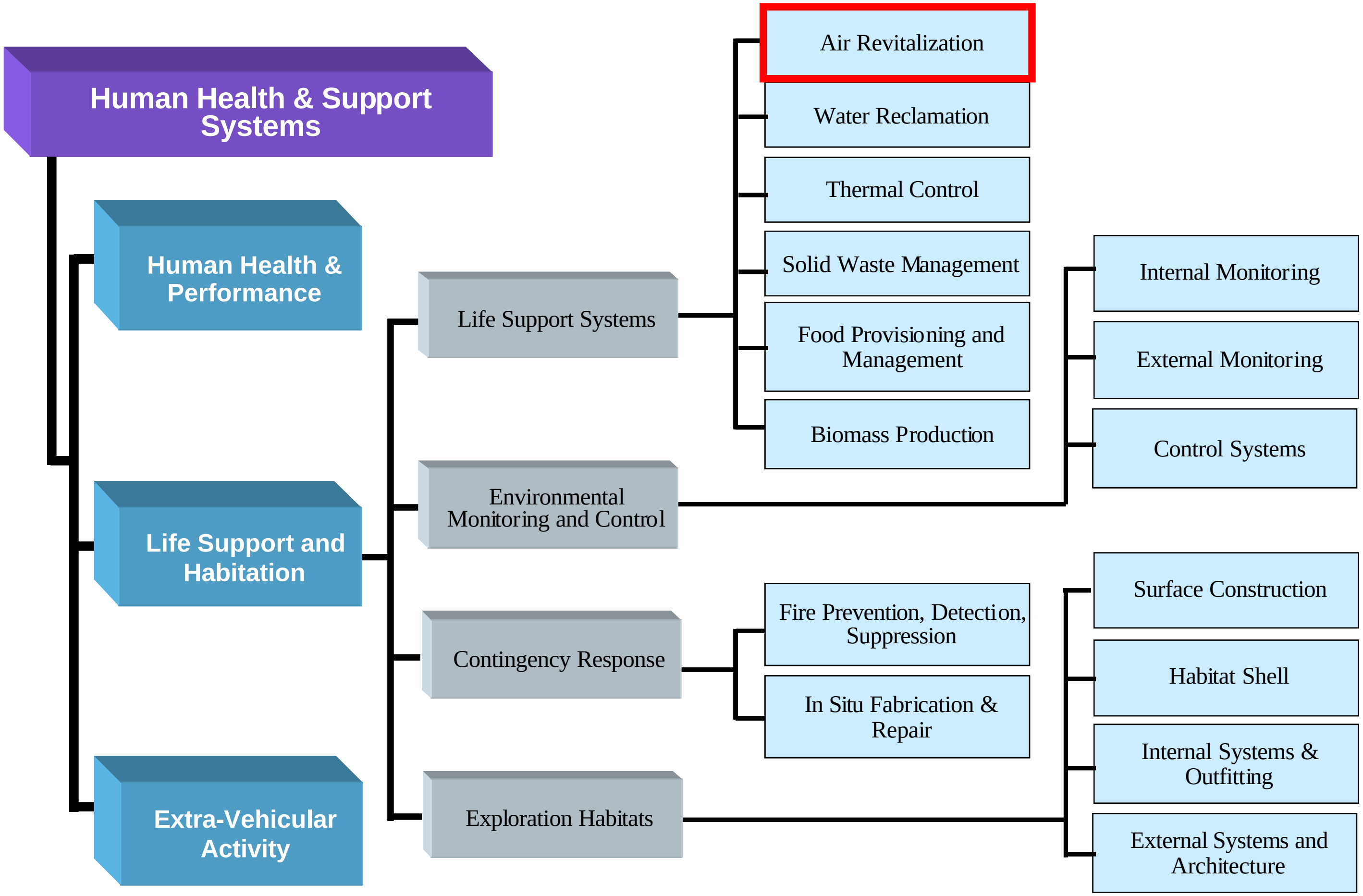


Requirements / Supporting Documents

In addition to the Design Reference Mission and other documents described in introductory slides, many other documents have been considered which have applicability to Life Support and Habitation. This list is for example purposes and is not complete.

- **Advanced Life Support Program Documents**
  - Advanced Life Support Baseline Values and Assumptions Document (2004)
  - Advanced Life Support Requirements Document (2003)
  - Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document (2001)
  - Solid Waste Processing and Resource Recovery Workshop Report (2001)
  - Advanced Food Technology Workshop Final Report (2003)
- **Spacecraft Requirements Documents**
  - Medical Operations and Requirements Documents
  - Manned Systems Integration Standards
- **National Research Council Reports and Guidelines**
  - Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies (2003)
  - Spacecraft Maximum Allowable Concentrations for Selected Airborne Contaminants (1994-)
  - Spacecraft Water Exposure Guidelines for Selected Contaminants (2000-)
  - Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (2002)
  - Safe Passage: Astronaut Care for Exploration Missions (2001)
  - Advanced Technology for Human Support in Space (1997)

Atmosphere Revitalization



Atmosphere Revitalization Description

- **Air quality control technologies for enabling long duration exploration missions**
  - **Meet or exceed mission requirements**
    - Constraints for mass, volume, power, thermal management, and maintainability, i.e. crew time and logistics
  - **Provide sustainable operational robustness**
    - Crew and mission safety
    - Mission success
    - Autonomous operation
- **Key functional areas for development**
  - **Atmospheric gas supply, distribution, and partial pressure control**
  - **Air quality control during normal mission operations**
    - Carbon dioxide, trace chemical contaminant, and particulate matter removal
    - Humidity control
  - **Waste gas processing**
    - Convert to useable forms
    - Enable higher degree of life support system closure
  - **Operational robustness to respond and recover from off-nominal situations**
  - **Process design and integration**
    - Interaction with other life support process functions and resources

Atmosphere Revitalization Benefits

- Control atmospheric quality by maintaining carbon dioxide, humidity, trace chemical components, and particulate matter within specified limits for maintaining crew health and safety
- Robust capability to store and distribute atmospheric gases necessary to control major constituent partial pressure
- Provide operational robustness to respond to and recover from off-nominal cabin atmospheric quality events
- Emphasize maintainability and operational autonomy to achieve minimal crew intervention and logistics resupply
- Minimize equipment mass, volume, power, and thermal loads relative to existing applications
- Advance a functional design approach to achieve life support system oxygen loop closure
- Simplify process design and operations to significantly contribute to advances in system reliability and crew and mission safety

Atmosphere Revitalization State-of-the-Art

Advanced Planning & Integration Office

- **Atmosphere revitalization technologies in operation on board the International Space Station, Space Shuttle, and Spacelab**
  - **Carbon Dioxide Partial Pressure Control**
    - **Shuttle and Spacelab : consumable lithium hydroxide (LiOH) canisters**
    - **ISS: regenerable 4-bed molecular sieve process that provides for water recovery; regeneration accomplished by combined thermal-vacuum swing**
  - **Oxygen Generation**
    - **Shuttle and Spacelab: None**
    - **ISS: Solid Polymer Electrolyte (SPE) Oxygen Generation Assembly (OGA)**
  - **Trace Chemical Contaminant and Particulate Matter Control**
    - **Shuttle: expendable activated charcoal upstream of the LiOH; expendable ambient temperature catalytic oxidation of CO and H_2; 280-micron nominal filters for particulate matter**
    - **Spacelab: same as Shuttle except added an expendable mixed-media scrubber for trace contaminant and CO control**
    - **ISS: expendable activated charcoal with a high temperature catalytic oxidation and expendable LiOH for acid gas control; HEPA (0.3-micron nominal) filters for particulate matter**
  - **Atmospheric Gas Storage**
    - Shuttle: High pressure storage; supercritical cryogenic storage for metabolic O_2
    - ISS: High pressure storage; Oxygen recharge capability.
  - **Gas Recovery for System Loop Closure**
    - **Presently not on board Shuttle or ISS; CO_2 reduction risk mitigation in work**

Atmosphere Revitalization Requirements & Assumptions

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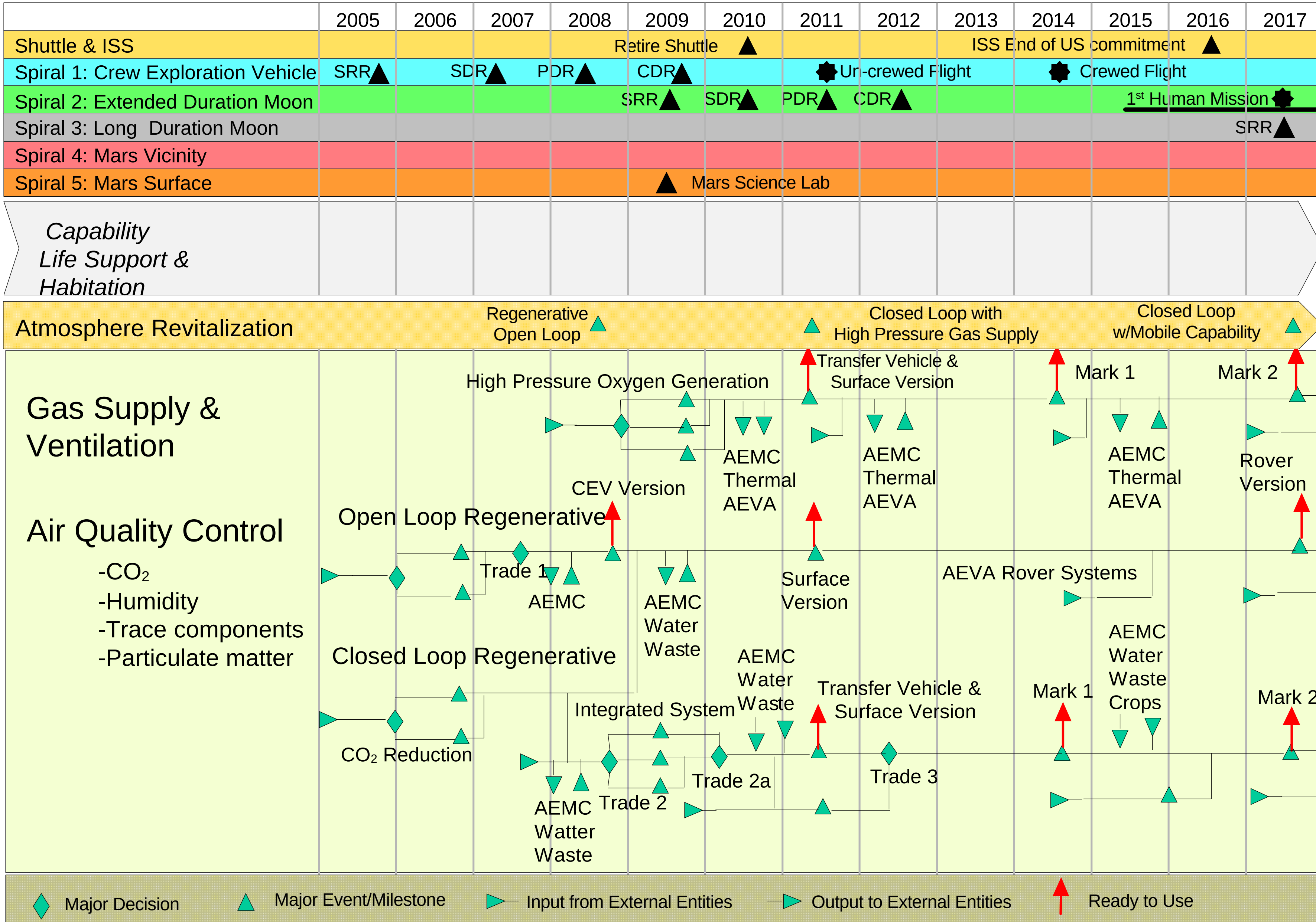
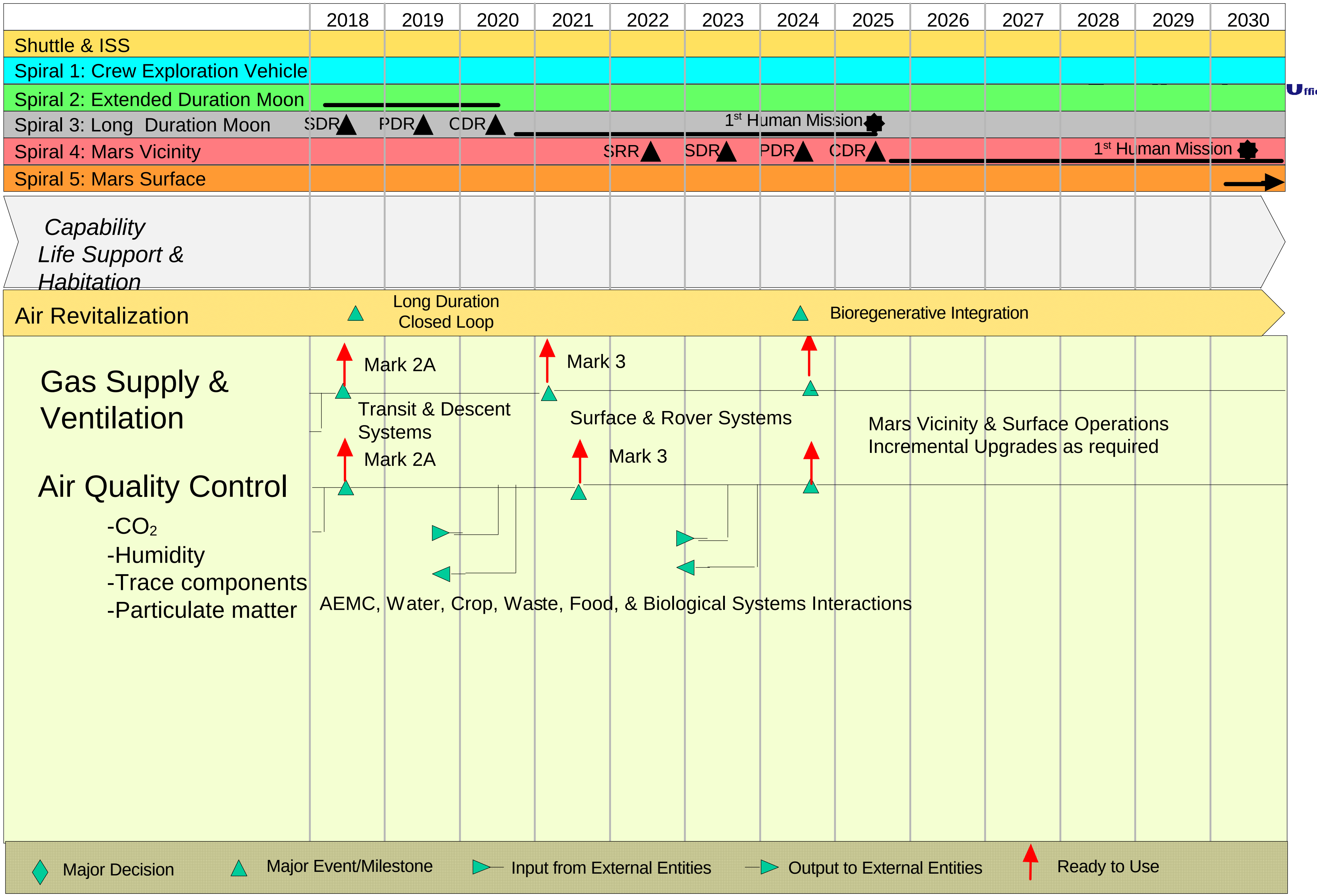
- **Long Duration Missions Drive Requirements**
  - Missions to ISS and other LEO operations can use existing SOA with some modification
    - Potential for extended duration Lunar and Mars transit flight demonstration on ISS
  - Extended duration Lunar missions and Mars transit/Mars vicinity drive technological needs and departures from existing SOA
- **Additional Assumptions**
  - Loop closure and water recovery from CO_2 a priority for extended duration missions
  - Mission duration beyond 6 months will result in more challenging air quality standards for carbon dioxide, trace contaminants, and particulate matter
  - Long duration, continuous exposure to suspended particulate matter and the need to protect the crew and equipment from planetary dust will drive particulate filtration
  - Hypogravity environments (Lunar and Mars surface) may alleviate some microgravity issues but may also require Lunar demonstration testing
  - Mission requirements will drive multi-element technology commonality and architectural/functional interfaces with AEVA, ISRU, AEMC, etc
  - Trade studies based on performance testing data support decision points.
  - Consider reduced pressure vehicle and habitat applications. May drive range of developmental testing conditions.

Atmosphere Revitalization Roadmap



Atmosphere Revitalization Roadmap



Atmosphere Revitalization Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Supply O_2 & N_2 Control O_2 & N_2 partial pressure Regeneratively control CO_2 partial pressure, relative humidity, and remove trace contaminants from cabin atmosphere Remove suspended particulate matter Provide ventilation & atmospheric mixing	No development needed No development needed Improve mass, power, reliability, and maintainability by integrating CO_2, humidity, and trace contaminant control functions; select and characterize adsorbents & catalysts Filter media selection and element configuration Means for pressure drop monitoring Methods for reducing fan noise	6 6 2 6 1 1
Spiral 2 Lunar Surface (2011)	Spiral 1 plus demonstrate closed loop: Provide ambient/high pressure O_2 generation Provide CO_2 reduction/demonstrate loop closure Provide means to control migration of lunar dust into habitat	Mark 1 systems: Extend oxygen generation to high pressures Process design & integration with Spiral 1 regenerable air quality control equipment with scar for CO_2 reduction	2 3 1
Spiral 3 Long Duration Lunar Surface (2014)	Spiral 2 plus full loop closure: Provide ambient/high pressure O_2 generation Open loop systems for EVA support Demonstrate CO_2 reduction to carbon Mark 1 air quality control equipment Improved means to control migration of lunar dust into habitat	Mark 2 systems: Improve mass, power, reliability, and maintainability of Spiral 2 system Extend Spiral 1 systems to mobile applications Develop flight demonstration for carbon formation reactor Improve mass, power, reliability, and maintainability of Spiral 2 system, fully integrated with CO_2 reduction, plus scar for carbon formation Develop habitat isolation and filtration methods/processes	2 1 2 2 1
Spiral 4 Mars Vicinity (2017)	Spiral 3 full loop closure plus: Provide carbon formation process Adapt Spiral 2/3 integrated systems to transfer vehicle application	Mark 2A systems: Develop flight carbon formation process Further improve mass, power, reliability, and maintainability of Spiral 2/3 integrated systems	2 1
Spiral 5 Initial Mission Mars Surface (2021)	Spiral 3 plus: Adapt Spiral 1 systems to descent vehicle Adapt Spiral 3 systems to habitat and mobile applications Adapt Spiral 2/3 dust isolation methods	Mark 3 systems: Potential use of in-situ resource (oxygen from CO_2 atmosphere and ground water) Further reduction in weight and/or expendables Improve mass, power, reliability, and maintainability of habitat isolation methods	1 1 1

Atmosphere Revitalization Maturity Level – Technologies

Sub-Capability (Level 5/6 CBS)	Leading Technology Candidates	Spiral(s)	Current TRL
Control Carbon Dioxide Partial Pressure	**Expendable chemisorbents (LiOH)** **Vacuum swing adsorption** **Combined temperature/vacuum swing adsorption** **Bioregenerative Systems**	**1-3** **1-5** **1-5** **4-5**	**4-9** **4** **3-9** **3-5**
Control Humidity	**Vacuum swing adsorption** **Combined temperature/vacuum swing adsorption** **Condenser with phase separation**	**1-5** **2-5** **2-5**	**4** **4** **9**
Control Trace Atmospheric Components	**Expendable adsorbents (activated charcoal)** **Combined temperature/vacuum swing adsorption** **Thermal catalytic oxidation (CH_4 and light VOCs)** **Ambient temperature catalytic oxidation (CO and H_2)**	**1-3** **2-5** **2-5** **1-3**	**9** **4** **3-9** **3-9**
Remove Suspended Particulate Matter	**Macrofiltration (10 microns)** **HEPA filtration (0.3 micron)** **Electrofiltration – (<0.1 micron)** **Regenerative filters**	**1-2** **2-5** **2-5** **2-5**	**9** **9** **4+** **3**
Store & Distribute Nitrogen	**High pressure storage and Cryogenic storage** **Chemical storage**	**1-5** **1-5**	**9** **1-2**
Generate, Store, & Distribute Oxygen	**Cryogenic storage** **Water electrolysis – solid polymer electrolyte** **Water electrolysis – high pressure products** **Oxygen transfer compressor (ORCA)** **Bioregenerative Systems**	**1-5** **2-5** **2-5** **1-5** **4-5**	**9** **5** **2** **9** **3-5**
Recover Resources	**Carbon dioxide reduction (Sabatier, Bosch)** **Carbon formation reactor (Sabatier post-processing)**	**2-5** **2-5**	**4+** **2**
Provide Ventilation	**Fixed and portable axial fans** **Ion discharge air movement systems** **Low power low noise fans**	**1-5** **1-5** **1-5**	**9** **4+** **1-4**

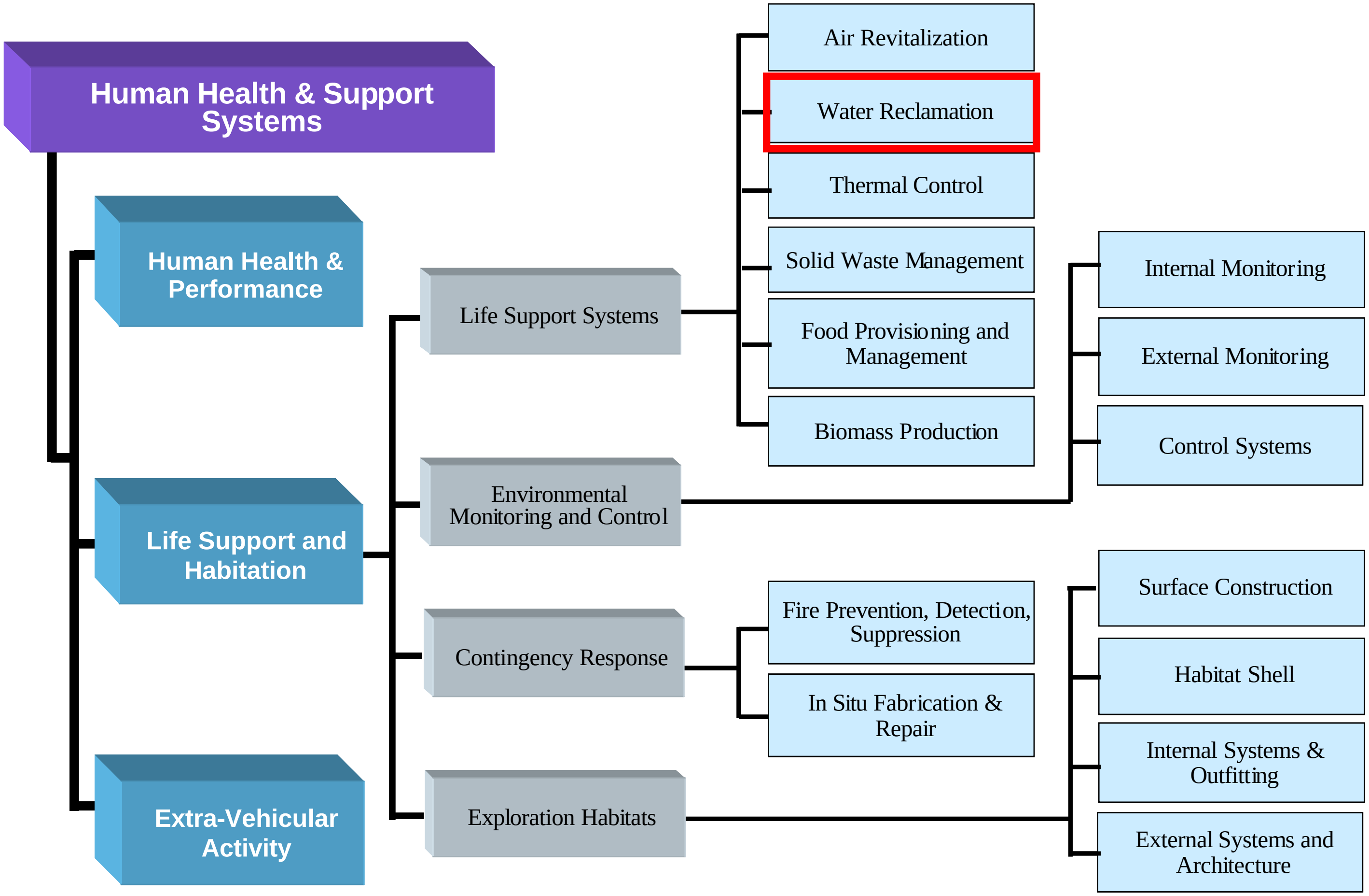
Atmosphere Revitalization Metrics

Integration Office

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Control Carbon Dioxide Partial Pressure	Equipment equivalent cube volume Hourly specific power Equivalent system mass for equipment Daily specific crew hours Daily specific logistics mass	m^3 Watt-h/kg air kg h/kg air/day kg/kg air/day
Control Humidity	Equipment equivalent cube volume Hourly specific power Equivalent system mass for equipment Daily specific crew hours Daily specific logistics mass	m^3 Watt-h/kg air kg h/kg air/day kg/kg air/day
Control Trace Atmospheric Components	Equipment equivalent cube volume Hourly specific power Equivalent system mass for equipment Daily specific crew hours Daily specific logistics mass	m^3 Watt-h/kg air kg h/kg air/day kg/kg air/day
Store & Distribute Nitrogen	Equipment equivalent cube volume Equivalent system mass for equipment Daily logistics mass	m^3 kg kg/day
Generate, Store, & Distribute Oxygen	Equipment equivalent cube volume Hourly specific power Equivalent system mass for equipment Daily specific crew hours Daily specific logistics mass	m^3 Watt-h/kg O_2 kg h/kg O_2/day kg/kg O_2/day
Recover Resources	Equipment equivalent cube volume Hourly specific power Equivalent system mass for equipment Daily specific crew hours Daily specific logistics mass Hourly specific CO_2 and H_2 recovery percentage	m^3 Watt-h/kg H_2O made kg h/kg H_2O/day kg/kg H_2O/day %-h/kg air
Provide Ventilation	Equipment equivalent cube volume Hourly specific power Equivalent system mass for equipment Acoustic noise	m^3 Watt-h/kg air kg db

Water Recovery Systems

Advanced Planning & Integration Office



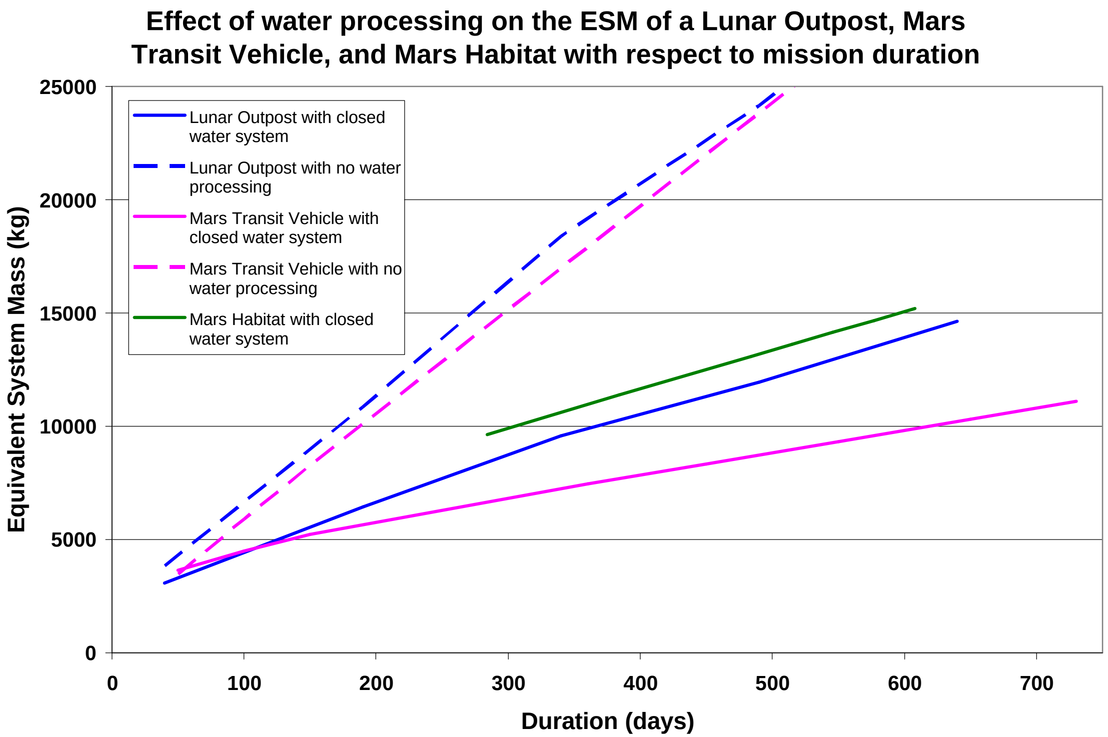
Water Recovery Systems Description

Advanced Planning & Integration Office

- Water recovery systems transform crew and system wastewater into potable water for crew and system reuse.
- Biological and/or physical/chemical methods employed to remove contaminants
- Biocides added for residual disinfection to inhibit microbial growth in storage tanks.
- Processing strategy
  - Transport and storage of wastewater from human interfaces
  - Primary processing: organic and nitrogenous contaminant reduction
  - Secondary processing: inorganic contaminant reduction
  - Brine dewatering: water removal from highly concentrated brine
  - Post-processing and disinfection: polishing to meet potability standards
  - Storage and transport of potable water prior to consumption

Water Recovery Systems Benefits

- Potable water ensures crew health
- Recovery of potable water from wastewater reduces mass of consumables required for mission



from Ewert, M., Van Buskirk, J. Evaluation of Human Life Support Across Mission Scenarios, SIMA-Lockheed Martin Study, 2004.

Water Recovery Systems
Current State-of-the-Art

Advanced Planning & Integration Office

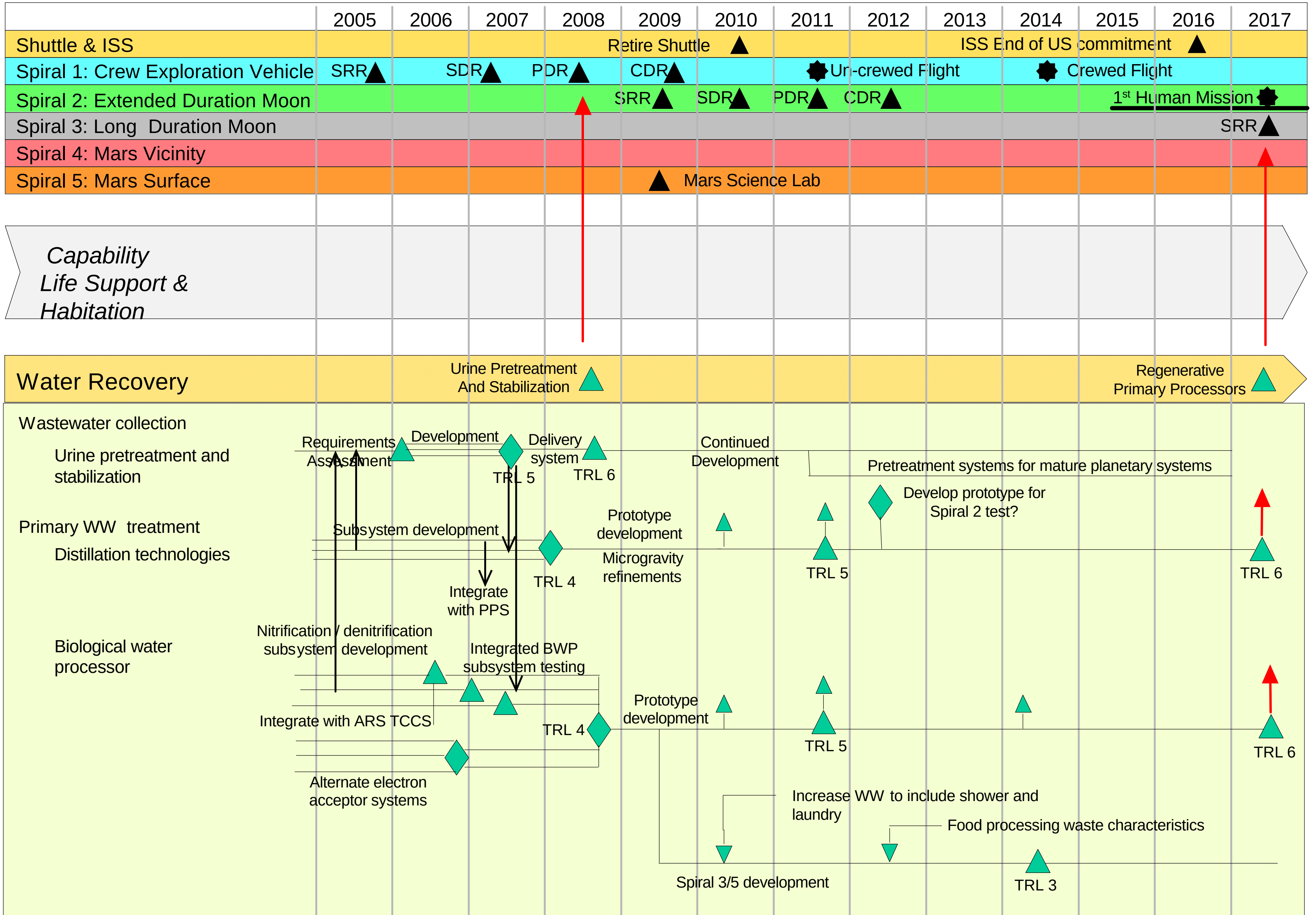
- Vapor compression distillation technology
  - Rotating distillation process
  - Used for urine treatment
  - Organic and inorganic removal
  - Produces brine
  - Distillate requires further treatment to reach potable quality
- Multifiltration beds
  - Organic and inorganic removal
  - Requires consumable adsorption / ion exchange beds
- Volatile removal assembly
  - Catalytic oxidation
  - Operates at high temperature conditions
  - Requires adsorption bed for residual organic acid removal
- Microbial check valve
  - Dispenses iodine for disinfection of potable water
  - Iodine must be removed prior to consumption of water by crew

Water Recovery Systems Requirements /Assumptions

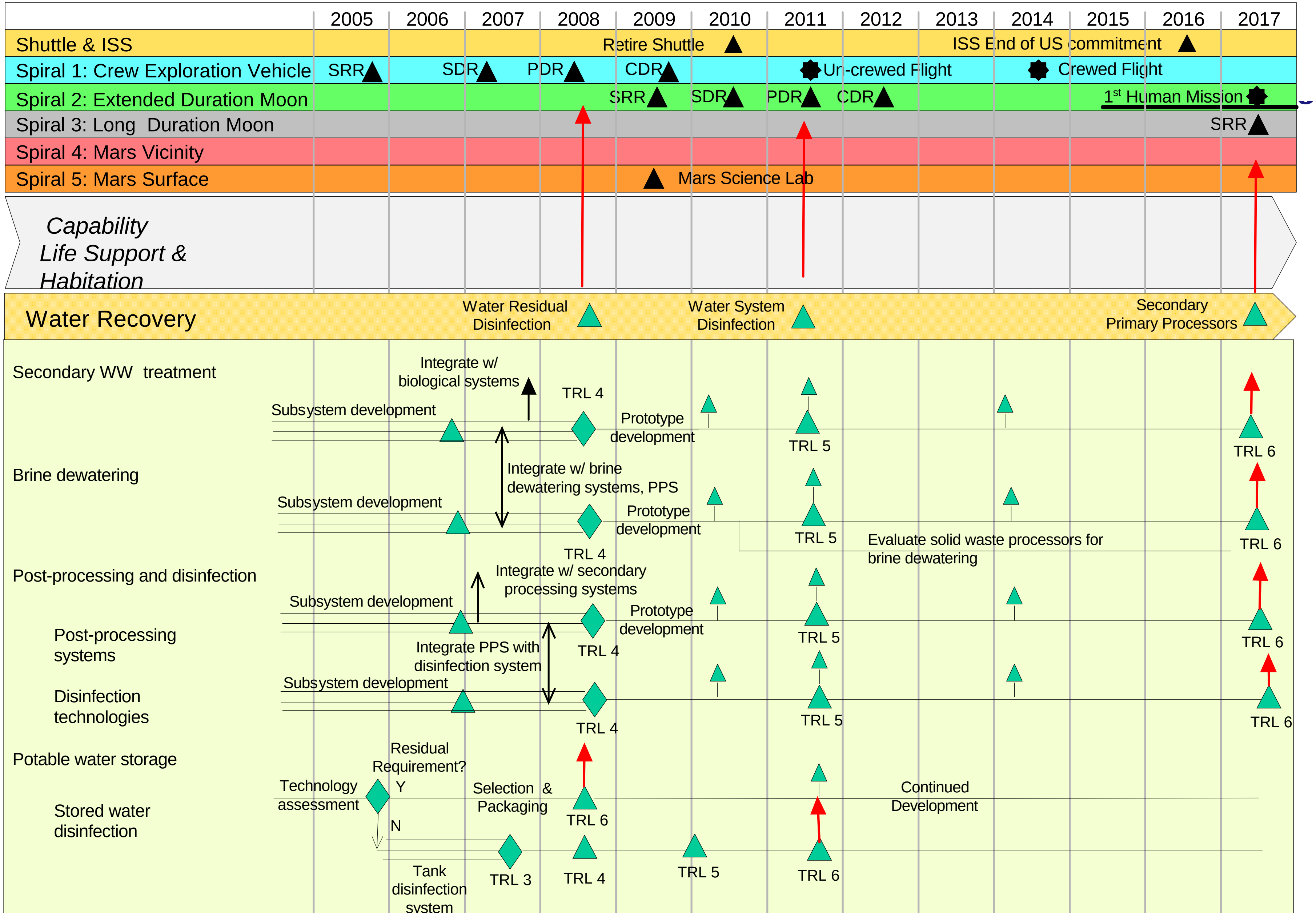
Advanced Planning & Integration Office

- Driving issue for Water Recovery Systems is the need to reduce the dependency on resupply for long duration missions
- Spirals 3, 4 and 5 drive the need for Water Recovery Systems
- Additional Assumptions:
  - Personal care cleanser will need to be defined early
  - WRS will drive selection of urine pretreat system, with input from waste collection system
  - Prototype urine pretreatment system will be tested in Spiral 1
  - Wastewater sources for Spiral 4 will be pretreated urine and humidity condensate
  - Wastewater sources for Spirals 3 and initial Spiral 5 will be pretreated urine, hygiene wastewater, laundry, and humidity condensate
  - Later Spiral 5 mission will include food processing waste, inputs from ISRU
  - If ISRU water is available, water quality information will be available from prior robotics missions

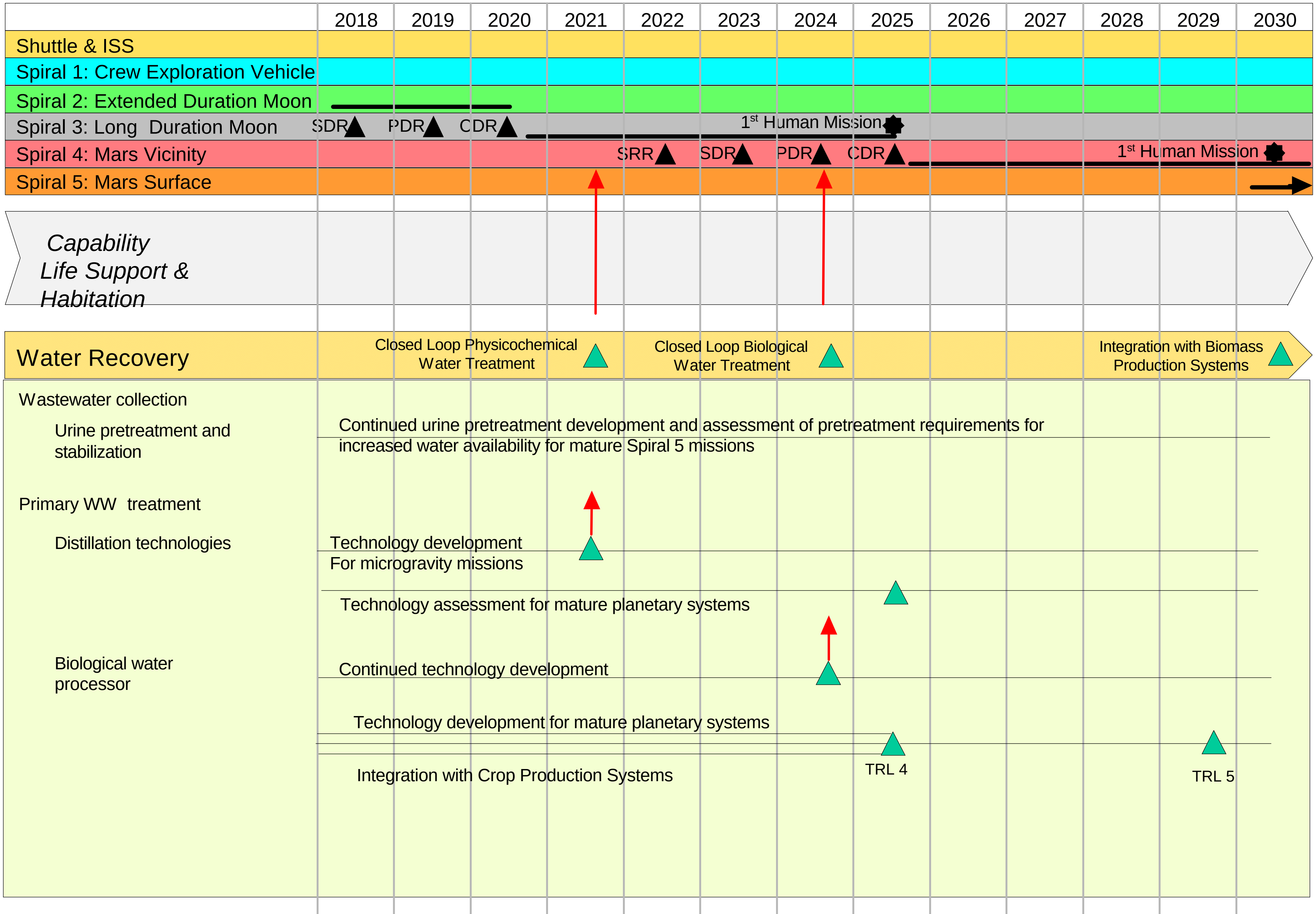
Water Recovery Systems Roadmap



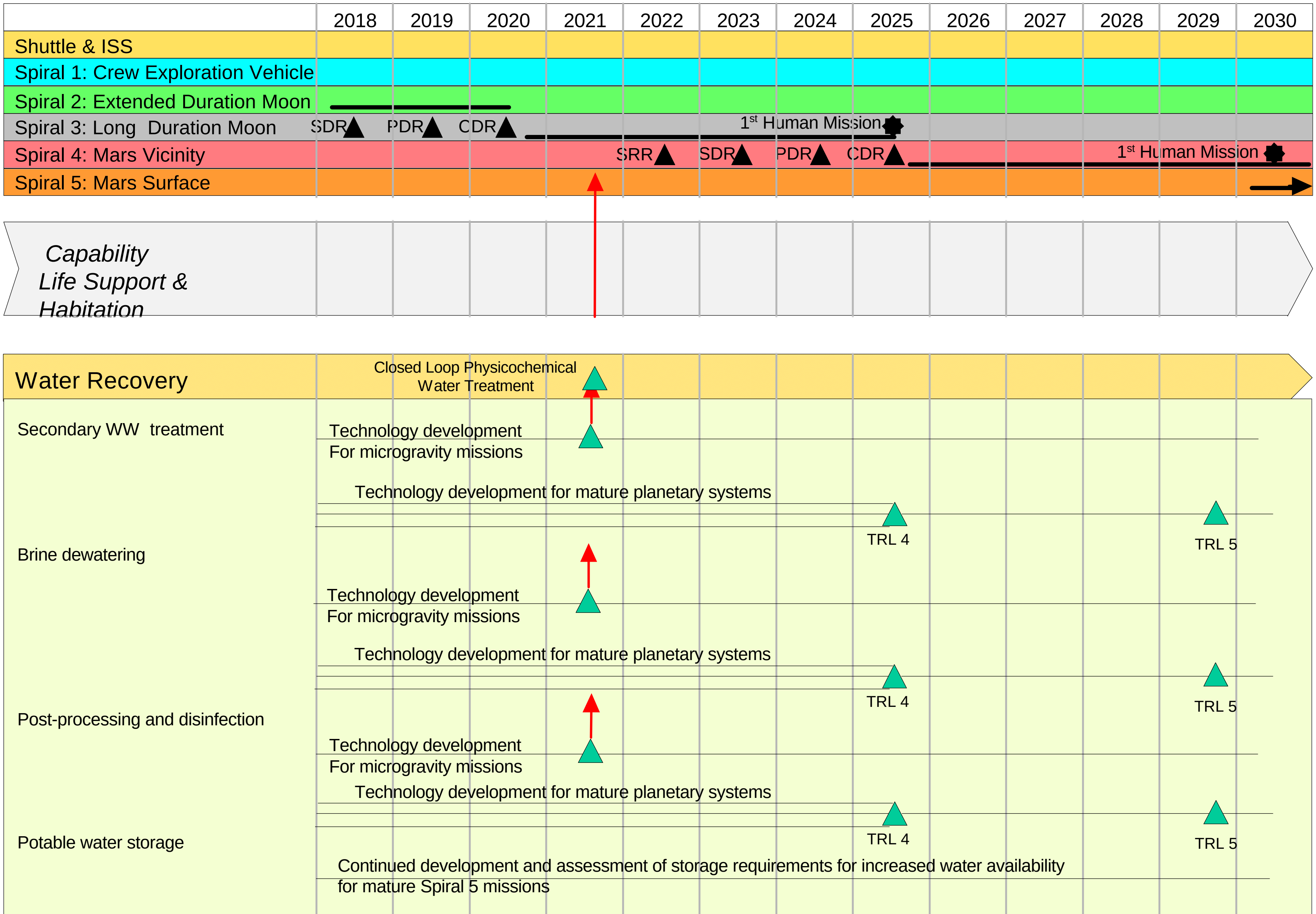
Water Recovery Systems Roadmap



Water Recovery Systems Roadmap



Water Recovery Systems Roadmap



Water Recovery Systems Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Pretreat urine for stability Provide residual disinfection for stored water Store potable water	Less toxic urine pretreatment Residual disinfectant that does not require removal prior to water consumption None needed	2 1 3
Spiral 2 Lunar Surface (2011)	Same as Spiral 1	Spiral 1 development supports Spiral 2 except Prototype Spiral 3 distillation system available for testing in Spiral 2	2
Spiral 3 Long Duration Lunar Surface (2014)	Wastewater storage Remove organic contaminants from water Remove inorganic contaminants Recover brine solutions Provide polishing and disinfection Store potable water and provide residual disinfection	Same as Spiral 1 Improve energy efficiency and recovery of distillation systems; minimize size of biological systems Increase recovery of secondary processing systems Reduce power requirements, adapt to microgravity Reduce operating temperature and pressure	3 2 2 1 2
Spiral 4 Mars Vicinity (2017)	Same as Spiral 3	Same as Spiral 3 except technologies must operate in a microgravity environment Further reduction in weight and/or expendables	2 1
Spiral 5 Initial Mission Mars Surface (2021)	Same as Spiral 3	Same as Spiral 3 except Wastewater sources include food processing Integration with crop systems and solid waste processing Potential use of in-situ resources Further reduction in weight and/or expendables	1 1 1 1

Water Recovery Systems Maturity Level – Technologies

Advanced Planning & Integration Office

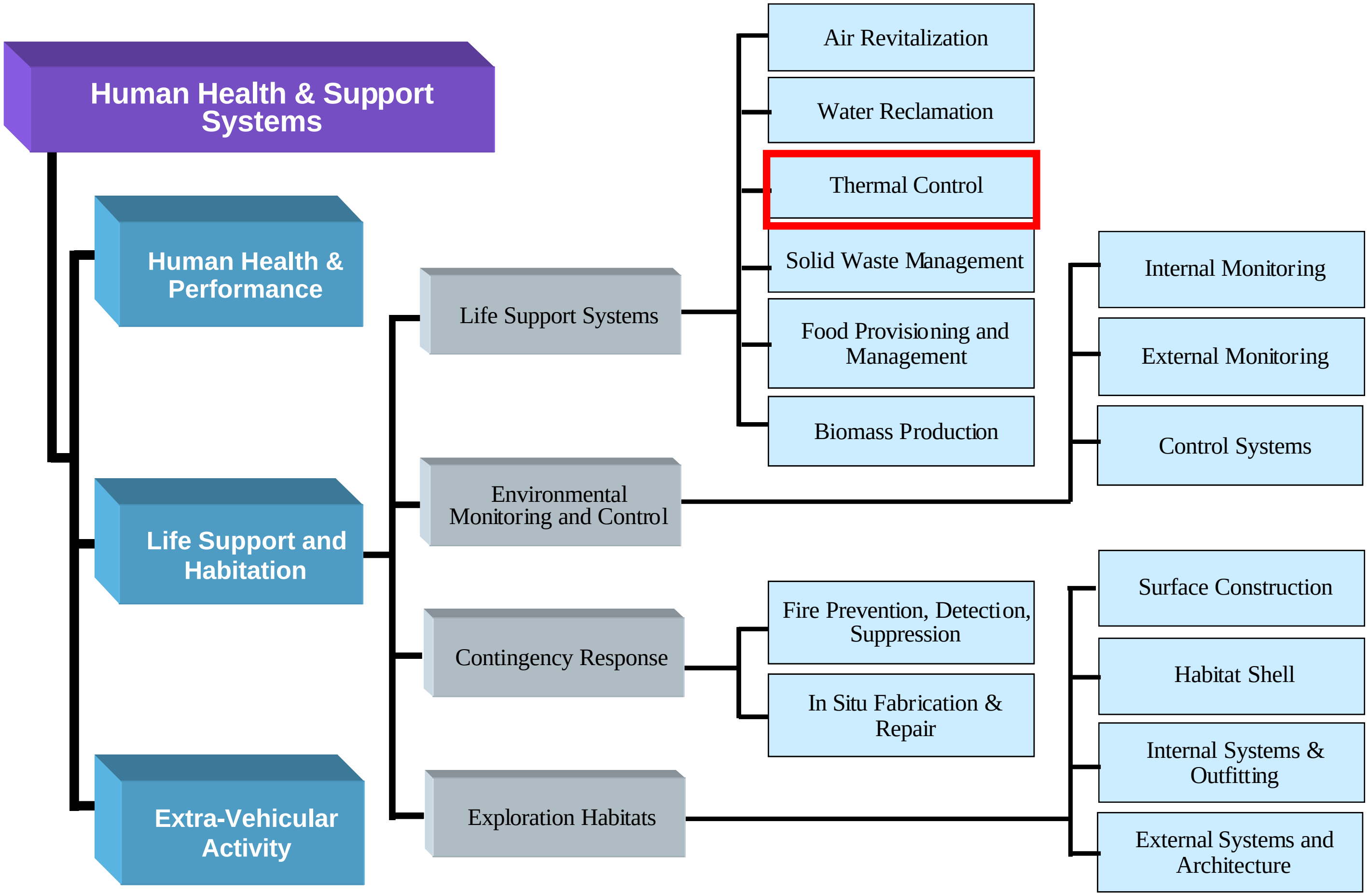
Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Development Needed	Current TRL	Spiral(s)
Urine Pretreatment	Organic acid Increased water flush volume	Effectiveness assessment and delivery system	2 3	1-5
Primary Treatment (organic removal)	Rotating distillation process (combines primary and secondary treatment) Biological systems Crop systems	System integration Microgravity capability Sizing, integration dev. System, integration dev.	3 – 5 3 2	3-5 3-5 5
Secondary Treatment (Inorganic removal)	Membrane process Rotating distillation system	Membrane development System integration	3 3-5	3-5 3-5
Brine recovery	Distillation system Membrane process Solid waste processors		3-5 3 2	3-5 3-5 5
Post-processing and disinfection	Low temperature catalysis Photocatalysis Photolysis Ion exchange	Catalyst development Catalyst and system development System test and integration	3 2 3 5	3-5 3-5 3-5 3-5
Potable water storage	Silver Residual requirement replaced with recirculating tank disinfection and point of use disinfection	Technology assessment and development	6 2	1-5 1-5

Water Recovery Systems Figures of Merit

Advanced Planning & Integration Office

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Waste water storage	Toxicity of urine pretreatment	N/A
Primary processing	Percent water recovered	%
Secondary processing	Power	W / liter
Brine recovery	System mass / volume	kg / m^3
Post-processing and disinfection	Water quality	Varies
	Consumable mass	kg
Potable water storage	Consumable required for residual disinfection	kg
	Microbial water quality	CFU/ml

Active Thermal Control



Active Thermal Control Description

- **Active Thermal Control Systems (ATCS) are required to control cabin and hardware temperatures within a vehicle**
  - **Heat Acquisition and Humidity Control** – acquire waste heat from cabin air and vehicle hardware
  - **Heat Transport** – transport heat within the vehicle or habitat
  - **Heat Rejection** – reject energy from the vehicle or habitat, in the form of heat, to the environment

Active Thermal Control Benefits

- Benefits
  - Maintain a comfortable temperature and humidity environment for crew
  - Maintain hardware temperatures within operating limits
- Benefits of advanced developments in Active Thermal Control System hardware
  - Decreased mass, power, or volume
  - Decreased risk
  - Enable heat rejection in new environments (higher temperatures or different ambient pressures)
  - Increased life

Active Thermal Control
Current State-of-the-Art

Advanced Planning & Integration Office

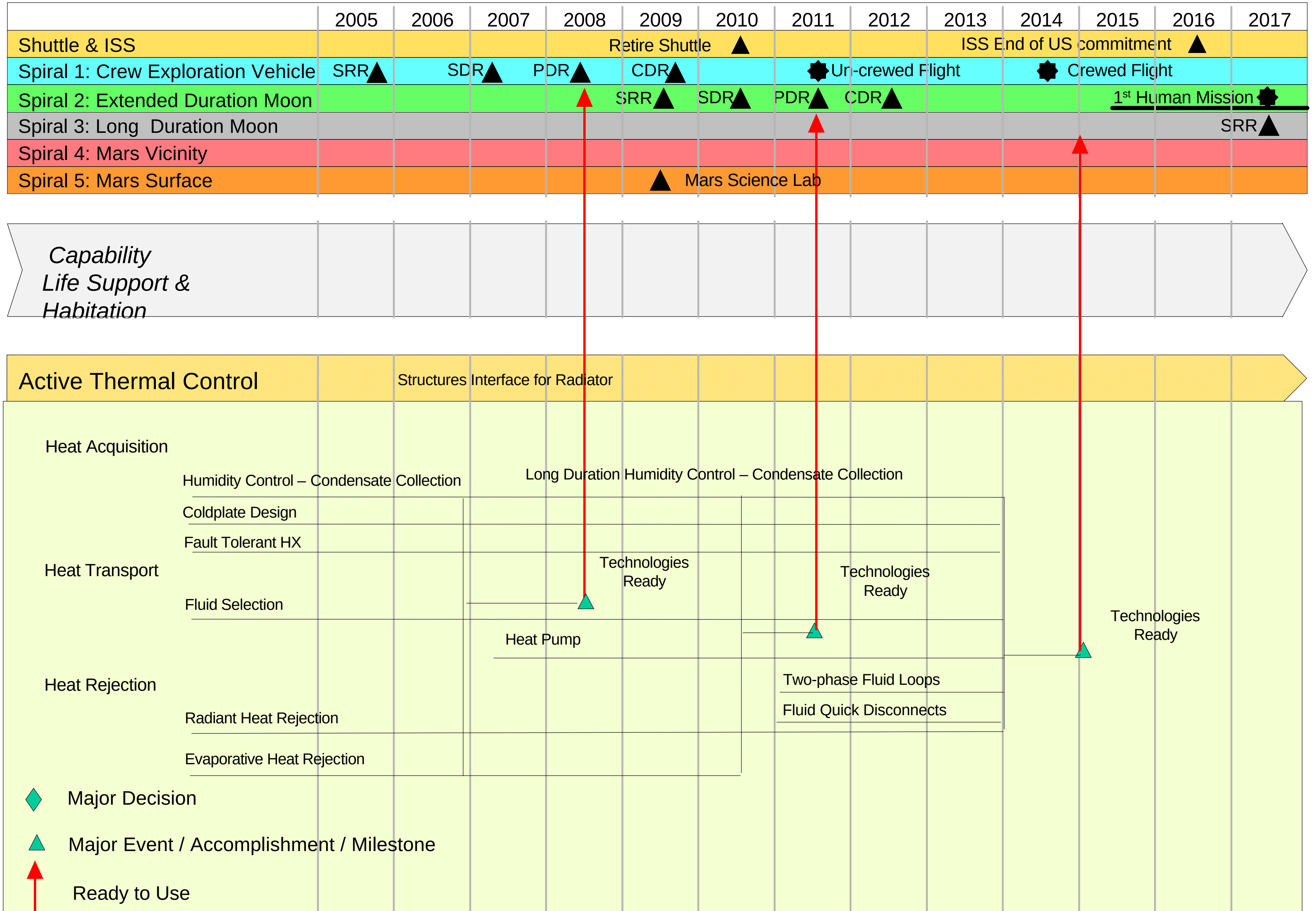
- Heat Acquisition and Humidity Control
  - Metal coldplates
  - Liquid-to-liquid compact heat exchangers
  - Air-to-liquid heat exchangers
  - Slurper bars and rotary separators for condensate collection
- Heat Transfer Technologies
  - Pumped liquid loops
  - Internal water loops and external refrigerant loops (Freon 21, ammonia)
  - Metal bellows accumulators
- Heat Rejection
  - Aluminum radiators (Z93 or Silver teflon coatings)
  - Porous plate sublimators
  - Flash Evaporator System (FES) – water spray boiler
  - Ammonia boiler

Active Thermal Control Requirements /Assumptions

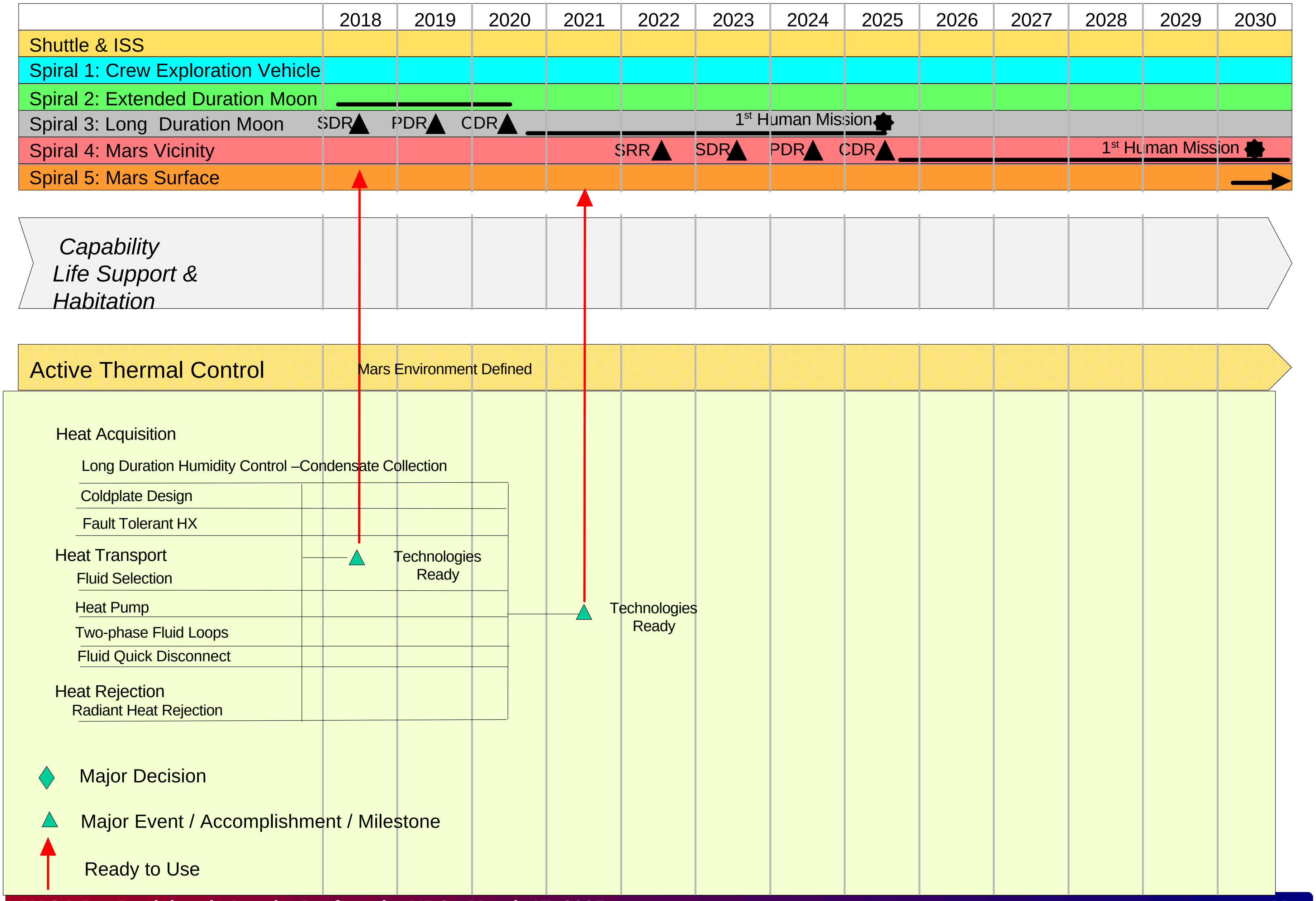
Advanced Planning & Integration Office

- **Driving Mission Requirements and Assumptions**
  - General Assumptions
    - Vehicle heat load
    - Heat rejection environment
      - Radiation sink temperature
      - Pressure
      - Micrometeoroid and Orbital Debris
      - Dust – unique to Lunar and Mars surface missions
    - Available vehicle surface area for mounting radiators
    - Mission duration
    - Availability of heat transfer fluid that enables a single loop for inside both the cabin and radiators
  - Mission Specific Requirements and Assumptions
    - Requirement for cabin pressure & depressurization (Spirals 1-5)
    - Requirement for collecting humidity condensate (Spirals 3 – 5)
    - Requirement for assembly and maintenance during the mission (Spirals 3 – 5)

Active Thermal Control Roadmap



Active Thermal Control Roadmap



Active Thermal Control Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Provide cooling to avionics and other heat producing hardware Transfer energy from one fluid loop to another Provide temperature and humidity control for cabin air Transport energy throughout the vehicle Provide radiant heat rejection Provide evaporative heat rejection	Mass reduction for coldplates Fault tolerance for interpath leakage No development needed Fluids that can be used inside the cabin and in radiators Mass reductions and ability to handle mission transients for radiators Extended operating range that included vacuum and post landing; decreased sensitivity to feedwater contamination	1 2 7 2 2 2
Spiral 2 Lunar Surface (2011)	Same as Spiral 1 except Provide heat rejection in hot Lunar environments	Same as Spiral 1 except Heat pump systems are needed	2
Spiral 3 Long Duration Lunar Surface (2014)	Same as Spiral 1 except Evaporative heat rejection is not required Requirements for assembly and maintenance during the mission Increased heat loads	Same as Spiral 1 except Long duration systems are needed for humidity control and condensate collection Fluid Quick disconnect Two-phase fluid loops	1 1 2
Spiral 4 Mars Vicinity (2017)	Same as Spiral 3	Same as Spiral 3	
Spiral 5 Initial Mission Mars Surface (2021)	Same as Spiral 3	Same as Spiral 3	

Active Thermal Control Maturity Level – Technologies

Advanced Planning & Integration Office

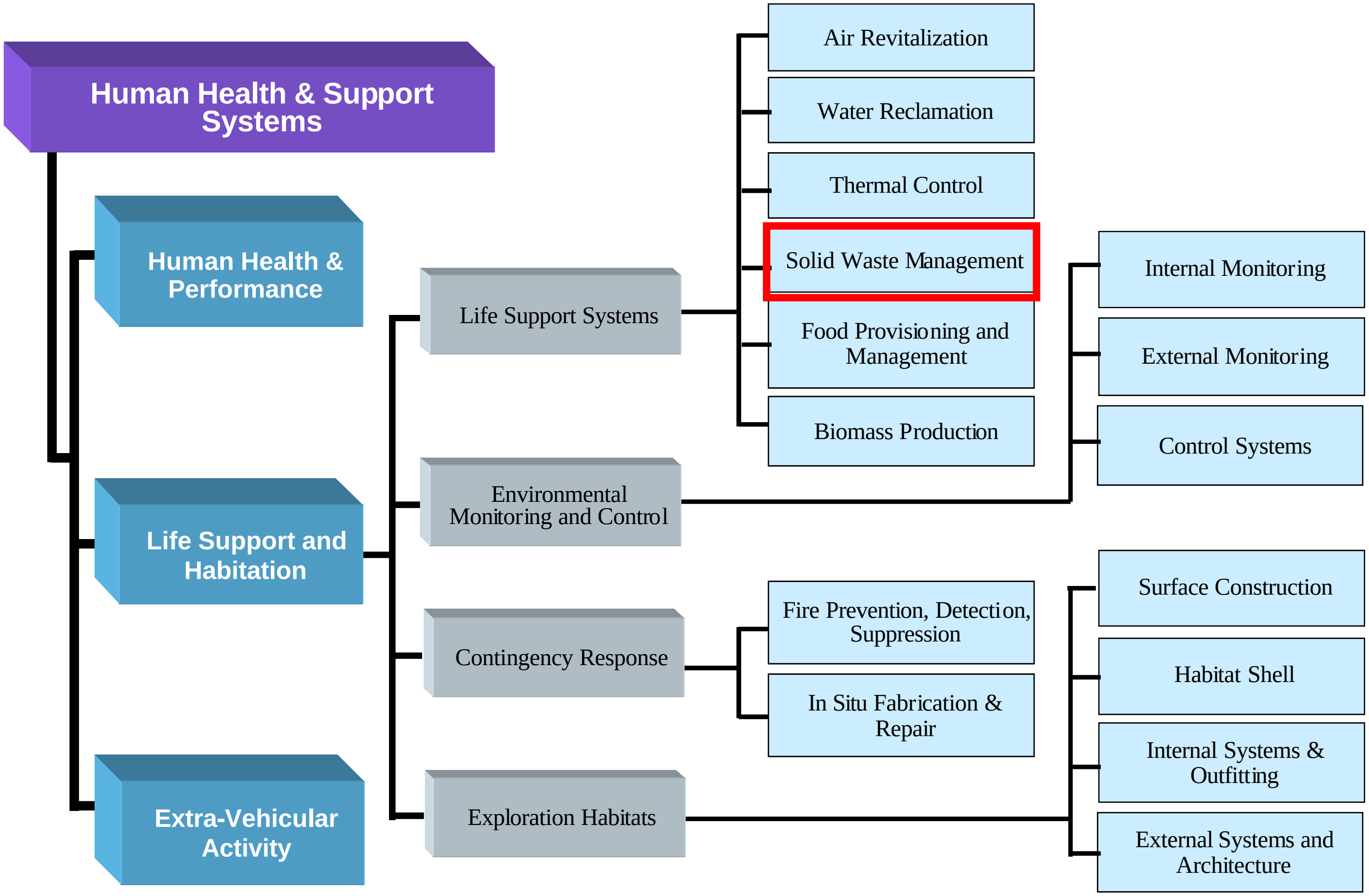
Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Development Needed	Current TRL	Spiral(s)
Heat Acquisition				
Provide cooling to avionics and other heat producing hardware	Composite Coldplate Shelf	Mass reduction	3	1-5
Transfer energy from one fluid loop to another	Fault Tolerant Heat Exchanger	Additional barrier for interpath leakage	4	1-5
Provide temperature and humidity control for cabin air	Porous Media Condensing Heat Exchanger; Vortex Dehumidification	Long duration humidity control and condensate collection	3; 4	3-5
Heat Transport				
Transport energy throughout the vehicle	Fluids that enable single loop systems	Performance, safety, compatibility	3	1-5
Provide heat rejection in hot Lunar environments	Vapor Compression Heat Pump	Gravity independent performance	3	2-5
Increased heat loads	Low Power Two-phase ATCS	Decrease mass and power	3	3-5
Requirements for assembly and maintenance during the mission	none	Reliable and EVA compatible	-	3-5
Heat Rejection				
Provide radiant heat rejection	Lightweight radiator; structural radiator	Mass reduction; ability to handle mission transients	5; 3	1-5
Provide evaporative heat rejection	Multi-environment evap; Contamination Insensitive Sublimator	Larger operating envelope; longer life	3; 3	1, 2

Active Thermal Control Figures of Merit

Advanced Planning & Integration Office

Sub-Capability (Level 5 CBS)	Figures of Merit: Description	Figures of Merit: Units
Heat Acquisition Provide cooling to avionics and other heat producing hardware Transfer energy from one fluid loop to another Provide temperature and humidity control for cabin air	Heat transfer per coldplate mass Barriers between fluids Operational life	W/kg Number of barriers Hours
Heat Transport Transport energy throughout the vehicle Provide heat rejection in hot Lunar environments Increased heat loads Requirements for assembly and maintenance during the mission	Heat transfer per system mass Radiator fluid temperature Heat transfer per power input Reliability	W/kg K W_{th}/W_{power} Time between failure
Heat Rejection Provide radiant heat rejection Provide evaporative heat rejection	Mass per surface area Operating pressure range Operational life	Kg/m^2 kPa Hours

Waste Management



Waste Management Description

Advanced Planning & Integration Office

Volume Reduction

Storage space for wastes is very limited on space vehicles. Volume reduction or compaction saves valuable space.

Water Removal and Recovery

Many wastes such as concentrated water brines or food scraps contain substantial quantities of water that can be recovered.

Safening – Stabilization

Safening means processing the waste to make it safe for the crew or harmless to planetary surfaces. Once safened, stabilization assures that the waste does not change its state.

Containment and Disposal

Contained waste is isolated from the crew and the rest of the world. Waste is disposed when the final act of handling or accessing is completed. Disposal can be onboard, overboard, in space, and on planetary surfaces.

Resource Recovery

Waste can be processed for reuse for the initial function, or it can be converted to new useful materials. Examples include cleaning clothes for reuse, converting waste to minerals for use as food growth nutrients, and pyrolyzing waste to form activated carbon.

Waste Management Benefits

The general benefit of waste management capabilities is to reduce mission cost and satisfy mission requirements:

- **Crew health and safety**
- **Crew quality of life**
- **Planetary protection – forward protection of Mars for instance, and backward protection of Earth**

Specific benefits:

- **Compaction** minimizes volume occupied by waste and thereby recovers volume. Used in conjunction with heat, compaction can also recover water and stabilize waste.
- **Mineralization** recovers resources such as water and decreases waste volume. Depending on extent of processing, mineralized products are rendered partially to completely biologically nonhazardous and inert.
- **Water removal and recovery** contributes to closure of the water loop and also results in reduced volume. Microbiological and pathogenic activity is inhibited in dried residue thus protecting crew health.
- **Overboard disposal** eliminates the need to provide stowage volume, eliminates the need to process waste to protect the crew, and reduces propulsion needs.
- **Containment** of waste protects the crew from physical, chemical, and biological waste hazards onboard the spacecraft. It also protects planetary surfaces from contamination with microbes and biomarkers and protects Earth from back-contamination.
- **Resource Recovery** reduces the cost of resupply of items such as clothing and nutrients for plant growth.

Waste Management Benefits

Advanced Planning & Integration Office

Mission Cost (measured by Equivalent System Mass - ESM) Reduction

A Comparison of International Space Station (ISS)Technology with Advanced Life Support (ALS) Technology. For 1000 day Mars mission with 6 crew.

Name	ISS ESM	ALS ESM	delta	comment
Waste (clothing,feces, food packaging, scraps, etc.) safener - e.g. container vs. mineralizer	3,933	1,000	2,933	assume containers for ISS - processor for ALS
Waste Disposal on Mars surface	5,899	1,000	4,899	savings on return propulsion
Water in feces and waste	2,000	500	1,500	water saving vs cost
Clothing	6,780	1,200	5,579	clothing washer
Compaction	3,000	1,000	2,000	assume crewed vol=200 kg/m^3, ISS is 1/2 compact by hand

Waste Management Current State-of-the-Art

Waste management technologies for space life support systems are currently at low development levels. Manual compaction of waste, collection in plastic bags (general waste) and hard containers (feces), and disposal to earth return vehicles are the primary current waste management practices.

Without improvement of capabilities, such practices on future missions will expose the crew to biological and chemical waste hazards, obstruct crew quarters with accumulated waste, forfeit recoverable resources such as water, consume valuable crew time, contaminate planetary surfaces, and risk return to Earth of extraterrestrial life.

Disposable
Feces container
Untreated

Waste Collection System

Hand Compacted Waste - Shuttle

Waste Management Requirements /Assumptions

- **Requirements**
  - **Crew health and safety**

    The longer duration of future missions without access to routine resupply and disposal resupply missions means that waste needs improved management to assure crew safety. Detailed requirements in this area are not yet established. Safening is required. It is assumed drying is the minimum level of safening. Mineralization can also dry waste and may provide better protection from hazards at the same cost.
  - **Crew quality of life**

    Odor, clutter, and other qualities of waste can negatively affect crew outlook and performance. Detailed requirements for waste are not yet established. It is assumed that this requirement supports the need for improved management of waste via deodorization, compaction, drying, and mineralization.
  - **Planetary protection – forward protection of Mars, and backward protection of Earth**

    International agreements prohibit harm to planetary surfaces such as Mars. Mars biota and the search for life must be protected from Earth biology. Clearly Earth must also be protected from possible Mars biology. Until unknowns are resolved for Mars, early missions may need to manage wastes more carefully than later missions (as was the case for the moon). Bringing all wastes back is prohibitively expensive, hence waste must be managed to allow disposal on Mars. Development of detailed planetary protection requirements is currently being pursued.

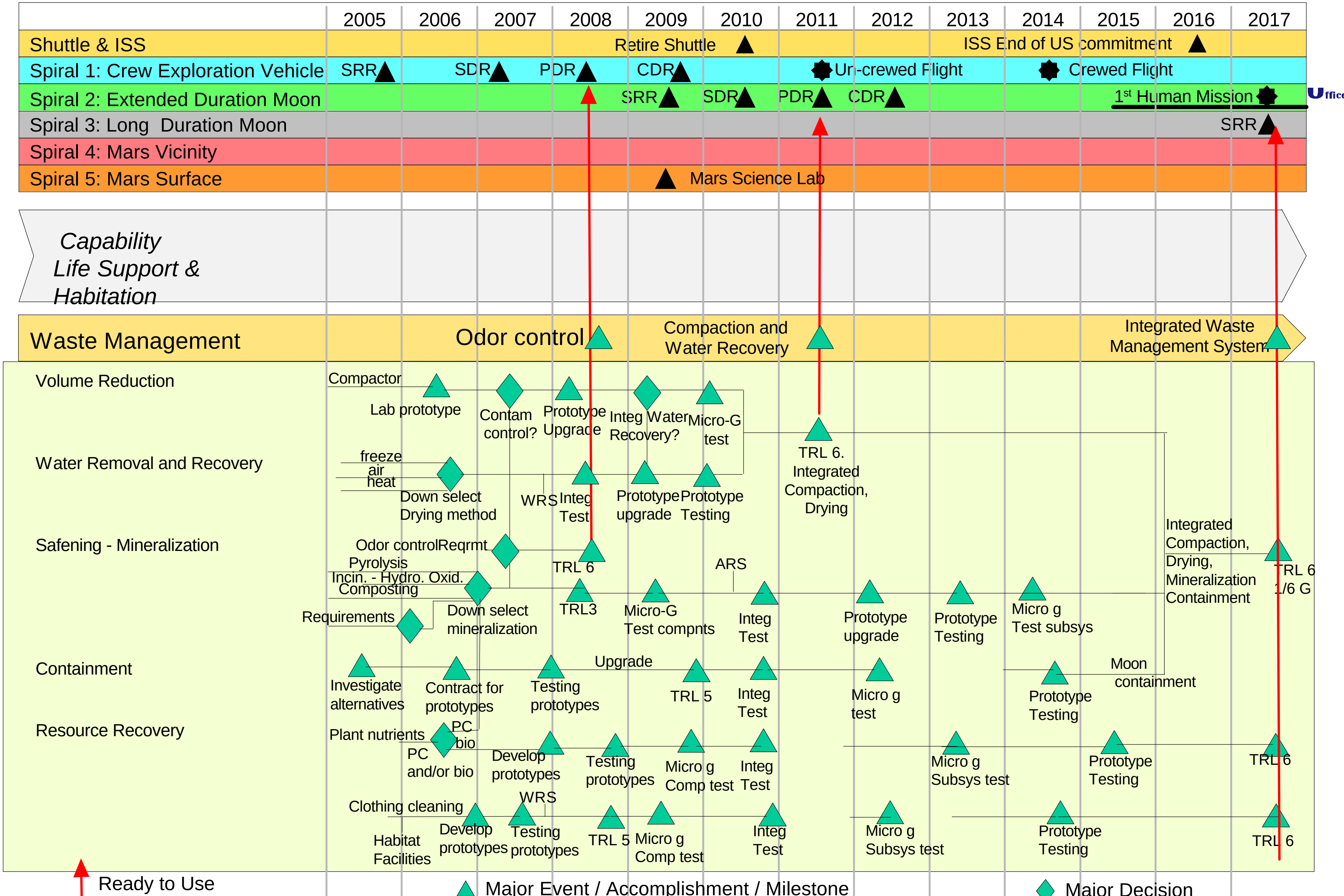
Waste Management Requirements /Assumptions

- **Missions and assumptions driving the development plan**

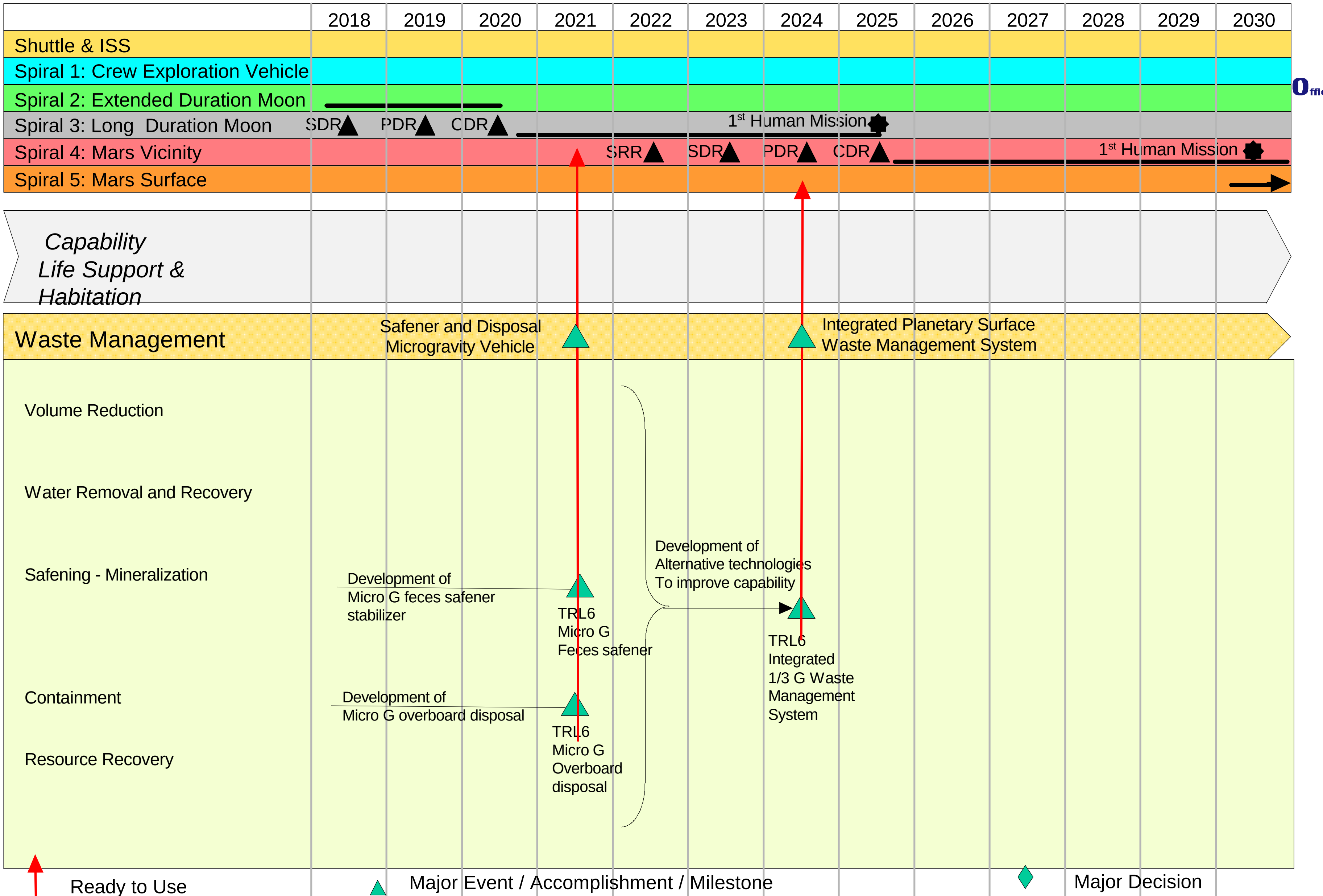
  – **For near term missions such as Spirals 1 and 2:**
    - Odor control and mechanical waste compaction must be ready for these spirals because these capabilities are justified by requirement and/or cost.

  – **As missions progress to longer duration and further distances (Spirals 3 to 5)**
    - Water recovery, and clothes washing are payout projects and must be ready by spiral 3.
    - Capabilities needed for Mars are to be tested on the moon, and hence at least advanced prototypes for capabilities such as mineralization and nutrient recovery must be ready for moon testing.
    - Containment will need development specific to missions because requirements differ by mission: the moon (bio contamination not an issue), transit (in-space overboard disposal), and Mars (bio contamination of Mars prohibited).

Waste Management Roadmap



Waste Management Roadmap



Waste Management Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs - Gaps	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Volume reduction and stabilization	Existing waste management can support spiral 1, although some benefits could be obtained from odor control	2
Spiral 2 Lunar Surface (2014)	Volume reduction Stabilization	There is no automated or mechanical volume reduction capability ready for flight Odor control and some vacuum drying stabilization may be needed	2 1
Spiral 3 Long Duration Lunar Surface (2017)	Volume reduction Water Recovery Safening- stabilization (mineralization) Containment and Disposal Resource Recovery	Need flight ready mechanical volume reduction Need flight ready capability for water recovery from solid waste Need to test advanced prototypes for safening and stabilization of waste on long duration missions Need flight ready moon containment and test prototype for Mars containment and disposal Need flight ready capability as clothing cleaning and advanced test prototype for nutrient recovery	2 2 2 1 1
Spiral 4 Mars Vicinity (2021)	Same as Spiral 3	Much the same as Spiral 3 except technologies must operate in a Micro-gravity environment and must all (except nutrient recovery) be operational rather than test prototypes Overboard disposal is in space	 1 1
Spiral 5 Initial Mission Mars Surface (2024)	Same as Spiral 3	Same as Spiral 3 except Operation on 1/3 rather than 1/6 g Operational rather than test prototypes	 1

Waste Management Maturity Level - Technologies

Advanced Planning & Integration Office

Sub-Capability (Level 5/6 CBS)	Leading Technology Candidates	Spiral(s)	Current TRL
Volume reduction Safening - Stabilization	Plastic heat melt compactor	2,3,4,5	2
Water removal and recovery Safening - Stabilization	Lyophiliization	3,4,5	3
Water removal and recovery Safening - Stabilization	Air drying	3,4,5	2
Water removal and recovery Safening - Stabilization	Vacuum drying	3,4,5	1
Volume reduction Water removal and recovery Safening - Stabilization	Pyrolysis	3,4,5	3
Volume reduction Water removal and recovery Safening - Stabilization Resource recovery - nutrients	Incineration	3,4,5	3
Volume reduction Water removal and recovery Safening - Stabilization Resource recovery - nutrients	Hydrothermal oxidation	3,4,5	3

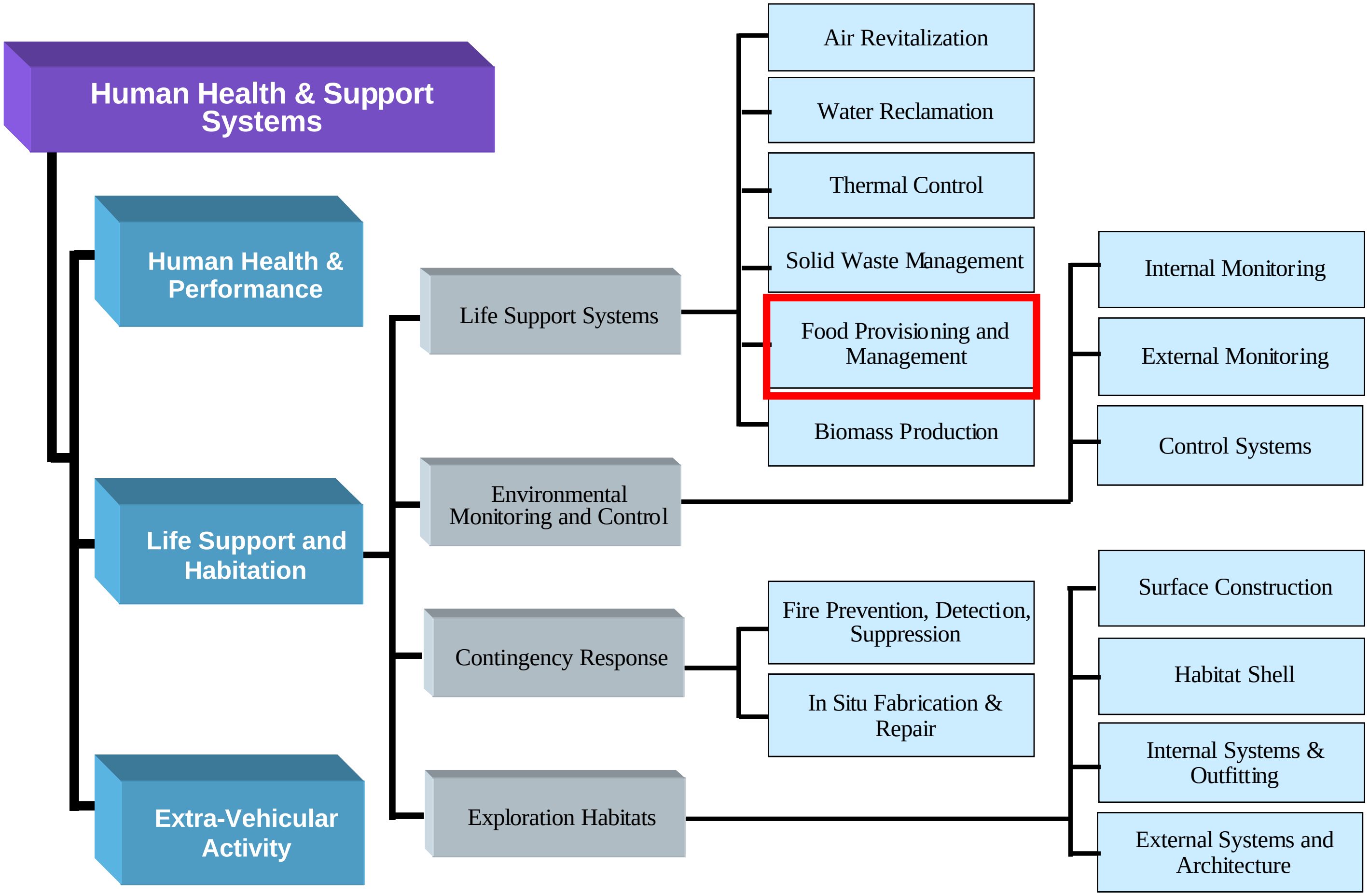
Waste Management Maturity Level - Technologies

Sub-Capability (Level 5/6 CBS)	Leading Technology Candidates	Spiral(s)	Current TRL
Volume reduction Water removal and recovery Resource recovery - nutrients Safening - Stabilization	Composting - aerobic	3,4,5	2
Volume reduction Resource recovery - nutrients Safening - Stabilization	Composting - anaerobic	3,4,5	2
Resource Recovery -clothes	Clothes washer	3,4,5	1
Containment	Containers	3,4,5	1

Waste Management Figures of Merit

Sub-Capability (Level 5 CBS)	Technology Type	Figures of Merit
Volume Reduction	Compactors Mineralizers (Bio and PC) Particle size reducers	Density of compacted material (kg/m^3)
Water Removal and Recovery	Dryers Mineralizers (Bio and PC)	Percent water recovered (%)
Safening - Stabilization	Deodorizers Dryers Mineralizers (Bio and PC)	Probability of harm Time that waste is safe and stable (years)
Containment and Disposal	Containers (on board and surface) Containment via use of in situ materials Ejectors and container jets (in space disposal)	Time that waste is safe and stable or contained (years)
Resource Recovery	Dryers Mineralizers (Bio and PC) Clothes Washers	Percent recovery (%)

Food Provisioning and Management



Food Provisioning and Management Description

- **Advanced Food System is required to maintain health of the crew during the entire mission**
  - **Stored Ready-to-Eat Foods – prepackaged food items will be used during transit and surface missions**
    - **Food packaging**
    - **Food preservation**
    - **Stored food stowage**
  - **Raw Commodity Processing and Stowage – fresh fruits and vegetables can be used throughout mission. The processed food system will be used on lunar or planetary surface.**
    - **Raw commodity stowage**
    - **Raw commodity processing**
    - **Processed ingredient stowage**
  - **Menu Development and Galley Procedures – development of nutritionally complete menu with corresponding galley procedures**
    - **Food preparation**
    - **Prepared food stowage**
    - **Meets nutritional needs of crew**

Food Provisioning and Management Benefits

Advanced Planning & Integration Office

- The development of an advanced food system will enable support of humans beyond Low Earth Orbit (LEO).
- Food must be safe, nutritious and acceptable to maintain crew health and well being throughout the entire mission.
  - Food has a psychosocial element in addition to nutrition
  - Crew performance and well-being dependant on a high quality food system.
  - Use of resources will be minimized.
- Fresh vegetables provide the crew with bright colors, aromas, and improved nutrition
- Food processing will provide the crew with a variety of fresh and nutritious foods throughout the entire mission

Food Provisioning and Management Current State-of-the-Art

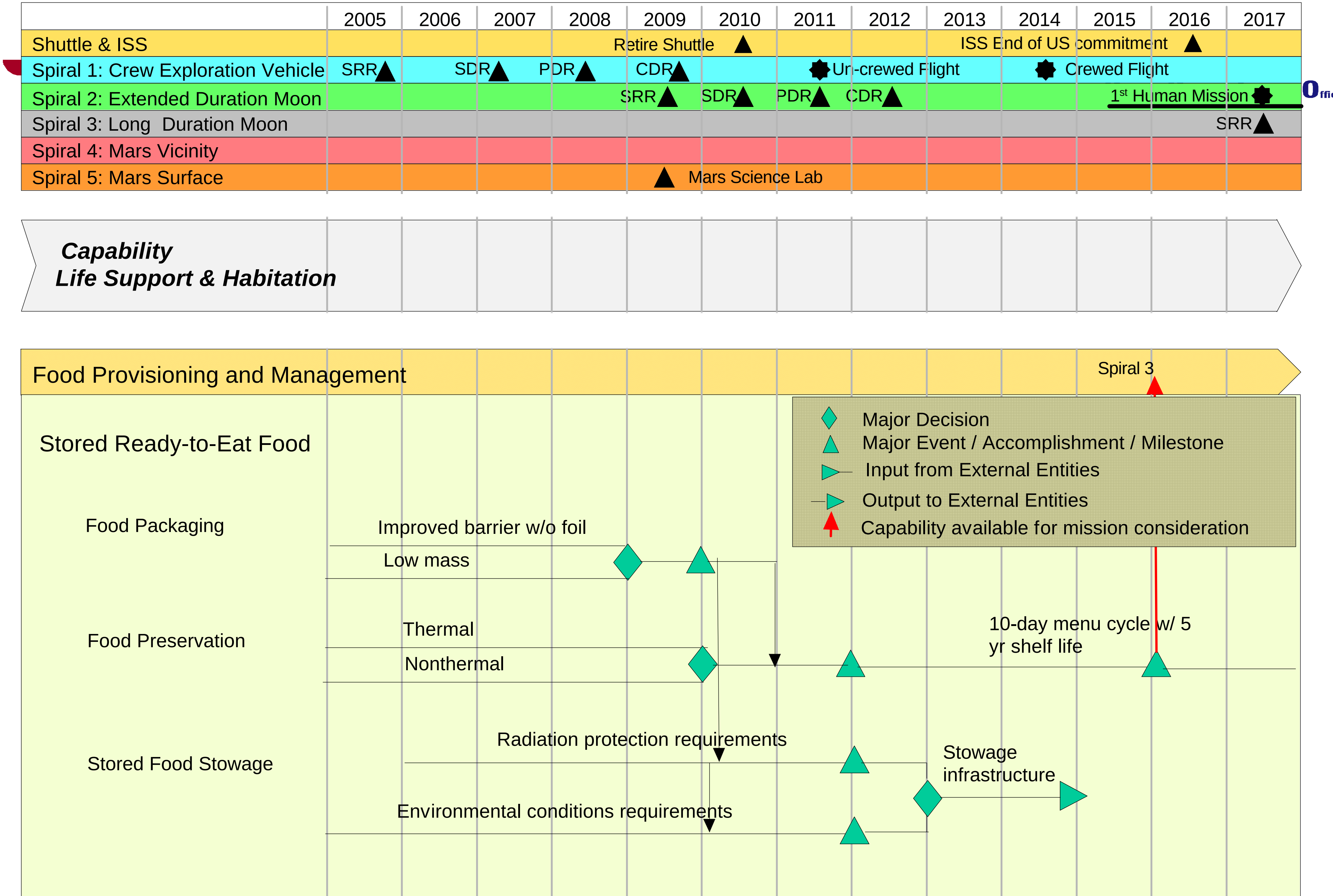
Advanced Planning & Integration Office

- Stored Ready-to-Eat Foods
  - Food packaging
    - MRE pouch used for thermostabilized and irradiated foods has a high barrier to moisture and oxygen due to the aluminum layer. However, it is dense and hard to process by solid waste processing team
    - Poly material used for freeze dried foods and natural form foods has poor barrier materials and is overwrapped with a foil pouch for ISS
  - Food preservation
    - Freeze dried and natural form foods have a shelf life of 12 months
    - Thermostabilized and irradiated foods have a shelf life of 3 years
- Raw Commodity Processing and Stowage – there is no available processing equipment
- Menu Development and Galley Procedures
  - Have capability to determine nutritional content of menu
  - Have capability to heat and rehydrate stored food system
  - Have capability of a 10-day menu cycle

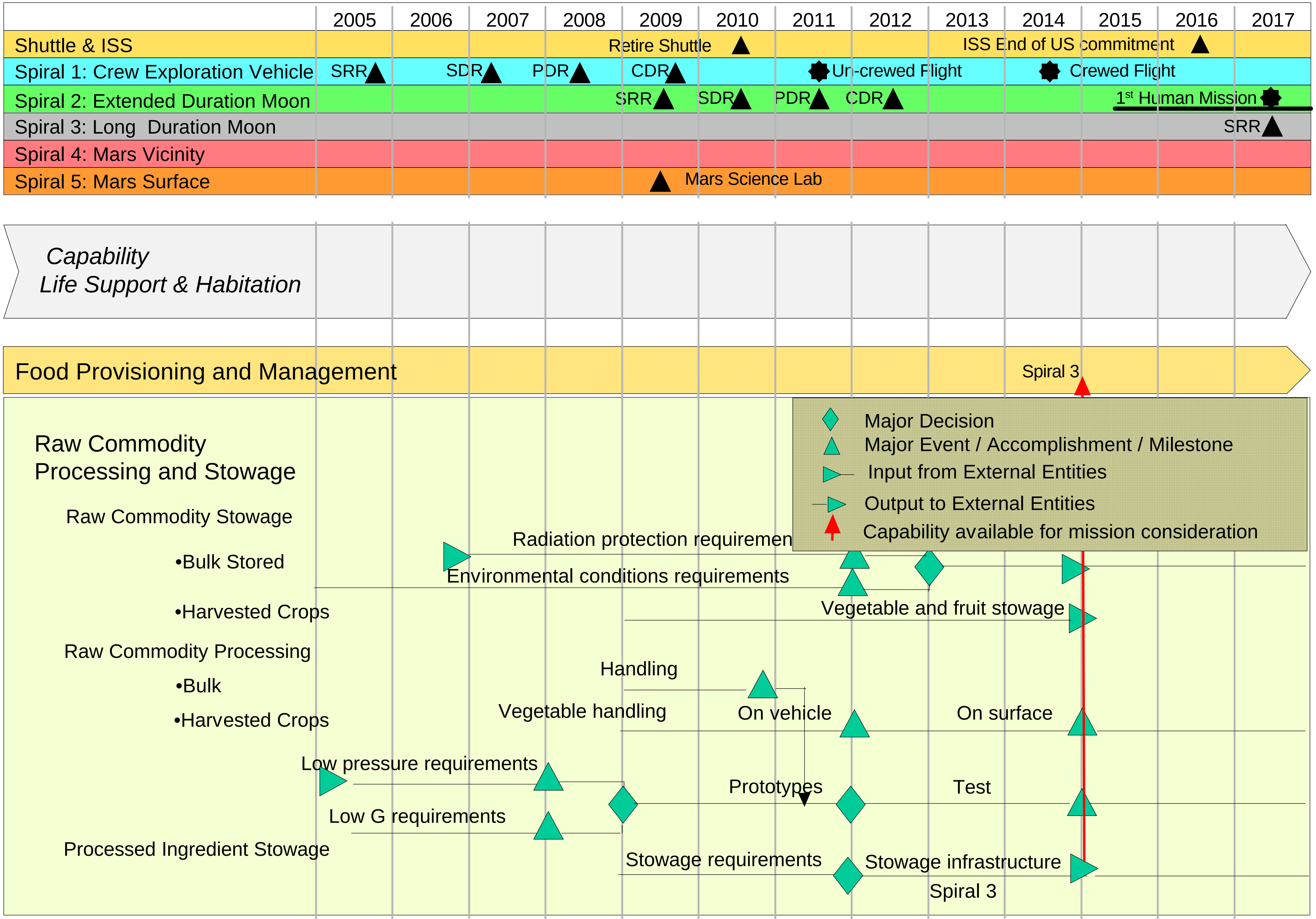
Food Provisioning and Management Requirements /Assumptions

- Spirals 1 and 2
  - Able to use current ISS food system
  - Depending on vehicle design, may need to develop food warmer and rehydration station
- Spiral 3
  - Moon will be used as a test bed for Mars missions
  - Fresh vegetables and fruits will be available for consumption (hypogravity)
  - Some food processing and food preparation will be available during the mission
  - Packaging materials with an aluminum layer will be more difficult for solid waste processing
  - Hypogravity and lower atmospheric pressure will affect food processing and food preparation procedures
- Spiral 4
  - Stored ready-to-eat foods will require at least a 3-year shelf life
  - Fresh vegetables and fruits will be available for consumption (microgravity)
- Spiral 5
  - Stored ready-to-eat foods, raw commodities, and resupply items will require at least a 5-year shelf life
  - Radiation may affect quality and functionality of ready-to-eat foods
  - Fresh vegetables and fruits will be available for consumption (hypogravity)
  - Radiation may affect quality and functionality of stored raw commodities
  - Hypogravity and lower atmospheric pressure will affect food processing and food preparation procedures
  - All available raw commodities will be processed into edible food ingredients
  - Recipes will be prepared utilizing all available processed food ingredients, resupply items, and freshly harvested vegetables and fruits
  - During a long duration mission, food acceptability and variety will contribute to the crew's psychosocial well-being

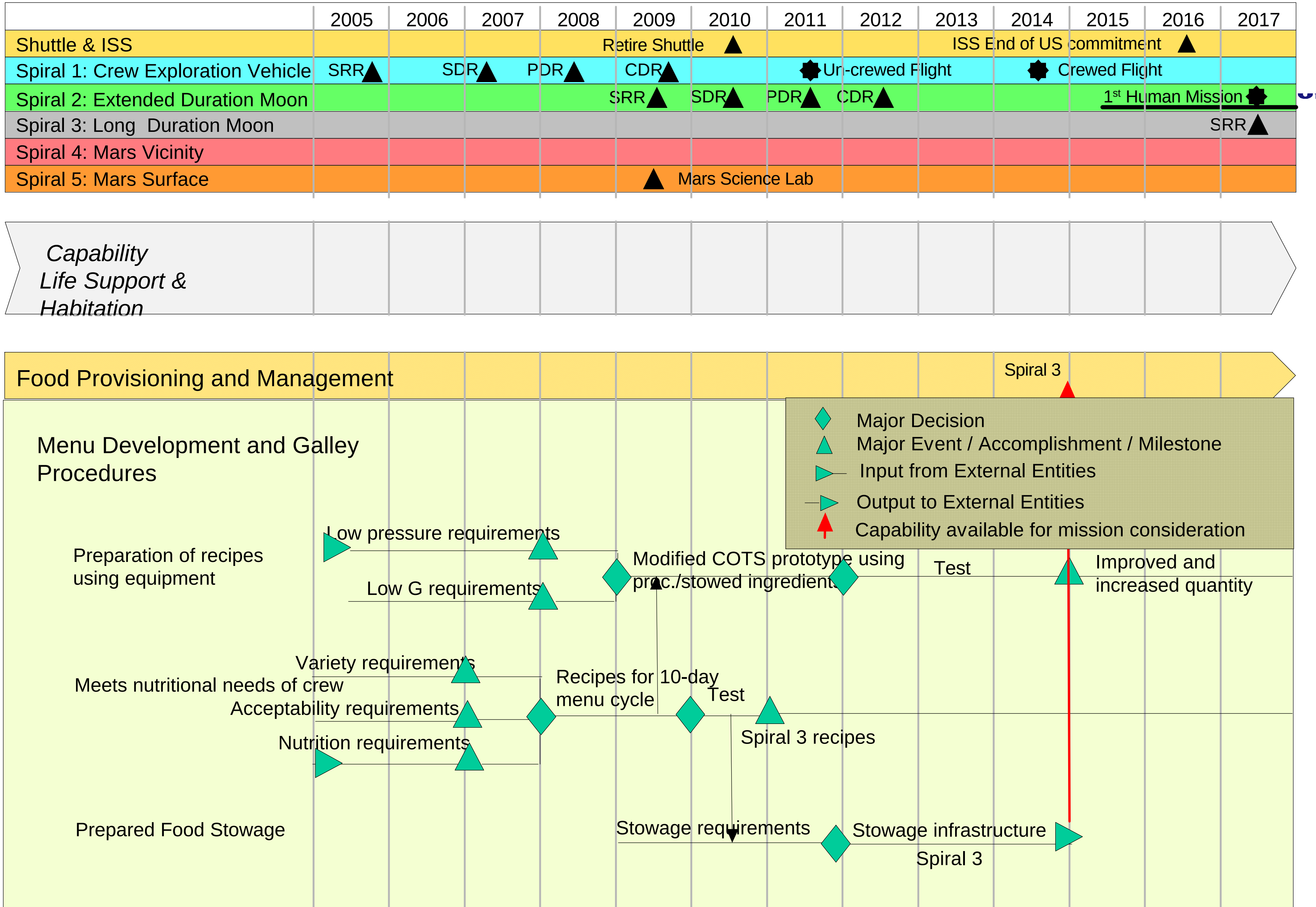
Food Provisioning and Management Roadmap



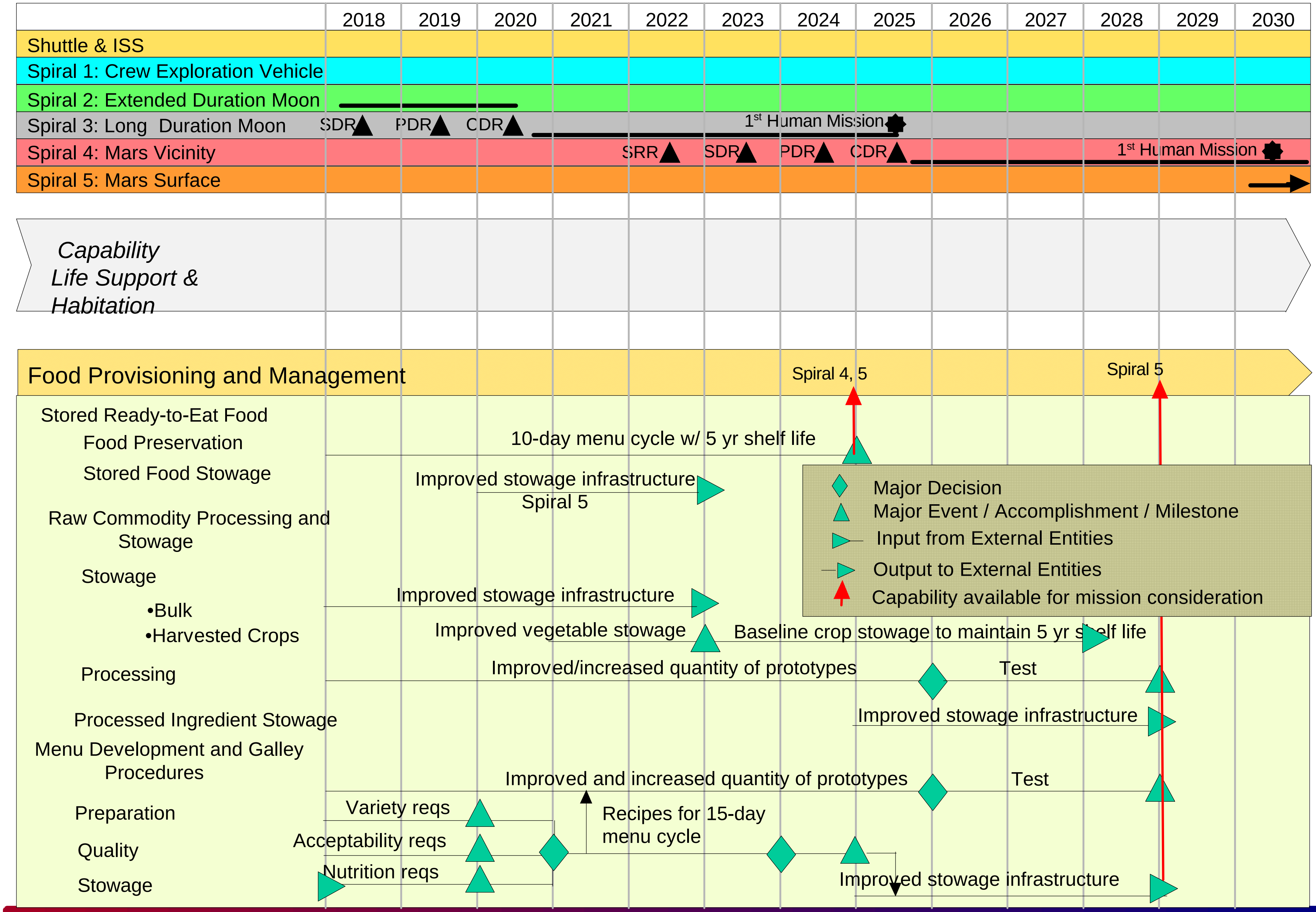
Food Provisioning and Management Roadmap



Food Provisioning and Management Roadmap



Food Provisioning and Management Roadmap



Food Provisioning and Management Maturity Level - Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Stored Ready-to-Eat Food	Improved barrier packaging with easier solid waste processing capability. Current food preservation and stowage capabilities supports Spiral 1.	1 7
Spiral 2 Lunar Surface (2011)	Same as Spiral 1	Spiral 1 development supports Spiral 2	1, 7
Spiral 3 Long Duration Lunar Surface (2014)	Stored Ready-to-Eat Food Raw commodity processing and stowage Menu development and galley procedures	Same as Spiral 2 except Improved quality of extended shelf life stored food items Limited food processing capabilities in reduced gravity Limited food preparation capabilities in reduced gravity Handling procedures of fresh food	2 1 2 2
Spiral 4 Mars Vicinity (2017)	Stored Ready-to-Eat Food	Same as Spiral 2 except 5-yr shelf life stored food system with 10-day menu cycle	2
Spiral 5 Initial Mission Mars Surface (2021)	Stored Ready-to-Eat Food Raw commodity processing and stowage Menu development and galley procedures	Same as Spiral 4 except 5-yr shelf life stored food system with 15-day menu cycle Food processing of all available ingredients and crops Stowage of bulk ingredients Food preparation using all available ingredients and crops	2 1 2 2

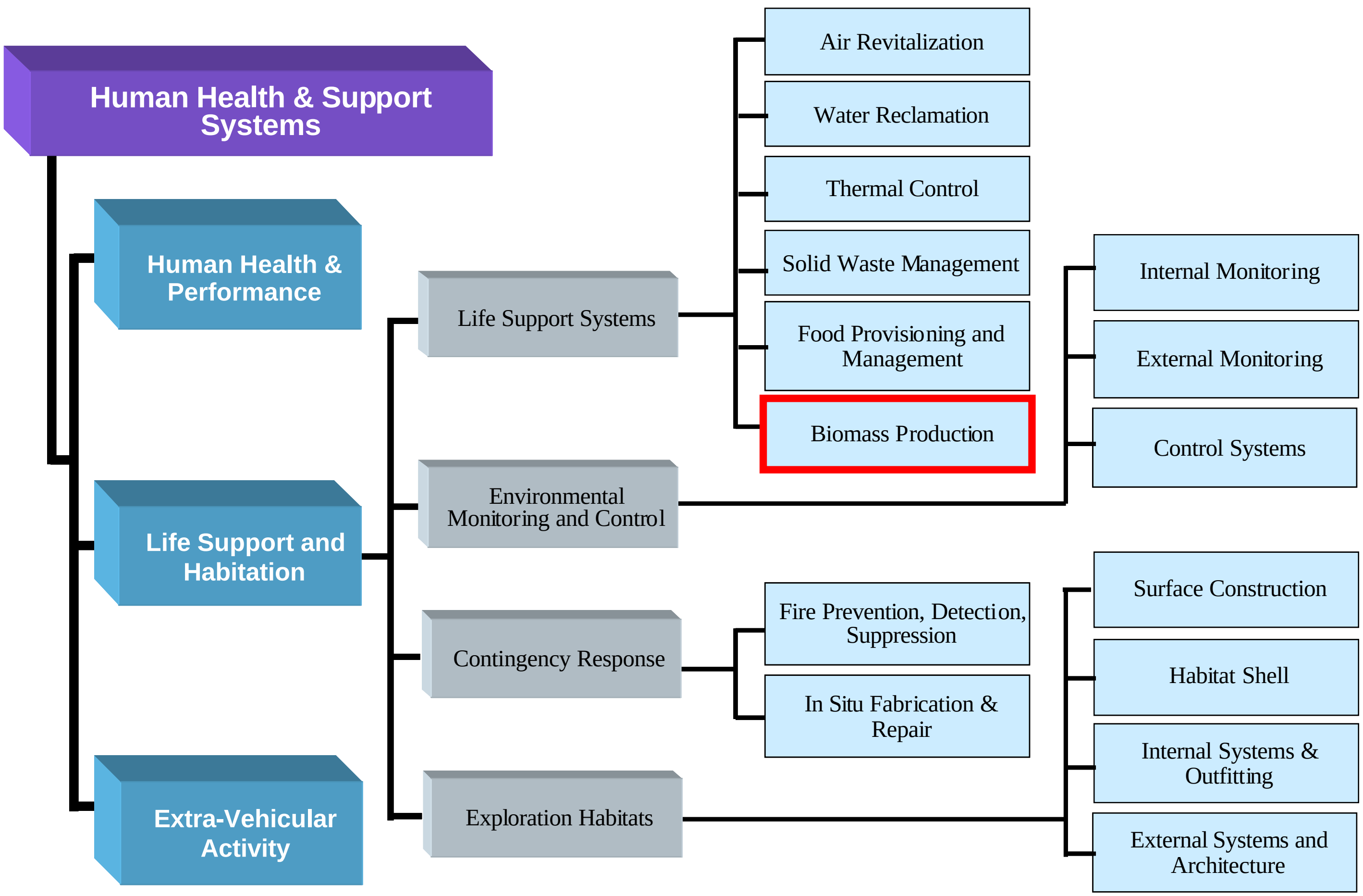
Food Provisioning and Management Maturity Level - Technologies

Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Development Needed	Current TRL	Spiral(s)
Stored Ready-to-Eat Foods	Preservation technologies which allows safe ambient stowage	Development of emerging technologies to allow ambient temperature storage for up to 5 years	2-9	3-5
	High barrier food packaging technologies	Development of emerging technologies of high barrier packaging materials which allows for easier solid waste processing	2-9	1-5
	Develop stored food items with 3 – 5yr shelf life	Integration of preservation and packaging technologies to develop new stored food items with adequate nutrition, variety, and acceptability for duration of mission	2-9	3-5
	Stowage compartments – environmental conditions and inventory management	Develop stowage specifications based on the effect of environmental conditions (e.g., radiation, temperature, oxygen, relative humidity) on shelf life	2-5	3-5
		Determine easy-to-use inventory management system	3	2-5
Raw Commodities Processing and Stowage	Raw commodity and resupply item stowage compartments	Develop stowage specifications based on the effect of environmental conditions (e.g., radiation, temperature, oxygen, relative humidity) on shelf life	2	3-5
	Handling procedures of fresh food	Confirm use of hydrogen peroxide or other sanitizer on chamber-grown vegetables	3	3-5
	Miniaturized food processing equipment	Design, fabricate and build processing equipment	2	3, 5
	Processed foods stowage compartments	Determine volume of ambient, refrigerated, and frozen storage needs	4	3, 5
Menu Development and Galley Procedures	Food preparation equipment	Modify appropriate gourmet home appliances for use in hypogravity	3	3, 5
		Design, fabricate and build preparation equipment that is not available as COTS	2	3, 5
	Recipes utilizing processed ingredients, fresh foods, and resupply items	Develop recipes and preparation procedures that will provide a nutritionally complete menu with adequate variety and acceptability for duration of mission	3	3, 5
	Stowage compartments of prepared menu items	Determine volume of ambient, refrigerated, and frozen storage needs	3	3, 5

Food Provisioning and Management Figures of Merit

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Stored ready-to-eat foods shelf life	Safety and quality maintenance	Years
Percent of expendable mass within food system	Expendable mass (e.g., food packaging) needs to be disposed of	%
Stored raw commodity shelf life	Safety and functionality maintenance	Years
Number of food processing pieces of equipment to TRL 6	Processing of raw commodities (stored or harvested)	Quantity
Number of food preparation pieces of equipment to TRL 6	For galley preparation of meals	Quantity
Number of recipes utilizing crops and bulk commodities	To provide adequate nutrition to the crew	Quantity

Biomass Production



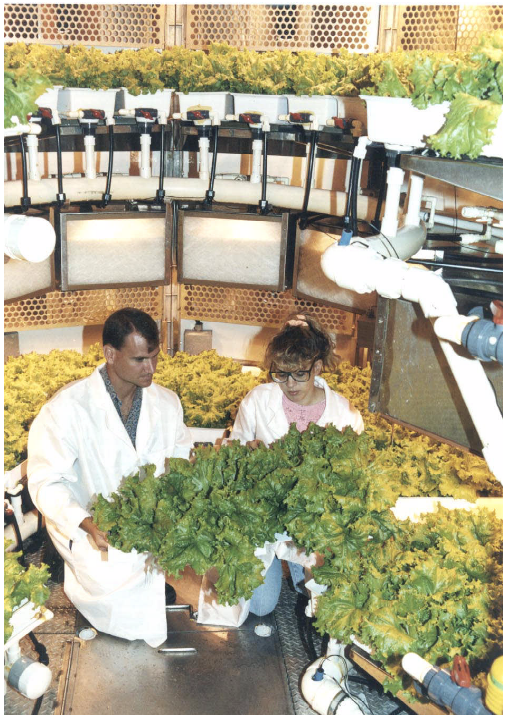
Biomass Production Description

Production of Fresh Food Supplements for Transit

Operate and maintain a transit crop production system to provide:
1) fresh vegetables to supplement the crew diet, and
2) psychological benefits.

Production of Fresh Food Supplements for Planetary Surface

Operate and maintain a surface crop production system (CPS) to provide fresh crop foods for 10% of crew's diet. The unit would also provide 20% of the crew's O_2 needs and 20% of the CO_2 removal.



Bioregenerative Life Support

Expanded or multiple CPS units to provide 25% of the diet and 50% of atmospheric regeneration.

Assess alternative biomass production technologies such as algae, aquaculture, etc.

Biomass Production Benefits

- **Crops produce a continuous supply of fresh foods that can supplement the crew's diet.**
  - **Color, flavor, and variety in the diet**
  - **Bio-available nutrients and antioxidants**

- **Living plants provide a positive influence on crew well-being and performance.**
- **Crops contribute to CO_2 reduction, O_2 production, and water purification, thereby unloading other ECLSS components.**
- **Bioregenerative systems with crops or other photosynthetic organisms provide the only means for achieving a high level of mission (life support) autonomy.**

Biomass Production
Current State-of-the-Art

Advanced Planning & Integration Office

- **Earth-Based Systems**
  - **Terrestrial greenhouses are used for crop production but are not constrained by energy, mass, volume, pressure difference, radiation, and gravity.**

- **Space-Based Systems**
  - **Short-duration experiments have been carried out on Shuttle and ISS, but we know little about operating sustained crop production systems in space.**

    Current small plant chambers* include:
    - **SVET (Russian) (lost with Mir)**
    - **Lada (Russian)**
    - **PGBA (Plant Generic Bioprocessing Apparatus)**
    - **Advanced Astroculture**
    - **PGF (Plant Growth Facility)**
    - **BPS (Biomass Production System)**
    - **CPBF (Commercial Plant Biotechnology Facility) (not flown)**

  - **Component technology challenges include:**
    - **Energy efficient lighting**
    - **Reliable water / nutrient delivery systems for μ- and fractional g.**
    - **Thorough understanding of crop responses to space environments.**
    - **Appropriate species and cultivars for space.**
    - **Mechanized and/or automated approaches to reduce crew time.**
    - **Demonstrated capability to sustain production over mission durations.**

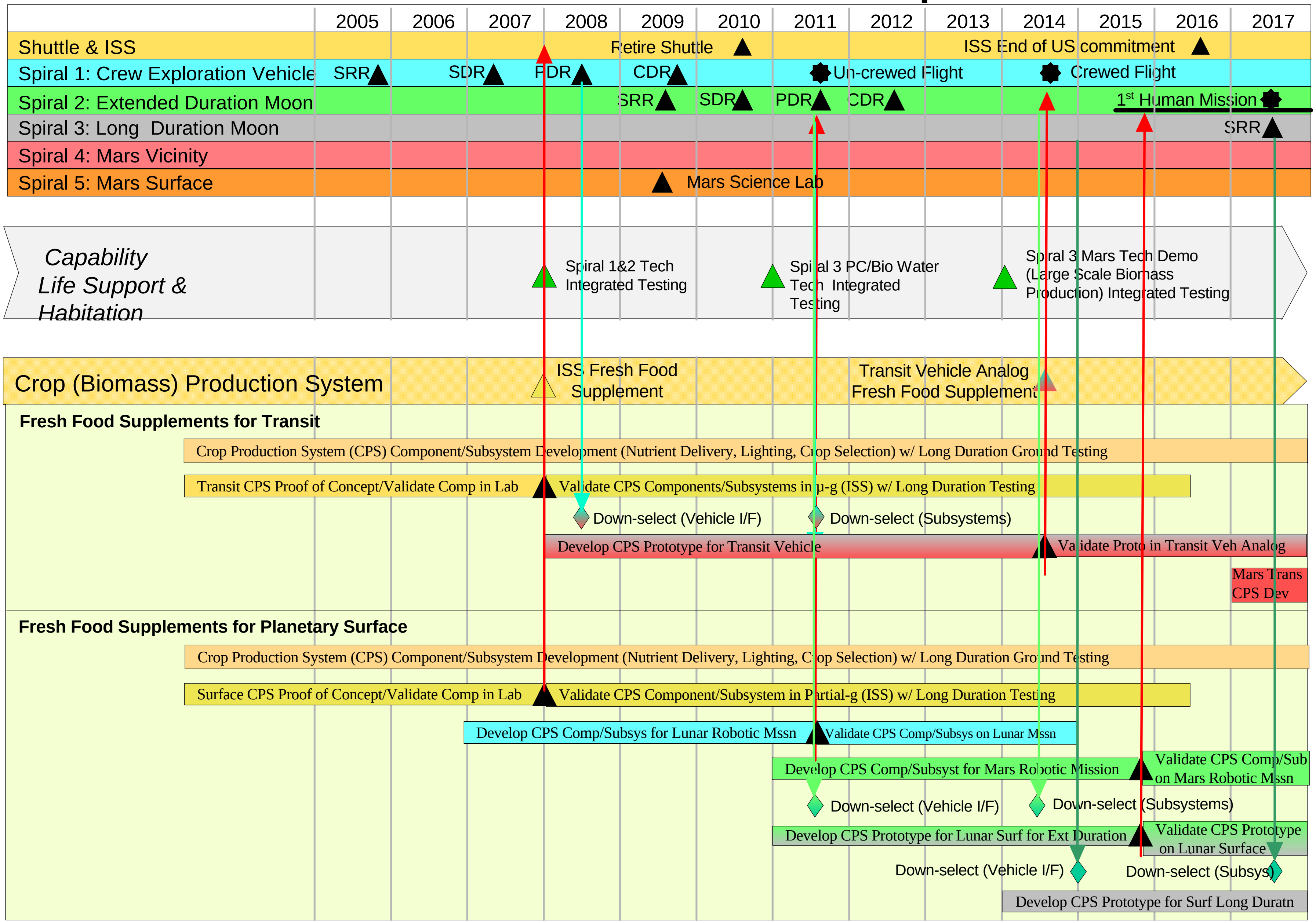
** All of these systems provide less than 0.25 m^2 growing area, and most < 0.1 m^2.*

Biomass Production Requirements /Assumptions

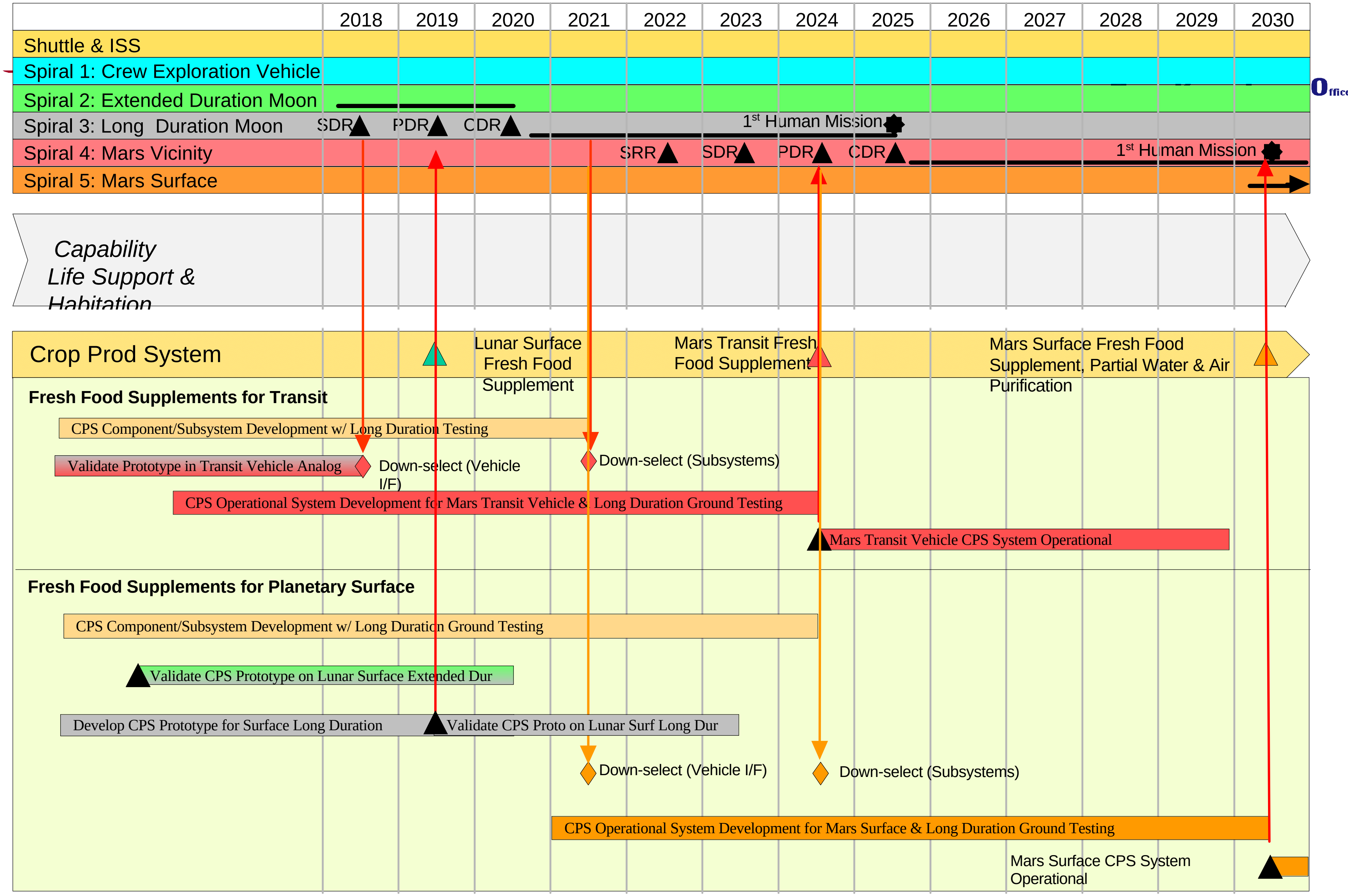
- Assumptions that drove the need for the capability
  - Continuous need for fresh foods in the crew's diet.
  - Positive effects of living plants on crew well-being and performance.
  - Eventual need to rely on bioregenerative technologies for food, air, and water regeneration for true mission autonomy.
  - ISS can be used for component testing of transit technologies.

- Crop (biomass) production technologies are appropriate for the following missions:
  - Spiral 1 (Robotic Lunar Mission Payload), test regolith, remote operations, and materials for plant growth chambers.
  - Spiral 2 (Robotic Mars Mission Payload), test regolith, remote operations, materials, and pre-deploy potential for surface crop production system.
  - Spiral 3 (Long-Duration Lunar), validation of planetary surface crop production system.
  - Spiral 4 (Mars Vicinity - Transit), operational m–g crop production system.
  - Spiral 5 (Mars Surface), operational planetary surface crop production system. Expansion of bioregenerative life support capability.

Biomass Production Roadmap



Biomass Production Roadmap



Biomass Production
Maturity Level – Capabilities

Advanced Planning & Integration Office

Mission	Capability (Level 4 CBS)	Leading Capability Candidates	CRL	Date Needed
Spiral 1	**Robotic Lunar Mission Payload (CPS Component Testing)**	**Integration with Lunar Surface Lander Mission**		**2008**
Spiral 2 Extended Duration Lunar Surface	**Robotic Mars Mission Payload (CPS Component Testing)**	**Integration with Mars Surface Lander Mission**		**2010**
Spiral 3 Long Duration Lunar Surface	**Production of Fresh Food for Surface (Prototype CPS)**	**• CPS Inside the Lander • CPS Attached to Lander • CPS Deployed on Surface**	**2 1 1**	**2014**
Spiral 4 Mars Vicinity	**Production of Fresh Food for Transit (Operational VPU)**	**Closed, fixed-volume chamber Open, fixed-volume chamber Open, expandable volume chamber Open, conveyor system**	**3 4 2 2**	**2019**
Spiral 5 Initial Mission Mars Surface	**Production of Fresh Food for Surface (Operational CPS) Bioregenerative Integrated Crop Production System (ICPS)**	**• CPS Inside the Lander, Electric or Solar Lighting • CPS Attached to Hab Module, Electric or Solar Light • CPS Deployed on Surface, Electric or Solar Lighting • Multiple CPS Modules**	**• 2 • 1 • 1 • 1**	**• 2024 • 2024**

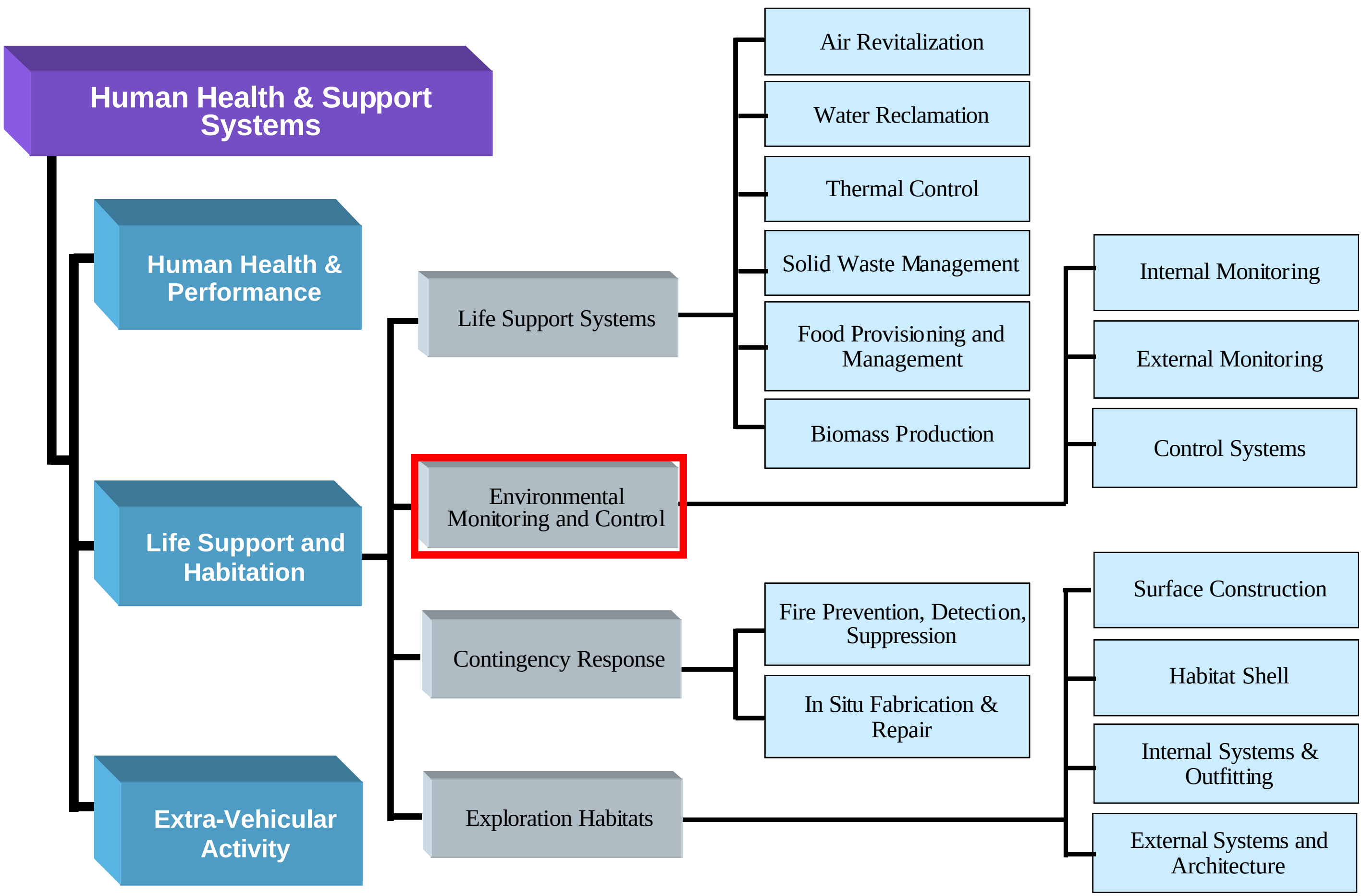
Biomass Production
Maturity Level – Technologies

Mission	Capability (Level 4 CBS)	Leading Technology Candidates	Current TRL	Date Needed (TRL 6)
Spiral 1	**Robotic Lunar Mission Payload (CPS Component Testing)**	**Transparent materials Regolith for crop rooting Remote operations**		**2008**
Spiral 2 Extended Duration Lunar Surface	**Robotic Mars Mission Payload (CPS Component Testing)**	**Transparent materials Regolith for crop rooting Remote operations Predeployment potential**		**2010**
Spiral 3 Long Duration Lunar Surface	**Production of Fresh Food for Surface (Prototype CPS)**	**• LEDs and μ-wave sulfur lamps lighting • Surface solar collectors and light conduits • Recirculating hydroponics • Salad and staple crop cultivars**	**3 2 3**	**2014**
Spiral 4 Mars Vicinity	**Production of Fresh Food for Transit (Operational Transit CPS)**	**LEDs for lighting Transit solar collectors and light conduits Porous tube watering with or without media Dwarf salad crop cultivars**	**4 2 4 2**	**2019**
Spiral 5 Initial Mission Mars Surface	**Production of Fresh Food for Surface (Operational Surface CPS) • Bioregenerative Integrated Crop Production System (ICPS)**	**• LEDs and μ-wave sulfur lamps lighting • Surface solar collectors and light conduits • Recirculating hydroponics • Salad and staple crop cultivars • Mechanized / automated planting and harvesting • Integrated crop / water system • Integrated crop / air system**	**• 2 • 1 • 2 • 2 • 1 • 2 • 2**	**• 2024**

Biomass Production Figures of Merit

Mission	Capability (Level 4 CBS)	Figures of Merit				
		Description	Units	+/-	Current Level	Required Level
Spiral 1 **Lunar Capable Low Earth Orbit CEV**	**Robotic Lunar Mission Payload**	**ESM**	**kg**			
Spiral 2 **Extended Duration Lunar Surface**	**Robotic Mars Mission Payload**	**ESM**	**kg**			
Spiral 3 **Long Duration Lunar Surface**	**Prototype of Planetary Surface Crop Production System (CPS)**	**ESM Edible Productivity Biomass / Unit Energy Efficiency Elec. Lamps**	**kg g m^{-2} d^{-1} g MJ^{-1} %**			
Spiral 4 **Mars Vicinity**	**Operational Vegetable Production Unit (VPU) for Transit**	**ESM Edible Productivity Biomass / Unit Energy Efficiency Elec. Lamps Eff. Solar Collectors**	**kg g m^{-2} d^{-1} g MJ^{-1} % %**		**-- 7 g m^{-2} d^{-1} 0.4 g MJ^{-1} 20% 30%**	**-- 5 g m^{-2} d^{-1} 0.3 g MJ^{-1} 30% 40%**
Spiral 5 Initial Mission Mars Surface	• **Operational Crop Production System (CPS) for Surface**	**ESM Edible Productivity Biomass / Unit Energy Efficiency Elec. Lamps Eff. Solar Collectors**	**kg g m^{-2} d^{-1} g MJ^{-1} % %**		**• -- • 12 g m^{-2} d^{-1} • 0.4 g MJ^{-1} • 20 % • 30 %**	**• -- 25 g m^{-2} d^{-1} • 1.0 g MJ^{-1} • 40 % • 50%**
	• **Bioregenerative Integrated Crop Production System (ICPS)**	**ESM Edible Productivity Biomass / Energy**	**kg g m^{-2} d^{-1} g MJ^{-1}**		**• -- • 12 g m^{-2} d^{-1} • 0.4 g MJ^{-1}**	**• -- 25 g m^{-2} d^{-1} • 1.0 g MJ^{-1}**

Environmental Monitoring & Control



Environmental Monitoring & Control Description

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- Monitor the Internal environment
  - In a closed environment, trace chemicals can build up
    - Like sick building syndrome, but worse--crew cannot go outside for fresh air
  - Indicators of equipment status
    - For example, a malfunction in air processing may be indicated by a tiny methane leak: not toxic, but the malfunction is hazardous
- Monitor the External environment
  - Look for leaks and other indications of problems
  - Verify that areas such as airlocks are adequately free of lunar or martian dust
  - Monitor for TBD surface environment hazards
- System Integration & Control to reliably and efficiently maintain a safe environment
  - Ground control must play a lesser role since future missions will have long time delays in communications with Earth.
  - Maintaining a large support team 24/7 is expensive, just as it is in manufacturing and other industry
  - Large crew to continuously operate systems is not affordable

Environmental Monitoring & Control Benefits

Advanced Planning & Integration Office

- Environmental monitoring needed to
  - Detect trace buildup so that countermeasures are implemented before it becomes hazardous
    - Closed loop life support has potential for gradual chemical buildup
  - Detect hazardous events rapidly
    - Events such as spills and leaks can be especially hazardous in the closed environment
    - Many events have proven to be unpredictable, so identification and quantification of unknowns is important
  - Must be done in flight since sample return not feasible
- System Integration & Control benefits:
  - Automation of many processes reduces crew and ground support needs
  - Efficient use of resources: mass, volume, power,…
  - Efficient and safe recovery from environmental perturbations
  - Stable, reliable operation
  - Assistance in predicting, diagnosing, and solving problems

Environmental Monitoring & Control Current State-of-the-Art

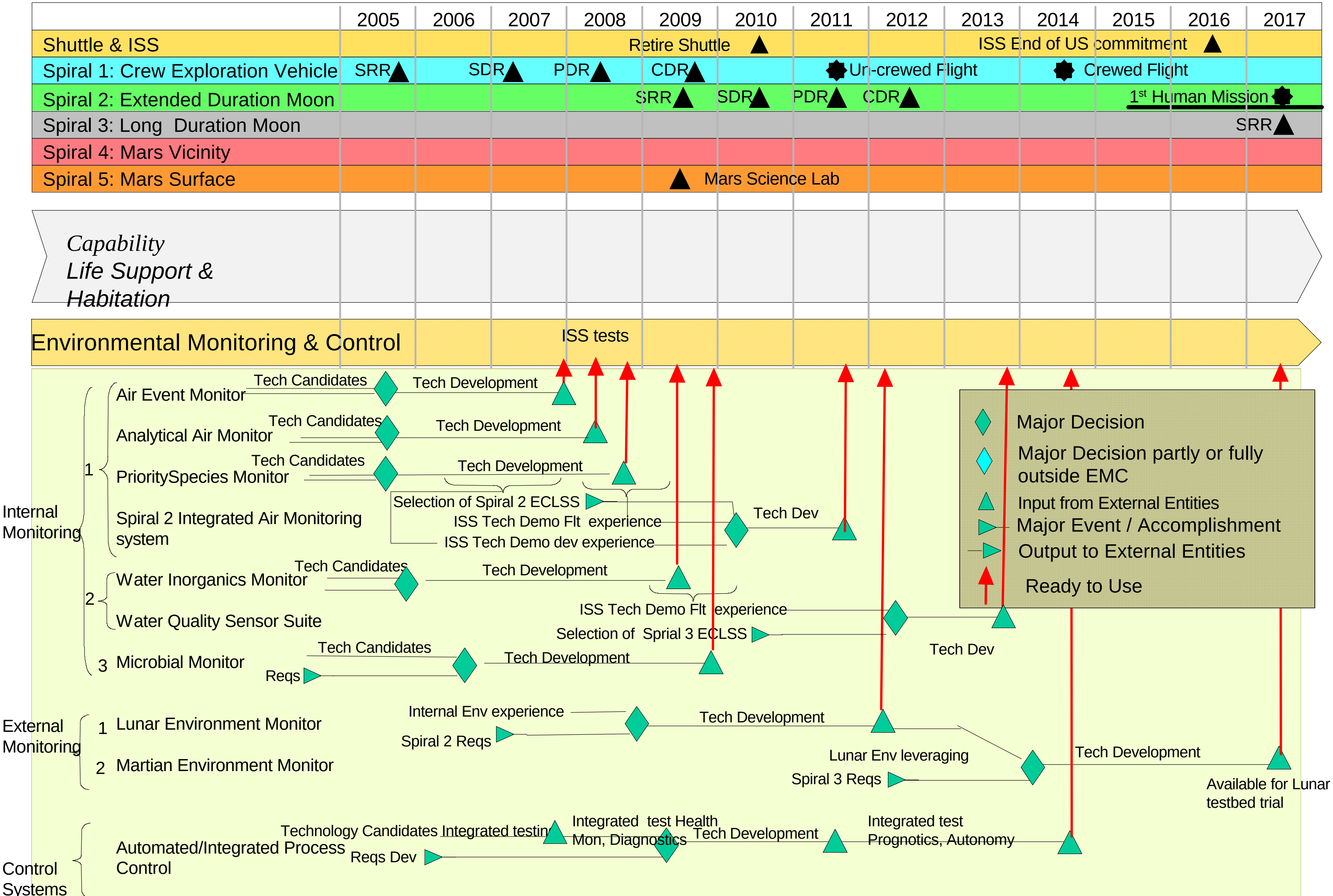
Advanced Planning & Integration Office

- SOA in flight (Space Station):
  - Volatile Organic Analyzer: Gas Chromatograph/Ion Mobility Spectrometer, has been nonfunctional for several months
  - Major Constituent Analyzer: Magnetic Sector Mass Spectrometer, has been serviced
  - Compound Specific Analyzer/Combustion Products: handheld commercial device
  - Russian monitoring devices of unknown technology
  - Simple thresholding process control
- Ground SOA Monitoring technologies
  - Laboratory benchtop instruments: Highly capable, but
    - Still relatively high in mass & power requirements
    - Require considerable training, regular calibration, consumables
    - Often require gravity to operate
  - Industrial monitors
    - Usually not sensitive enough for NASA purposes
    - Limited to a few targets, so that many devices are needed to cover the dozens of targets required by NASA
- Ground SOA Industrial Control
  - Steady state, vs NASA needs which are dynamic
  - Input/output vs closed loop life support

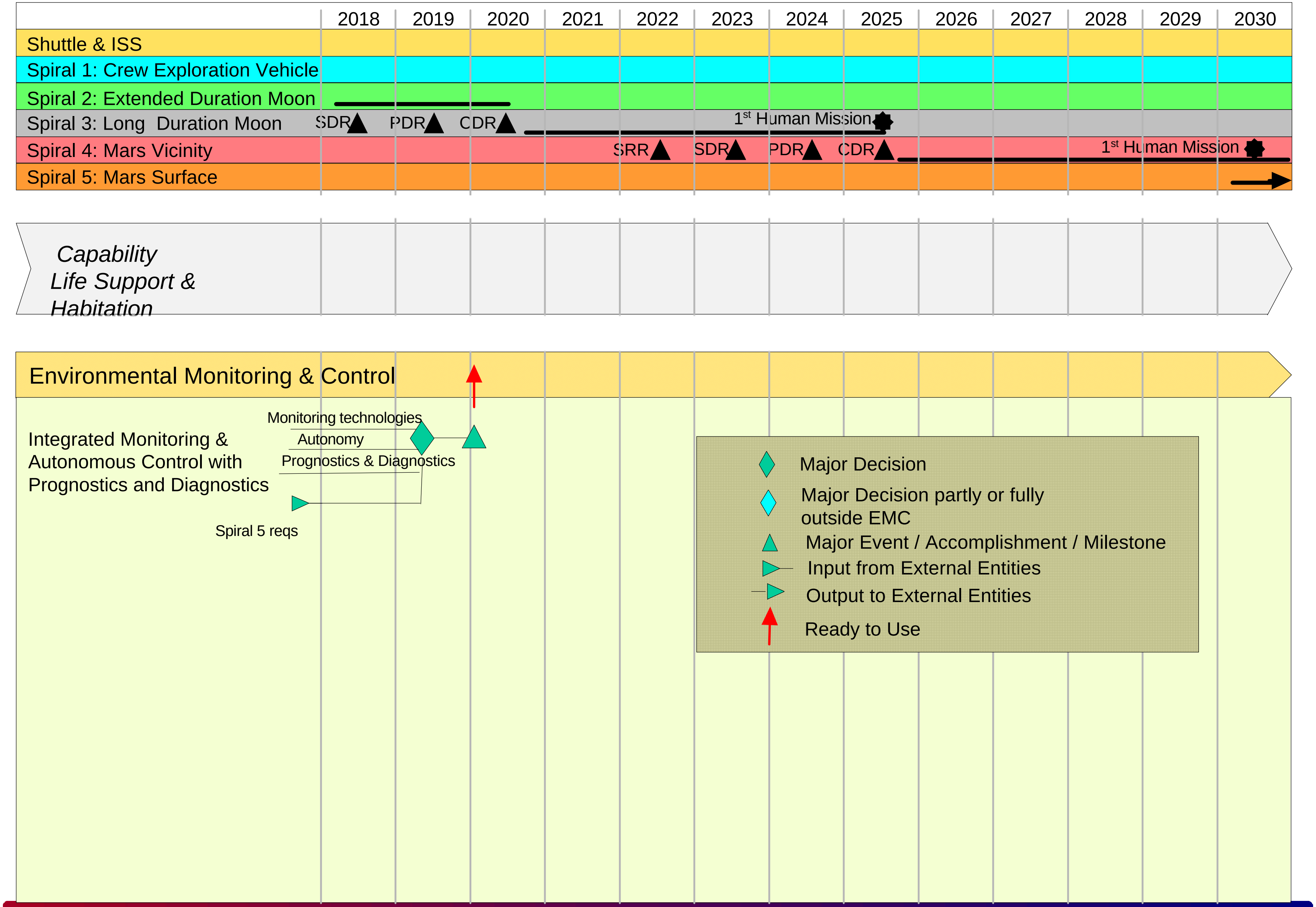
Environmental Monitoring & Control Requirements /Assumptions

- All crewed missions require environmental monitoring
  - The shortest missions may need as little as grab sample bottles for later ground analysis
  - The longer the mission, the greater the complexity and number of failure modes, and the greater the monitoring needs
  - Regenerated water quality should be tested before consumption
    - Realtime analysis to avoid need to carry days of stored water while waiting for water test results
  - Regeneration of water and air may have contamination issues which have not yet been seen
    - Chemical buildup, microbial growth
- Process control
  - Offers assistance in diagnosis/prognostics in shorter missions
  - Is crucial for longer missions using closed loop life support
  - Health monitoring with process control helps identify failures earlier, before they become more serious, and can reduce downtime

Environmental Monitoring & Control Roadmap



Environmental Monitoring & Control Roadmap



Environmental Monitoring & Control Maturity Level – Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Event monitoring Air analysis non-realtime	Detection of Hg and SO_2, other gases doable Grab sample bottle technology in use	1-5 7
Spiral 2 Lunar Surface (2011)	Event monitoring Water inorganics monitor Integrated realtime air monitoring Lunar Environment monitor	Same as above Flight hardware addressing micro-G operation Reliability of chemical analyzer Requirements, lunar surface operation	1-5 3 3 1
Spiral 3 Long Duration Lunar Surface (2014)	Event monitoring Integrated realtime air analysis Water quality suite Lunar Environment Monitor Autonomous Integrated Process Control	Same as above Same as above Organics analysis Above plus tests of simulated Martian conditions if possible Assisted diagnostics and operation	1-5 3 2 1 1
Spiral 4 Mars Vicinity (2017)	As above, tailored to Mars mission Longer communication lags	As above, tailored to Mars mission More autonomous operation	As above
Spiral 5 Initial Mission Mars Surface (2021)	• As above, tailored to Mars surface mission –Martian environment	• As above, tailored to Mars surface mission •Chemically reactive dust	As above

Environmental Monitoring & Control Maturity Level – Technologies

Advanced Planning & Integration Office

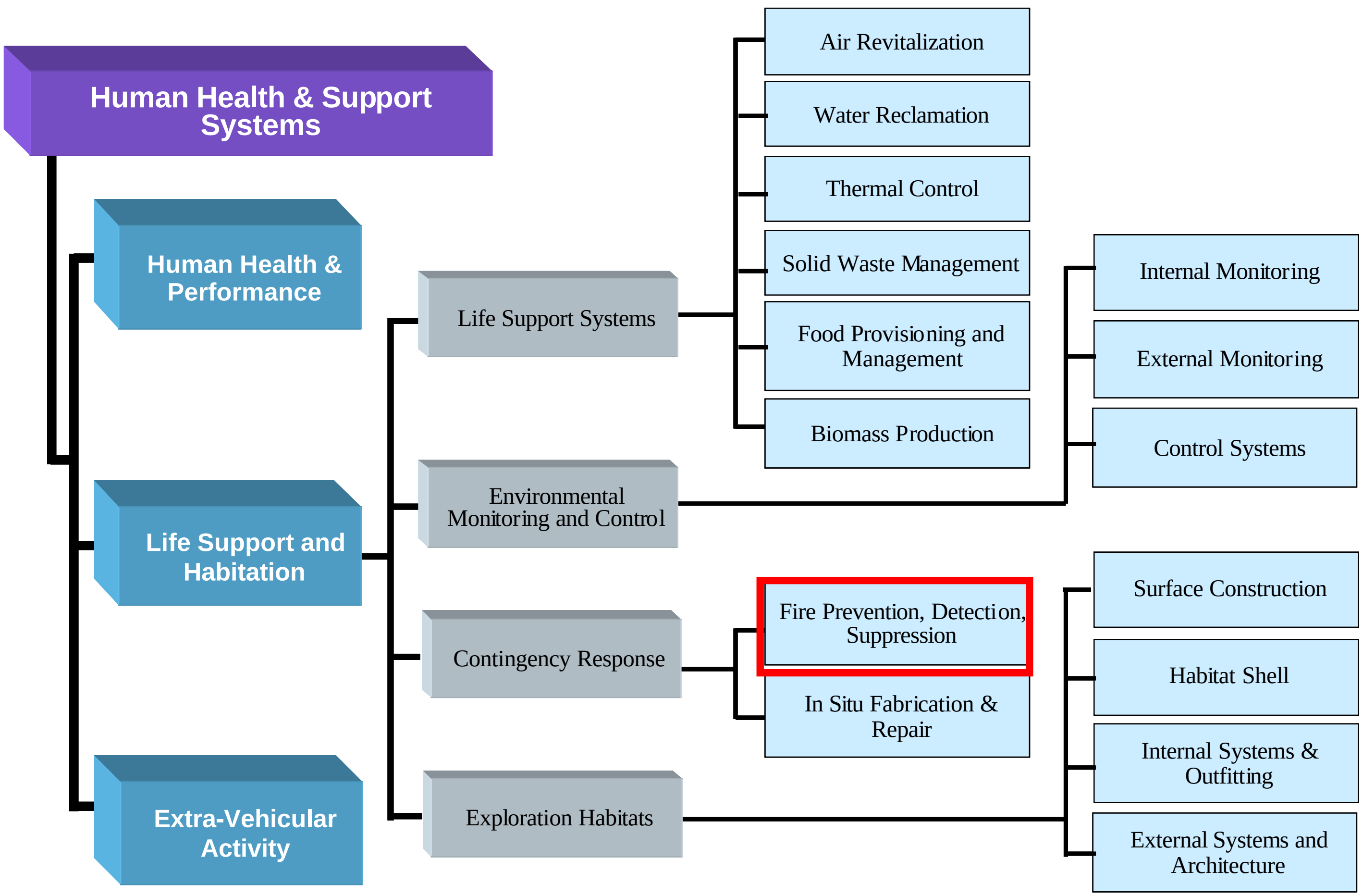
Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Development Needed	Current TRL	Spiral(s)
Event monitoring	Electronic Nose	Additional target gases	5	1-5
Integrated realtime air analysis	GCMS FTIR GCIMS TDL, to be used with one of the above	Test in relevant environment Flight testing Reliability MWIR laser development	3 5 6 3	2-5 3-5 2-5 1-5
Water quality suite	CSPE Microfluidic ion analyzer	Micro-G functionality Lab demo	4 3	3-5 3-5
Lunar, Martian Environmental Monitoring	TBD	TBD	1	3-5
Autonomous Integrated Process Control	Integrated system modeling, system design, and process control Diagnostics and Prognostics Autonomous operation	System models and designs coordinated with control needs	1 1	3-5 3-5

Environmental Monitoring & Control Figures of Merit

Advanced Planning & Integration Office

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Event monitoring Integrated realtime air analysis Water quality suite Lunar Environment Monitor	% priority targets measured Number of targets/resource demands Mean Time Between Failure Mean Time Between Maintenance	% #targets/mass months months
Autonomous Integrated Process Control	Reduced Number of human interactions Reduced resource req'ts Reduced downtime Reduced time to detect fault	#events or hours Mass, power Time Time

Fire Prevention, Detection, & Suppression (FPDS)



Fire Prevention, Detection, and Suppression Description & Introduction

Advanced Planning & Integration Office

Critical Issue

Fire in spacecraft is classified as a catastrophic risk.
The risk of fires in crew spacecraft and habitats cannot be eliminated.
The FPDS element seeks to quantify and minimize the risk (both probability and severity).

Scope

- *Materials* must be selected throughout system design and operation stages to minimize the probability of a fire
  - Material flammability acceptance criteria
- Atmosphere selection is a trade-off between material flammability, EVA constraints, and hypoxic limits
  - Ignition, heat release rates, and flammability limits in candidate atmospheres
- Detection of a fire event must be accurate, timely and location-specific
  - Network of appropriate sensors and associated fire detection logic
  - Knowledge of fire signatures in low- and partial gravity
- A robust means to suppress a fire event must be available and compatible with vehicle design
  - Effectiveness of suppressants and delivery method in low and partial gravity
  - Mitigation of post-fire toxic by-products and collateral damage; minimize impact to crew, system, and mission

Benefits of Fire Prevention, Detection, and Suppression

Advanced Planning & Integration Office

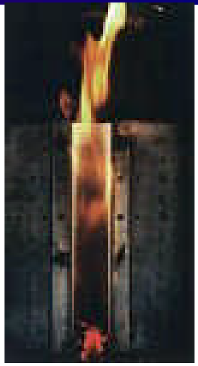
- Increase the probability of continuing the mission in the event of fire
  - Systematically reduce risk and severity of fire
  - Minimize impact of a fire on the crew, equipment, and mission
- Reduction in vehicle mass through appropriate selection/evaluation of materials
  - Use of COTS hardware typically requires application of fire breaks to pass flammability tests
  - Use reduced mass components where appropriate as determined by quantifiable flammability/risk assessment
- Significantly reduce false positive (nuisance) alarms
  - Susceptibility of ISS smoke detectors to dust requires unnecessary crew action and reduces confidence
- Reduction in suppressant system mass and amount of suppressant dispersed during fire response
  - Reduction of suppressant discharged reduces the impact on the crew and consumables required for clean-up/recovery
- Increased efficiency of fire response through simulation of realistic fire scenarios and crew training

Current State-of-the-Art for FPDS

- **NASA-STD-6001: Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion**
  - **Test 1: Upward Flame Spread Test**
- **Smoke Detectors**
  - **STS: ionization**
  - **ISS RS and FGB: ionization**
  - **ISS US: photoelectric**
- **Fire Extinguishers**
  - **STS: Fixed and portable Halon**
  - **ISS US: CO_2**
  - **ISS RS: Water-based foam**

➢ All existing technology and requirements are based on 1-g fire behavior

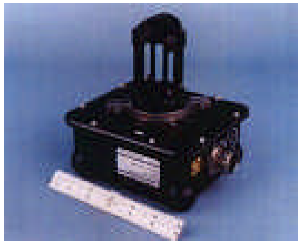
➢ Effectiveness in low-g is unproven as evidenced by the inconsistent approaches



Sample failing NASA-STD-6001: Test 1

STS SD

FGB SD



US SD

SM SD

US CO_2 fire extinguisher

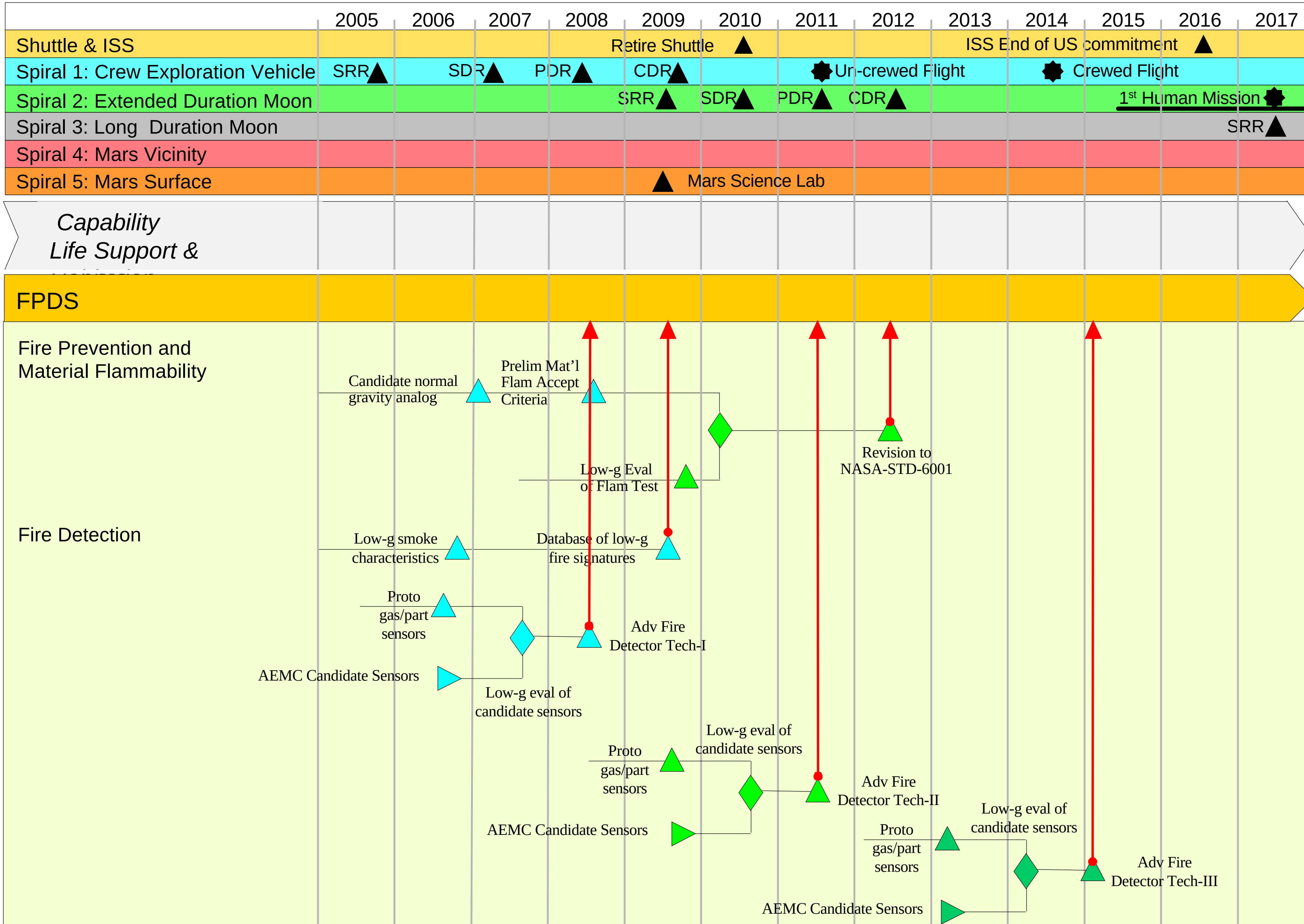
Requirements/Assumptions for Fire Prevention, Detection, and Suppression

Advanced Planning & Integration Office

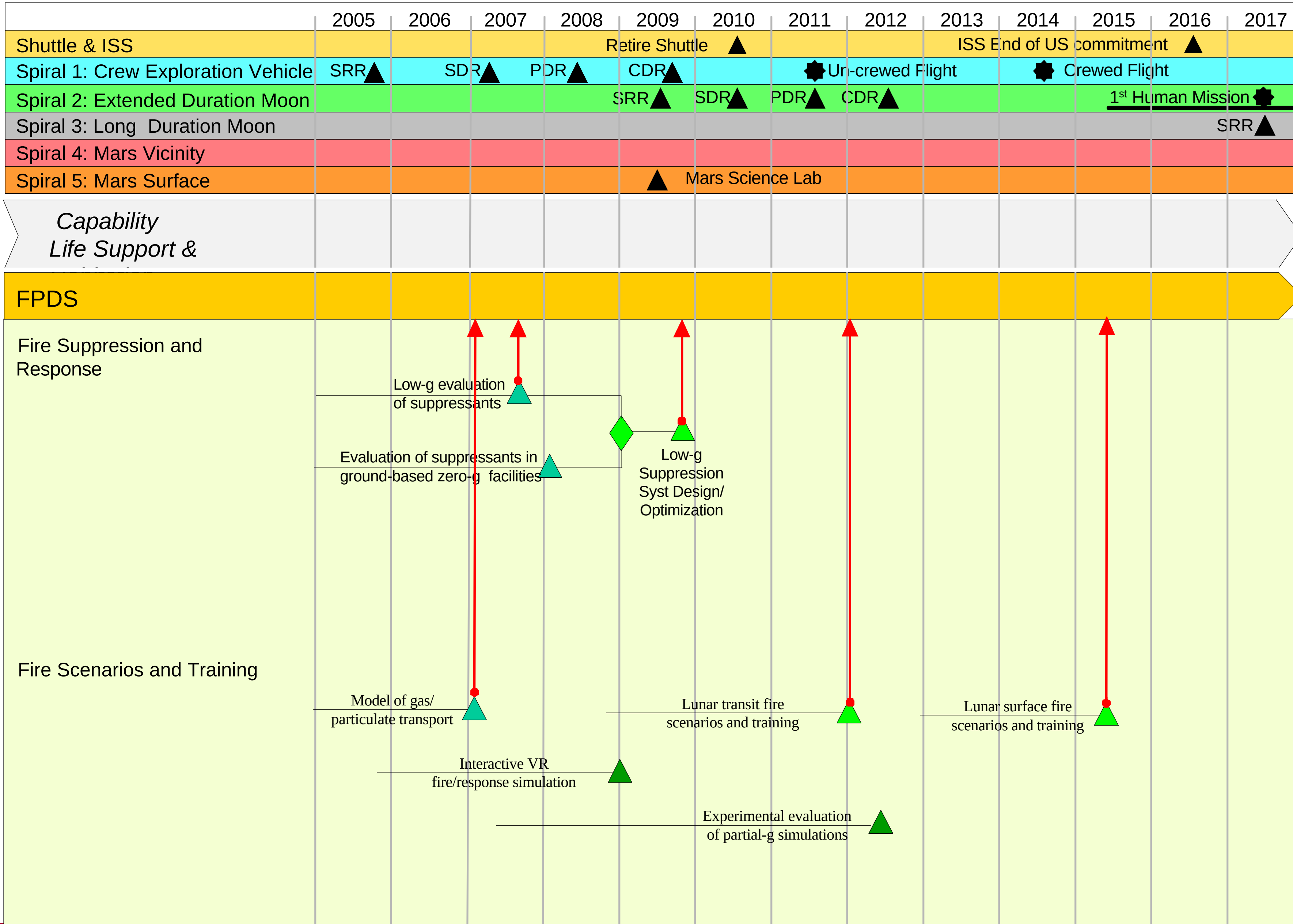
- **FPDS capability is driven by the mission requirements of all spirals**
  - **Fire Prevention and Material Flammability**
    - Selection of atmosphere for habitable volumes
    - Flammability in partial gravity (Spirals 3, 5: Lunar and Martian habitats) is different than zero-gravity (Spirals 1-5: transit vehicles)
  - **Fire Detection**
    - Driven by experience on ISS
      - Nuisance alarms caused by dust
    - Detectors must be sensitive to appropriate pre-fire and fire signatures
      - Will vary with materials used, atmosphere and gravity level
  - **Fire Suppression and Response**
    - Selection of a suppressant and definition of response strategy will change with gravity level and habitable atmosphere

- **Additional Assumptions**
  - **Habitable atmosphere will be the same for all spirals and different than ISS/STS**
    - If not, material assessment/selection and design criteria for fire detection and suppression systems must be re-evaluated for each spiral

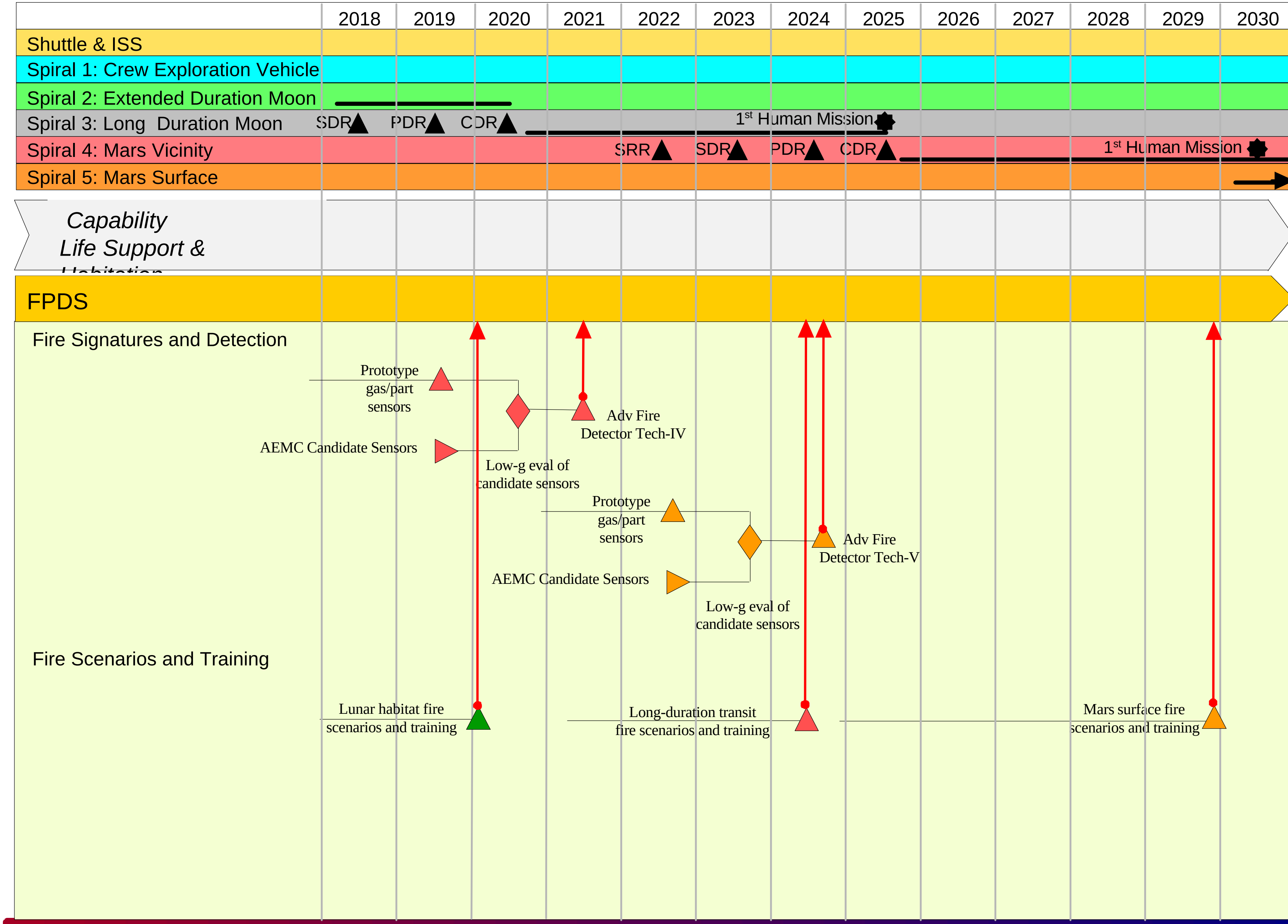
Fire Prevention Detection & Suppression Roadmap



Fire Prevention Detection & Suppression Roadmap



FPDS Road Map



Maturity Level – Fire Prevention, Detection, and Suppression

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	• Fire Prevention and Material Flammability • Fire Signatures and Detection • Fire Suppression and Response • Fire Scenarios and Training	Low-gravity material flammability acceptance criteria Advanced fire detection system Fire signatures in reduced gravity Verified models of fire precursor/contaminant transport in low gravity Design rules for reduced gravity fire suppression system	2 4 2 3 3
Spiral 2 Lunar Surface (2011)	Same as Spiral 1	Evaluation of material flammability relevant for partial gravity Assessment of material flammability in CEV atmosphere • Advanced fire detection system (assessment and implementation of future sensor technology) Evaluation of fire suppression in partial gravity	1 3 2 2
Spiral 3 Long Duration Lunar Surface (2014)	Same as Spiral 1	• Advanced fire detection system (assessment and implementation of future sensor technology)	1
Spiral 4 Mars Vicinity (2017)	Same as Spiral 1	Same as Spiral 3	1
Spiral 5 Initial Mission Mars Surface (2021)	Same as Spiral 1	Same as Spiral 3	1 1

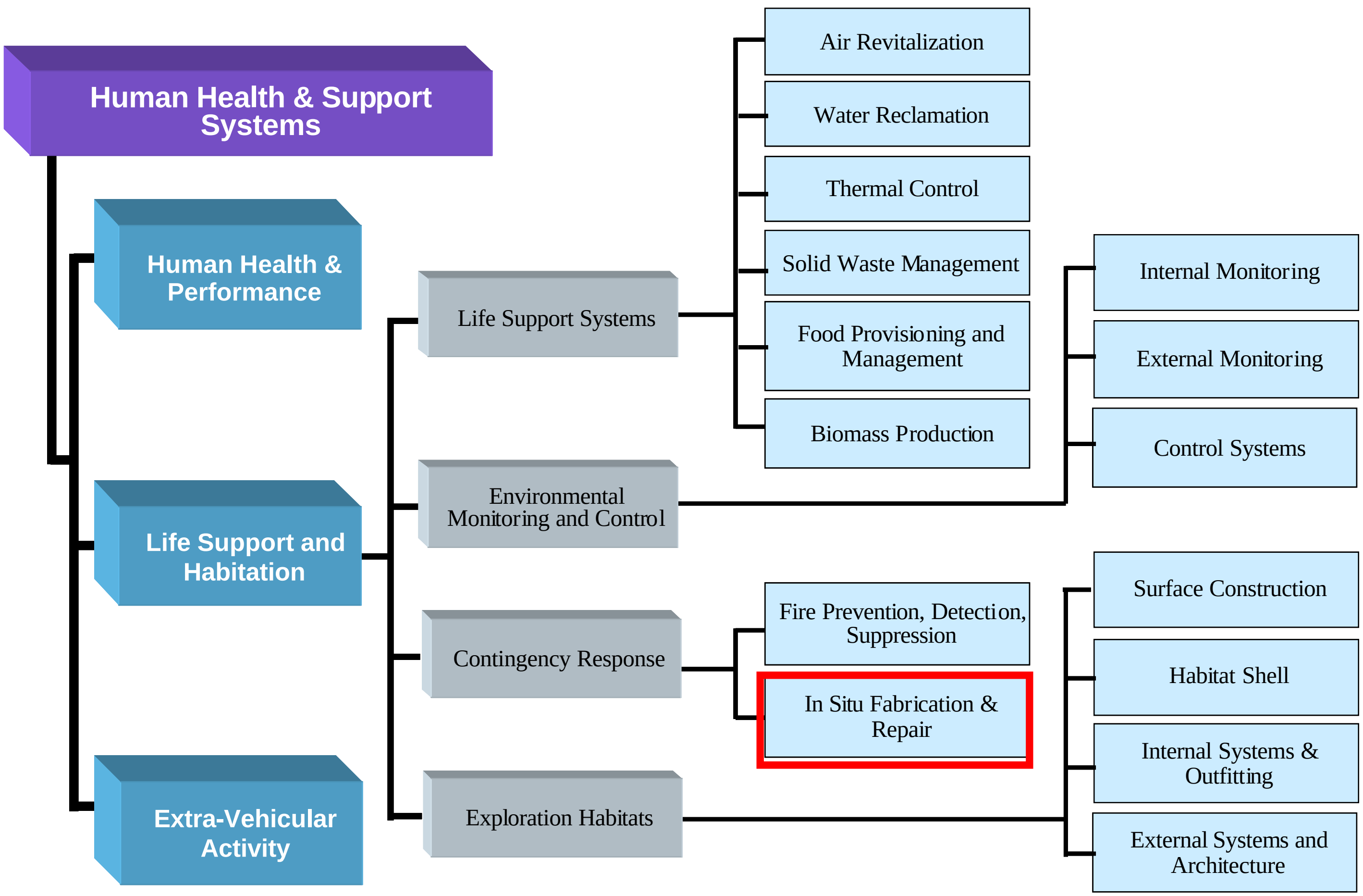
Maturity Level – Technologies
Fire Prevention, Detection, & Suppression

Capability (Level 5 CBS)	Leading Technology Candidates	TRL	Products (Spirals Needed)
Fire Prevention and Material Flammability	**Low-stretch scaling of ignition delay, mass loss rate, heat release, production of toxic products**	**2**	**Low gravity material flammability acceptance criteria (Spirals 2-5)**
	Flight hardware to validate scaling of ignition delay, flame spread, heat release, and release of toxic products (FEANICS/Combustion Integrated Rack (CIR)	**6**	
	Normal gravity analog for reduced gravity flammability	**2**	
Fire Signatures and Detection	**MEMS chemical sensors for species measurements**	**4**	**Fire signatures in reduced gravity (Spirals 2-5)** **Advanced fire detector and detection logic Verified models of fire precursor transport in low gravity (Spirals 1-5)**
	Electronic nose technology for detection of pre-fire signatures	**4**	
	Particulate sensors and size classifiers	**3**	
	Database of reduced gravity fire signatures	**3**	
	Flight hardware to quantify reduced gravity signatures of pre-fire particulate (Smoke Aerosol Measurement Experiment)	**6**	
Fire Suppression and Response	**Low-gravity evaluation of candidate fire suppressants**	**3**	**Design rules for reduced gravity fire suppression system (Spirals 1-5)**
	Flight hardware for initial screening of effectiveness of fire suppressants (Flame Extinguishment Experiment/CIR)	**6**	
Fire Scenarios and Training	**Simulation of relevant fire scenarios in a low-g habitable volume**	**4**	• **Simulation and evaluation of relevant fire scenarios** • **Realistic crew training modules (Spirals 2-5)**
	Realistic visualization of fire/smoke transport	**2**	
	Development of fire response training module	**2**	

Metrics
Fire Prevention, Detection, & Suppression

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Fire Prevention and Material Flammability	Reduce mass Decrease risk of fire	kg %
Fire Signatures and Detection	Reduce mass Reduce power Reduce detection time	kg W sec
Fire Suppression	Reduce system mass Reduce suppressant mass released Reduce response time Reduce consumables for clean-up/recovery	kg kg (or ppm) sec kg
Fire Scenarios and Training	Decrease risk of fire Decrease response time	% sec

In Situ Fabrication & Repair



In Situ Fabrication and Repair Capabilities

- **Multi-Material Fabrication (MMF) Capability**
  - Will utilize shop level equipment to provide a means of fabricating new or replacing existing parts, tools, components, etc.
  - Fabricated products will include various material types such as metals, plastics, ceramics and composites to fulfill requirements for all functioning elements used in the in situ equipment and habitat
  - Products include newly defined parts or tools within an element of the transport vehicle, other vehicle equipment, habitat equipment, and necessary medical products (such as syringes, needles, surgical instruments, inflatable casts, IV bags, etc.)

- **Electrical/Electronics Fabrication (EF) Capability**
  - Will utilize printed electronics techniques to provide a means of fabricating new or replace existing electronic boards and components

- **Multi-Material Repair (MMR) Capability**
  - Multi-material patching, bonding, and filling techniques will be developed to provide repair capabilities for most or all materials subject to in-situ failures
  - MMR will utilize in-situ, imported, and recycled materials as provided by a logistics support function
  - Repairs will target the inclusion of all system and element material types utilized during transport and while on extraterrestrial bodies

- **Electrical/Electronics Repair (ER) Capability**
  - Self-healing materials and metal joining techniques will be developed to provide repair capabilities for electrical/electronics materials subject to in-situ failures
  - ER capabilities will utilize in-situ, imported, and recycled materials as provided by a logistics support function

Benefits of In Situ Fabrication & Repair

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In Situ Fabrication & Repair Benefits

- In Situ Fabrication capabilities will reduce/eliminate the need for spares through the utilization of in-situ, imported, and recycled materials in the restoration of system and element functionality, thereby decreasing risk to crew and system functionality and enhancing mission safety
- Fabrication capabilities minimize mission risk due to equipment design flaws, by providing the capability to fabricate new parts, in situ, with updated design specifications (spares would be worthless in this case)
- Providing just-in-time fabrication of parts and tools to meet maintenance requirements of system failures via closed loop quality controlled solid freeform fabrication technologies, thereby reducing spare parts inventory
- In Situ Repair capabilities will reduce/eliminate the need for spares through the utilization of in-situ, imported, and recycled materials in the restoration of system and component functionality
- Repairs will minimize risk due to functional backup for critical systems and greater flexibility in recovering from failures – enabling self-sufficiency
- Repairs will utilize shop, portable, handheld, and robotic equipment to perform functions, providing portability and ease-of-use
- Autonomous robotic systems will reduce/eliminate man-in-the-loop requirements.
  - Will use available feedstocks which include materials delivered from Earth or materials produced in situ on moon/mars

Current SOA for In Situ Fabrication & Repair

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- Current SOA for Multi-Material Fabrication
  - Multiple technologies with various ranges of materials processing capabilities
  - Evolving additive techniques for solid freeform fabrication (SFF) improving yearly, with focus on multi-material & direct manufacturing
- Current SOA for Electrical/Electronics Fabrication
  - PCB manufacturing is multi-step process, steps include artwork preparation, developing, etching, cleaning, drilling, and finishing using subtractive techniques
  - Electronics/Electrical manufacturing require use of chemicals, metals, plastics, and resins
  - Discrete components are fabricated separately from PCB and attached in assembly build-up
  - Emerging technologies use additive printing techniques
  - Emerging material include flexible electronics - Flextronics
  - Emerging technologies are developing Thin Film Transistor Circuits (TFTC) using additive techniques
- Current SOA Multi-Material Repair
  - Extensive commercial, aerospace, and defense applications and adhesive materials available and in place
  - Low to extremely high temperature bonding methods possible
  - Diverse material compatibility
  - Few actual space-based toolkit single or multi-component adhesive systems applied
- Current SOA for Electrical/Electronics Repair
  - Current soldering methods include Standard Hot resistive Tip, Hot Air Station, Laser Soldering Station, COLDHEAT Soldering iron
  - Laser soldering repair stations are in current commercial use
  - Self-healing wire insulation proof of concept testing completed for embedded healing agent wire insulation repair
  - Concept development for wire repair using Shape Memory Alloys (SMA)
  - Concept development for wire insulation repair using viscous polyisobutane
  - All experimental runs of In-Space Soldering Investigation (ISSI) on ISS have been completed, to provide valuable data with return of experimental coupons on Shuttle RTF mission

Requirements / Assumptions for In Situ Fabrication & Repair

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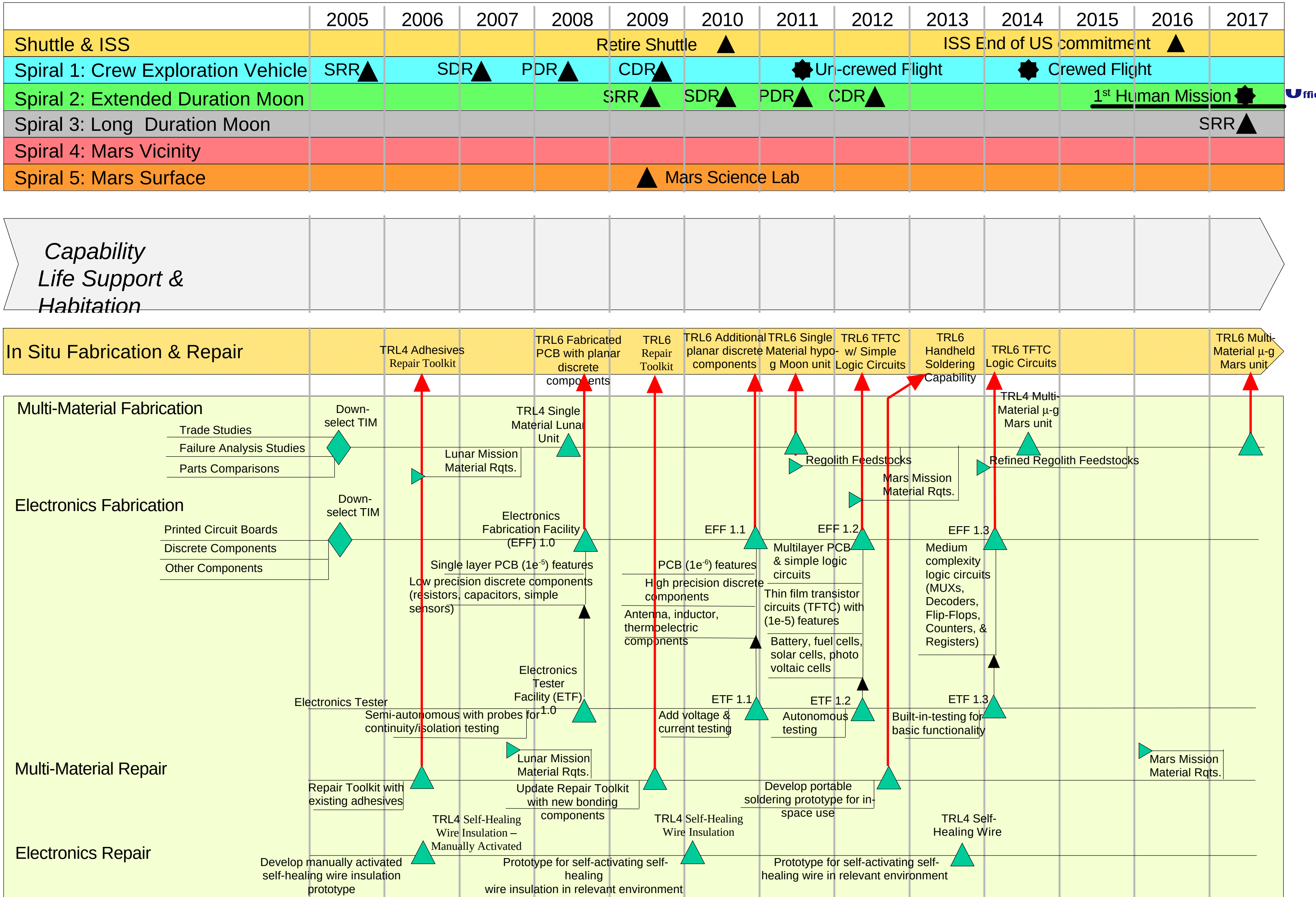
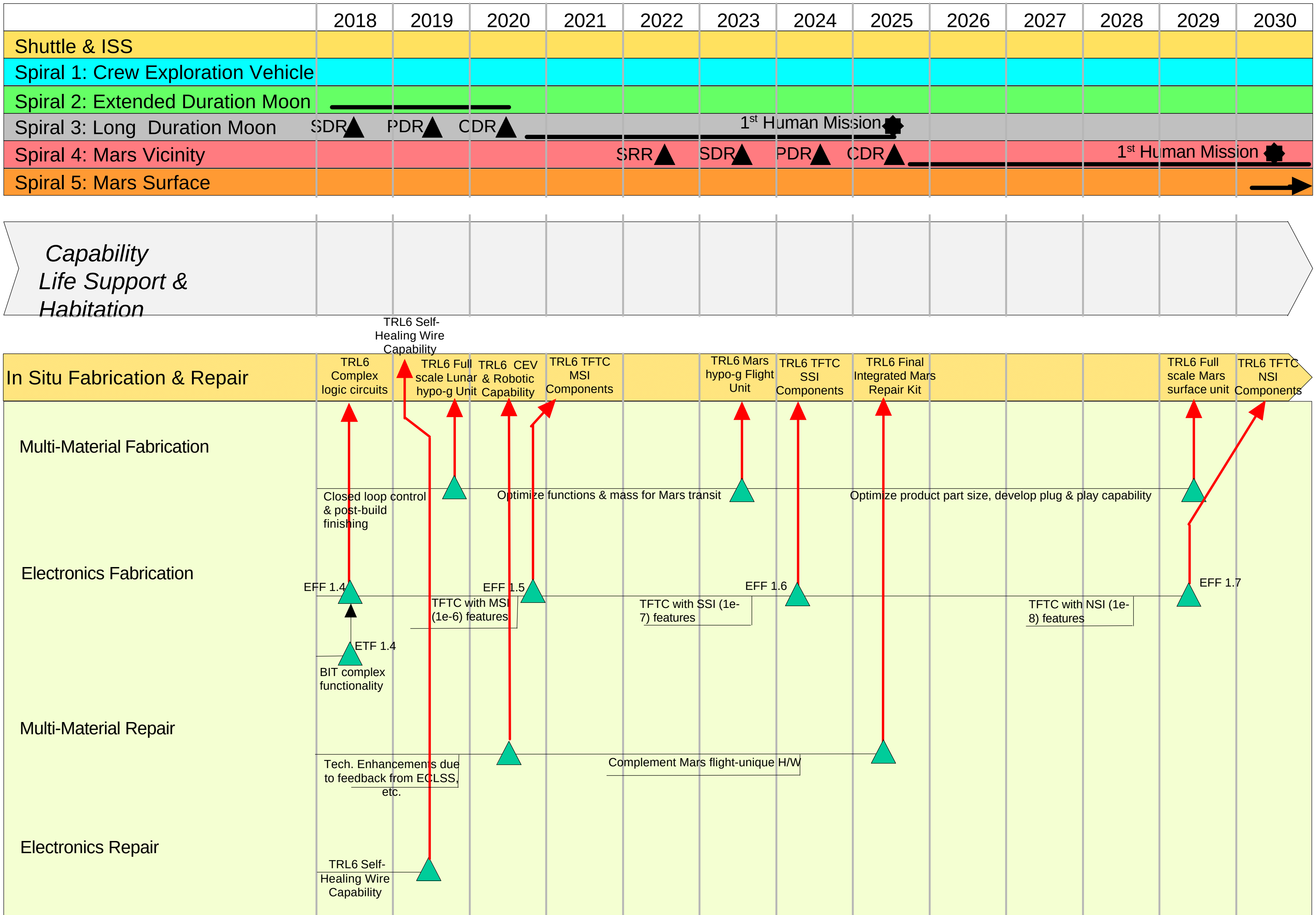
- **Design Framework/Reference Missions**
  - **Infrastructure Characteristics**
    - **Operational Gravity: Hypo-g (Lunar 1/6-g & Martian 1/3-g) for Spiral 2**
    - **Operational Gravity: Hypo-g *and Micro-g* for Spirals 3-5**
    - **Operational Environment: Cabin IVA; T=10-35C, P=10-15psia**
    - **Operating Mode:**
      - **Crew tended for Fabrication capability (exchange feedstock, transfer parts, perform parts cleaning, etc.)**
      - **Crew or robotic operation for Repair capability**
    - **System Reliability: ^{3} 95% Uptime**
    - **Power available up to 48 hours continuously to perform complete build cycle for fabrication capability**
    - **Power Requirement: TBD**
- **Additional Assumptions that drove the need for the capability**
  - **Electrical Failures comprise a high percentage of failures, based on prior mission data**
  - **Unpredicted Failures will always occur, introducing mission risk. Methods for correcting failures will always be a major factor for reducing mission risk**
  - **Crew Time will always be a premium commodity. Any autonomous repair capability will be value-added**

In Situ Fabrication & Repair Road Map



In Situ Fabrication & Repair Road Map



Maturity Level – In Situ Fabrication & Repair

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 2 Lunar Surface (2011)	Multi-Material Patching, Filling, Joining	Develop Adhesives Repair Toolkit Demo with existing adhesives for demo on ISS and/or lunar surface	4
Spiral 3 Long Duration Lunar Surface (2014)	Multi-Material Fabrication - Fabricator	Multi-material fabricator with closed loop control in hypo-g moon capability.	1
	Multi-Material Fabrication - Fabricator	Full scale lunar hypo-g flight unit with closed loop control and post-build finishing for pressurized cargo module launch to moon	1
	Multi-Material Fabrication - Fabricator	Full scale system stand alone cargo element testbed for lunar surface for independent deployment ahead of manned expedition	1
	• Multi-Material Patching, Filling, Joining	Identify, develop & apply new in-situ bonding components press & unpress areas.	1
	Multi-Material Patching, Filling, Joining	Apply learned soldering methods & technology to development of prototype portable soldering equipment for ISS	1
	Repair – Self-Healing Wire	Develop manually activated self-healing wire insulation prototype	1
Spiral 4 Mars Vicinity (2017)	Multi-Material Fabrication - Fabricator	Breadboard of Mars transit μ-g for CEV cabin	2
	Multi-Material Fabrication - Fabricator	Full scale μ-g Mars transit TRL6 unit for controlled CEV cabin w/ closed loop control & post finishing; μ-g Mars transit flight unit with restricted part size up to 12x12x12	2
	Multi-Material Fabrication - Fabricator	Full scale system stand alone cargo element testbed for lunar surface for independent deployment ahead of manned expedition	2
	Electronics Fabrication	Single layer printed circuit boards (PCB) with 10 micron (1e-5) features and low precision planar discrete components (resistors, capacitors, and simple sensors)	2
	Electronics Fabrication	Single layer PCBs with 1 micron (1e-6) features and high precision planar discrete components (resistors, capacitors, and simple sensors)	1
	Electronics Fabrication	Addition of antenna and inductor components, thermoelectric components	1
	Electronics Fabrication	Multilayer PCBs with large scale implementation (LSI) of simple logic Thin Film Transistor Circuit (TFTC) components with 10 micron (1e-5) features (AND, OR, NAND, NOR, Invertors)	1
	Electronics Fabrication	Addition of energy components (batteries, fuel cells, and solar cells)	1
	Electronics Fabrication	Addition of LSI of medium complexity logic TFTC components with 10 micron (1e-5) features (MUX, Decoders, Flip-flops, Counters, and Registers)	1
	Electronics Fabrication	Addition of LSI of complex logic TFTC components with 10 micron (1e-5) features (PLA, ROM, and FPGA)	1
	Electronics Fabrication	Semi-autonomous test/verification and validation tester with probes for testing continuity/isolation of PCB boards; probes for basic continuity/isolation testing, voltages, and currents of PCB boards; probes for testing continuity/isolation, voltages, and currents of PCB boards	1
	Electronics Fabrication	Autonomous Built-in-Test (BIT) test/verification and validation tester with probes for electrical testing and basic functionality of PCB boards	1
	Electronics Fabrication	Autonomous test/verification and validation tester with probes for electrical testing and complex functionality testing of PCB boards	1

Maturity Level – In Situ Fabrication & Repair (cont.)

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Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 4 Mars Vicinity (2017)	Multi-Material Patching, Filling, Joining	Evaluate Program flight H/W development status for new applications. Assemble multi-flight h/w repair kit. Perform validation of lunar repair kit. ECLSS, lander integration demo	2
	Multi-Material Patching, Filling, Joining	CEV/Robotic performance feedback for design deltas. Technology enhancement due to ECLSS, logistics, or lander variations, etc. Complement Mars flight-unique H/W.	1
	Multi-Material Patching, Filling, Joining	Apply ISS lessons learned to portable flight prototype soldering equipment for Mars flight	2
	Repair – Self-Healing Wire	TRL6 Self-activating self-healing wire demo for Mars Flight	1
Spiral 5 Initial Mission Mars Surface (2021)	Multi-Material Fabrication - Fabricator	• Optimize functions & mass of μ-g design for Mars transit; build & test ground unit modified for transition from lunar to Mars surface gravity	1
	Multi-Material Fabrication - Fabricator	Full scale Mars version w/ optimized functionality for independent deployment ahead of manned Mars expedition	1
	Electronics Fabrication	• Refine TFTC components to medium scale implementation with 1 micron (1e-6) features, to small scale implementation with 100 nanometers (1e-7) features and to nano scale implementation with 10 nanometers (1e-8) features	1
	Multi-Material Patching, Filling, Joining	• Final integrated Mars adhesive kit contents. Flight H/W and environment compatibility.	2

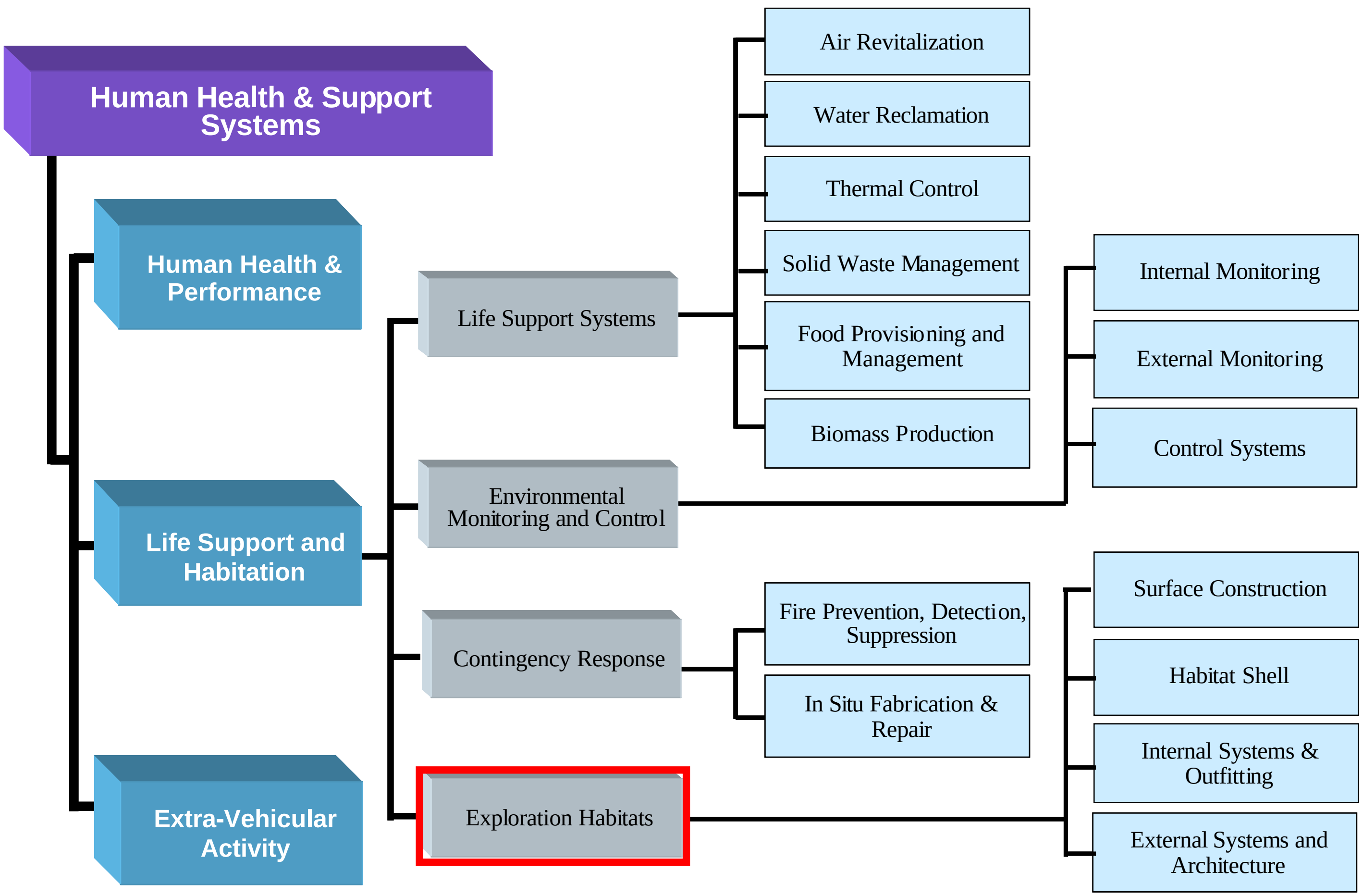
Maturity Level – Technologies In Situ Fabrication & Repair

Sub-Capability (Level 5 CBS)	Leading Technology Candidates	Current TRL	Spiral(s)
Multi-Material Fabrication	**Multi-Material Fabricator**	**2**	**3-5**
Electronics Fabrication	**Printed Electronics**	**2**	**3-5**
Multi-Material Repair	**Amalgams** **Adhesives** **Soldering**	**3** **5** **3**	**3-5** **2-5** **3-5**
Electronics Repair	**Self-Healing Wire** **Self-Healing Wire Insulation**	**1** **1**	**4-5** **3-5**

Metrics In Situ Fabrication & Repair

Sub-Capability (Level 5 CBS)	Figures of Merit	
	Description	Units
Multi-Material Fabrication	Product Strength Product Surface Finish Product Tolerances	% m-in RMS in/in
Electronics Fabrication	Trace Width Fabrication Tolerance	mm mm
Multi-Material Repair	Strength Temperature Tolerance	% Degrees
Electronics Repair	Strength Environmental Compatibility of repair	% %

Exploration Habitats



Exploration Habitats
Introduction & Definition

Advanced Planning & Integration Office

- Habitats for crew and crew systems will be required to provide shelter and facilities both in transport vehicles and on the surface of the moon and Mars.
- These Habitats and their systems will provide crew interfaces to all major systems as well as safe haven, recreation, relaxation, sleep, cooking, and work areas
- Habitat subsystems include Habitat Structure (vehicle, shell, structural, & in-situ components), all Internal Systems (Life support, Habitation elements, Maintenance, Safety, Racks, Systems Integration Tools & Environmental Systems), and all External Systems (Airlock, Micrometeoroid protection, Storage systems, rover accommodations)

Exploration Habitats Introduction & Definition

Advanced Planning & Integration Office

- Habitat design and development process is equivalent to that of vehicle design
  - An individual Habitat's structure and functionality will be driven by its specific mission's operational requirements
    - Various habitat structure and styles will be required to support the exploration program
    - Habitat, Mission scope, and Vehicle design will trade requirements to meet available resources
  - Habitats consists of an Integrated system of systems and subsystems
    - Each subsystem will be chosen, per spiral, from available capabilities and traded within design resource constraints
    - Overall integration of designs is key to successful implementation
    - Each subsystem has it's own defined roadmap and development process (see CBS on next page for details)

Exploration Habitats Capability Breakdown Structure

Advanced Planning & Integration Office

Surface Construction – to be covered in ISRU Road map (Unique to Surface Habitats)

Habitat Shell

- Alloy Module (integrated)
- Inflatable
- Composites
- In-Situ

Internal Systems & Outfitting

- Environmental control Systems
  - ALS (Capability Roadmaps under ALS section)
  - Radiation Protection (Capability Roadmap under HHP)
  - **Dust control/seals**
  - Trash processing (Capability Roadmaps under ALS section)
  - **Lighting**
- Habitat Facilities
  - Sleep station (including Entertainment system, sleep systems, privacy areas)
  - Galley (Capability Roadmaps under ALS section)
  - Exercise (Capability Roadmap under HHP)
  - Science & Work Stations (including mechanical and electrical repair shop, fabrication shop, computer hardware/software maintenance station, comm, & Robotics station)
  - WCS (Capability Roadmaps under ALS section)
  - Laundry (Capability Roadmaps under ALS section)
  - Medical facility (Capability Roadmap under HHP)
- Utility centers (Included in other Capability Roadmaps) (power, water, comm, data)

External Systems and Architecture

- Airlock (Capability Roadmap under EVA)
- Micrometeoroid protection
- Rover Accommodations (Included in other Capability Roadmaps)
- Greenhouse (Capability Roadmaps under ALS section)

Exploration Habitats Benefits

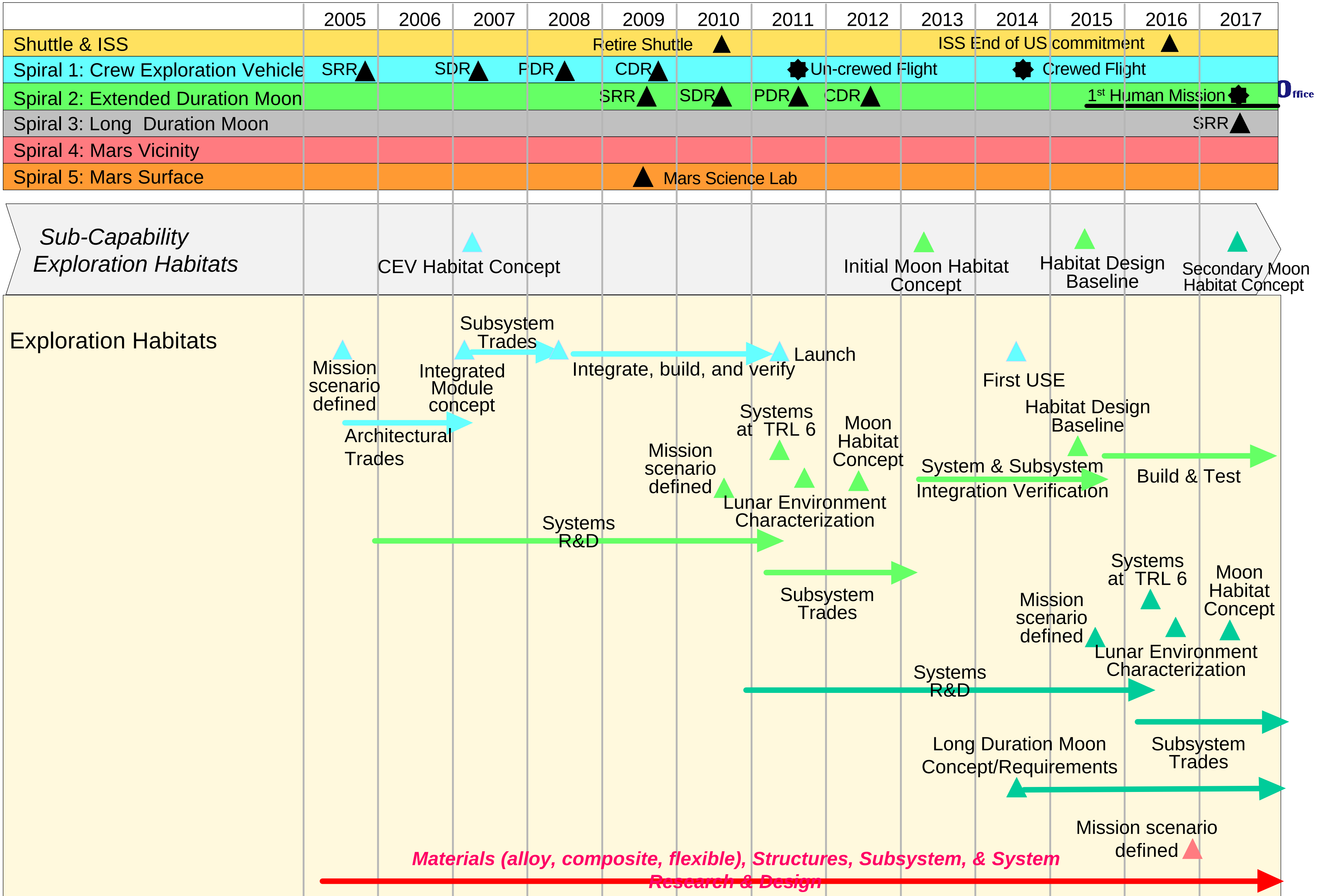
Benefits

- Well designed habitats will provide for maximum crew safety
- Integrated Habitats will support overall mission success in all phases of the Manned Exploration Program
- Reconfigurable Habitat systems architectures will enable multiple configurations
- State of the art living, communication, and work centers will facilitate crew work efforts and crew-ground interaction
- Advanced life support and environmental systems (lighting, dust control, etc) will increase crew comfort, decrease the amount of required consumables, increase autonomous operations, self sufficiency, and reliability of habitats to provide for more efficient mission and crew operations
- Utilization of common hardware with other vehicles will decrease mission mass through common sparing (e.g., power, communication, instrumentation, life support, thermal control)

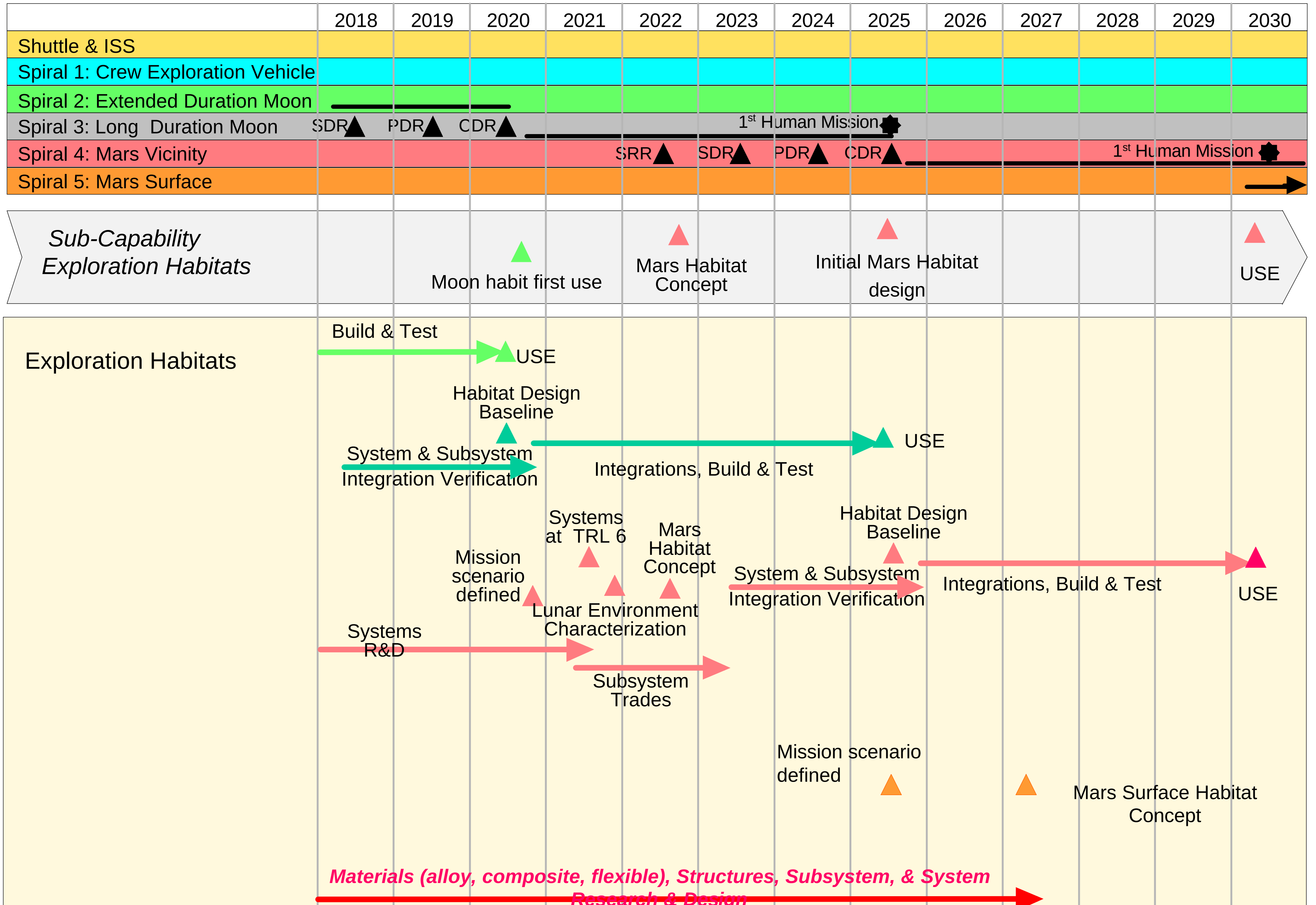
Exploration Habitats
Current State-of-the-Art

- Shuttle provides crew living and working environments for short duration LEO flights
- ISS provides orbital habitation facilities for 3 crew members with resupply.
- Apollo era moon lander is only existing design for a tested moon surface habitat
- Many terrestrial facilities incorporate well designed facilities necessary in a crew transport or surface habitat, but these are not micro-g or low-g designs

Exploration Habitats Roadmap



Exploration Habitats Roadmap



NOTE: Milestone colors correspond to spiral color bars above

Exploration Habitats Maturity Level - Capabilities

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Integration Approach

- Preliminary Mission Requirements Define Preliminary Architecture
- Primary System Concept Trade Studies Performed
- Ancillary System Concept Trades Performed (ISRU, Rover Accom, Science Ops)
- Concept Down Selects Performed
- Concept Evaluated in Simulators, Earth Analog Test Beds, &/or Moon Test Bed
- Concepts refined
- Final Requirement/Specs
- Final Design
- Build, Test & Verification of Integrated Habitat systems

Capability Readiness Level

1 Concept of Use Defined, Capability Constituent Sub-capabilities* and Requirements Specified

The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Exploration Habitats
Maturity Level - Capabilities

Mission (Need Date)	Sub-Capability (Level 5 CBS)	Capability Development Needs	Current CRL
Spiral 1 Lunar Capable Low Earth Orbit CEV (2008)	Integrated Vehicle habitat Vehicle life support systems Crew habitation facilities	ISS and Shuttle type system upgrades Reduce weight, crew maintenance time and ground processing through use of new materials and current state of the art capabilities Improve overall human environmental conditions	3
Spiral 2 Lunar Surface (2011)	Initial Lunar Surface Habitat with airlock Environmental Control Systems Habitat Facilities External systems and interfaces	Lighter weight structural materials (composites and/or inflatable material) Reduced use of consumables resources/increased recycling processes Seals & Mechanisms for Dust control systems Shielding (radiation and micrometeoroid)	1
Spiral 3 Long Duration Lunar Surface (2014)	Expanded Lunar Surface Habitat utilizing ISRU capabilities Environmental Control Systems Habitat Facilities External systems and interfaces Crew habitation facilities	Construction materials and processes Reduced use of consumables resources/increased recycling processes Closed loop environmental systems/ISRU systems Module mating technologies Improved Shielding (radiation and micrometeoroid) “greenhouse” technologies	1
Spiral 4 Mars Vicinity (2017)	Long term Vehicle habitat Closed loop life support systems Crew habitation facilities	Above plus: Lighter weight structural materials	1
Spiral 5 Initial Mission Mars Surface (2021)	Initial Mars Surface Habitat	Above plus: Automated setup/construction Logistical supply Surface launch support system Seal technology	1

Exploration Habitats - Habitat Shell Maturity Level - Technologies

Gaps (not identified on other roadmaps)	Deliverables	Current TRL/ Need Date
Inflatable Structures	Environmental and Pressure tested materials and concepts	5/2014
Composite Structures	Environmental and Pressure tested materials and concepts	7/2011
Alloy Structures	Environmental and Pressure tested materials and concepts	9/2011
Integrated Module concepts	Vehicle and Surface requirements/concepts	na/2011
In situ structures	Verifiable Surface build concepts and processes	1/2025

Assumes need date as date of mission to first use capability

Habitats – Internal Systems & Outfitting Maturity Level - Technologies

Gaps (not identified on other roadmaps)	Deliverables	Current TRL/ Need Date
Dust control Systems	Requirements for robotic precursor mission Analysis of Lunar/Martian environment Seals & Filtration technology	2/2014
Habitat Facilities	Detailed specification of mandatory crew and habitat facilities Technology and concepts for each facility (galley, sleep stations, work stations,…)	2-6/2014
Lighting systems	Standards and guidelines for lighting Technology and concepts for lighting across habitats	5-6/2014
Overall integration of Habitat systems and interface dependencies	System Trade Studies Habitats	na/2014

Note: Assumes mission worst case scenario (Mars)

Habitats – External Systems and Architecture Maturity Level - Technologies

Advanced Planning & Integration Office

Gaps (not identified on other roadmaps)	Deliverables	Current TRL/ Need Date
Micrometeoroid Protection System (vehicle and surface)	Requirements for robotic precursor mission Analysis of Lunar/Martian/Transport environment Micrometeoroid and exhaust plume protection technologies	2-4/2014
Module Interfaces/Connects (airlocks, transportation systems, greenhouse)	Environmental and Pressure tested materials and concepts	4/2014
External storage systems (rover accommodation…)	Requirements and integrated concepts	2/2014

Note: Assumes all ISRU external systems and gaps identified in ISRU Roadmap

Exploration Habitats Figures of Merit

- **Ultimate**:
  - Increase autonomy of habitat operations/Decrease in mission time required for habitat maintenance
  - Increased operational redundancy, usability, and reliability
  - Decreased transport mass, consumable usage, and resupply requirements
  - Decrease in likelihood of errors, effects of errors

- **Annual**:
  - Increasing percentage of human support requirements incorporated into design concepts
  - Increasing usability ratings
  - Reduction in rework required as a result of integrated testing
  - Less crew time needed for ground-based training, on-orbit training, and system procedure execution
  - Increasing reliability/maintainability (MTBF=Mean Time Between Failures, maintenance time) measures of systems
  - Progression of TRL/CRL levels of technology components

Life Support and Habitation Key Challenges

- Uncertainty of requirements that impact LSH systems: location, duration, spacecraft resource allocation, planetary protection.
- Acquiring manifests on future space vehicles/platforms for flight testing
  - Many LSH capabilities will require validation in relevant environment of space.
  - There will be competition for limited resources on Shuttle, ISS
  - There is a lack of defined microgravity resources between ISS and Spiral 4
- Infusing lessons learned from Spiral 3 Lunar planetary surface demonstrations into capabilities under development for Spiral 4
  - Spirals 3 & 4 are closely spaced on proposed strategic timelines
  - May be resolved during upcoming interchange between Roadmap Teams
- Obtaining adequate & timely information from precursor missions that characterize local environments and *in situ* resources to infuse into capability development
- Reducing complexity of regenerative and closed loop systems, reducing equivalent system mass and improving reliability
- Adequately addressing reliability to reduce mission risk
- Development of monitoring and control capabilities in parallel with development of capabilities that will be monitored and controlled.

Life Support and Habitation Summary

- Life Support and Habitation Systems, including Advanced Life Support, Environmental Monitoring and Control, Contingency Response and Exploration Habitats, represents a suite of enabling capabilities necessary to support human exploration missions as outlined in the U.S. Vision for Exploration.
- Advanced regenerative life support systems, with integrated components, including air revitalization, water reclamation, thermal control, solid waste management, food provisioning and biomass production, are key capabilities needed to dramatically decrease the mass of future spacecraft for human exploration and to decrease dependency on resupply.
- Key aspects will include "closing the loop" to recover usable mass, utilize *in situ* resources, decrease requirements for expendables, energy, volume, heat rejection and crew time, while providing a high degree of reliability.
- Remote missions far from Earth will require Contingency Response capabilities for prevention and recovery from anomalies that may threaten mission success and crew safety, including fire and hardware failure.
- Vehicle and surface habitats will need additional capabilities to accommodate new environments, longer periods of service, unique mission operations and configurations, and includes focus on the habitat shell, internal systems and outfitting, and external systems and architecture.

Life Support and Habitation Acknowledgements

The draft content within this progress report includes content from many different individuals within the NASA community

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Solid Waste Management	John Fisher/ARC
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Biomass Production	Raymond Wheeler/KSC
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Public Workshop

White Papers from numerous individuals from private industry, academia, other government institutions and the general public.

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Advanced EVA Systems

Presenter:

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The brains behind the words…

Advanced Planning & Integration Office

Between this capability road-mapping effort and the previous CRAI road-mapping effort, the following individuals provided either endless technical knowledge, philosophical insight or content review:

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JSC/Luis Trevino (Thermal, Airlocks)
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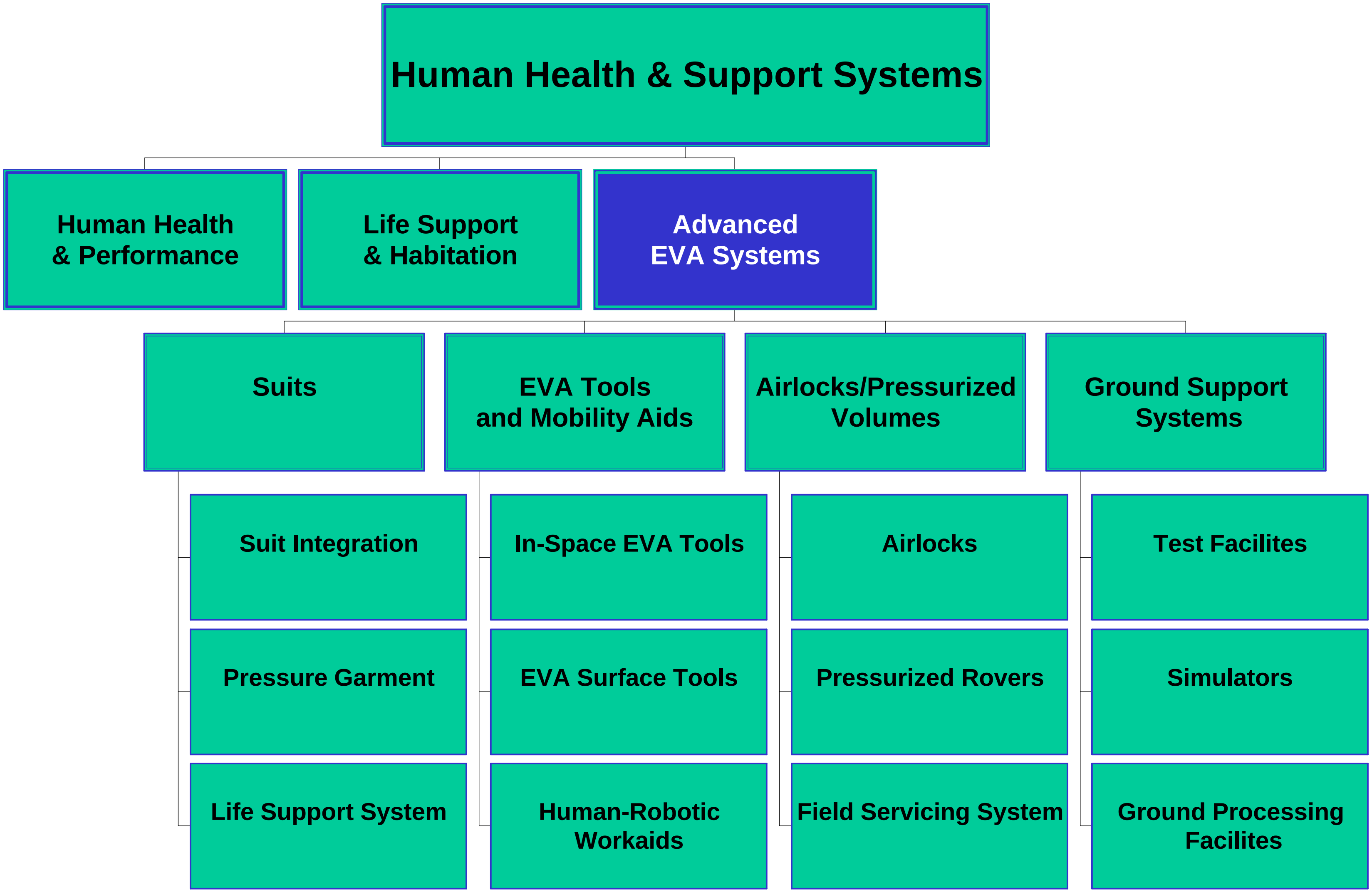
Advanced EVA Systems

- The Advanced Extravehicular Activity (AEVA) system includes the hardware and software necessary to allow a crewperson to perform tasks outside of the primary vehicle.
- As a fundamental capability within the Exploration Super-System, the AEVA system will require System-of-Systems integration, with contributions and dependencies from across many areas such as life support, power, communications, avionics, robotics, materials, pressure systems and thermal systems.
- The complete EVA system includes the highly-integrated human-centric EVA suit, and also consists of ancillary EVA tools and equipment, EVA translation and mobility aids, rover vehicles interfaces, human-robotic interactions, vehicle sub-system interfaces, airlocks and ground support systems.

Advanced EVA Systems



Requirements /Assumptions for Advanced EVA Systems

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- Various Design Reference Missions and studies were referenced during the development of this roadmap, not limited to the following:
  - RTF0004/ RTF0016 (Lunar Scenarios)
  - Initial Capability Roadmap Framework
  - Interviews with the Apollo Lunar Surface Astronauts in Support of Planning for EVA System Design, NASA Tech Memo 108846
  - Many EVA LSS related studies
- Based on the current Exploration Concept of Operations (Con Ops) and Crew Exploration Vehicle (CEV) Level I Requirements, the following capabilities are needed:
  - Contingency EVA capability for CEV
  - Crew survivability capability and protection from vehicle depress
  - Surface exploration capability
- Therefore, pressurized suits are needed to support the three distinct sub-capabilities: crew protection during launch and landing, in-space contingency EVA and planetary surface exploration
  - The technical challenges for these three capabilities are very different and depending on the mission, 2 or 3 suit designs may be necessary, imposing a logistical penalty

Suits

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- **Advanced EVA Systems**
  - Suits
    - Suit Integration
    - Pressure Garment
    - Life Support System
  - EVA Tools and Mobility Aids
    - In-Space EVA Tools
    - EVA Surface Tools
    - Human-Robotic Workaids
  - Airlocks/Pressurized Volumes
    - Airlocks
    - Pressurized Rovers
    - Field Servicing System
  - Ground Support Systems
    - Test Facilites
    - Simulators
    - Ground Processing Facilites

Suits

- **The EVA suits will support launch and entry capability, in-space contingency EVA capability and surface exploration. These highly-integrated suits will allow autonomous human operation outside the pressurized environment and contain the following critical sub-capabilities:**
  - **Livable Pressure Containment (Pressure Garment)**
  - **Breathable Atmosphere (Ventilation System)**
    - **The ventilation system capabilities include the primary and emergency oxygen systems; CO2, trace gas and humidity removal; pressure regulation; ventilation flow, as well as, monitoring, sensing, command and control and caution and warning functions**
  - **Thermal Control: heat acquisition, heat transfer and heat rejection**
  - **Power: power generation, power storage and power transfer**
  - **Communications and Informatics**
  - **Environmental Protection**
  - **Cross-cutting System Adaptability (Vehicle Interface: CEV, LSAM, Habitats, Airlocks, Rovers)**
  - **Self Rescue**

Benefits of the Suits

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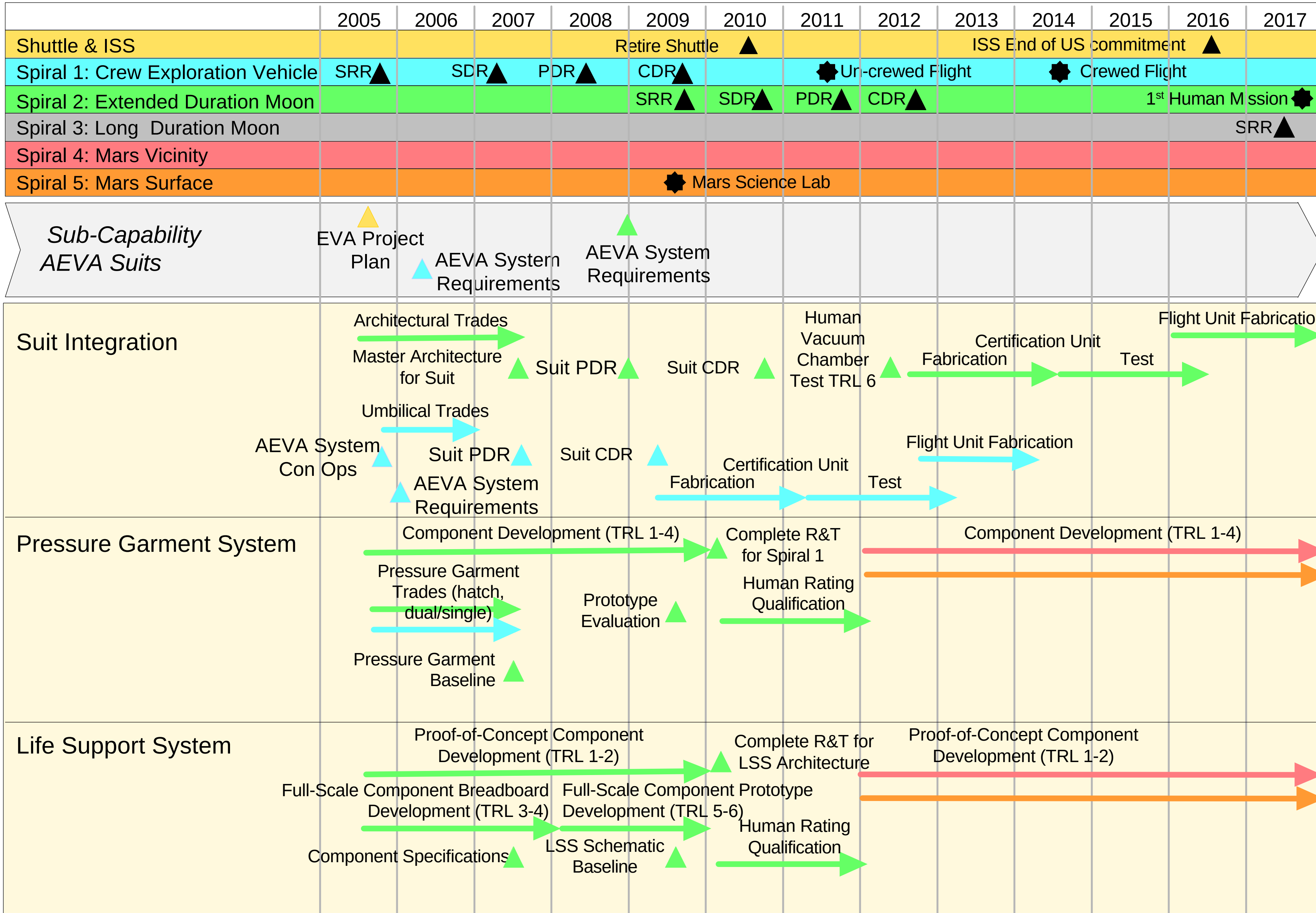
- An in-space suit (s) will support launch and entry crew survivability and CEV-based on-orbit operations
- A surface EVA suit will be based on a flexible, open architecture which will support multi-destination operation with minimal system reconfiguration
- Benefits of maximizing commonality between suit designs
  - Maintainable life support system architecture that is easily reconfigurable to enable multiple destinations
  - Lightweight, highly mobile suits and dexterous gloves to increase crew productivity, enable long-duration missions and high EVA use rates, mitigate crewmember injury and fit the full range of EVA crewmember sizes
  - Integrated human-robotic work capability to increase safety, efficiency, & productivity
  - State of the art communications and computing capability for multi-media crew-ground interaction (e.g., integrated communications, high tech information systems, and heads-up displays)
  - Operating pressure regimes which decrease EVA overhead by drastically reducing or even eliminating pre-breathe protocols
  - Advanced thermal control to increase crew comfort, decrease consumables, and enable multiple destinations (e.g., aerogel insulation, active cooling and heating
  - Common hardware with other vehicle systems to increase vehicle safety & decrease mission mass through common sparing (e.g., power, communication, instrumentation, life support, thermal control)

Current State-of-the-Art for Suits

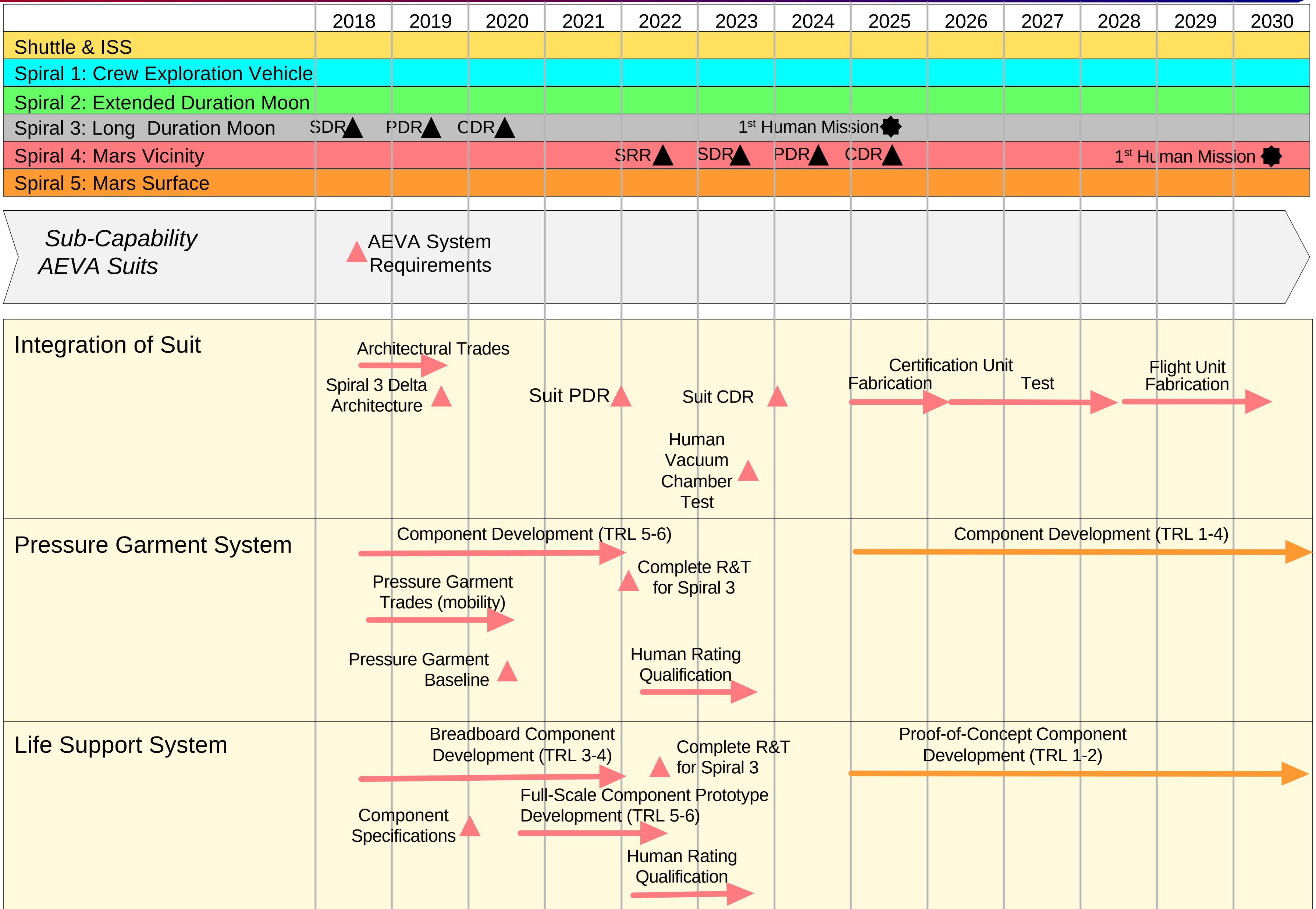
- **The current state-of-the-art for this capability is the Shuttle/ISS Extravehicular Mobility Unit (EMU) and the Russian Orlan**
  - The EMU is over is over 25 years old and is facing significant obsolescence issues. In addition, it is not compatible with the planetary environments of either the Moon or Mars and does not support the logistical requirements of long term missions.
  - Similarly, the Orlan is not compatible with the planetary environments of either the Moon or Mars
- **EVA overhead penalties are high in terms of mass, volume and time.**
- **Suit consumables are expended and require frequent replenishment or considerable time/power to recharge. No in-situ resource utilization is possible.**
- **Lack of suit maintenance capability beyond limited resizing, ORU replacement and consumables replacement.**
- **Suit mass, mobility, visibility and comfort are not compatible with partial gravity planetary environments. Inertial control and useful work/reach area in zero gravity is hampered.**
- **Suit protection from dust intrusion is inadequate.**
- **Available thermal insulation materials either only work in vacuum conditions or are thick and impede suit mobility and glove dexterity. Even with active heating, touch temperatures are limited to short durations and narrow ranges (-120 to +150F).**
- **Radiation definition, monitoring and protection are inadequate beyond earth's ionosphere.**
- **Sensitive environments and science devices are contaminated from suit by-products**
- **Lack of integrated voice, high quality video, smart suit sensor technology, and informatics software to provide mission autonomy.**

Suits Roadmap



NASA Pre-Decisional - Interim Draft to the NRC - March 17, 2005   *NOTE: Milestone colors correspond to spiral color bars above*

Suits Roadmap



Maturity Level - Capabilities

Advanced EVA Systems Capabilities (CRL 1:5)

Suits (CRL 1:5)
- Pressure Garments (TRL 2 → 6)
- Ventilation System (TRL 1 → 9)
- Thermal System (TRL 1 → 9)
- Power System (TRL 3→ 4)
- Communication and Informatics (TRL 2 → 5)
- Environmental Protection (TRL 1 → 8)
- Vehicle Interfaces (TRL 2 → 5)
- Self rescue (TRL 4 → 9)

EVA Tools and Mobility Aids (CRL 1:5)
- In-space EVA Tools (TRL 3 → 7)
- EVA Surface Tools (TRL 1 → 9)
- Human-Robotic Work-aids (TRL 2 → 5)

Airlocks/Pressurized Volumes (CRL 1:5)
- Airlocks (TRL 2 → 5)
- Pressurized Rovers (TRL 2 → 3)
- Field Servicing System (TRL 2 → 4)

Ground Support Systems (GSS) (CRL 1:5)
- Test Facilities (TRL 3 → 9)
- Trainers and Simulators (TRL 3 → 9)
- Ground Processing Facilities (TRL 3 → 9)

***CRL shown is in terms of the starting/ending level (to TRL 6). TRL shown is the range covered in that technology area.**

Technology Maturity Level – Suits

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Pressure Garments	• Shuttle Launch and Entry Suit (LES) • Sokol • Extravehicular Mobility Unit (EMU) • Orlan • Apollo Suit	• Launch, entry and abort pressure protection	• Vehicle Requirements Definition	• Modified LES,/ACES • Modified Sokol	6	0
		• In-space and surface pressure protection	• Lighter weight • Increased Mobility	• Modified LES/ACES for contingency EVA • Mark III, I-suit, D-suit	2	4-6
		• IVA comfort and mobility	• Vehicle Requirements Definition	• Modified LES,/ACES • Modified Sokol	6	0
		• In-space EVA mobility	• In-space EVA requirements	• Modified LES/ACES for contingency EVA • Mark III, I-suit, D-suit	2 5	2-4 1
		• Surface EVA mobility	• Increased Mobility • Low torque joints • Increased dexterity gloves/boots • Custom sizing manufacturing • Helmet/Visor technology	• Mark III, I-suit, D-suit	5	1

Technology Maturity Level – Suits

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Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Ventilation	• Expendable LiOH canisters • Regenerable Metox • Low pressure primary O2 (900 psia) • High pressure secondary O2 (6000 psia) • Condensing Heat Exchanger • Regenerable Activated charcoal • Fan • Mechanical regulator	• CO2/trace gas removal • Humidity control • Ventilation flow • Primary/Secondary oxygen supply • Pressure regulation	• Lightweight • Regenerable • Low Venting and Low Resupply Penalties • Increased Recharge Safety (i.e., lower pressure recharge) • Increased component and system reliability • Increased cycle life • CO2 rejection into Mars' CO2 atmosphere	Absorption/Regeneration Rapid Cycle Amine Pellets Geodes Rapid Cycle Molecular Sieve Zirconia Cell Photo-ionization LiOH Pellets Plastic Metal Oxides (Metox) Perm-Selective Venting Membrane Cryogenic Freeze Out Desiccant Condensing Heat Exchanger	3-4 1 3-4 2 2 9 2 9 2 3 8 9	1 3 1 3-4 3-4 2-3 3-5 2

Technology Maturity Level – Suits

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Ventilation (cont.)	• Expendable LiOH canisters • Regenerable Metox • Low pressure primary O2 (900 psia) • High pressure secondary O2 (6000 psia) • Condensing Heat Exchanger • Regenerable Activated charcoal • Fan • Mechanical regulator	• CO2/trace gas removal • Humidity control • Ventilation flow • Primary/Secondary oxygen supply • Pressure regulation	• Lightweight • Regenerable • Low Venting and Low Resupply Penalties • Increased Recharge Safety (i.e., lower pressure recharge) • Increased component and system reliability • Increased cycle life • CO2 rejection into Mars' CO2 atmosphere	<u>Containment vessels</u> High Pressure Low Pressure Nitrous Oxide Chlorate Candles Fullerene Storage Cryogenic Storage Potassium Super Oxide Emergency Oxygen High Pressure Low Pressure Recirculation with Venting <u>Other Ventilation</u> Traditional Fan Air Bearing Fan Ejector/Transvector Regulators Mechanical Proportional Control Solenoid Valve MEMS	9 9 4 7-8 3 3-4 2 9 9 3-5 9 4 2-4 9 4 1-2	1 2 2 2-3 1 2 2 2 3-5

Technology Maturity Level – Suits

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Thermal	• *Multi-layer Insulation* • *Sublimator* • *Liquid Cooling Garment* • *Manual temperature control*	• *Heat Acquisition* • *Heat Transfer* • *Heat Rejection*	• *Lightweight* • *Regenerable* • *Low Venting and Low Resupply Penalties* • *Increased component and system reliability* • *Increased cycle life* • *Utilization of Mars' convection environment to increase heat rejection* • *High insulation and heat rejection performance in a non-vacuum environment*	*Aerogel Thermal Insulating Materials*	*2*	*2-3*
				Heat Management and Rejection		
				Sublimator	*9*	
				Water Boiler	*3-4*	*2-3*
				Thermal Storage		
				Ice pack	*4-5*	*1*
				Wax	*4-5*	*1*
				Chemical Heat Pumps		
				Lithium Chloride	*3*	*2-3*
				Lithium Bromide	*3*	*2-3*
				Miniature Mechanical Heat Pumps		
				Vapor Compression	*3-4*	*1*
				Thermoelectric	*4*	*1*
				Cryogenic Cooler	*4*	*1*
				Venting Hydride	*4*	*1*
				Highly Conductive LCG	*2*	*3*
				Tubeless LCG	*1*	*5*

Technology Maturity Level – Suits

Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Thermal (Cont.)	• Multi-layer Insulation • Sublimator • Liquid Cooling Garment • Manual temperature control	• Heat Acquisition • Heat Transfer • Heat Rejection	• Lightweight • Regenerable • Low Venting and Low Resupply Penalties • Increased component and system reliability • Increased cycle life • Utilization of Mars' convection environment to increase heat rejection • High insulation and heat rejection performance in a non-vacuum environment	Radiator Convection Flow-through Variable Conductance Heat Pipe Control Valves Structure Coatings Auto cooling control	 2-4 3 1 2-4 3 3 2-4 3	 2 2 5 2 1 2-3 2-3 2
Power	• Batteries Silver Zinc Lithium Ion Nickel Metal Hydride	• Lightweight, high power • Standardized units	• High Energy Density • High Specific Energy • Long Shelf Life • High Cycle Life • Low Resupply Penalties • Increased component and system reliability • Lightweight • Regenerable	Batteries (increasing performance over current SOTA batts) Silver Zinc Lithium Ion Nickel Metal Hydride Super Capacitors Fuel cells PEM H2-O2 Methane CO-O2	 3 3 3 3-4 3-4 3-4 3-4 3-4	 1-5 1-5 1-5 2 2-3 2-3 2-3 2-3

Technology Maturity Level – Suits

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Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6 (yrs)
Comm and informatics	• Paper cuff checklist • Single band Radio • IR CO2 sensor • Limited sensor data for suit performance monitoring	Wireless comm Integrated comm Maintenance and diagnostic trending	• Increased crew communication and data transfer • Lightweight informatics system • Higher crew efficiency for real-time data acquisition • Increased data insight for maintainability • High reliability sensors	• Wireless sensors and electronics • Heads up display • Ultra Wideband Communication • Solid state CO2 sensors • IR CO2 sensors • Voice Control • Maintainability systems • Diagnostics	3-4 2-3 3-4 2-3 5 2-3 2 2	1-2 2-3 2-3 2-3 1 2-3 2-3 2-3
Environ mental Protection	• EMU MLI • EMU Ortho fabric • Orlan	• In-space contingency EVA protection • Surface exploration protection	• Dust protection/resistant materials and bearings • Radiation protective materials • Lightweight • Flexible	• Micrometeoroid Protection • Dust mitigating material • Puncture resistant material • Radiation protective material • Biochemical protective material	8 1-5 2 2 2-4	 2-3 3-5 3-5 1-3

Metrics for Suits

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Quantitative measures will be established in the future from the results of early trade studies and requirements development. However, the following will be the high-level goals of this sub-capability:

- Decrease consumable use
- Minimize crew on-back weight
- Decrease weight and volume minimizing vehicle logistical penalty
- Increased modularity and maintainability
- Increased useful EVA work duration
    - High Work Efficiency Index (WEI)
- Maximize commonality across all Constellation vehicles
- Maximize crew comfort

EVA Tools and Mobility Aids

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- **Advanced EVA Systems**
  - **Suits**
    - Suit Integration
    - Pressure Garment
    - Life Support System
  - **EVA Tools and Mobility Aids**
    - In-Space EVA Tools
    - EVA Surface Tools
    - Human-Robotic Workaids
  - **Airlocks/Pressurized Volumes**
    - Airlocks
    - Pressurized Rovers
    - Field Servicing System
  - **Ground Support Systems**
    - Test Facilites
    - Simulators
    - Ground Processing Facilites

EVA Tools and Mobility Aids

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- **Ancillary EVA tools and equipment include items that attach to a space suit, such as lighting and cameras, sensors, task-specific devices and safety gear. EVA tools, such as power and hand tools, provide the capability for a space suited human to conduct exploration and on-orbit operations. In a micro-gravity environment, EVA translation aids will be required to enable an EVA crewmember to translate, react forces and loads, and restrain themselves in order to do useful work.**
- **Surface exploration will require a new complement of tools for sample acquisition, archiving, and handling. Surface infrastructure (habitats, rovers, robotic assistants) will require maintenance and servicing, which will in turn necessitate handling of substantial objects in a gravitational field. This new cadre of tools will be determined as surface exploration requirements are further defined.**
- **Mobility aids provide the capability for controlled mobility with reduced metabolic workloads, and allow self-rescue from contingency or emergency situations**
- **Technological challenges in this area are typically related to adapting existing design devices to space requirements and do not represent a huge risk to constellation planning. However, surface exploration requirements will determine the specific tool development needs.**

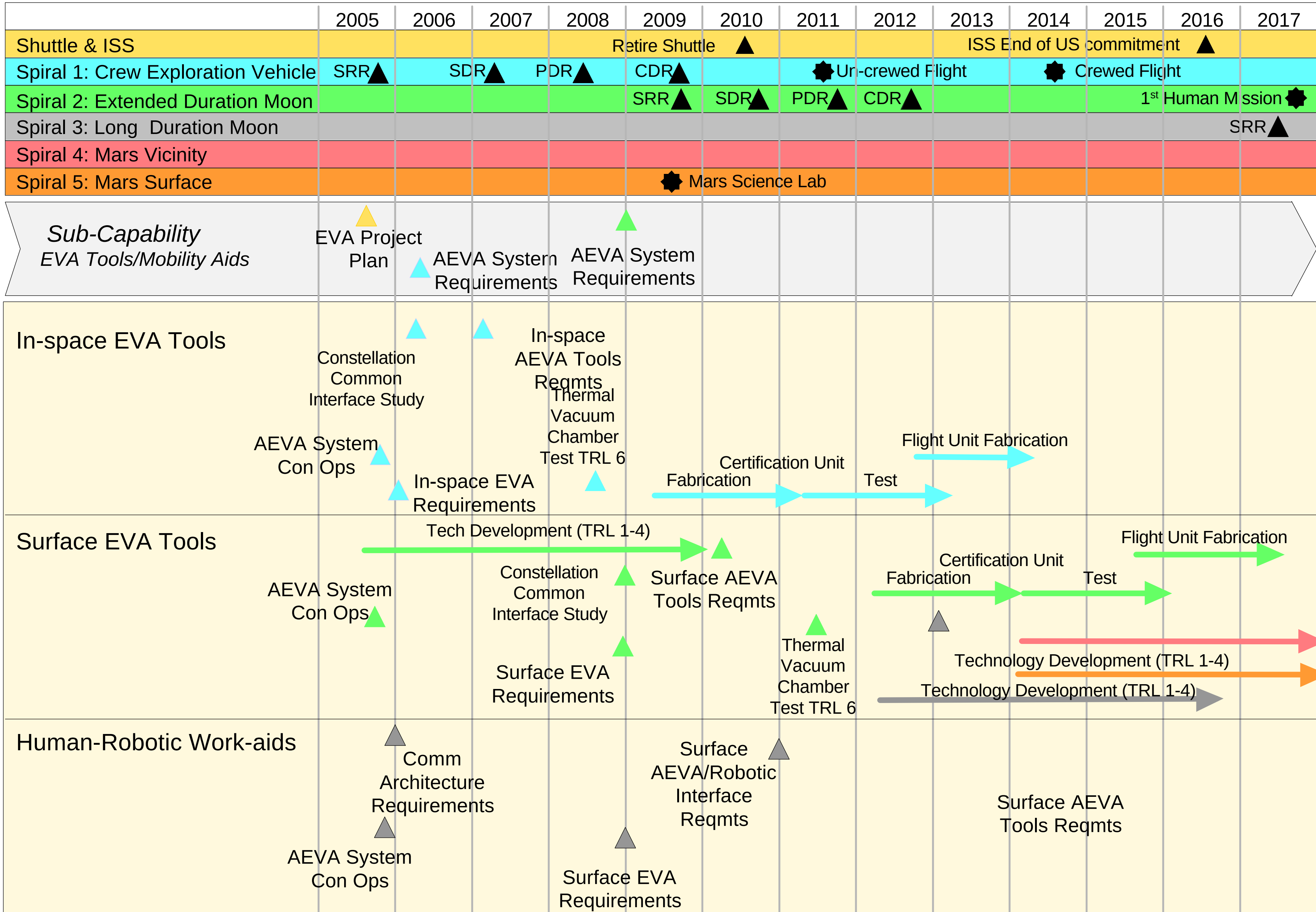
Benefits of the EVA Tools and Mobility Aids

- Increased EVA efficiency, greater work (task) efficiency index
- Lower metabolic expenditures from physical tasks
- Increased productivity with assistance from human-interactive robotic assistants
- Task reallocation, optimizing human involvement to high payoff/high dexterity/highly complex task sets
- Greater assurance of mission success, as robotic and EVA capabilities overlap to provide multiple options for achieving mission goals
- Safer work sites, due to robotic replacement or support of EVA in hazardous or demanding tasks

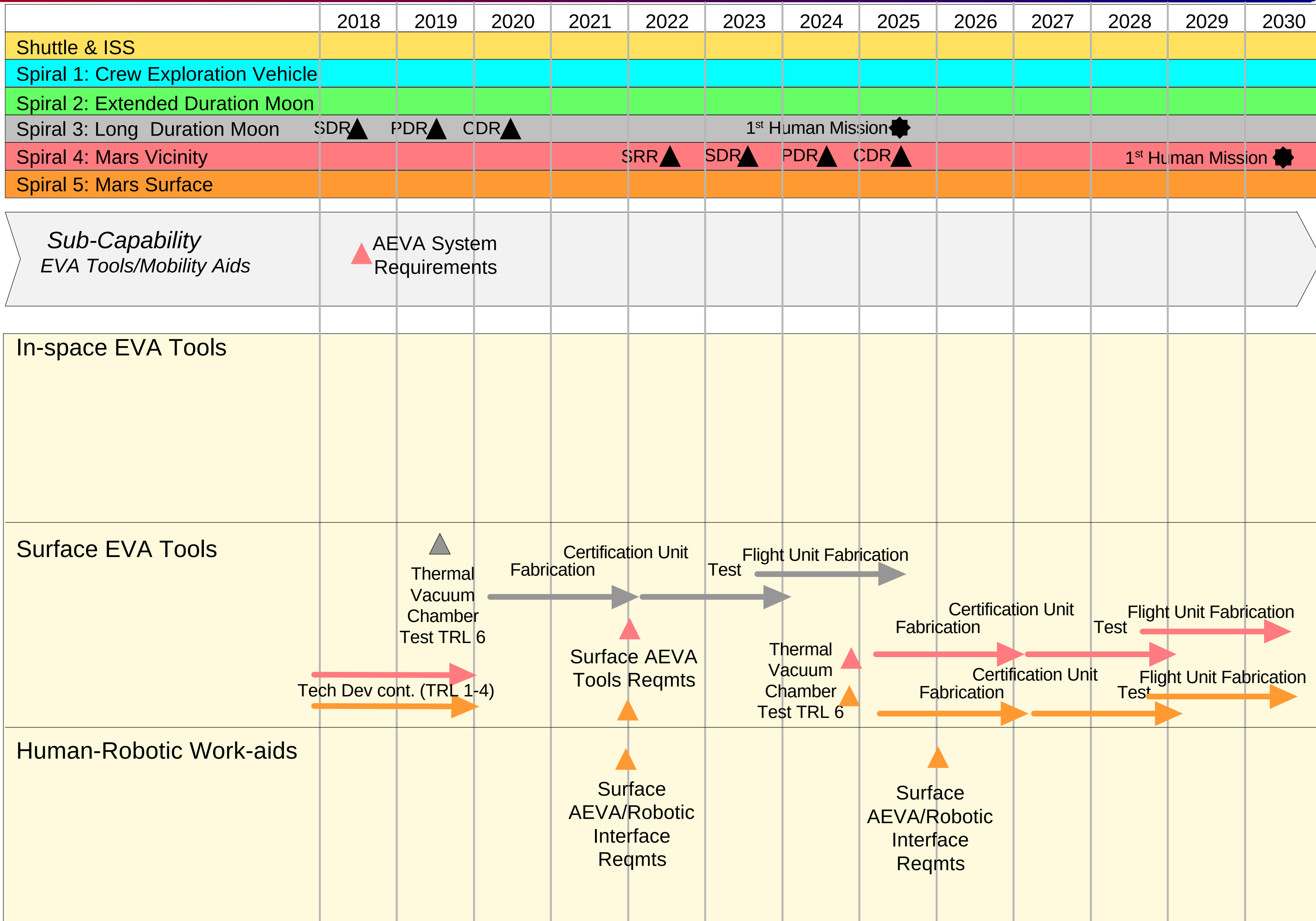
Current State-of-the-Art for EVA Tools and Mobility Aids

- Current tools are limited to manual force/torque reaction and zero-gravity transport/restraint.
- There is limited environmental and mechanical analysis
- Delicate materials are not easily handled.
- There is very limited ability to interact with spacecraft systems other than at the preplanned ORU level.
- Robotic EVA aids currently in use are primarily large positioning arms with limited mobility and dexterity. Current robotic aids are too reliant upon low-latency remote human control, and unique visual alignment targets and handling interfaces.
- Human capable rovers and dexterous robots for EVA support are conceptual and will require development by other agency experts. Interfaces to the suited crew will be defined by advanced EVA systems expertise.

EVA Tools/Mobility Aids Roadmap



EVA Tools/Mobility Aids Roadmap



Maturity Level - Capabilities for EVA Tools and Mobility Aids

Advanced EVA Systems Capabilities (CRL 1:5)

Suits (CRL 1:5)
- Pressure Garments (TRL 2 → 6)
- Ventilation System (TRL 1 → 9)
- Thermal System (TRL 1 → 9)
- Power System (TRL 3 → 4)
- Communication and Informatics (TRL 2 → 5)
- Environmental Protection (TRL 1 → 8)
- Vehicle Interfaces (TRL 2 → 5)
- Self rescue (TRL 4 → 9)

EVA Tools and Mobility Aids (CRL 1:5)
- In-space EVA Tools (TRL 3 → 7)
- EVA Surface Tools (TRL 1 → 9)
- Human-Robotic Work-aids (TRL 2 → 5)

Airlocks/Pressurized Volumes (CRL 1:5)
- Airlocks (TRL 2 → 5)
- Pressurized Rovers (TRL 2 → 3)
- Field Servicing System (TRL 2 → 4)

Ground Support Systems (GSS) (CRL 1:5)
- Test Facilities (TRL 3 → 9)
- Trainers and Simulators (TRL 3 → 9)
- Ground Processing Facilities (TRL 3 → 9)

***CRL shown is in terms of the starting/ending level (to TRL 6). TRL shown is the range covered in that technology area.**

Technology Maturity Level – Tools & Mobility Aids

Advanced Planning & Integration Office

Roadmap Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area/Candidates	TRL	Time to TRL =6
In-Space EVA Tools	• Shuttle & Space Station Tool Set (~1900 pieces)	• Common EVA/Robotic Tool Set • Simple Operation • Low Maintainability	•EVA compatible Common with other systems •Decrease EVA overhead time/effort	• Common Constellation Tool Set •Training •Robotic •Human	7	-
Surface Tools and Mobility Aids	• Apollo Era Tool Set	• Common EVA/Robotic Tool Set • Dust Tolerant • Low Maintainability • Simple Operation • Science Objectives	•EVA compatible tools •Common with other systems •Decrease EVA overhead time/effort •Deep surface penetration (Science)	• Common Constellation Tool Set •Training •Robotic •Human • Dust Tolerance • Shallow Surface • Deep Surface • Field Analyzers • Incapacitated Crew Rescue	5 3 7 2 3 1-2	2 6 - 8?
Human/Robotic Work-Aids	• NA	• Assistants • Common Tool Set	• Decrease EVA overhead time/effort • Increase crew task efficiency • Increase safety	• Communications • Human/robotic interfaces	2 5	6-8 2

Metrics for EVA Tools and Mobility Aids

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Quantitative measures will be established in the future from the results of early trade studies and requirements development. However, the following will be the high-level goals of this sub-capability:

- Major reduction in tool complement supporting EVA
- Decrease weight and volume minimizing vehicle logistical penalty
- Increased commonality among Constellation vehicles
- Increased maintainability
- Lower metabolic expenditures from physical tasks
- Increased EVA efficiency (EVA work duration)
  - High Work Efficiency Index
- Increased productivity with assistance from human-interactive robotic assistants
- Maximize commonality across all Constellation vehicles

Airlocks/Pressurized Volumes

- An airlock is the system that permits an EVA crewmember to go from a pressurized space craft environment to a uninhabitable external environment
  - Hard vacuum, low pressure, toxic atmospheres
  - Microgravity, reduced gravity
- Microgravity assembly and servicing systems (non-anthropomorphic work volumes) are potential extensions of more traditional EVA, allowing use of both suit-type arms and integral robotics while maintaining the operator in a comfortable shirtsleeve environment.
- Pressurized rovers will provide a shirtsleeve habitat on a mobility platform to allow multi-day exploration sorties for the moon and Mars. The rover will also support repeated EVA operations during each sortie.
- Mobile habitats, although the design responsibility of other agency experts, enable the development of advanced infrastructure while visiting multiple science exploration sites. Habitat elements will autonomously navigate across the planetary surface between human missions, allowing reuse of surface systems at multiple locations. Interface definition will be provided by Advanced EVA discipline.

Airlocks/Pressurized Volumes

Advanced Planning & Integration Office

- **Advanced EVA Systems**
  - Suits
    - Suit Integration
    - Pressure Garment
    - Life Support System
  - EVA Tools and Mobility Aids
    - In-Space EVA Tools
    - EVA Surface Tools
    - Human-Robotic Workaids
  - Airlocks/Pressurized Volumes
    - Airlocks
    - Pressurized Rovers
    - Field Servicing System
  - Ground Support Systems
    - Test Facilites
    - Simulators
    - Ground Processing Facilites

Benefits of the Airlocks/Pressurized Volumes

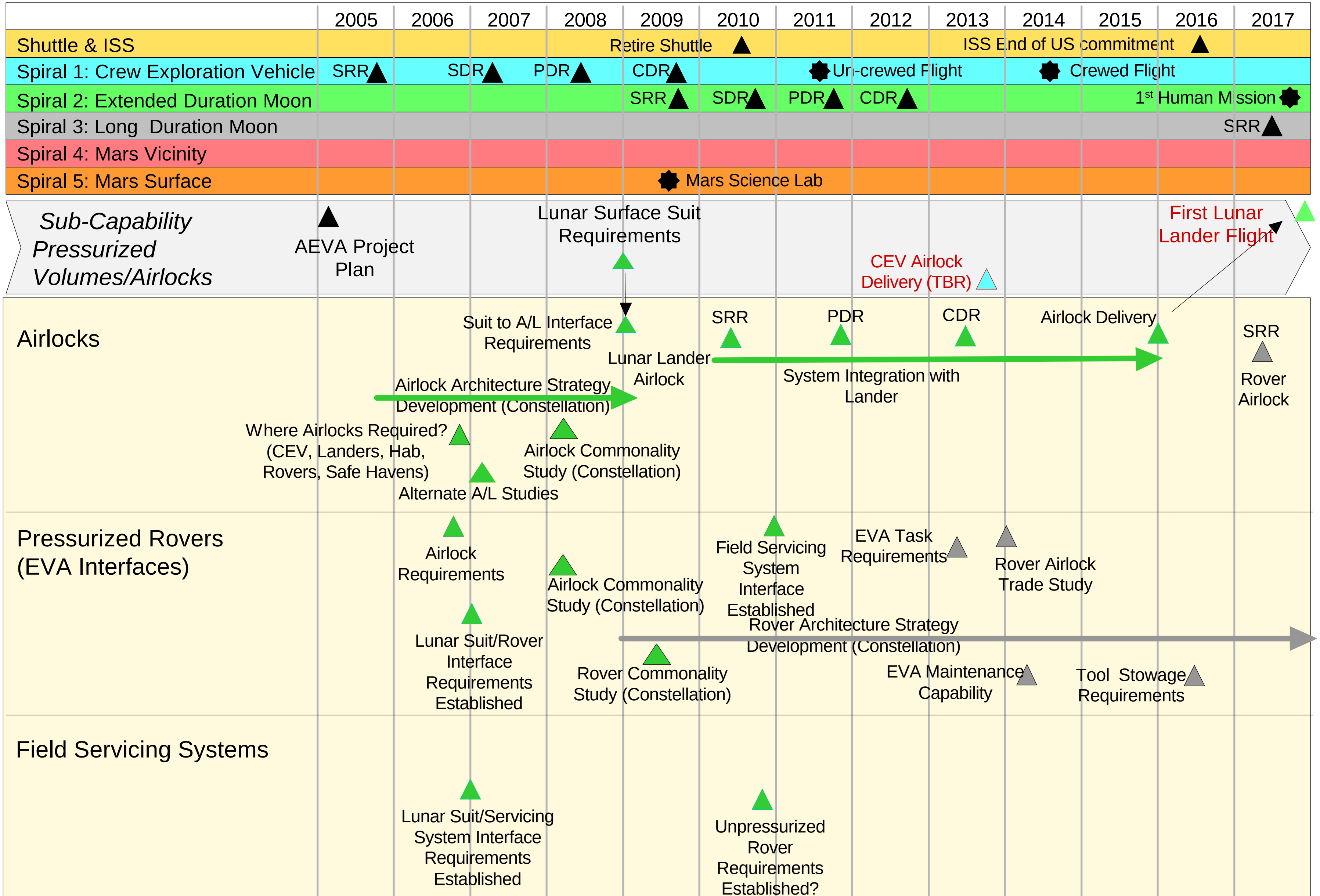
- Airlocks provide external access without additional operational demands on pressurized cabins to tolerate routine depressurization cycles.
- Airlocks provide separable constrained volumes to deal with dust mitigation and other contamination issues from planetary surfaces
- Shirtsleeve microgravity assembly and servicing systems may enable extended operations in environments beyond low earth orbit, mitigating radiation and micrometeorite issues with deep space operations
- Pressurized rovers and mobile habitats will enable extended human exploration on planetary surfaces, taking advantage of extended stay times to expand range of exploration activities

Current State-of-the-Art for Airlocks/Pressurized Volumes

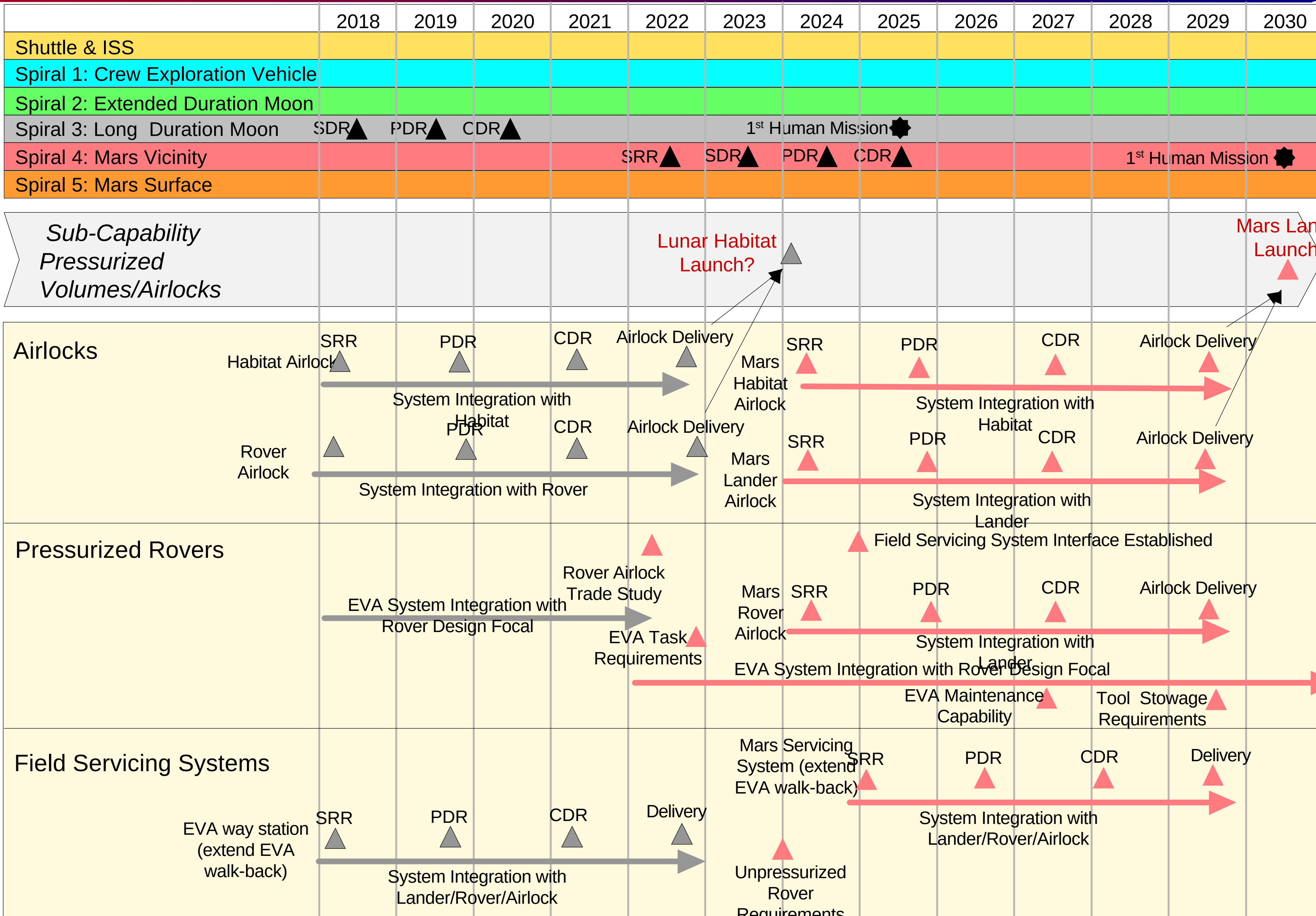
Advanced Planning & Integration Office

- Current airlock designs waste atmosphere and are not compatible with dust/biologic isolation.
- Dust contamination will be a significant issue on the surface of both the Moon and Mars. Dust mitigation and control must be considered in the design of planetary vehicles and EVA suit systems so that dust particles are not brought into the breathing volume. Along with dust-repelling suit technology advancements, habitat and vehicle design play a key role in preventing dust from entering the habitable volume.
- Other pressurized systems (atmospheric assembly and maintenance systems, pressurized rovers, mobile habitats) are at early TRL levels and need focused development support.

Pressurized Volumes/Airlocks Roadmap



Pressurized Volumes/Airlocks Roadmap



NOTE: Milestone colors correspond to spiral color bars above

Maturity Level - Capabilities for Pressurized Volumes

Advanced Planning & Integration Office

Advanced EVA Systems Capabilities (CRL 1:5)

Suits (CRL 1:5)
- Pressure Garments (TRL 2 → 6)
- Ventilation System (TRL 1 → 9)
- Thermal System (TRL 1 → 9)
- Power System (TRL 3→ 4)
- Communication and Informatics (TRL 2 → 5)
- Environmental Protection (TRL 1 → 8)
- Vehicle Interfaces (TRL 2 → 5)
- Self rescue (TRL 4 → 9)

EVA Tools and Mobility Aids (CRL 1:5)
In-space EVA Tools (TRL 3 → 7)
EVA Surface Tools (TRL 1 → 9)
Human-Robotic Work-aids (TRL 2 → 5)

Airlocks/Pressurized Volumes (CRL 1:5)
Airlocks (TRL 2 → 5)
Pressurized Rovers (TRL 2 → 3)
Field Servicing System (TRL 2 → 4)

Ground Support Systems (GSS) (CRL 1:5)
Test Facilities (TRL 3 → 9)
Trainers and Simulators (TRL 3 → 9)
Ground Processing Facilities (TRL 3 → 9)

***CRL shown is in terms of the starting/ending level (to TRL 6). TRL shown is the range covered in that technology area.**

Technology Maturity Level – Airlocks/ Pressurized Volumes

Advanced Planning & Integration Office

Roadmap Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area/ Candidates	TRL	Time to TRL= 6
Airlock	• Shuttle Airlock • Space Station Joint Airlock • Russian Space Station Airlock (DC-1) • Skylab Airlock	• Ingress/Egress • Suit Supportability	• Minimum consumable use (air and power) • Time efficiency • Dust Tolerance • Rapid Consumable Re-supply • Low Mass	• Lightweight Structure • Inflatable • Minimum Volume (Clamshell, suit ports) • Environmental Protection (e.g. Dust Mitigation) • Hatch Mechanisms • Rapid Suit Checkout & Recharge	3 3 3 2 5 3	6 6 6 8 2 6
Pressurized Rovers (EVA Interface)	• Lunar Rover	• Airlock • Suit Supportability • Tool Stowage • Commonality • EVA Maintainable	• See airlocks	• See airlocks • EVA Suit/rover consumable commonality • Simple external maintenance	3 2 3	6 8 6
EVA Field Service Stations	• NA	• Service Stations • Safe havens	• Rapid Recharge • Deployable (lightweight)	• Life Support Commonality • Communications • Suit Checkout and Recharge • Environmental protection	2 4 2 2	8 4 8 8

Metrics for Airlocks/Pressurized Volumes

- Quantitative measures will be established in the future from the results of early trade studies and requirements development. However, the following will be the high-level goals of this sub-capability:
  - Decrease consumable use
  - Decrease consumable recharge time
  - Maximize dust/contamination control
  - Decrease weight and volume minimizing vehicle logistical penalty
  - Increased maintainability
  - Maximize commonality across all Constellation vehicles

EVA Ground Support System

- **Advanced EVA Systems**
  - **Suits**
    - Suit Integration
    - Pressure Garment
    - Life Support System
  - **EVA Tools and Mobility Aids**
    - In-Space EVA Tools
    - EVA Surface Tools
    - Human-Robotic Workaids
  - **Airlocks/Pressurized Volumes**
    - Airlocks
    - Pressurized Rovers
    - Field Servicing System
  - **Ground Support Systems**
    - Test Facilites
    - Simulators
    - Ground Processing Facilites

EVA Ground Support System

- The EVA Ground Support System includes the necessary facilities and associated infrastructure to support EVA-related testing, technology development and flight program simulations and EVA system ground processing.
- Ground Support Systems include:
  - Component and integrated system test facilities
  - Ground facilities for processing training and flight hardware
  - Analogs and trainers for planetary environments for testing suit components, subsystem and integrated systems in relevant environments, proving operational concepts and conducting training.
    - Dust
    - Radiation
    - Micrometeorite
    - Biochemical
    - Pressure
    - Terrain
    - Vacuum
    - Low-gravity
    - Virtual reality

Benefits of the EVA Ground Support System

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- EVA Ground Support Systems decrease technical and safety risk of human exploration by testing candidate technologies in applicable environments to validate system safety and reliability.
- EVA Ground Support Systems decrease cost risk by supporting testing of competing technologies for cost-benefit evaluation.
- EVA Ground Support Systems decrease schedule risk by providing testing of high value/high risk technologies while allowing testing of lower risk off-ramp technologies.

Current State-of-the-Art for EVA Ground Support System

Advanced Planning & Integration Office

- Because EVA testing, training, execution and ground-processing functions for previous EVA programs have been primarily run out of the Johnson Space Center, the following chart lists JSC facilities that could support Advanced EVA Systems if an upgrade plan is implemented.
  - A detailed survey of laboratory capability across NASA centers, industry, and academia should be performed to create a baseline of all capability in existence at presence.
  - Testing requirements for components, subsystems and integrated system testing should be performed.
  - A gap analysis should be performed to identify gaps between existing capability and test requirements.
  - Facility upgrades should be developed to fill capability gaps.

Current State-of-the-Art for EVA Ground Support System

Advanced Planning & Integration Office

• JSC facilities that could support the Advanced EVA subsystem testing if an upgrade plan is implemented:

Advanced Extravehicular Development Laboratory

- The Advanced EVA Development Lab is a "hands on" lab for development, fabrication, and test of proof of concept and new technology space suit components and mobility systems. The lab supports ground based (sea level) manned suited testing as well as unmanned life cycle, mobility, and torque range testing of suit components.

Advanced Portable Life Support System (PLSS) Lab

- The Advanced PLSS lab consists of the Ventilation Benchtop laboratory and the Thermal Loop benchtop laboratory that support the Advanced Technology Spacesuit activities. The Ventilation Benchtop is a laboratory setup to help define, try out, and design the ventilation module of the Advanced Technology Spacesuit. The Thermal Loop benchtop is a laboratory setup to test and verify the thermal loop systems for the Advanced Technology Spacesuit project.

Sonny Carter Training Facility (SCTF)/Neutral Buoyancy Laboratory (NBL)

- The Sonny Carter Training Facility provides controlled neutral buoyancy operations to simulate zero-g or weightless condition that is experienced by spacecraft and crew during space flight. It is an essential tool for the design, testing and development of the International Space Station and future NASA space programs.

Planetary Surface Simulated Field Test Site

- A JSC facility that provides a realistic 1-acre test site representative of a Mars-like strewn rock field and cap-rock hill structure to conduct a series of engineering evaluations and functionality testing of advanced space suit system mobility test activities, prototype rover vehicle driving dynamic and human-interface ergonomic studies, human/robot interactive task development activities, and advanced communications voice, video and data transmission to JSC mission control "remote science team" members. This facility enables the integrated testing of various advanced technology hardware systems that are being developed for future planetary exploration in a realistic (out-of-the-lab) terrestrial analog setting and representative of extraterrestrial surface conditions.

Reduced Gravity Aircraft

- In order to investigate human and hardware reactions to operating in a weightless/reduced gravity environment, a reduced gravity environment is obtained with a specially modified C-9 aircraft, which flies parabolic arcs to produce weightless periods of 20 to 25 seconds. The C-9 can also provide short periods of lunar (1/6) and Martian (1/3) gravity. Approximately 80,000 parabolas have been flown in support of the Mercury, Gemini, Apollo, Skylab, Space Shuttle, and Space Station programs.

Partial-Gravity Counterbalance System (PGCS) Laboratory

- A CTSD facility located at JSC (Bldg 29) that provides for the simulation of a Lunar or Mars gravity environment for conducting a wide variety of both shirtsleeve and spacesuit isolated joint mobility, system walking dynamics studies as well as engineering assessment evaluations of advanced space suit and portable life support system elements. The facility contains a treadmill that is used to conduct engineering evaluation and assessment of various planetary surface flexible boot designs while under a variety of simulated walking conditions, and reduced gravity conditions. Simulants representative of Lunar and Mars surface materials are also available for introducing more realistic surface conditions for space suit and boot material abrasion resistance and dust abatement studies.

Human-Rated Thermal Vacuum Chambers

- The six Altitude Chambers, two Thermal-Vacuum Chambers and necessary Test Support systems are utilized primarily for development, certification and parametric testing of life support systems for man in the hostile environments of space. Each of the Altitude Chambers is configured for a particular type of testing. However, within the chamber's capabilities, each chamber complex may be used to perform other types of tests.

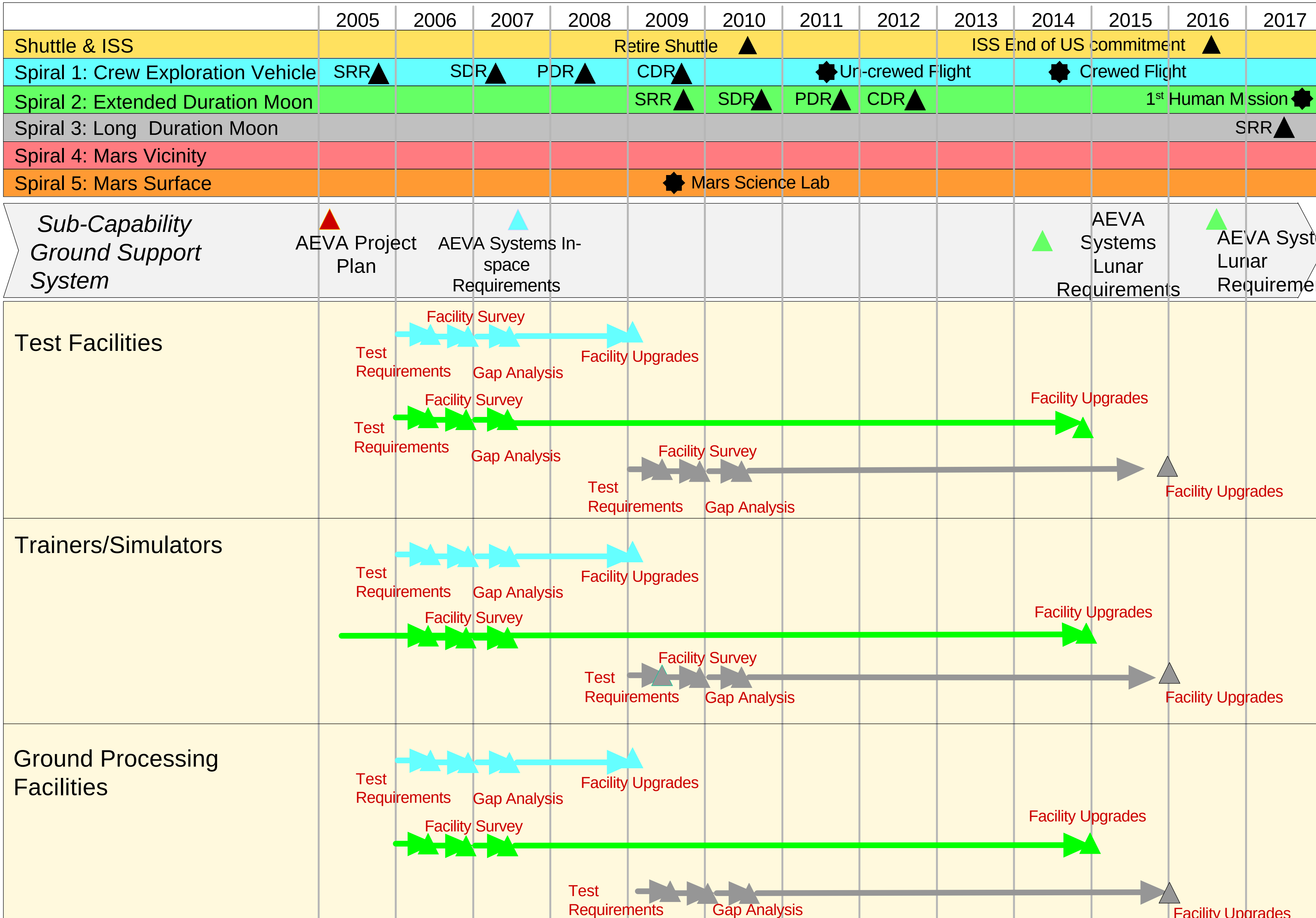
Chamber V Thermal-Vacuum

- Chamber V is a high vacuum system consisting of a mechanical pump and oil diffusion pump. The test section is accessible through a removable bell jar. The system is configured with a guarded hot plate thermal conductance measuring system for determining the thermal performance of insulations and other materials of relatively low thermal conductance.

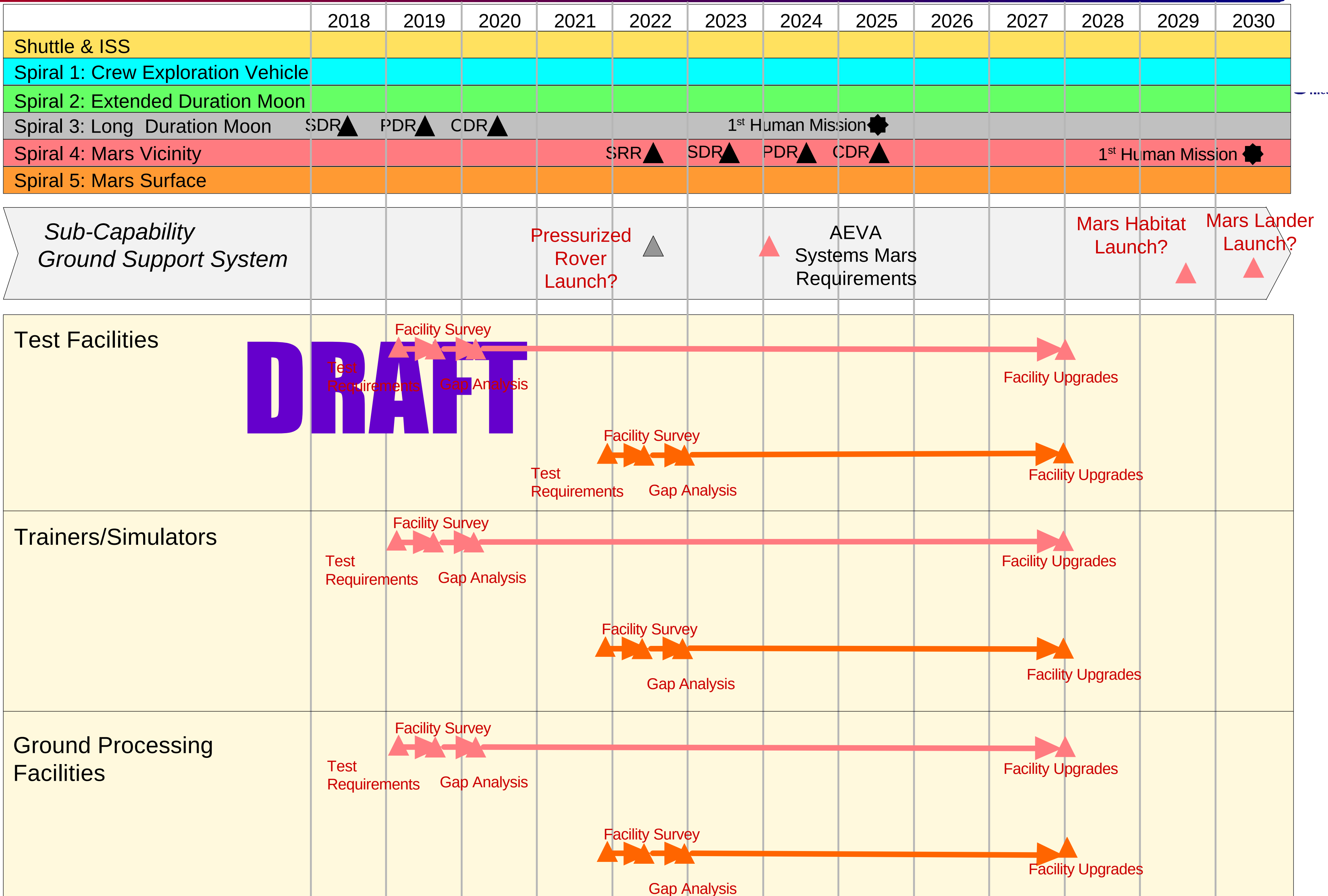
Building 32 Chambers

- The facility provides full scale testing of large systems and human testing/training in a high fidelity simulated space environment. In addition to the chambers, a high bay area supports test article buildup and preparation for installation into the chambers.

Ground Support System Roadmap



Ground Support System Roadmap



Maturity Level - Capabilities for EVA Ground Support System

Advanced EVA Systems Capabilities (CRL 1:5)

Suits (CRL 1:5)
1. Pressure Garments (TRL 2 → 6)
2. Ventilation System (TRL 1 → 9)
3. Thermal System (TRL 1 → 9)
4. Power System (TRL 3→ 4)
5. Communication and Informatics (TRL 2 → 5)
6. Environmental Protection (TRL 1 → 8)
7. Vehicle Interfaces (TRL 2 → 5)
8. Self rescue (TRL 4 → 9)

EVA Tools and Mobility Aids (CRL 1:5)
1. In-space EVA Tools (TRL 3 → 7)
2. EVA Surface Tools (TRL 1 → 9)
3. Human-Robotic Work-aids (TRL 2 → 5)

Airlocks/Pressurized Volumes (CRL 1:5)
1. Airlocks (TRL 2 → 5)
2. Pressurized Rovers (TRL 2 → 3)
3. Field Servicing System (TRL 2 → 4)

Ground Support Systems (GSS) (CRL 1:5)
1. Test Facilities (TRL 3 → 9)
2. Trainers and Simulators (TRL 3 → 9)
3. Ground Processing Facilities (TRL 3 → 9)

***CRL shown is in terms of the starting/ending level (to TRL 6). TRL shown is the range covered in that technology area.**

Technology Maturity Level – EVA Ground Support System

Roadmap Sub-Capability	Current Capabilities	Capability Required	Sub-Capability Development Needs	Technology Area Candidates	TRL	Time to TRL 6
Test Facilities	• Shuttle & Space Station Test Facilities	• Human Rated Vacuum Chambers • Systems Integration Lab • Simulated Surface Sites • 0G Environment • Partial Gravity Environment • Micrometeorite testing • Radiation testing • Dust effects testing	Updates/consolidation required ➢ Simulated integrated gravity, pressure, dust, radiation, atmosphere, micrometeoroid Martian Environment ➢ Simulated integrated gravity, dust, radiation, micrometeoroid Lunar Environment	• Lunar and Martian Simulants • Integrated Lunar and Martian environmental conditions • Software for Simulation Based Acquisition • Emission and leak testing • Boot and Glove Sizing • Advanced Processing for suit components • Advanced AEVA Life Support lab upgrades	NA	NA
Training Facilities	• Shuttle & Space Station Training Facilities	• NBL • Systems Integration Lab • Simulated Surface Sites • 0G Environment • Partial Gravity Environment	Updates/consolidation required ➢ Simulated integrated gravity, pressure, dust, radiation, atmosphere, micrometeoroid Martian Environment ➢ Simulated integrated gravity, dust, radiation, micrometeoroid Lunar Environment	• Lunar and Martian Simulants • Integrated Lunar and Martian environmental conditions	NA	NA

Ground Processing Facilities	• Shuttle & Space Station Ground Processing Facilities	• EVA Systems:
		  • Prep
		  • Storage
		  • Maintain
		  • Test
		  • Troubleshoot
			Updates/consolidation required
			➢ Needs Analysis
			➢ Gap Analysis
			➢ Facility Upgrades
				• Crew escape and EVA Integrated processing facility	3	NA

Metrics for EVA Ground Support System

- Quantitative measures will be established in the future from the results of early requirements development. However, the following will be the high-level goals of this sub-capability area:
  - Maximize reliability
  - Maximize maintainability
  - Maximize safety
  - Maximize operational life time
  - Maximize evolvability

Key technical challenges:

- Major challenges in meeting required technologies/capabilities
  - Exploration Concept of Operations and Architecture
    - Number of crew
    - Vehicle configurations
    - EVA operational requirements
  - Vehicle pressure versus suit pressure
    - Suit operating pressure
    - EVA prebreathe time
  - Anthropometric size range
  - Integration with other Constellation systems

- Alternatives or off ramps
  - Number of suits to support spirals is a major decision point that drives the rest of the roadmap

EVA Critical Capabilities for Exploration

- Highly-integrated human-centric EVA suits for in-space operations and planetary surface operations
- Task efficient EVA tools and equipment
- Safe and effective EVA translation and mobility aids
- Human-interactive robotic assistants and human-centric rover vehicles interfaces
- Standard EVA sub-system interfaces
- Functionally efficient airlocks
- Ground support systems that effectively produce, test, train and maintain EVA systems

Back Up

Bioastronautics Roadmap

Advanced Planning & Integration Office

- The Bioastronautics Roadmap guides the prioritized research and technology development that, coupled with operational space medicine, will inform:
  - the development of medical standards and policies;
  - the specification of requirements for the human system;
  - the implementation of medical operations.
- The Roadmap provides information that helps
  - establish tolerances (i.e. operating bands or exposure limits) for humans exposed to the effects of space travel and develop countermeasures to maintain crew health and function within those limits; and
  - develop technologies that make human space flight safe and productive.

Return

CRM 2

Advanced Planning & Integration Office

High Energy Power & Propulsion		Human Health & Support Systems	
Sub-Topic or Subsidiary Capability	**Capability Flow & Criticality**	Sub-Topic or Subsidiary Capability	Nature of Relationship
Nuclear Propulsion		Human Health Performance	Reqmts for vehicle/ nuclear power separation is also beneficial for artificial gravity
Nuclear Propulsion		Human Health Countermeasures/ Radiation Protection	transit times/ exposure time
Nuclear Propulsion		EVA	Induced radiation/ thermal/ hazard environment relative to space craft
Power		Human Support Systems	Power reqmts/constraints affects technology
Red - Critical			
Blue - Moderate			

Return

CRM 3

Advanced Planning & Integration Office

In-Space transportation	Human Health & Support Systems			
Sub-Topic or Sub-sub-topic		Sub-Topic or Sub-sub-topic		Relationship
All of In-space transportation		Life Support/ Human Health & Performance/ EVA		Design of vehicle - reqmts/ trade-offs/ habitable volume/ heat rejection (mass rich or poor) Degree of in-space assy required
Red - Critical				
Blue - Moderate				

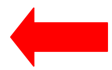
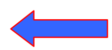
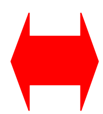
Return

CRM 4

Advanced Planning & Integration Office

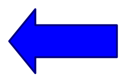
Advanced Telescopes & Observatories	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	⟷	EVA	Mission timing- Humans required to deploy? - concept of ops/ design compatibility contamination structural loads
All	⟷	Advanced Life Support	contamination
Red - Critical			
Blue - Moderate			

Return

Communication & Navigation	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All		Human Health/Radiation	Direct access to space weather systems for Mars
All		Human Health/Artificial Gravity	Antennae design & location
All		Human Health	Secure comm/ private conference/ psych consults Embedded human performance measures Bandwidth
		EVA	Surface navigation/ information display Communication within & between EVA/ vehicle/ rover/ base
Red - Critical			
Blue - Moderate			

Return

CRM 6

Robotic Access to Planetary Surfaces	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Entry, Descent, and Landing/ Observations		Human Health/Radiation	Rqmts for radiation definition on moon & Mars
Entry, Descent, and Landing/ Observations		Human Support	Rqmts for site characterization
Entry, Descent, and Landing/ Observations		Human Health/Life Support/EVA	environment characterization (dust, toxicity, radiation, etc.)
Red - Critical			
Blue - Moderate			

Return

CRM 7

Human planetary landing systems	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	⟷ (red)	Habitats	Architecture - integrated habitat? / Precision landing/ pressure
All	⟷ (red)	Human Health	human performance - g-load
	⟷ (red)	EVA	Routine access to planetary surface
Red - Critical			
Blue - Moderate			

Return

Human Exploration Systems & Mobility	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Rovers, in-space systems	⟷ (red)	Human Health/Space Human Factors/EVA	Rover interface
Rovers	⟷ (red)	Habitat	Rover interface
Rovers	← (red)	Human Health/Radiation	Reqmts
Red - Critical			
Blue - Moderate			

Return

Autonomous systems & robotics	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Human-Machine Interaction	⟷ (red)	Human Health/EVA	Robotic interface Application versus task functional allocation Robotic assistance for medical care?
Red - Critical			
Blue - Moderate			

Return

CRM 12

Advanced Planning & Integration Office

Scientific instruments and sensors	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
Surface Sample Acquisition & Analysis	←	Human Support	Site selection reqmts
Red - Critical			
Blue - Moderate			

Return

CRM 13

In situ resource utilization	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	⟷	Human Support	reqmts for composition, quality, quantity
All	⟷	EVA	tools and functional reqmts
All	⟷	Radiation	potential shielding
All	⟷	Life Support	Water, oxygen production
Red - Critical			
Blue - Moderate			

Return

CRMs 14, 15, 16, & 11

Advanced modeling, simulation, analysis Systems engineering cost/risk analysis Nanotechnology/advanced technology concepts Transformation Spaceport/Range	Capability Flow and Criticaltiy	Human Health & Support Systems	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
All	Unknown	All	Unknown
Red - Critical			
Blue - Moderate			

Return

Capability Readiness Level 1

Advanced Planning & Integration Office

1 Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

The Capability is defined in written form. The uses and/or applications of the Capability are described and an initial Proof-of-Concept analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 2

Advanced Planning & Integration Office

2 **Sub-Capabilities* Demonstrated in a Laboratory Environment**

Proof-of-Concept analyses of the Sub-capabilities are performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.

Return

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

3 Sub-Capabilities* Demonstrated in a Relevant Environment

Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

- -of appropriate scale
- -functionally equivalent flight articles
- -major system interactions and interfaces identified

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 4

Advanced Planning & Integration Office

4 **Integrated Capability Demonstrated in a Laboratory Environment**

A representative model or prototype of the integrated Capability is tested in an ambient laboratory environment. Performance of the constituent Sub-capabilities is observed in addition to the Capability as an integrated system. Analytical modeling of the integrated Capability is performed.

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 5

Advanced Planning & Integration Office

5 **Integrated Capability Demonstrated in a Relevant Environment**

An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment to the Capability.

-of appropriate scale

-functionally equivalent flight articles

-all system interactions and interfaces identified

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

Capability Readiness Level 6

Advanced Planning & Integration Office

6 **Integrated Capability Demonstrated in an Operational Environment**

The Capability is near or at the completed system stage. The integrated Capability is demonstrated in an operational environment with the intended user organization(s).

-full scale flight articles

-demonstrated in the intended operational ‘envelope’

Return

Capability Readiness Level 7

Advanced Planning & Integration Office

7 Capability Operational Readiness

The Capability has been proven to work in its final form under expected operational condition. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

-heritage? (multiple missions…?)

Return

* Subcapabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

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National Research Council Dialogue to Assess Progress on

NASA's Human Exploration Systems and Mobility Capability Roadmap Development

General Background and Introduction

Thomas Inman

March 29, 2005

Why Are We Here?

Advanced Planning & Integration Office

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:
  - Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?
  - Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels [TRLs] and Capability Readiness Levels [CRLs] or other appropriate methodologies)
  - Are proper metric for measuring advancement of technical maturity included?
  - Do the Capability Roadmaps have connection points to each other when appropriate

Agenda

- **General Background and Introduction of Capability Roadmaps**
  - **Agency Objective**
  - **Strategic Planning Transformation**
  - **Advanced Planning Organizational Roles**
  - **Public Involvement in Strategic Planning**
  - **Strategic Roadmaps and Schedule**
  - **Capability Roadmaps and Schedule**
  - **Technology and Capability Readiness Levels**
  - **Relationships Between Roadmaps**
  - **Purpose of NRC Review**
- **Capability Roadmap Development (Team Progress to Date)**

Agency Goals and Objectives

Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	1. Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	6. Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	7. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	8. Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	4. Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	9. Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	5. Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	10. Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

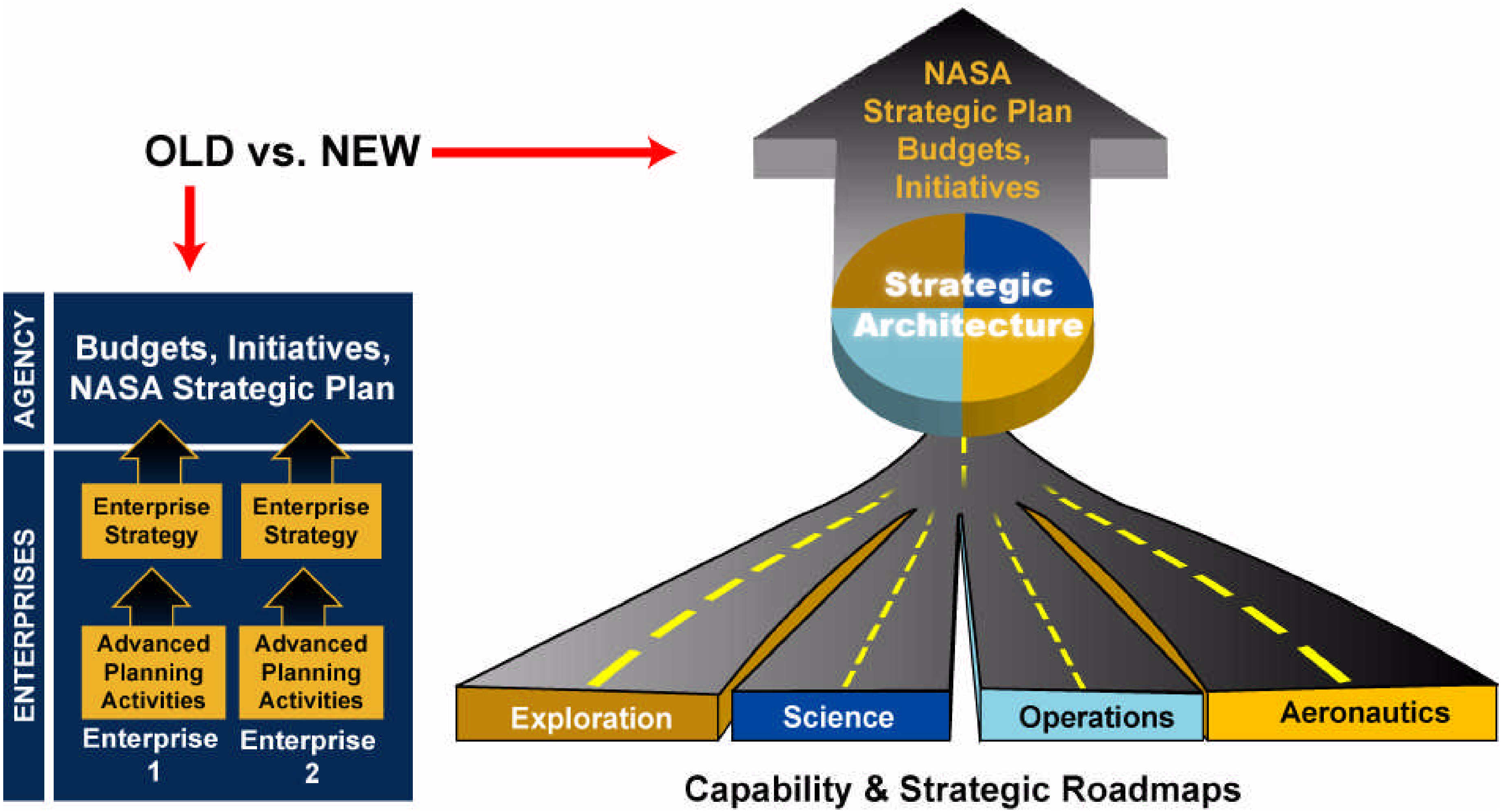
Agency Goals and Objectives

Advanced Planning & Integration Office

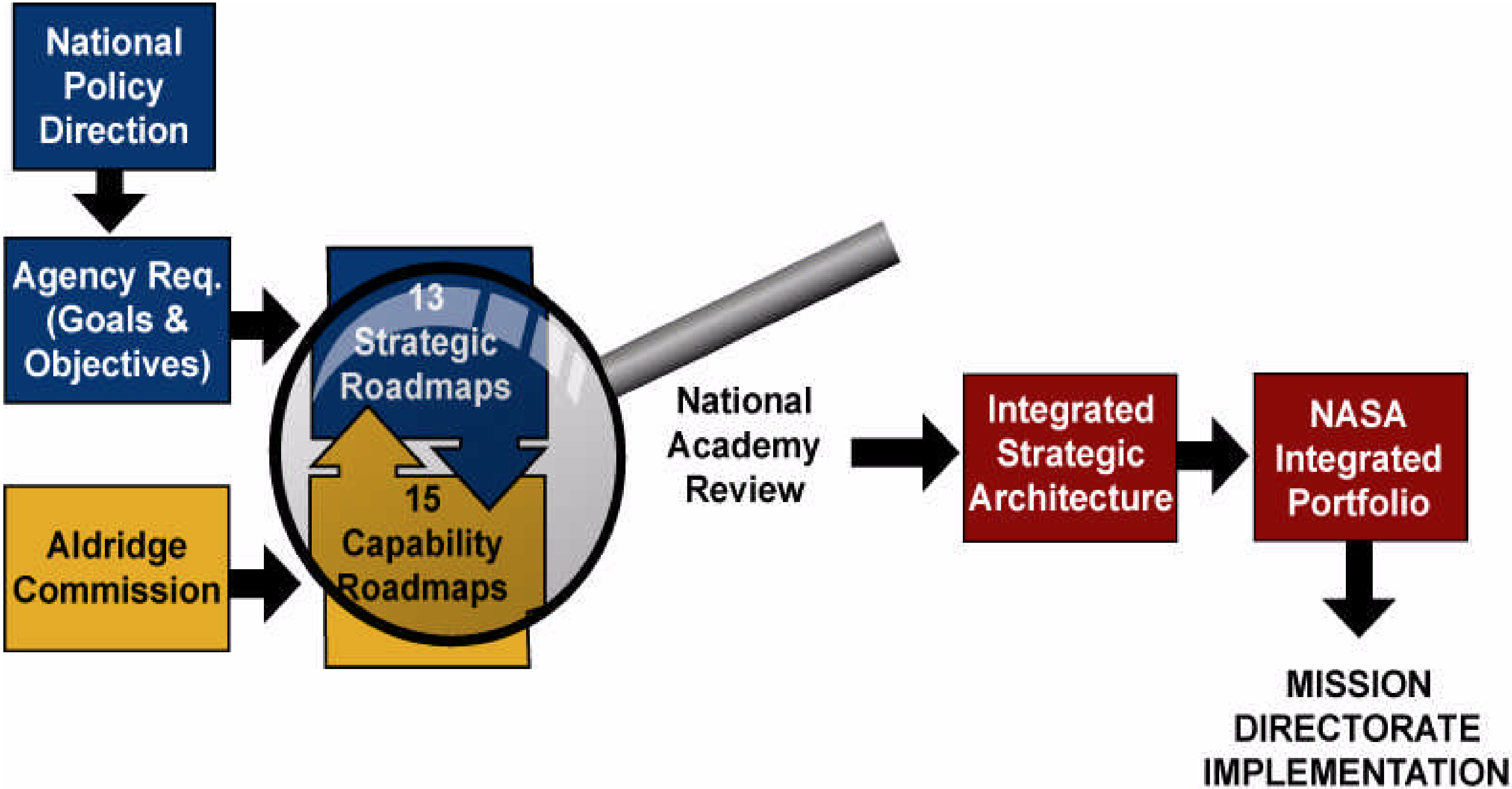
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	3. Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration.	4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	5. Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	11. Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	14. Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems. (SRM 9)	17. Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)
	12. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	15. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)	18. Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)
	13. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	16. Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	

Strategic Planning Transformation

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Charles Elachi)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - ➢ RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - ➢ Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - ➢ Review by the National Research Council (NRC)
    - ➢ Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration

- Roadmaps will include:
  - Broad human and robotic science and exploration goals, priorities, anticipated discoveries
  - High-level milestones, options, and decision points
  - Implementation approaches, suggested missions

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators also with each team

◤ = DoD Participation (marked: Solar System Exploration; Search for Earth-Like Planets)

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Directorate and APIO Coordinators also with each team

= DoD Participation

Strategic Roadmaps Schedule

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Milestone	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Plan Approved and Co-chairs Signed Up	▬	▲										
Complete Team Formation, Begin Work	▬	▲										
Interim Roadmap Products	▲	▬	▬	▲								
Teams Mid-term Status Review					▲							
Interim Roadmap Deliverable						▲						
First Synthesis Workshop							▲					
Roadmaps Submitted for NRC Review								▲				
NRC Reviews Complete								▲				
Second Synthesis Workshop								▲				
NAC Workshop										▲		
Integrated Strategic Architecture												▲

Capability Roadmaps

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- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.
- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

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- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmaps are based on the Presidential Commission's recommendation of technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

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- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

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- **Guidelines for Team Member Selection**
  - Small teams of 12 -15 members with participation from:
    - 1/3 Industry
    - 1/3 NASA & other Government Agencies
    - 1/3 Academia
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

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Capability	NASA chair	External chair
◤ High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
◤ In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
◤ Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
◤ Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
◤ Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators also with each team

◤ = DoD Participation

Capability Roadmaps - continued

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Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Directorate and APIO Coordinators also with each team

◤ = DoD Participation

Capability Roadmap Schedule

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MILESTONE	Nov	De	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Begin Roadmap Teams Formation	▲										
Public Workshop in Washington	▲										
Working First Drafts of Roadmaps	▲	━	━	━	▲						
Strategic Planning Council Preview				▲							
Engineering Academy (NRC) Dialogues					▲	▲					
Identify Potential Gaps for POP Input						▲	━	▲			
Strategic Roadmap Drafts Complete						▲					
Align with Strategic Roadmaps						▲	━	▲			
Phase 2 - Engineering Academy (NRC) Summary Review								▲	━	▲	
Brief Strategic Planning Council									▲		
Finalize Roadmaps										▲	▲

Technology Readiness Levels

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- 9 Actual System Proven in Operation
- 8 Actual System Qualified by Demonstration
- 7 System Prototype Demonstration in an Operational Environment
- 6 System/Subsystem Model or Prototype Demonstration in a Relevant Environment
- 5 Component and/or Breadboard Validation in a Relevant Environment
- 4 Component and/or Breadboard Validation in a Laboratory Environment
- 3 Analytical and Experimental Critical Functions Characteristic Proof-of-Concept
- 2 Technology Concept and/or Application Formulated
- 1 Basic Principles Observed and Reported

Capability Readiness Levels

Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

❖ A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

❖ Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities).

Relationships between Roadmaps

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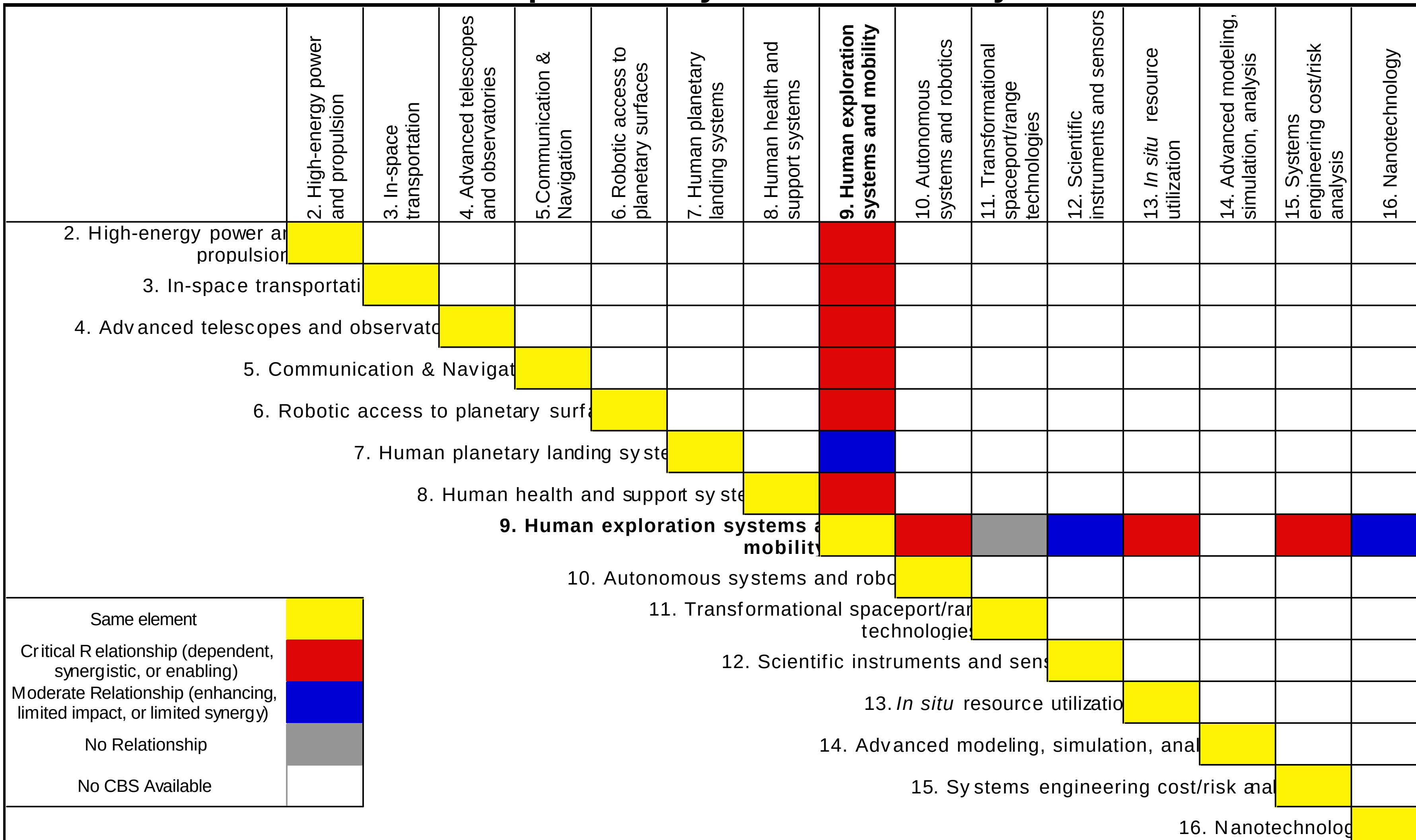
Human Exploration Systems and Mobility



Relationships between Roadmaps, cont'd

Advanced Planning & Integration Office

[9] Human Exploration Systems an Mobility	Capability Flow and Criticaltiy	[10] Autonomous Systems and Robotics	Nature of Relationship
Sub-Topic or Subsidiary Capability		Sub-Topic or Subsidiary Capability	
9.1 Exploration Activities; Operations	→	10.1 Crew-Centered Operations; Logistics, Support Tools, EVA Support	EVA/IVA performance and support, Analysis and operations tools
9.1 Exploration Activities; Command and Control	↔	10.5 Robotics for Solar System Exploration	Telerobotic and crew-assist operations
9.1 Exploration Activities; Observation	↔	10.7 Robotics for In-Space Operations	Telerobotic and crew-assist remote sensing
9.2 Mobility; Surface Transportation of Crew/Robots	←	10.6 Robotics for Lunar and Planetary Habitation	Crew transportation (rovers, tethers, je packs, etc.), Robot and equipment transportation (hoppers, crawlers, rail carts, wagons, etc.)
9.2 Mobility; In-Space Transportation of Crew/Robots	←	10.7 Robotics for In-Space Operations	Crew transportation (tethers, jet packs, etc.), Robot and equipment transportation (manipulation arms, cranes, rail carts, etc.)
9.3 Assembly and Deployment; Staging and Construction	→	10.3 Autonomous Vehicle Control	AR&D, Capture and berthing systems
9.3 Assembly and Deployment; Staging and Construction	→	10.7 Robotics for In-Space Operations	Positioning, joining and assembly of systems
9.4 Servicing; Inspection, Maintenance and Repair	↔	10.2 Integrated Systems Health Management	Monitoring, inspection and repair of vehicle systems
9.4 Servicing; Inspection, Maintenance and Repair	↔	10.4 Autonomous Process Control and Embedded Autonomy	"Smart" systems and crew-assisted operations
9.5 Construction; Habitat Outfitting	←	10.6 Robotics for Lunar and Planetary Habitation	Robotic or crew-assisted assembly an verification (manipulation arms, tools, instruments, etc.)

Purpose of NRC Review

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- **NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:**
  - **Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?**
  - **Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels [TRLs] and Capability Readiness Levels [CRLs] or other appropriate methodologies)**
  - **Are proper metric for measuring advancement of technical maturity included?**
  - **Do the Capability Roadmaps have connection points to each other when appropriate**

Back-up charts

Capability Readiness Levels Defined

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- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  - The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  - A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modeling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  - A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  - An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  - The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).
    - -full scale flight articles
    - -demonstration in appropriate operational ‘envelope’
- **CRL 7: Capability Operational Readiness**
  - The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under “mission” conditions.

Capability 9.1
Exploration

Presenters: Rick Eckelkamp, Team Coordinator
Jim Blacic

9.1 Exploration Activities

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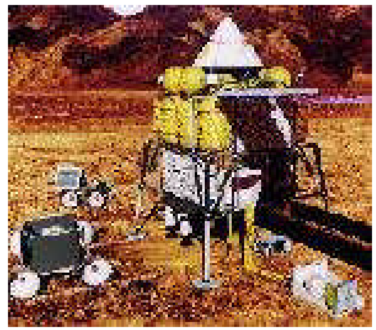

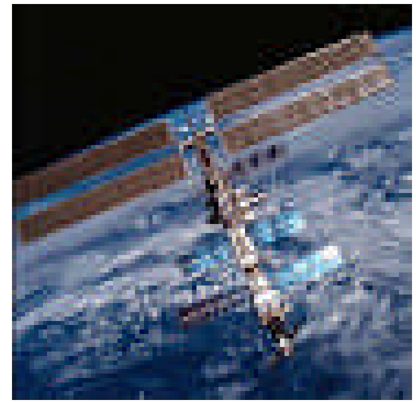

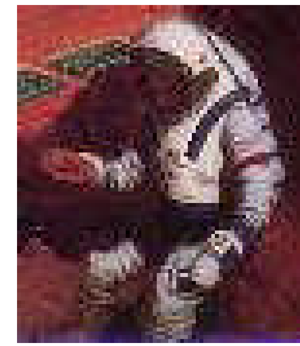

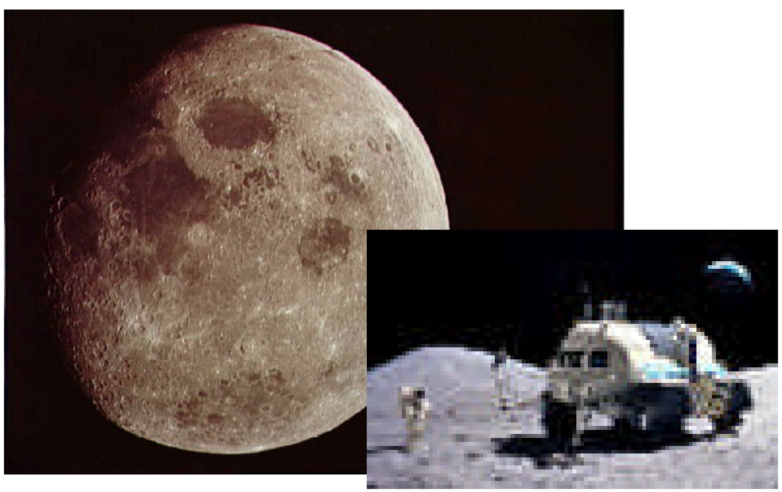

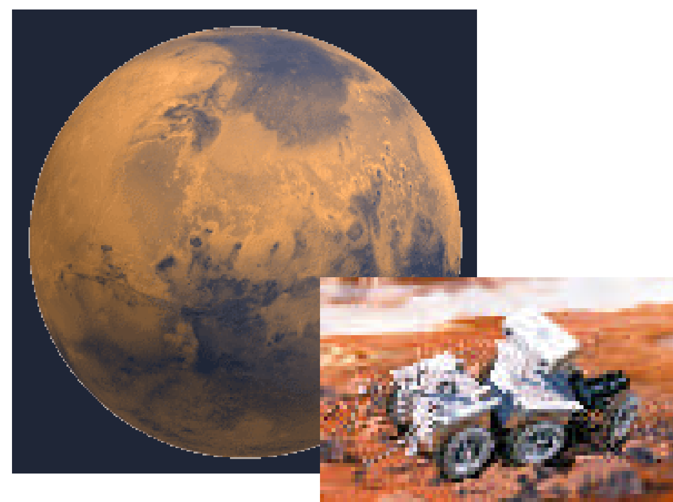

Exploration Challenge

- To build an efficient, cost effective exploration infrastructure,
- To coordinate exploration robots & crews from multiple earth sites to accomplish science and exploration objectives, and
- To maximize self-sufficiency of the lunar/planetary exploration team.

Exploration Challenge Focused

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- The challenge is to preserve exploration and science participation by essential Earth-based personnel within the new context of an operationally efficient, crew-centered system.
- Efficiency and safety concerns dictate heavy use of automation and robots working in cooperation with humans.
- This summary pitch and the appendix material outline the capabilities required to accomplish these objectives.

Capability Breakdown Structure
9.1 Exploration

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9.1
Exploration Activities

- **9.1.1** Physical Access to Exploration Targets
- **9.1.2** Observation
- **9.1.3** Analysis
- **9.1.4** Operate
- **9.1.5** Command and Control Information

More details for all sections are given in the Appendix

Drivers/Assumptions for Exploration

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- Lunar missions will develop the capabilities to send humans to Mars (hence must be of long duration, > 6 months)
- Scientific exploration will require:
  - Advanced sampling techniques (surface and subsurface)
  - Analytical capability available on the Moon and Mars
  - Global access
- Power will be readily available (100s of KW available to bases)
- Communications – very high bandwidth will be provided at least locally
- Crew will need rapid access to large databases for both exploration and maintenance
- Robotic devices must be capable of significant autonomous operation
- Environment protection will be available for radiation (including solar flares), dust, and other environmental hazards on the Moon and Mars

Exploration Activities
Themes and Goals

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- This sub-team treats three integrated themes:
  - What are the required elements/tools of lunar/planetary field science and field exploration? (9.1 - 9.3)
  - What kind of operational issues need to be addressed for exploration efforts? (9.4)
  - What are the associated elements of a command and control system? (9.5)

- Exploration Sub-team Goals:
  - Identify specific capabilities (hardware, software, techniques, and processes) that must be developed to achieve successful exploration.
  - Outline operations trades to accomplish exploration in an efficient and affordable manner.

Exploration Mission Evolution Flow

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Earth-based control of multiple reconnaissance robots

Earth-based control of teams of infrastructure-building robots

Astronauts arrive and work in cooperation with robots.

– Building infrastructures
– Exploring
– (Astronauts' stays start with days; then, proceed to months)

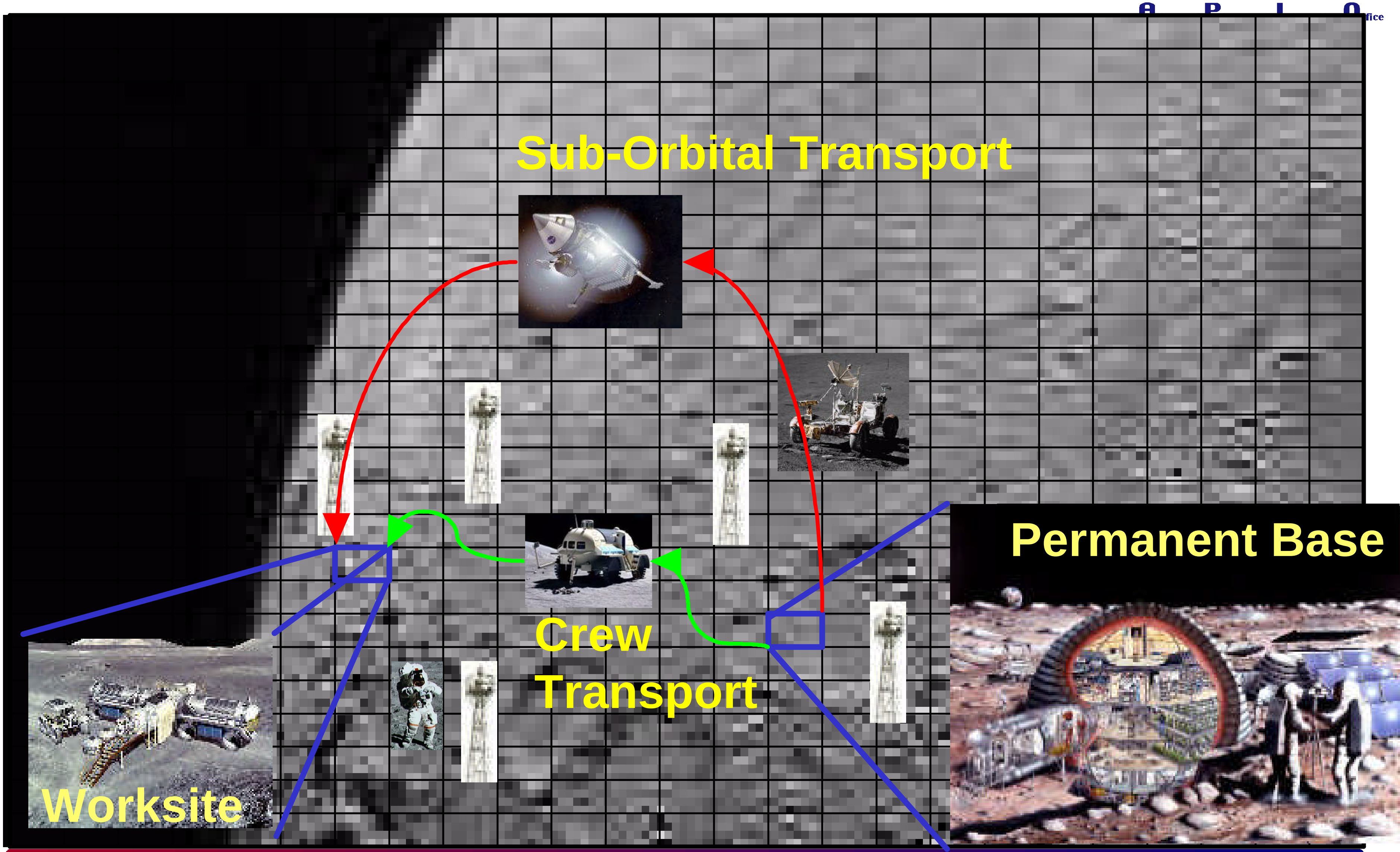
The surface base comes online.

Remote site sorties begin, supported by surface base.

Exploration Activities Context

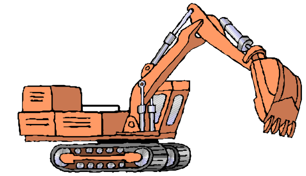
- The Capabilities presented herein are in the context of conducting lunar/planetary remote work missions with the following profile:
  - Earth-based operations performing strategic planning and on-call in-depth failure and contingency analysis
  - A permanent lunar/planetary base staffed with a large crew performing surface and remote site support functions
  - Field EVA personnel performing tasks at one or more remote sites
    - 3-4 crew per site, staying for up to two weeks
    - Remote crew housed in pressurized crew mobile unit with normal background radiation protection (rapid surface transport & early warning high radiation warning system assumed)
    - Substantial highly-automated operational capabilities in addition to rovers and robotic assistants
    - Automated mobile units can be sent to an unstaffed site ahead of the crew
    - Crew arrival via high-speed transport
- Missions are assumed to be as self-sufficient as possible.
  - Lunar Missions Operations are analogues for Mars Mission Operations

Exploration Mission Context

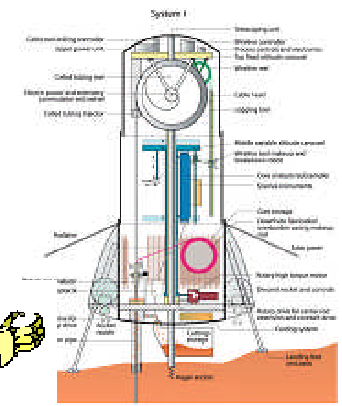


Summary of Strong needs for Surface Exploration

Capabilities in most need of development:

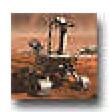



- Early teleoperated or equivalent machine(s) to construct large trenches for habitat "cut and cover" and to move dirt in general

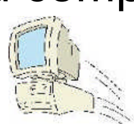


- Drilling and subsurface sampling at depths beyond 1 m
- Other advanced planetary science tools and techniques

- Multi-sensor field exploration robots, human assistant robots, and other construction robots



- Robust space-qualified computers and advanced operational software



- <u>Robust human exploration operations control architecture</u>

9.1 Exploration Summary Roadmap

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Major milestones:
- 2008 CEV Test Flight
- 2010 Recon Robots at the Moon
- 2012 Robotic Infrastructure Building Begins
- 2015 Initial Human Lunar Presence
- 2017 ISRU Production Starts
- 2020 Surface Base Opens

Key Assumptions: Human Exploration of Moon & Mars
- 2008 Lunar Orbiter
- 2010 Integrated Field Demonstration
- 2014 CEV LEO
- 2020 Long Term Human Lunar Presence

Area	Milestones
Reconnaissance Tools/Robots	2008 Orbital, Robot Rovers; 2010 Surface Resource; 2011 Subsurface Structure; 2015 Prospecting Fields Selection
Sample Collection Tools/Robots	2008 Trenching; 2010 Shallow Drilling; 2016 Deep Drilling; 2020 Remote Site Science Tools online
Infrastructure Tools/Robots	2012 Trenching, Earth Moving; 2014 Structure Utility Roughing In; 2015 Shell Structure Utility; 2017 Fine Detail Construction
Operations Advanced Software Capability	2007 Trajectory Design; 2008 FDIR 1; 2009 Planning; 2011 Re-planning, Contingency Analysis; 2012 FDIR 2; 2015 On-surface Training; 2017 FDIR 3; 2020 Field Science Data & Execution Support
Command and Control Infrastructure	2008 Initial Centers online for vehicle & robotic control; 2011 Inter-control center systems data sharing & backup for systems/robotic control; 2015 Inter-control center shared planning & re-planning; 2019 US control centers connect to international control centers
Essential Command and Control Support Infrastructure Development	2012 – 2016 Initial surface navigation and communication beacon deployment; 2017 – 2020 High bandwidth surface base communication system deployment
Distributed Command and Control Process Development	2006 First draft of centers' process and functional allocation trades; 2007 C&C functional allocation trades finalized; 2009 U.S. distributed C&C operational plan in place; 2011-2015 International C&C plan development

Timeline: 2005 — 2010 — 2015 — 2020

◆ Major Decision

▲ Major Event / Accomplishment / Milestone

Explorations Cost Advisory: NASA Programs' Budget History

- Due to yearly budget pressures, NASA has historically concentrated mostly on vehicle hardware development and low initial costs.
- The focus has not been on providing efficient operational systems that would lower total lifetime costs.
- As a result, high operations costs have prevented NASA from sponsoring many worthwhile programs.
- A sustainable exploration program should allocate funds from the onset to develop an efficient operational exploration system.
- Besides saving money, an efficient operational system will be essential for Mars operations.

Additional Detail 9.1 Exploration

9.1.4
Operate

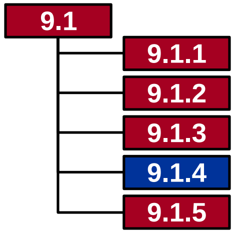
- **9.1 Exploration Activities**
  - **9.1.4 Operate**
    - 9.1.4.1 Plan/Re-Plan
    - 9.1.4.2 Setup/Teardown
    - 9.1.4.3 Train
    - 9.1.4.4 Perform
    - 9.1.4.5 Recover
    - 9.1.4.6 Maintain
    - 9.1.4.7 Document

- 9.1
  - 9.1.1
  - 9.1.2
  - 9.1.3
  - 9.1.4
  - 9.1.5

9.1.4 Operate

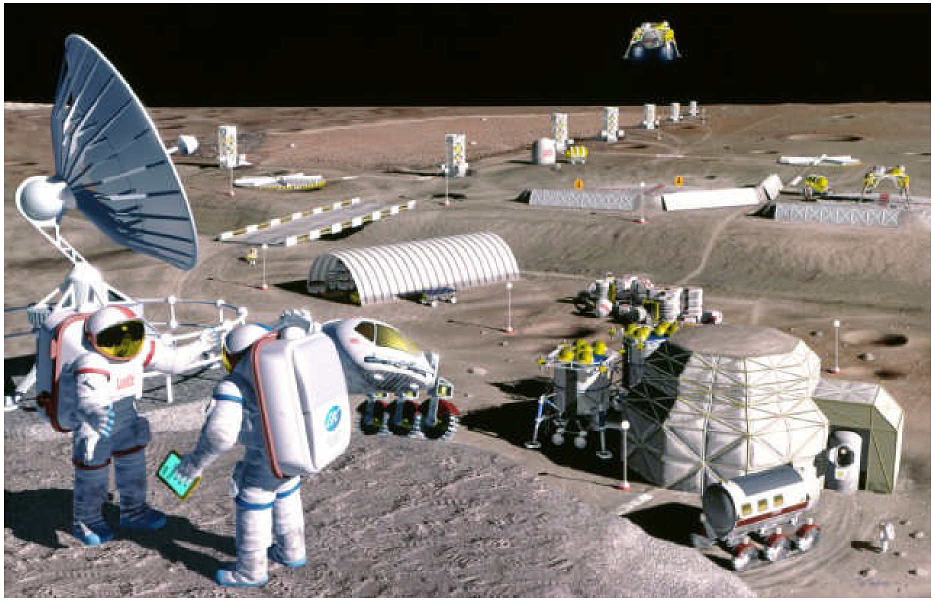
- **Description**:
  - “Operate” is the full-life cycle of an activity from concept to close-out for Assembly, Science and Exploration.

- **The crew performs Exploration Activities to;**
  - Study geologic features
  - Explore for resources
  - Install scientific equipment
  - Conduct engineering activities
  - Explore the environment



9.1.4 Operate

- **The Crew/System must operate these activities in a self-sufficient manner**
  - Plan/Replan
  - Setup/Teardown
  - Train
  - Perform
  - Recover
  - Maintain
  - Document



9.1.4.1
Plan/Replan (Surface IVA/Earth)

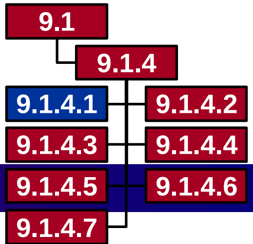
- **Description**:
  - Define missions, suites of activities
  - Perform pre-mission contingency analyses
  - Construct trajectory profiles, activity timelines, automated process scripts, supporting data
  - ***Examples***:
    - On-board crew activity scheduler/resource planner
    - Robotic failure contingency planning

- **Benefits**:
  - Ability to manage activities against limited resources (power, time, consumables, etc).
  - Identify significant contingent plans (strategic/tactical)

- **Figures of Merit**:
  - number of crew tasks done in a work day; rate of resource use; number of planning personnel

- **General Assessment**:
  - Mostly manual processes requiring many personnel; no off-earth capability; promising partial prototypes exist

- **Development Required**: **Medium**



9.1.4.2
Setup/Teardown (EVA/IVA)

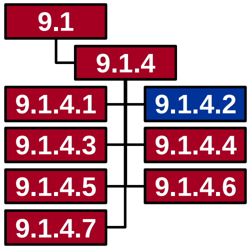
- **Description**:
  - Identify areas of exploration
  - Deploy tools/support equipment and consumables
  - Tear-down and retrieve equipment, pack samples
  - ***Examples***:
    - Deploy navigation/communications surface beacons
    - Robots prepare in-space EVA site before crew egresses
    - Robotic planetary surface reconnaissance

- **Benefits**:
  - Timely preparation for exploration activities, use of robots increases crew EVA efficiency

- **Figures of Merit:**
  - Amount of crew EVA time and resources needed, number of parallel activities accomplished per unit time

- **General Assessment:**
  - Some planetary & ISS robotic successes, more progress needed in robot autonomous activity control

- **Development Required**: Medium



9.1.4.3
Train (IVA/Earth)

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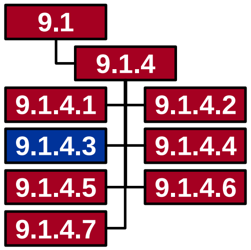
- **Description**:
  - Preparing for an activity by practicing activities using equipment and/or computer models, virtual reality (VR), etc.
  - ***Examples***:
    - **On-board "just-in-time" training for science activities**
    - **Planetary surface system refresher training**
    - **Human tele-robotic robot training**
    - **Inter-robot task training transfer**

- **Benefits**:
  - Ability to familiarize the crew with work processes and practices, efficient training of robots

- **Figures of Merit:**
  - Time required to train crew and robots, ability to field new equipment & experiments without requiring crew training on Earth

- **General Assessment:**
  - 1&2) NSTS & ISS have some onboard training devices; ground-based VR training exists; 3) tele-robot training used in some industries; 4) robot-to-robot training in experimental stage

- **Development Required**: **1 & 2 – Low; 3 & 4 - Medium**



9.1.4.4
Perform (EVA/IVA)

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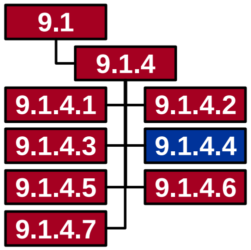
- **Description**:
  - To perform the activity that has been planned
  - Crew or robots using a repertoire of software aids, hardware tools, and vehicles
  - ***Examples***:
    - Automatic execution of scripted robotic activity plans
    - Surface-based resource planner
    - Crew Situational Awareness System
    - Robust data access systems for the EVA crew

- **Benefits**:
  - Actual achievement of science and exploration goals

- **Figures of Merit:**
  - Time to achieve activity completion per task; ability to manage multiple tasks at the same time; situational understand of the Crew about the activity; safety of the Crew during EVA/IVA

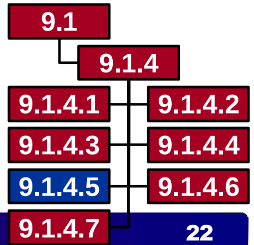
- **General Assessment:**
  - Tightly managed schedules and processes for most activities, Single sequential activities are the norm. Situational Awareness and Multi-modal interfaces limited.

- **Development Required**: Medium



9.1.4.5
Recover (EVA/IVA)

- **Description**:
  - To be able to adapt to a change in the activity or equipment status
  - To be able to implement backup/contigencies in a time-critical fashion
  - *Examples*:
    - Human and system health monitoring, fault detection, and reconfiguration
    - Invocation of contingent plans
- **Benefits**:
  - To continue an activity in the presence of changing requirements, system health, and environmental conditions.
  - Identify significant contingent plans (tactical/immediate)
  - Improves safety to systems and crew
- **Figures of Merit**:
  - Time to diagnose a problem, and modify plan accordingly
- **General Assessment**:
  - After-the-fact analysis is very robust; Real-Time Systems Health Management is limited by the on-board sensing capability (weight and power concerns). Caution and warning events require human expertise to resolve. Inflexible recovery schemes (typically scripted failover to backups).
- **Development Required**: High



9.1.4.6
Maintain (EVA/IVA)

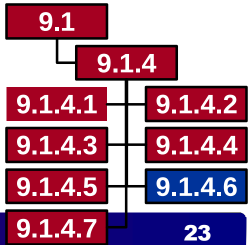
- **Description**:
  - To perform needed support, reconfiguration or repairs
  - ***Example***:
    - On-line documentation, procedures, manuals, videos
    - Embedded sensors for health management

- **Benefits**:
  - Ability to repair a defective system in-the-field
  - Reduced maintenance costs through adoption of condition-based maintenance policies
  - Faster turnaround of reusable systems

- **Figures of Merit**:
  - System down time; logistics required to maintain operations; Human intervention time required; # of replacements vs repairs required

- **General Assessment: Informed Logistics:**
  - Limited built-in troubleshooting aids in components and subsystems.
  - Condition-based maintenance (instead of fixed schedules) gaining ground in DoD and commercial aviation.
  - Early investigations into prognostics (notably JSF and 777).

- **Development Required**: High



9.1.4.7
Document (EVA/IVA)

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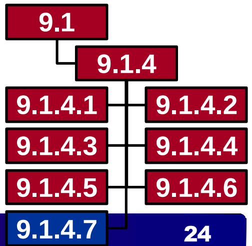
- **Description:**
  - To capture and record the results of activities that are occuring (or have occurred)
  - ***Examples***:
    - Automated Audio/visual capture and information linkage of Crew state and samples
    - Intelligent telemetry documentation
    - Spoken language recording/recognition
- **Benefits**:
  - Ability to share the Full context and record of all scientific and explorations activities; Ability for the Crew to stop and restart activities efficiently
- **Figures of Merit:**
  - % of the information and context recorded for every Exploration activity; time needed to understand what occurred in the activity by a 3rd party
- **General Assessment:**
  - Current SOA in space is recorded voice and video loops; manual digital pictures; Automated context recording systems are in initial development. Limited
- **Development Required**: **Medium - High**



Maturity Level – Capabilities for 9.1.4 Operate

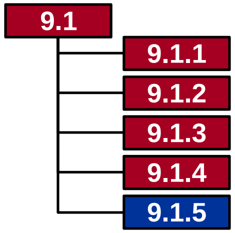
Capability / Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.4.1 Plan/Re-Plan. *Key Tech: Crew-centered tactical planning and adaption*	Ground-based: Timeplanner, MAPGEN, SPIFE	*6*	An on-board capability to plan activities and schedules against resources / time	2005	2010	5
9.1.4.2 Setup/Teardown *Key: Automated construction and site preparation*	Automated Bulldozers, Unfolding tents	*3*	Cooperative automation assembling and constructing systems	2009	2014	2
9.1.4.3 Train *Key: Just-in-time training for Crew while in field*	ISS systems; Military systems	*5*	VR and Multimodal portable training syetem. Human factors	2008	2012	5
9.1.4.4 Perform *Key: Coordinated human automation interaction*	Hubble repair; N/A	*3*	EVA Crew and Robotics coordinating together and with ground on common tasks	2009	2014	2
9.1.4.5 Recover *Key: Systems being able to gracefully degrade and reconfigure*	Ground-based after the fact.	*5*	Prognostic and onboard diagnosis and health management	2007	2010	4
9.1.4.6 Maintain *Key: In-situ repair and support of systems*	RFID, and military	*5*	Design and Logistics for Maintenance and common parts	2007	2010	4
9.1.4.7 Document *Key: Automatically capturing the complete record of all Crew and system actions*	Video, and Audio clips	*5*	Focus at depth Volatile capture mechanism	2007	2012	4

9.1
Exploration Activities

9.1.5
Command and Control & Informatio

9.1.5 Command and Control

- **Description**:
  - To control the timing and execution processes of exploration activities
  - Includes communication, procedural, software, and process methods
  - ***Examples***:
    - Lunar/planetary surface robot control
    - Communications reconfiguration
    - Sharing of exploration data among control centers
- **Benefits**:
  - Provides essential operational infrastructure that enables accomplishment of mission objectives
- **Figures of Merit:**
  - number of ground personnel required to:
    - control and plan operations and
    - maintain operational capabilities
  - cost per accomplished exploration objective
  - number of exploration objectives met
- **Development Required**: Medium to HIGH



Change is Necessary

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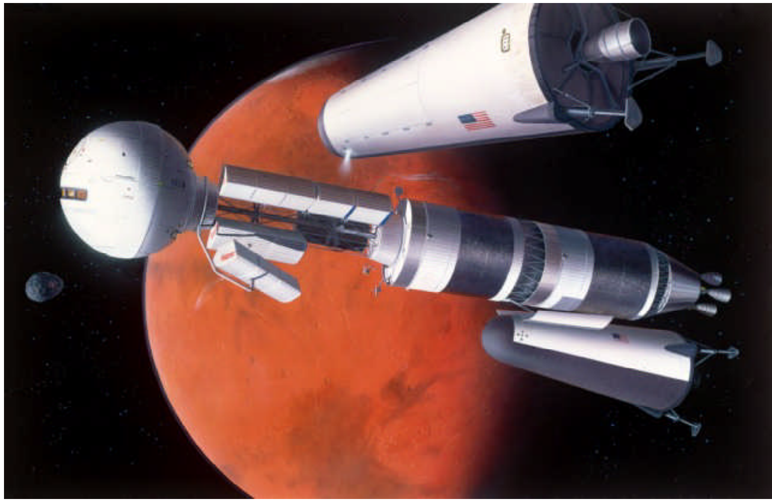
To have a successful and flourishing exploration program, we must make a "Earth-shaking change" in how we perform command and control.

- **From <u>ground-centered</u> control to <u>crew-centered</u> control**
- **"They that begin a program with a large marching army continue that program with a large marching army."**
- **Sheer economics and competition demand this change.**

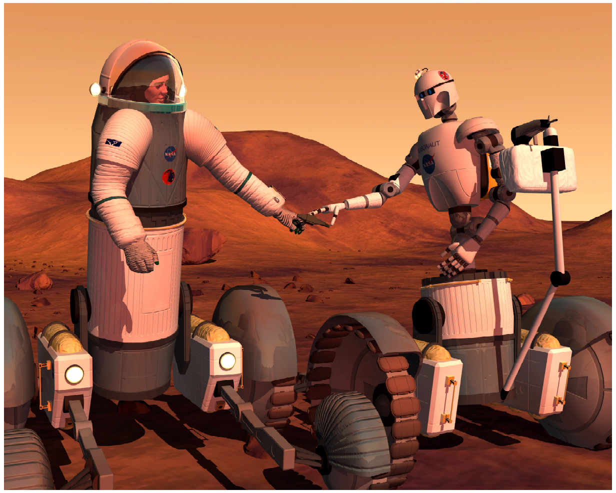
9.1.5 Command and Control

From today's ground-centered concept of Command and Control to a Crew-centered concept of Control



Mission Management Systems
- *Routine systems management*
- *Anomaly response and recovery*
- *Vehicle & mission level awareness*

Human-automation interaction
- *Adaptive decision support*
- *Situation awareness displays*
- *Crew Caution & Warning alerts*



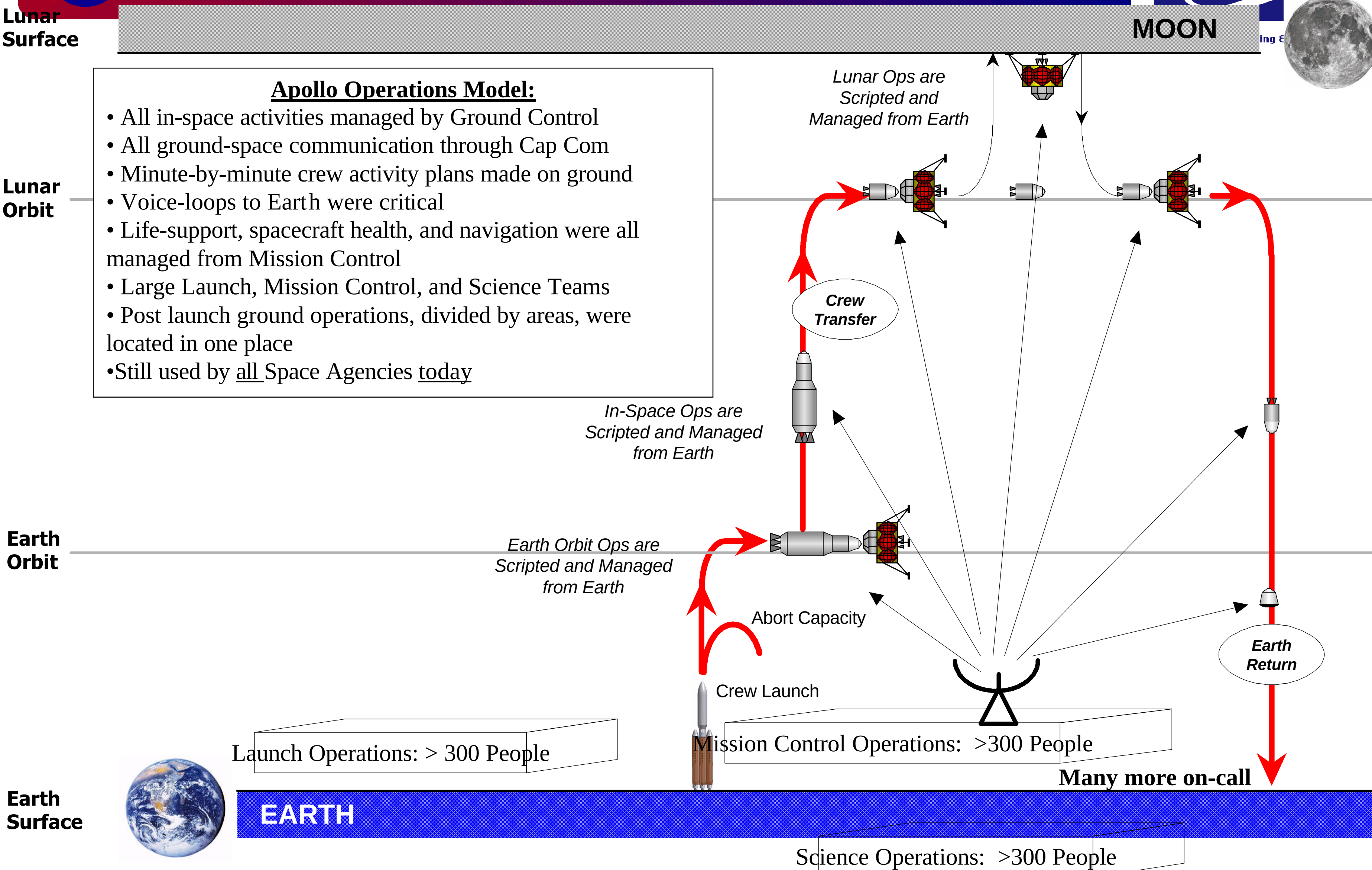
Robotic Systems Management
- *Human-machine multi-agent coordination*
- *Real-time activity planning and sequencing*

Networked Communication Infrastructure
- *Adaptable Communications to bring information to/from the Crew*

Apollo-Style Mission Operations

Apollo Operations Model:

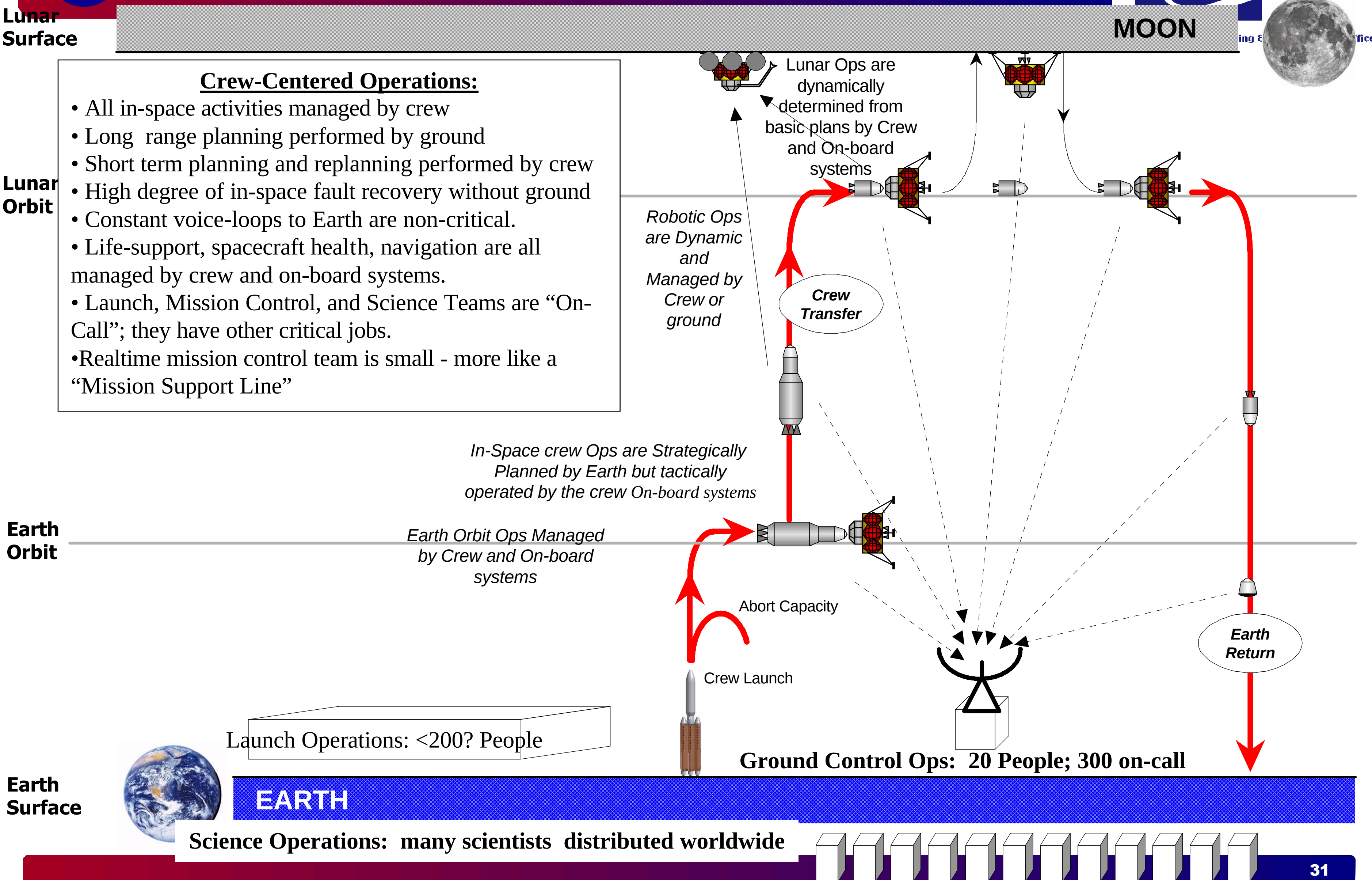
- All in-space activities managed by Ground Control
- All ground-space communication through Cap Com
- Minute-by-minute crew activity plans made on ground
- Voice-loops to Earth were critical
- Life-support, spacecraft health, and navigation were all managed from Mission Control
- Large Launch, Mission Control, and Science Teams
- Post launch ground operations, divided by areas, were located in one place
- Still used by all Space Agencies today



The Goal: Crew-Centered Operations

Crew-Centered Operations:

- All in-space activities managed by crew
- Long range planning performed by ground
- Short term planning and replanning performed by crew
- High degree of in-space fault recovery without ground
- Constant voice-loops to Earth are non-critical.
- Life-support, spacecraft health, navigation are all managed by crew and on-board systems.
- Launch, Mission Control, and Science Teams are "On-Call"; they have other critical jobs.
- Realtime mission control team is small - more like a "Mission Support Line"



Mission Control becomes Mission Support

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Distributed ground-flight support is the communication lifeline between crew, robotics, and earthbound operations.

- **The crew needs to**
  - **Perform scientific and engineering activities, and**
  - **Be at the center of command and control activities**
  - **Manage in-space facilities**
  - **Manage deployment of scientific/engineering equipment**
- **The ground is the support to enable this to happen.**

Robotic Control

Robotic Control	Earth	Surface Base	Field
Telerobotic Commanding			
Single-Joint	Yes	Yes	Yes
Coordinated Multi-Joint	Yes	Yes	Yes
Scripted Control			
Hand-Built Script Writing	Prime	Backup	No
Training-Method Script Writing	Yes	Yes	Yes
Script Execution	Yes	Yes	Yes
Voice/Visual Commanding			
Single/Multi-Joint Commanding	No	Backup	Prime
Auto-Sequence Control	Backup	Shared	Shared
Higher-Level Task Initiation	Backup	Shared	Shared
Autonomous Operations Monitoring	Backup	Shared	Shared
Reconnaissance Robot Control			
Long Duration	Prime	Backup	No
Short Duration	Backup	Prime	Backup
Field Robot Crew Assistant Control	No	Backup	Prime

Crew Operations Support

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Crew Operations Support	Earth	Surface Base	Field
Activity Planning			
Yearly/Monthly Planning	Yes	No	No
Contingency Planning	Yes	No	No
Weekly Planning	No	Prime	Support
Daily Planning	No	Shared	Shared
Detailed Activity Schedule Building	No	Backup	Prime
Daily Activity Monitoring	No	Support	Prime
Systems Monitoring	On-Call Expertise	Support	Automated
System Failure Analysis and Reconfiguration	On-Call Expertise	First Aid	Support

9.1.5 Requirements for Efficient Operations/Control

To accomplish efficient operations and control requires:

- **Substantial advances in some areas of autonomous systems, robots, and robotic control,**
- **Development of methods to perform crew-centered and integrated robot-human operations, and**
- **Space communications and computer structures that enable multiple Earth-based control centers to:**
  - **control lunar/planetary robots,**
  - **perform inter-center voice, data, and video exchanges**
  - **perform integrated command and control of in-transit and lunar/planetary operations.**

Maturity Levels for Command and Control

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Order of magnitude faster computers	1800+ MIPS rad. hardened	5	Space qualify, upgradeable	2007	2009	4
Large distributed data bases	Exist today	9	Populate with exploration data	n/a	2011	5
100 MBPS space comm link	1 MBPS	2	Space qualify, upgradeable	2012	2015	2
Web-based/similar space network	Earth equivalent exists totoday	4	Space qualify, upgradeable	2009	2012	3
Inter-control center voice, data, video	Essentials in-place today	8	Upgrade protocols	n/a	2008	5
Exploration Vehicle autonomous nav	NSTS rendezvous, Apollo TL-TE optical, ISS GPS, grnd-based STDN	4	Lunar/planetary surface & orbital nav, TLTE/TP onboard nav	2008-2012	2010-15	3 4
Advances in ground-based robotic control	ISS rudimentary, Robonaut demo, MER control	2	Fast comm link, time delay abatement s/w	2008	2010	3
Autonomous FDIR	NSTS, various fighter jets, deep-space probes, Freedom ISE	4	Inter-system FDIR, AI trend analysis advances	2008-2012	2010-15	3 4

9.1
Exploration Activities

Advanced Planning & Integration Office

9.1 Exploration Activities

- 9.1.1 Physical Access to Exploration Targets
- 9.1.2 Observation
- 9.1.3 Analysis
- 9.1.4 Operate
- 9.1.5 Command and Control Information

More details for all sections are given in the Appendix

9.1.1Physical Access to Exploration Targets

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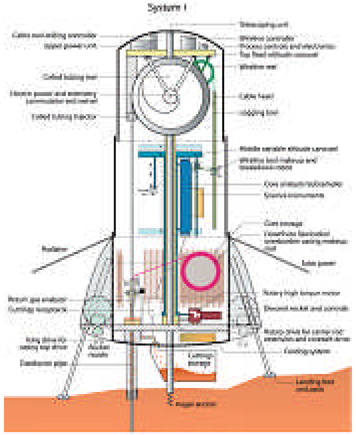
9.1
Exploration Activities

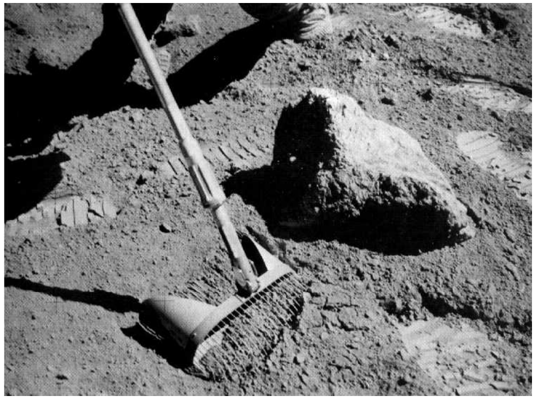
9.1.1
Physical Access to Exploration Targets



9.1.1.1
Sample Collection

9.1.1.2
Trenching

9.1.1.3
Drilling



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9.1.1.1 Sampling

Description – Physical acquisition of planetary solid, liquid or gaseous materials for scientific/engineering characterization or ISRU assessment

Benefits – Enables more accurate, precise and complete characterization of planetary materials than can be done in the field or *in situ*. Creates archive for future study by a larger body of investigators

FOM – Mass, volume, degree of contamination

General Assessment – solid sampling is adequate; gas/liquid technology is inadequate

Development Needed -- Medium

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9.1.1.2 Trenching

Description – Removal of planetary solid material to produce a linear space with vertical or sloping faces that exposes the subsurface for

a) sampling or *in situ* observation
b) placement of habitat modules
c) placement of utility conduits

Benefits – Exposes near-surface planetary materials for scientific investigations. Enables mass-efficient shielding of habitats or utility conduits by "cut and cover"

FOM – length, width, depth; time to construct

General Assessment – shallow trenching is adequate; deeper/longer trenching is inadequate

Development Needed -- a) Medium; b) High; c) Medium

9.1.1.3 Drilling

Description – Removal of planetary solid material to produce a cylindrical hole and core of material. Used for depths beyond the capability of trenching.

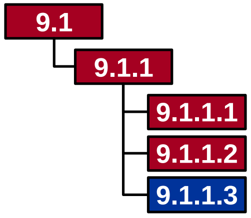
- **a) *Near-surface*: 10-100 cm in loose soils and 1-10 cm in hard rock**
- **b) *Shallow*: 10 cm – 10 m in all rock types**
- **c) *Intermediate*: 10 m- ~300 m in all rock types**
- **d) *Deep*: Beyond ~ 300 m in all rock types**

Benefits – Exposes the planetary subsurface for scientific investigations and discovery; production of resources such as ground water

FOM – % retrieval of cuttings or core; degree of contamination

General Assessment – a) & b) prototypes under development; c) & d) = TRL 1

Development Needed --a) = Low; b) = Med; c) = High; d) = High



9.1.1
Physical Access to Exploration Targets

Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.1.1 Sampling						
(a) Solid (regolith) *Key: sealing; cryogenic sample handling*	Apollo Viking	*9*	Retain volatiles; top-most layer of surface	-	2008	7
(b) Liquid (ground water) *Key: Well completion*	Terres-trial	*1*	Natural-state acquisition / handling;	2015	2030	0
(c) Gas (volatiles, atmosphere) *Key: GCMS, sealed sample container*	Viking	*4,2*	Natural-state acquisition / Handling	2008	2012	6
9.1.1.2 Trenching						
(a) Sampling Trench *Key: Scooping tools*	Apollo Viking MER	*9*		-	2008	7
(b) Habitat Trench *Key: Big "back hoe", explosives*	Terres-trial	*2,2*	Equipment development; explosives technique/materials development	2012	2015	0

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9.1.1
Physical Access to Exploration Targets

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Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
(c) Utility Trench *Key: Powered trencher*	Terr.	*2*	Equipment development	2012	2015	0
9.1.1.3 Drilling						
(a) Near-surface *Key: Very small coring drill*	Proto	*3*	Prototype testing in relevant environment	2008	2010	2
(b) Shallow *Key: Small drill, core capture*	Lab	*3,3*	Prototype testing in relevant environment; core acquisition development	2007	2012	2
(c) Intermediate *Key: Medium drill, core capture*	Terr.	*2,2*	Prototype development and testing	2010	2017	0
(d) Deep *Key: Big drill, core capture, hole completion*	Terr.	2,2,2	Prototype development and testing; well completion development	2018	2025	0

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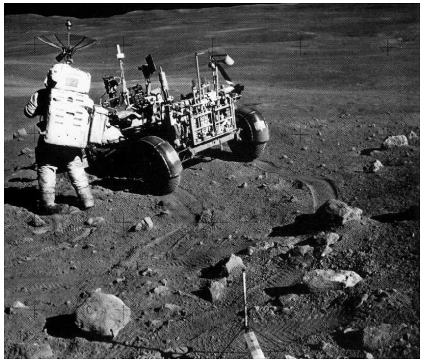
9.1
Exploration Activities

9.1.2
Observation

- 9.1.2.1 Orbital/Aerial Remote Sensing
- 9.1.2.2 Surface Sensing
- 9.1.2.3 Subsurface Remote Sensing
- 9.1.2.4 Surface Outward Observation



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9.1.2.1 Orbital /Aerial Remote Sensing

Descriptions -- a) Orbital: planet-wide imaging and sensing of composition, topography, gravity field, magnetic field; b) Suborbital/aerial: Imaging, composition & topography

Benefits – Determine elemental and mineralogic compositions, topography, geophysical fields; enable site evaluations and surface route planning

FOM – % of major/minor rock-forming elements; accuracy; precision; spatial resolution

General Assessment – Current flight instruments generally adequate; improvements in accuracy/precision and spatial resolution needed; suborbital/aerial platforms needed

Development Needed -- a) Low; b) High

9.1.2.2 Surface Sensing

9.1.2.2.1 Direct Contact

Description – Placement of sensors and/or interrogation energy sources directly in contact with soil or rock surface

- ***Passive*: natural energy emanated or reflected from surface and measured in contact; e.g., natural g radiation spectrometer**
- ***Active*: artificial energy introduced to surface material by contact to produce a characteristic signal measured in contact; e.g., Mossbauer spectrometer**

Benefits – Maximizes the accuracy and precision of measurement location; minimizes the effects of intervening medium such as an atmosphere; allows more time for signal integration compared to orbital/aerial

FOM – Accuracy/precision of major rock-forming elements

General Assessment -- Existing flight instruments adequate; some improvement in accuracy and precision needed

Development Needed -- a) Low; b) Low

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9.1.2.2 Surface Sensing
9.1.2.2.2 Stand-Off

Description – Placement of sensors and/or interrogation energy sources at some distance from the surface being interrogated

- ***Passive:*** Natural energy emanated or reflected from surface and received at a distance; e.g., Vis/IR imaging spectrometer
- ***Active:*** Artificial energy transmitted to the surface material from a distance to produce a characteristic signal; e.g., laser-induced break-down spectrometer

Benefits – Enables measurement at locations not directly accessible by contact, e.g., cliffs; enables simultaneous, contextual measurement of large areas from a single location

FOM – Accuracy/precision of major rock-forming elements

General Assessment -- Current passive flight instruments adequate; Active instruments inadequate

Development Needed -- a) Low; b) Medium

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9.1.2.3.1 Sub-Surface Sensing Automated Image Processing

Description – Use automated techniques to recognize key surface features in voluminous photographic data sets and to interpolate or extrapolate surface features to probable location of key features below the surface:

- Example A: Exposed rock in steep crater walls shows regolith depth (and resources) that extend to surrounding subsurface areas
- Example B: Breached lava tubes (rilles / "skylights") locate intact sections under the surface (up to 300 m diameter; many km length)

Benefits

A) Automated location of exposed rock areas and mapping of expected regolith depth will assist plans to bury habitats (trenching).

B) Automated location of lava tubes (natural shelters from radiation, dust, heat, and cold) may avoid energy-intensive trenching operations

FOM – Depth and size of features mapped; accuracy of predictions

General Assessment -- Improves accuracy, consistency, cost (vs. human)

Development Needed -- Medium

9.1.2.3.2 Sub-Surface Sensing Radiation Interactions

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Description – Assess sub-surface minerals by sensing secondary radiation (neutron, gamma ray/X-ray) from natural or artificial primary radiation interactions with subsurface material (up to ~ 1 meter depth).

Artificial radiation sources might potentially be integrated with radioisotope thermal generators (also used for electrical power or heat)

Benefits –

Neutron spectrometers on Lunar Prospector and Mars Observer located hydrogen and water which could have significant value for ISRU.

New instruments may allow rapid operation from a rover on the surface for precise mapping of resources for future human consumables (e.g., frozen H2O and other volatiles), and for propellant production.

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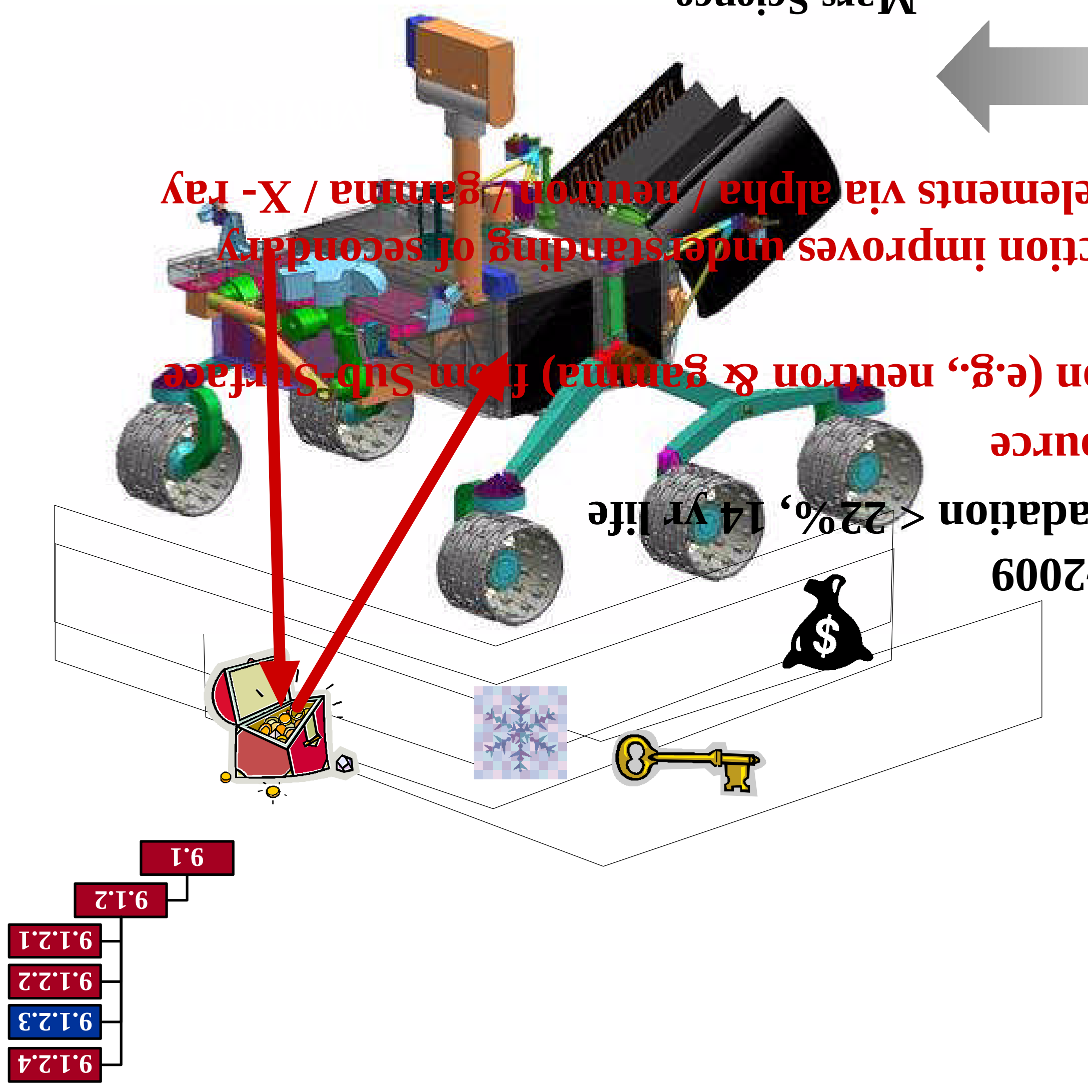
FOM – Depth of observation, energy required; accuracy & precision of data

General Assessment – Proven technique, integration with RTG is new

Development Needed -- Low

Sub-Surface Irradiation by "Multi-Mission Radioisotope Thermoelectric Generator"



9.1.2.3.3 Sub-Surface Sensing Radar Observations

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Description –Locate features and determine characteristics below the surface by illuminating areas of interest with radar. Radar may help locate key ISRU species (such as thick slabs of ice, which reflect circularly polarized radar with a high reverse circular polarization ratio)

A) Radar from Earth: High power, large apertures, long ranges (10^6 km)
B) Radar from Orbit: Intermediate power & aperture, Mid-range (10^2 km)
C) Radar on the surface: Low power, small aperture, short range (1 m)

Benefits –

A) Earth Radar finds ice in Mercury's polar craters (not yet on moon)
B) Orbital Radar (SAR) finds bedrock under dry soil, maybe metal ores (e.g., Chromite / Platinum Group Elements layers in impact melts)
C) Ground Penetrating Radar finds geotechnical features / strata

FOM – Depth of observation, energy required; accuracy & precision of data

General Assessment – Well characterized techniques

Development Needed -- low

9.1.2.3.4 Sub-Surface Sensing Impact Observation (Ejecta)

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Description – High velocity impact vaporizes material from below the surface, allowing spectroscopic observation to determine mineral content (like "LIBS", but with more energy):

A) Natural impacts (meteoroids)
B) Artificial impacts (penetrators, spacecraft components, explosions)

Benefits –Assesses minerals and resources for future human consumables (frozen H_2O and other volatiles) and propellant production

FOM –Knowledge of impact location, Energy used, Degree of contamination

General Assessment – Simple technique needs foresight and coordination

Development Needed -- low

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9.1.2.3.5 Sub-Surface Sensing Impact Sensing (Seismic)

Description – Network of seismic sensors to monitor and interpret surface waves following an impact / explosion on the surface or a "moonquake"

Use new "Spectral Analysis of Surface Waves" technique

Benefits –

- Improve prospects of physical access (e.g., avoid drilling into a subsurface boulder, with blocking and breaking of drill strings)
- Locate voids and deposits of lower density materials (e.g, natural caverns for shelter and condensed volatile deposits for ISRU)
- Potential to identify ice strata that record major comet impacts (and maybe even major Earth impacts) which brought water to the moon

FOM – Instrument mass, energy used; accuracy in lower density deposits

General Assessment -- Transfer geotechnical advances to spa ses

Development Needed -- Medium

9.1.2.3.6 Sub-Surface Sensing Microwave Beam Interactions

Description –

- Generate and focus microwaves via a surface reflector to heat regolith at selected depth(s) (up to ~1 meter)
- Determine composition of released volatiles via spectroscopy (or capture on a cold plate / Quartz Crystal Microbalance)

Benefits –

- Assess location, extent and composition of volatile condensates important for ISRU (water, Argon, etc.) without requiring drilling (thereby reducing time, energy, mass, risk, etc.)
- Microwave beams may also assist in recovery of resources and to sinter lunar regolith and thereby create ISRU-derived structures

FOM – Depth, Instrument mass and energy needs; Accuracy of data

General Assessment – New technique, also beneficial for ISRU processes (suggested by L. Taylor) to sinter lunar regolith and create structures

Development Needed -- **HIGH**

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9.1.2
Observation

Advanced Planning & Integration Office

Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.2.1 Orbital/Aerial Remote Sensing						
9.1.2.1.1 Orbital *Key: Hi-res instruments*	Mars Odyssey	*9*	Higher spatial resolution	-	2008	7
9.1.2.1.2 Suborbital/aerial *Key: Hi-res instruments*	Military UAV	*2*	Higher spatial resolution; vehicle development	2008	2012	0
9.1.2.2 Surface Sensing *Key: Specific instruments*		1-9		Variable	2008	1-6
9.1.2.2.1 Direct Contact (a) Passive *Key: Neutron spectrometer, g spectrometer*	Apollo; Robotic Landers	*9,9*	Higher data integration rate; higher accuracy/ precision	-	2008	6
(b) Active *Key: APXS, Mossbauer spectrometer*	MER	*9,9*	Higher data integration rate; higher accuracy/ precision	-	2008	6

9.1.2 OBSERVATION

Advanced Planning & Integration Office

Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.2.2.2 Stand-off **(a) Passive** ***Key: Vis-IR imaging spectrometer***	**Mars Odyssey,** **CRISM**	***9***	**Higher data integration rate; higher accuracy/ precision**	**-**	**2008**	**6**
(b) Active ***Key: LIBS***	**LANL LIBS**	***3***	**Flight prototype development**	**2005**	**2008**	**2**

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9.1.2.3
SUB-SURFACE OBSERVATION

Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.2.3.1 Auto. Image Process. *Key: Recognize surface features and extrapolate/interpolate*	CalTech JARTool; +human	*5*	Interpolate surface data to subsurface	-x	2008	7
9.1.2.3.2 Radiation Interaction *Key: Integration with powerful external radiation sources*	Neutron Detectors: MO&Lunar Prospector	*9*	Accelerate data rate via radiation Source integrated with Power/ Heat	-x	2008	7
9.1.2.3.3 Radar Observations *Key: Short wavelength circularly polarized for thin ice*	Arecibo & Goldstone	*9*	Higher spatial resolution; Access shadows	2008	2012	7
9.1.2.3.4 Impact Observation *Key: Coordinated observation during impact events*	"Deep Impact" mission	*7*	Coordination with astronomy and Japan's Lunar-A	x	2008	1-6
9.1.2.3.5 Impact Sensing *Key: Spectral Analysis of Surface Waves*	Geo-tech uses	*9*	Coordination with astronomy and Japan's Lunar-A	x	x	x
9.1.2.3.6 Microwave Beam *Key: Focus at depth, assessment (capture?) of volatiles*	Ovens on Earth	*4*	Focus at depth Volatile capture mechanism	-x	2008	6

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9.1.2.4 Platform Observations

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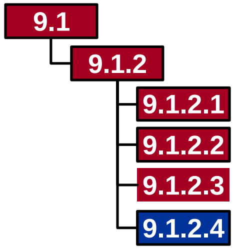
Description:

- The lack of a sensible atmosphere, the extreme stability of the surface, the low (but not too low) gravity, and the nature of its rotation make the lunar surface very useful for observations of objects or phenomena not associated with the Moon itself.
- Targets of Observations
  - The Universe
  - The Earth
  - The Sun
  - The space environment and phenomena in the Earth-Moon or Sun-Earth system such as interactions of the solar wind with the geomagnetic field.
  - Various experiments in the fields of physics and biology carried out in special facilities
- These functions may not be primary objectives for Exploration but would become attractive scientific investments as lunar surface capabilities and resources become available.
- The instruments would, for the most part, be described as telescopes in the sense that they would enable observations of distant phenomena.

Advantages of Moon for Astronomy

Advanced Planning & Integration Office

- Ultra-high vacuum- effectively no atmosphere
  - Perfect transmittance; diffraction-limited imaging
  - Dark sky - no scattered light allowing daytime as well as nighttime observing and observing close to the Sun in the sky
  - Cold sky everywhere and very cold surface environments in certain crates with permanent shadowing, allowing radiative cooling of telescopes
  - No wind, allowing simple sunshades and lightweight structures
- High lunar mass
  - Enormous moment of inertia permits smooth tracking and easy pointing
  - Low but sensible gravity
    - No co-orbiting debris as with spacecraft
    - Dropped tools and parts easily retrieved; favorable work environment compared to zero-g
  - Mass of the Moon shields farside radiotelescopes from Earth “noise”
    - The farside is the only place in the solar system shielded from Earth interference
- Slow sidereal rate
  - Sky sources available continuously for 14 days
    - Long-uninterrupted observation of variable phenomena
    - Long sensor integration times for faint sources
- Very large-scale instruments may be feasible only on the Moon
  - Giant filled-aperture telescopes
  - Large baseline interferometers
  - Farside radio receiver arrays with large areal expanse



Disadvantages of Moon for Astronomy (As seen by scientific community)

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- Expensive to operate human-tended or -emplaced observatories
  - Robotic soft landers cheaper overall although less capable
  - Dedicated human mission for observatory requires development of robotic cargo lander
  - Telescope itself is an expensive instrument (compared to freeflyer)
- Lack of solar power during lunar night
  - Energy storage solutions for lunar night have large mass (e.g., batteries)
  - Nuclear solutions required
    - RTG for small telescope
    - Reactor for large facility
- High radiation background - increased detector noise
- Day-night cycle limits efficiency of single observatory to 50% (compared to deep-space freeflyer)
  - If 100% of sky must be available 100% of time, 2 observatories required
  - Equatorial observatory sees whole sky but any single portion 50% of the time
  - Polar observatory sees 50% of the sky all the time
- Mobilized dust a concern for mirrors and moving parts over time

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Examples of Optical Observatory Instruments

9.1.2.4.1 Telescopes with Optical Elements (i.e., mirrors)

9.1.2.4.1.1 Large-Aperture UV/Optical/IR (UVOIR) Telescope
- Search for life and detection of Earth-like planets
- Formation & evolution of the early universe

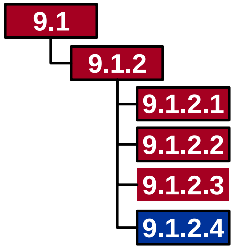
9.1.2.4.1.2 IR and Sub-mm Interferometers
- Studies of forming and evolved extrasolar planetary systems
- Processes and structure of galactic nuclei and quasars

9.1.2.4.1.3 Optical Interferometer
- Imaging nearby stars
- Validating distance scales in the universe

9.1.2.4.1.4 2-Meter Class UVOIR Telescope for Solar System Studies
- Origin of the solar system
- Properties of small bodies, particularly in the Kuiper Belt
- Dedicated study of Mars with monitoring of atmospheric phenomena

9.1.2.4.1.5 Solar monitor facility
- Solar flare physics and prediction
- Solar interior through heleoseismology

9.1.2.4.1.6 Nearside Earth Synoptic Earth Observation Facility
- Continuous monitoring of planetary-scale phenomena
  - Global radiation budget including albedo variation
  - Global climate modeling
  - Geomagnetic storms and aurorae
- Continuous monitoring of LEO and GEO
- Earth surface observation and surveillance



Examples of Observatory Instruments Not Based on Standard Optics

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9.1.2.4.2 Radio Telescopes

- Low-frequency observations not possible from Earth
- Long-baseline interferometer
- Shielding from terrestrial radio interference

9.1.2.4.3 Large-Aperture X-ray and Gamma-ray Telescopes

- Physics of neutron stars and black holes
- Stellar accretion disks

9.1.2.4.4 Solar-terrestrial physics facility

- Direct solar wind measurement
- Reconnection events in the geotail

9.1.2.4.5 Particle Physics, Cosmology, and Gravitational Waves

- Cosmic ray measurements
- Neutrino telescope
- Gravitational wave detector
- Moon-scale particle accelerator using ambient vacuum

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9.1.2.3
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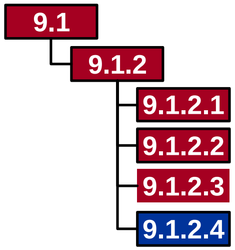
Details and Benefits of 9.1.4.1: Optical Observatory Instruments

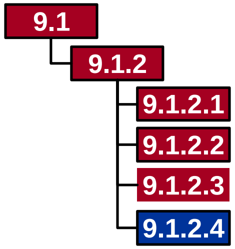
- *Description*: Much of the observation of other bodies from the Moon will be done at wavelengths ranging from ultraviolet to far infrared where telescopes having reflective optics can be used.
- *Examples*:
  - **Optical interferometer.**
  - **Nearside Earth Synoptic Earth Observation Facility.**
- *Benefits*: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate in synchronicity with its orbital velocity about the Earth. These characteristics are favorable for a variety of scientific observation and research.
- *FOM*: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
- *General Assessment*: Sophisticated instrumentation exists in terrestrial observatories and aboard robotic spacecraft. Instruments must be adapted for use in lunar setting. In some cases, this will be easy. In others, challenges exist to operate autonomously and continuously in the lunar environment.
- *Development needed*: LOW



Details and Benefits of 9.1.4.2: Radio Astronomy

Advanced Planning & Integration Office

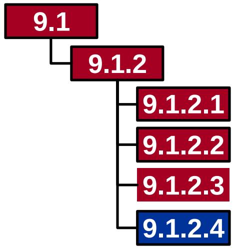
- *Description*: Radiotelescopes and interferometers, particularly those operating at low frequencies can observe the universe in unique ways**.** Interferometers can be designed with elements on the Moon and on the Earth, providing baselines at solar system scales.
- *Examples*:
  - **Low-frequency radiotelescope.**
  - **Long-baseline Moon-Earth radio interferometer**.
- *Benefits*: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate in synchronicity with its orbital velocity about the Earth. The lunar farside is the only location in the solar system that is perfectly shielded from terrestrial interference. These characteristics are favorable for a variety of scientific observation and research.
- *<u>FOM</u>*: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
- *General Assessment*: Antenna design is a highly advanced art. Adaptation to lunar conditions should present few problems.
- *Development needed*: LOW



Details and Benefits of 9.1.4.3: X-ray & Gamma-ray Telescopes

- *Description*: The lack of an atmosphere on the Moon allows observations of high energy photons using instruments with large throughput.
- *Examples*:
  - **X-ray radiotelescope.**
  - **Gamma-ray radiotelescope**.

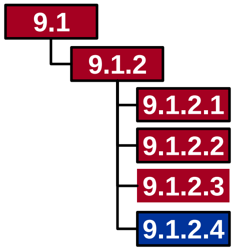
- *Benefits*: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate. The gravity field and extremely stable surface will permit construction of unique instruments for research into the high energies in the electromagnetic radiation from the universe.
- *<u>FOM</u>*: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
- *General Assessment*: The design of such telescopes is well understood, but the shipment and assembly of large apertures on the lunar surface will require careful operations. Adaptation to lunar conditions should present few problems.
- *Development needed*: MEDIUM



Details and Benefits of 9.1.4.4: Solar-terrestrial physics

Advanced Planning & Integration Office

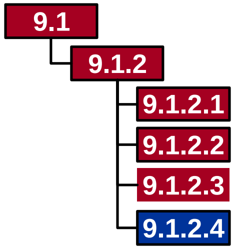
- *Description*: The lack of an atmosphere on the Moon allows direct access to the solar wind. The Moon fortuitously sits at a distance where reconnection occurs in the Earth's magnetic geotail. Observations at radio frequencies and data from satellite constellations anchored to the Moon can provide 3-dimensional information on the interaction between the solar wind and the geomagnetic field.
- *Examples*:
  - **The European Cluster mission.**
- *Benefits*: Continuous, long-term observation of the Earth-Sun interactions will permit greater sophistication in modeling the effects of solar events on the Earth's magnetic field, ionosphere, and climate.
- *FOM*: Continuous monitoring; simultaneous in-situ measurements of the solar field at the Earth.
- *General Assessment*: The technology for making these observations is well in hand.
- *Development needed*: LOW



Details and Benefits of 9.1.4.5: High-energy Physics & Relativity

Advanced Planning & Integration Office

- *Description*: Gravity wave detectors, very large particle accelerators, neutrino telescopes, and cosmic ray measurements are some of the possibilities for advances in cosmology and high-energy physics using research facilities on the lunar surface.
- *Examples*:
  - **LIGO**.
- *Benefits*: The lunar surface vacuum and the extreme surface stability allow new designs for research in high-energy physics and relativity.
- *<u>FOM</u>*: Long-term observations; extreme environmental stability; ready availability of vacuum environment.
- *General Assessment*: Lunar research facilities in these fields of study may well take on new forms from similar facilities on Earth. The scale of the facilities may be a challenge.
- *Development needed*: MEDIUM



9.1.4:
Facilities for Observation from the Moon

Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.4.1 Optical Observatory Instruments						
(a) Telescope (reflective optics) *Key: sensor; optics; data processing; construction; operation*	Hubble	*6*	Adapt to lunar setting; integrate into lunar ops	2019	2025	
(b) Interferometric arrays *Key: Optical fiber networks; precision alignment*	Earth facilities	*5*	Space qualification; ops in lunar setting	2024	2030	
(c) *Key:*						
9.1.4.2 Radio Astronomy						
(a) Antenna design; data processing *Key: Frequency response; detector sensitivity; signal reconstruction*	Earth facilities; S/C comm	*6*		2019	2025	
(b) Interferometric arrays *Key: Element communication; timing precision; ops*	Earth facilities	*5*		2024	2030	

9.1.4:
Facilities for Observation from the Moon

Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.4.3 X-ray & Gamma-ray telescopes						
(a) Optics design; sensor development ***Key: sensor; optics; data processing; construction; operation***	**Chandra; Compton**	***6***	**Adapt to lunar setting; integrate into lunar ops**	**2019**	**2025**	
9.1.4.4 Solar-terrestrial physics						
(a) Solar telescope ***Key: Long-term, uninterrupted imaging of Sun***	**Earth facilities**	***6***	**Adapt to lunar setting; integrate into lunar ops**	**2019**	**2025**	
(b) Array of spacecraft monitoring of solar wind interactions ***Key: Orbital coordination; communication; operations***	**CLUSTER**	***7***	Mission design	**2019**	**2025**	
9.1.4.5 High-energy Physics & Cosmology						
(a) Various research facilities ***Key: Innovative utilization of lunar environment; use of lunar mass (e.g., shielding and neutrino detection)***	**Earth facilities**	5	Facility concept and design; construction on Moon	2029	2035	

- **9.1 Exploration Activities**
  - **9.1.3 Analysis**
    - 9.1.3.1 InSitu Analysis
    - 9.1.3.2 Analysis at Base
    - 9.1.3.3 Sample Curation
    - 9.1.3.4 Sample Transport to Earth

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  - 9.1.4
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Description of 9.1.3:
Tools of Measurement & Observation

Description:

- Scientific investigations on the lunar surface will require some sort of measurement or characterization of lunar materials.
- Some observations or characterizations can be done on materials where they are found using robotic and/or human observers.
- Some observations are too complex or require too much time for in situ analysis and must be done at the base on selected samples.
- A limited number of special samples will be returned to Earth for curation by NASA and study by scientists around the world. These returned samples must be handled and documented by special procedures in accordance with NASA policy. :

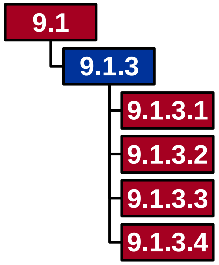
Major categories of activity are the following:

9.1.3.1 In Situ Analysis

9.1.3.2 Analysis at Base

9.1.3.3 Sample Curation

9.1.3.4 Sample transport to Earth



Details and Benefits of 9.1.3.1: In-Situ Analysis

- *Description*: Measurements and/or observations will be taken at a lunar surface site by teleoperated robots or human/robot field teams.
- *Examples*:
  - Spectral analysis of materials in a geologic formation
  - Measurement of soil compressibility with penetrometer
  - Documentation of geologic context of deposits or formations
- *Benefits*: Analysis tools built into a teleoperated robot allow reconnaissance for planning human traverses to a site of interest; acquire information for decisions in real time where spacesuit constraints limit the time available at the location.
- *<u>FOM</u>*: Ability to extract scientific information at high spatial resolution and high signal-to-noise from object of study; low mass, power, volume
- *General Assessment*: Instruments exist in laboratories and in flight-qualified form. Principal challenge is integration of sensors and data management in mobile platforms for lunar surface environment.
- *Development needed*: LOW

Details and Benefits of 9.1.3.2: Sample Analysis at the Base

- *Description*: In-situ analysis capability will be limited. Some samples deemed scientifically significant will require in-depth study. Analytical capability may be included at the base, subject to limits on mass, volume, technology, and crew time.
- *Examples*:
  - Optical microscopy of prepared geologic thin sections.
  - Elemental analysis by x-ray diffraction.
- *Benefits*: Lab environment permits sample preparation that is impossible in the field. Analysis at the base would facilitate planning scientific excursions, e.g., by allowing informed input by terrestrial support teams. It would provide information for selecting samples to be returned.
- _*FOM*_: Ability to extract information on chemical composition and physical state at submicroscopic dimensions high accuracy and sensitivity from a sample; low mass, power, volume
- *General Assessment*: Sophisticated instrumentation exists in terrestrial laboratories. Instruments must be adapted for use in lunar setting. In some cases, this will be easy. In others, challenges exist to reduce mass, power, and volume.
- *Development needed*: MEDIUM

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Details and Benefits of 9.1.3.3: Sample Curation

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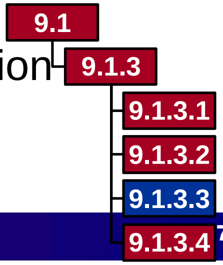
- *Description*: Some samples will be determined to have sufficient scientific importance as to be preserved and returned to the Earth for study by the global scientific community (as are the Apollo samples and Antarctic meteorites collected by U.S. expeditions).
- *Examples*:
  - Identification in the field of candidate samples for curation
  - Documented collection of samples for potential curation
    - Establish geologic context through photography, orientation, and location (selenographic coordinates).
    - Appropriate packaging for transport to base
  - Bonded storage at the base under lunar environmental conditions for candidate return samples
  - Analytical capability and communication for consultation to decide which candidates should actually be returned
- *Benefits*: The scientific integrity of returned samples must be preserved through strict adherence to documented collection, storage, and packaging procedures.
- <u>*FOM*</u>: Peer-reviewed configuration control processes acceptable to the scientific community.
- *General Assessment*: Well understood. Must be incorporated into mission requirements.
- *Development needed*: LOW



Details and Benefits of 9.1.3.4: Sample Transport to Earth

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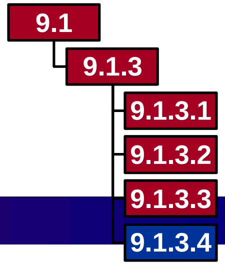
- *Description*: While properly documented and executed procedures are necessary to maintain scientific integrity of returned samples, the containers and packaging are also important.
- *Examples*:
  - The number of materials with which scientific lunar samples can come into contact is <u>severely</u> restricted.
  - Sealing containers under lunar vacuum in the presence of dust is challenging, particularly given material restrictions.
  - Containers must be physically robust while lightweight.
  - A variety of containers may be needed to return different types of sample.
  - Containers must be designed to be easily opened in the appropriate terrestrial lab environment where curation will take place (lesson learned from Apollo).
- *Benefits*: The scientific integrity of returned samples must be maintained through strict adherence to documented collection, storage, and packaging procedures.
- <u>*FOM*</u>: Peer-reviewed configuration control of processes and materials acceptable to the scientific community.
- *General Assessment*: Well understood. Must be incorporated into mission requirements.
- *Development needed*: LOW



9.1.3:
Tools of Measurement & Observation

Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.3.1 In-situ Analysis						
(a) Remote sensing (incl. imaging) *Key: sensor; optics; data processing*	MER	*8*	Adapt to lunar setting; integrate into lunar ops	-	2010	7
(b) Local measure. of physical state *Key: Ops environment*	Apollo, Lunakhod	*1*	Natural-state acquis-ition / handling;	2015	2030	0
(c) *Key:*		*4,2*	Natural-state acquisition / Handling	2008	2012	6
9.1.3.2 Sample Analysis at Base						
(a) Analytical Instrumentation *Key: Packaging current state of art*	Earth labs; ISS	*9*		-	2008	7
(b) Sample preparation equipment *Key: safety issues re habitat life support (e.g., dust, oil)*	Earth labs	*2,2*		2012	2015	0

Appendix

US Manned Space Program Relative Cost

	Apollo	ASTP	Skylab	NSTS	ISS	Exploration
Vehicle Development	High	Low	Moderate	High	High	High
Ops Systems Development	High	Low	Moderate	Moderate	Low	High
Vehicle Sustaining Eng./yr.	Low	N/A	N/A	Moderate	Low to Moderate?	?
Ops Systems Sustaining Eng./yr.	Low	Low	Low	Low	Low	?
Ops costs/yr.	High	High	High	High	High	?
# of years	2	1	1	38 +	5 +	50 +
Total program cost						

US Robotic Space Program Relative Cost

Advanced Planning & Integration Office

	Viking	Hubble	Pathfinder	MER	Exploration
Vehicle Development	High	High	Moderate	High	High
Ops Systems Development	Low	Low	Low	Low	High
Vehicle Sustaining Eng./yr.	n/a	High	n/a	n/a	?
Ops Systems Sustaining Eng./yr.	Low	Low	Low	Low	?
Ops costs/yr.	High	High	High	High	?
# of years	2 years	10	90 days	1-2 years	50 +
Total program cost					

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- 9.1.5

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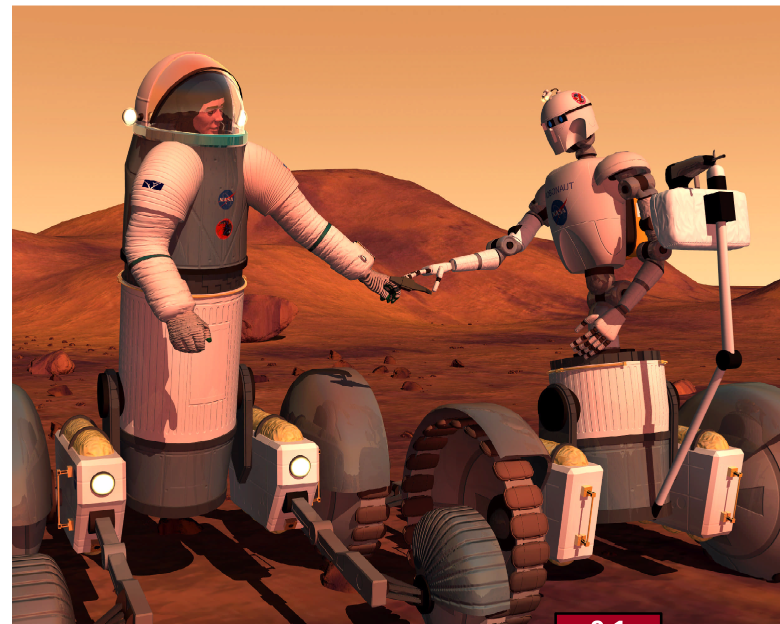
Concept of Operations: Robotic assistants explore while people monitor and control from safe havens

Machine systems

- physical strength, power, reach
- computational power, analysis
- communications
- continuous performance
- automation as a team player



People

- Active scientific discovery
- Hypothesis testing
- Creative problem-solving
- Strategic decision-making / Replanning
- First-hand experience and Communications to earth

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Lunar Mission Operations Functional Trade Space

Advanced Planning & Integration Office

Lunar Mission Scenarios

- Global Surface Access, 7 Day Duration
- South Pole Region, 30-90 Day Duration

Element Trades (Decision and Analysis Categories)

Lunar Network & Vicinity Operations

System Monitoring & Control
Earth-based vs. On-board *

Science & Payload Ops
Earth-based vs. On-board *

Element Trades:
- Communications
- Crew Activity Planning
- Life Support
- Robotic Activity Planning
- Vehicle Monitoring & Control
- Surface Asset Monitoring & Control

Earth-Moon Transit Operations

System Monitoring & Control
Earth-based vs. On-board *

Trajectory Management & Ascent / Descent
Earth-based vs. On-board *

Element Trades:
- Communications
- Crew Activity Planning
- Vehicle Monitoring & Control
- Life Support

Earth Network & Vicinity Operations

System Monitoring & Control
Earth-based vs. On-board *

Ascent / Descent & Landing
Earth-based vs. On-board *

Element Trades:
- Communications
- Crew Activity Planning
- Life Support
- Trajectory Management
- Vehicle Monitoring & Control

* Combined Options Allowed

9.1.5 Mobility/Hybrid Human/Robotic Control Roadmap

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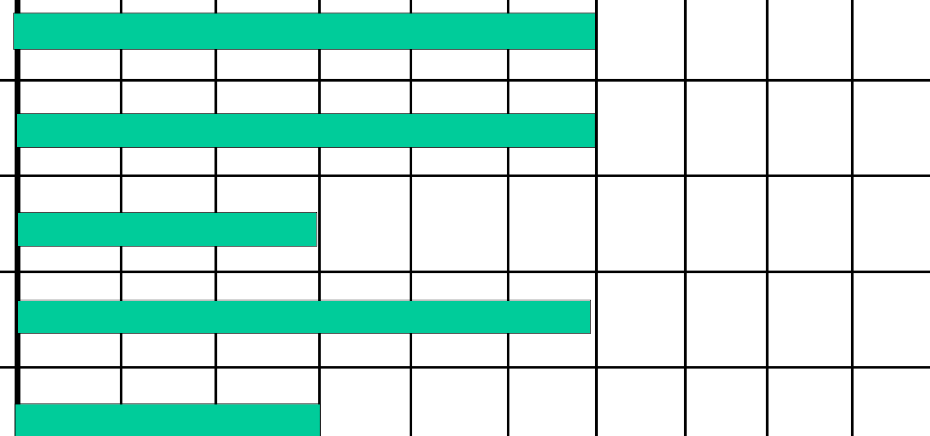
Technology	SOA TRL	Years to Develop to TRL 6									
		1	2	3	4	5	6	7	8	9	10
Hybrid human/autonomous mobility: proximity/long range traverse*	4-5										
Fused control sensor suite	4										
S/W control architecture	5										
Autonomous fault ID/management and early propagation detection	2-3										
Autonomous resource management	4										



Note: *While it is understood that both the Apollo rover (human controlled) and MER (semi-autonomous) are TRL8, the redesign of both systems to accommodate seamless hybrid control has not been achieved and will require significant design and integrated testing—this is somewhat reflected in the other critical technology development roadmaps.

Some Lunar Base Need Candidates

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Power generation, transmission, and storage

Fuel and water generation, transmission, and storage

Environmental control

Dust control

Communications

Building materials production

Dirt movement

Construction - buildings, roads, landing port, science/industrial facilities

Maintenance

Navigation

Surveying

Human and materials transportation

Redundancy – one more massive and expensive large capacity robot to do the job or several smaller less expensive and robots who together could do the job in the same time or the same job in a longer time in the presence of failures

Interoperability – using components of robotics in multiple machines, e.g., power supplies, computers, end effectors, …

COTS based – web-based packet communications, standard interfaces (e.g., USB, Firewire, data and mechanical connection), commonly-available components and subunits

Exploration Robotic Design Principles continued

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Generalized workers – robots that can perform a variety of tasks

Standardization – develop and use new international robotic standards

Alterability – be re-programmable and physically alterable for new tasks or to recover from unplanned events or failures

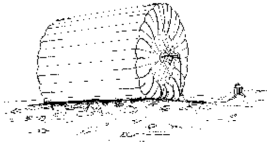
Controllability - autonomous operations with override capability and provisions for tele-robotic control

Potential Lunar Robot Examples

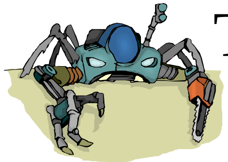
Scout

Dirt mover

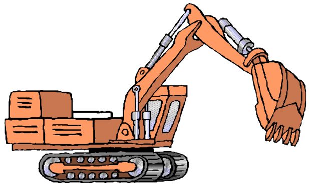
For Hire



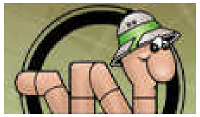
Transport



Trencher



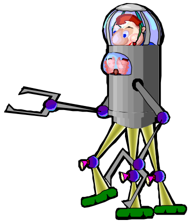
Burrower



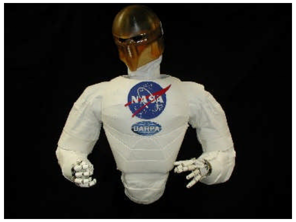
Lunar dirt settler

Dirt solidifier

Plumber/Wirer



Crew assistant



Crane

Challenges for Exploration Robotics

•Qualify robotic designs for outer space environments

•Minimize time latency effects for earth-based ground control methods

•Conduct surface robot operations near lunar noon

•Conduct surface robot operations during Martian blowing dust times

•Make further advances in perception and "cognition"
(see examples next page)

•Secure and redundant command paths

Needed Perception and "Cognition" Advances

•Intake of visual, auditory, and tactile sensory inputs → rapid recognition of objects

•Physical path planning in presence of many multiple types of constraints

•Logical layering of hierarchical control mechanisms
dumb behaviors building up to complex behaviors
[e.g., single joint movement …basic skill (grasp) … tasks with multiple skills (go fetch panel)]

•Transformation of high level commands to a sequence of skills including constraints checking and intelligent reaction to these constraints

•Inter –robot information and skill transfer

•Operating in the environment of non-cooperative agents (e.g., robots avoiding interference with the actions of other robots and with carbon-based units)

•Self-starting actions based on perceived needs (within constraints)

Capability 9.2
Mobility

Presenter: June Zakrasjek

9.2 Mobility Description

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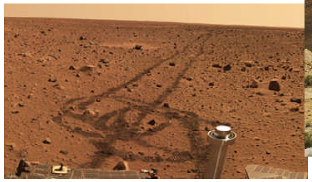
Essential for human operations In-Space and on planetary surfaces

In-Space Mobility

- Movement and positioning of astronaut ar equipment during construction and maintenance
- Deployment of scientific and monitoring equipment

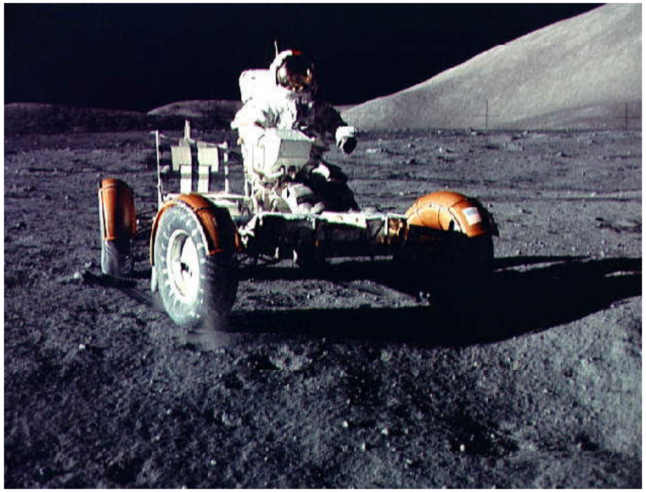


Surface Mobility

- Crew and equipment transport within:
  - Immediate vicinity (100 m) of a habitat/lander
  - Local area (10 km)
  - Regional areas (1000 km)
- Support of assembly, maintenance, and science tasks within immediate vicinity
- Autonomous, teleoperated, & direct crew control of mobility systems
- Scientific Exploration
- Site preparation, construction, Infrastructure deployment

9.2 Mobility Benefits

- Enables exploration of local site in detail
  - Immediate vicinity
  - Within approximately 10 km radius
- Provides for global access
- Enables efficient use of astronaut time
- Allows for human role in constructing and maintaining large facilities in space, thereby giving flexibility in design, construction and implementation
- Required In-Space and on the surfaces of the Moon, Mars, and other planetary environments



9.2 Mobility Challenges

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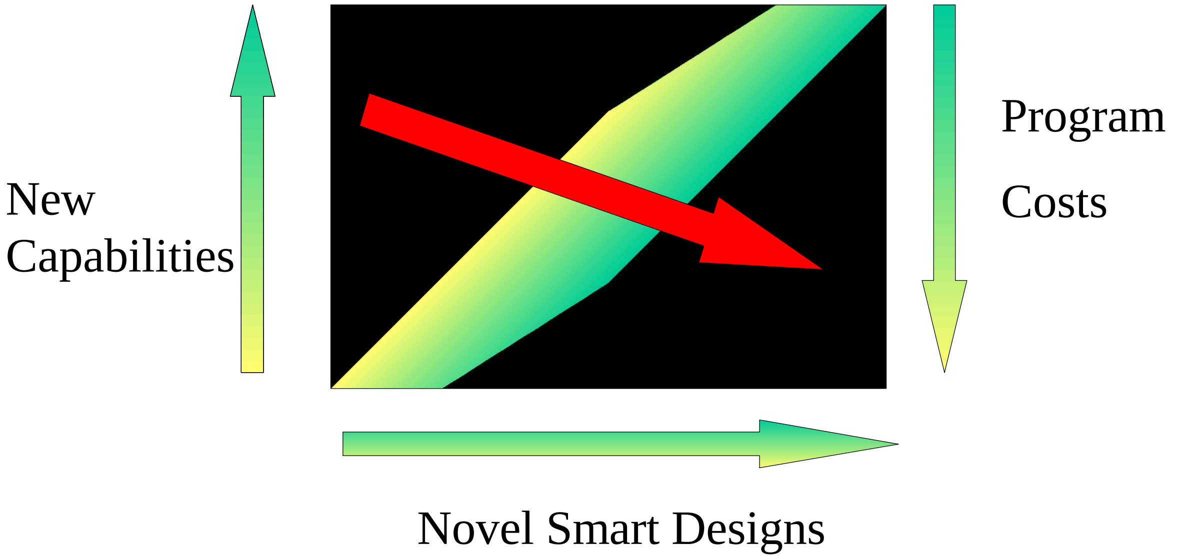
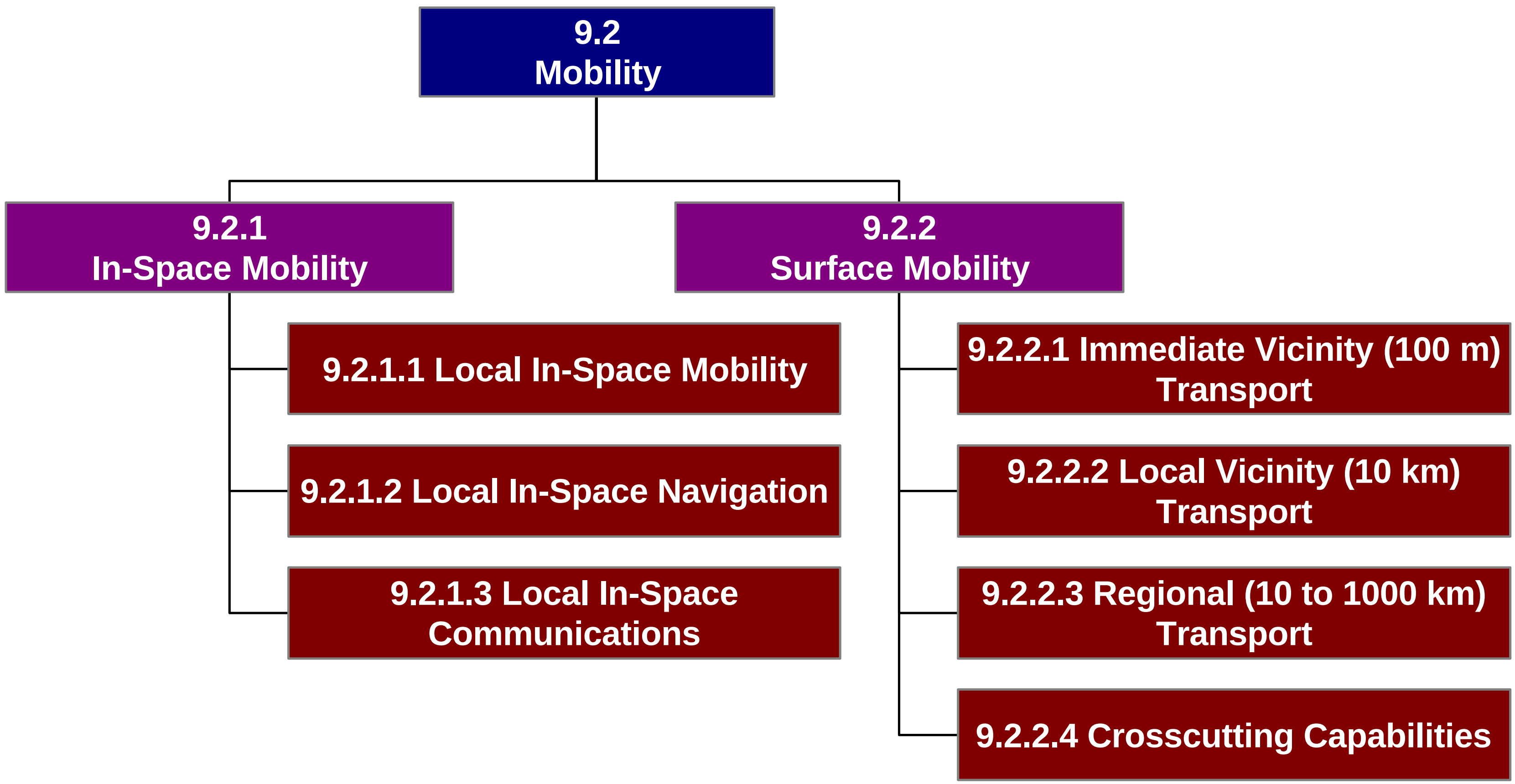
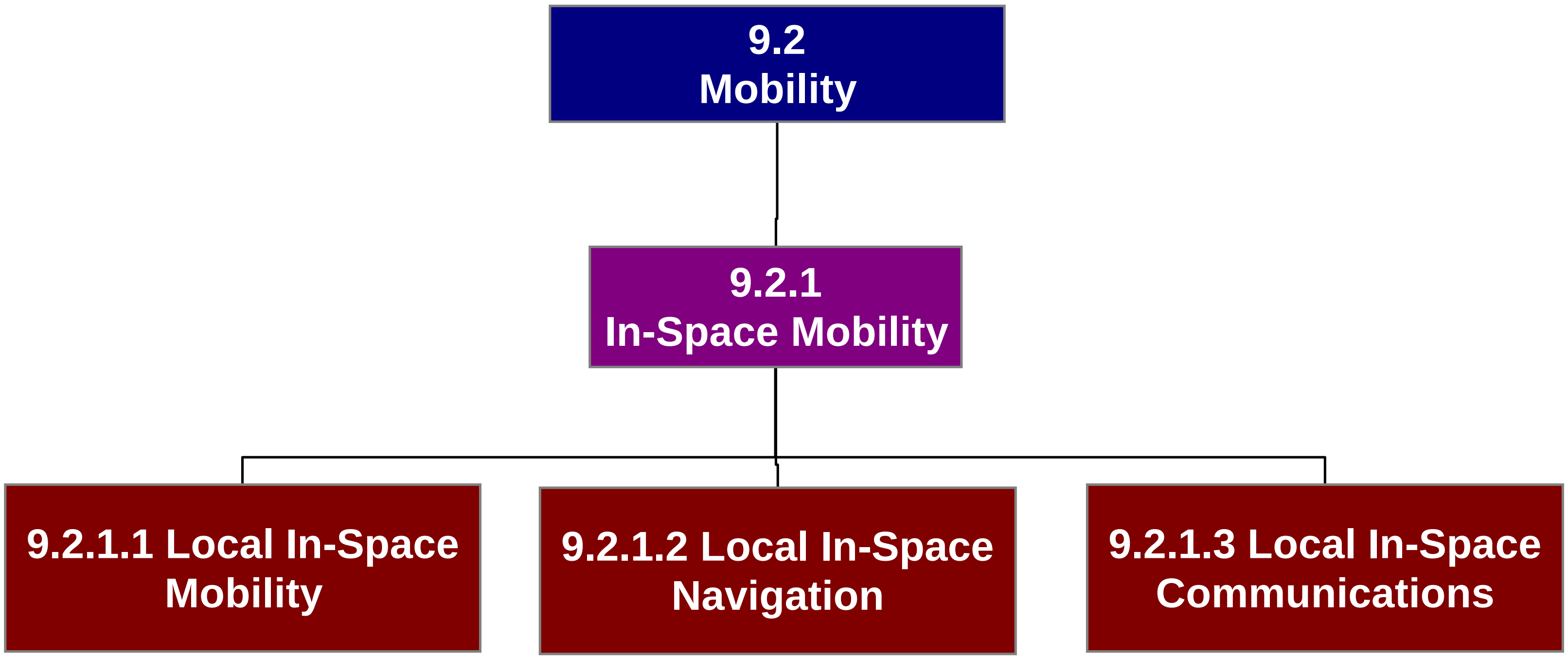
- Safely and effectively explore Moon and Mars
  - Operational differences
- Multiple systems required
- Limited budget
- Long distance travel
- Effective In-Space maintenance and deployment
- Environment

Requires a combination of cross-element commonality, smart design and capabilities



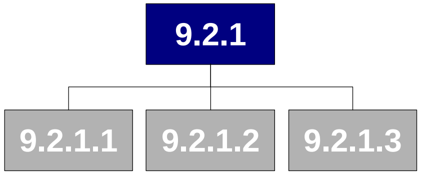

9.2
Mobility
9.2.1
In-Space Mobility
9.2.2
Surface Mobility
9.2.1.1 Local In-Space Mobility
9.2.1.2 Local In-Space Navigation
9.2.1.3 Local In-Space Communications
9.2.2.1 Immediate Vicinity (100 m) Transport
9.2.2.2 Local Vicinity (10 km) Transport
9.2.2.3 Regional (10 to 1000 km) Transport
9.2.2.4 Crosscutting Capabilities

Capability 9.2.1 In Space Mobility



9.2.1 In-Space Mobility Overview

- **Drivers/Assumptions for In-Space Mobility**
  - Capabilities driven by assembly of large observation platforms
  - Exploration systems will not rely heavily on planned EVA operations
  - Communications with surface bases (including Earth) are relayed through the spacecraft
- **Capabilities for In-Space Mobility are well developed through ISS and Shuttle Programs (SOA)**
  - Equipment, procedures, and safety measures in-place for EVA crew mobility
  - EVA manual translation provided by handrails and CETA
  - Positioning within worksite provided by SSRMS, APFR, Body Restraint Tethers (BTRs)
  - Robotics systems move crew and equipment between worksites following very well planned scripts
  - Safety measures: Tethers and SAFER
  - Communication and Navigation to coordinate actions of Crew and robotics during EVAs



Capabilities for Improvement

- Real time planning and obstacle avoidance for robotic positioning of crew and equipment
  - Reduces overhead associated with robotic operations
- Deployable mobility aids (handholds, tether points, stabilization interfaces)
  - Reduces system mass
  - Reduces/eliminates permanent protrusions (snag points, aerodynamic interference)
- Additional support systems for moving equipment
  - New support equipment to increase crew carrying capacity (volume and number of items carried but not mass)
  - Expanded equipment transporters (Deployable, powered clothesline, Tethered Free Flyer Transport, Robotic Walker Equipment Transport, …)

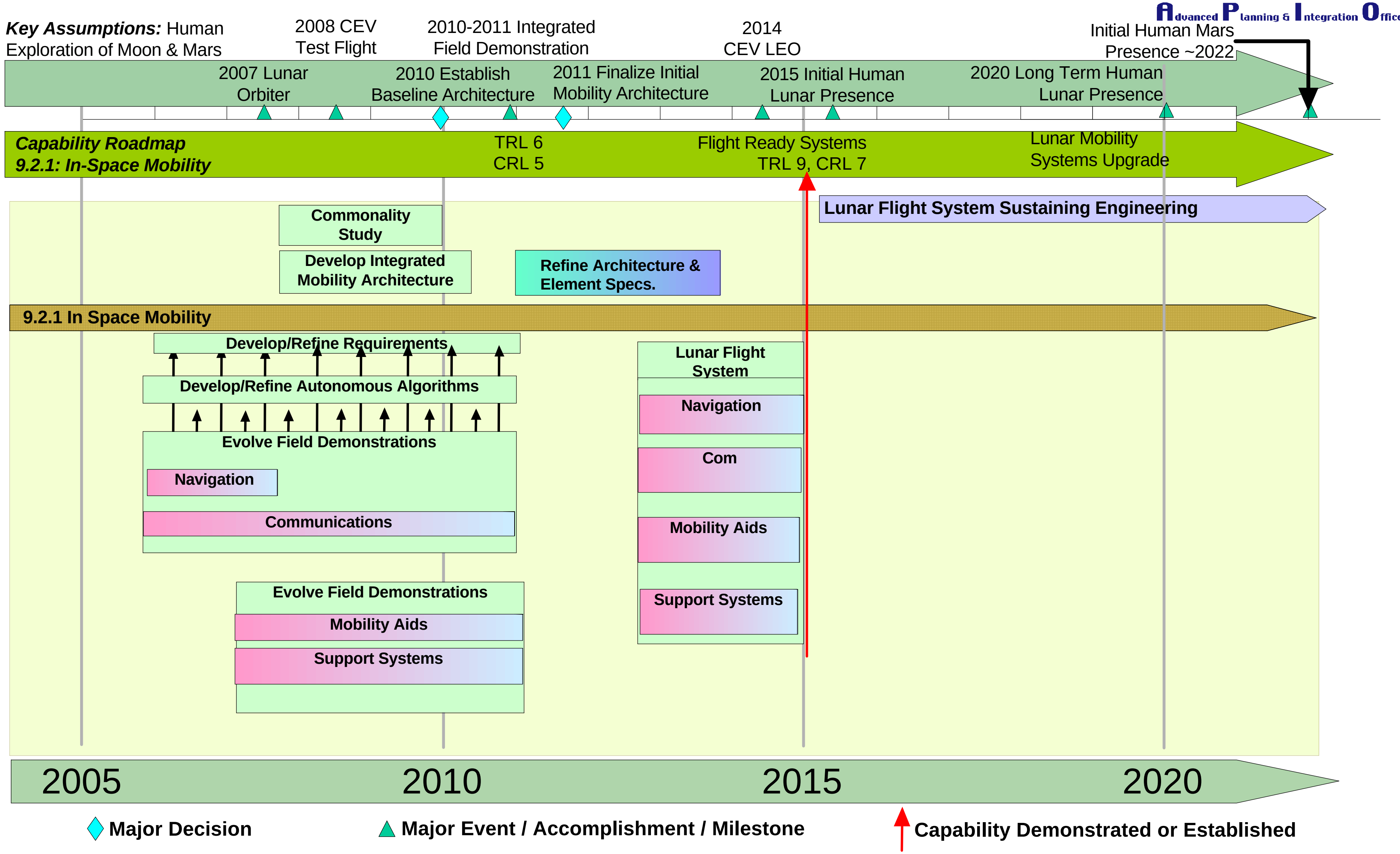
9.2.1 In-Space Mobility Assessment (Continued)

Capabilities for Improvement

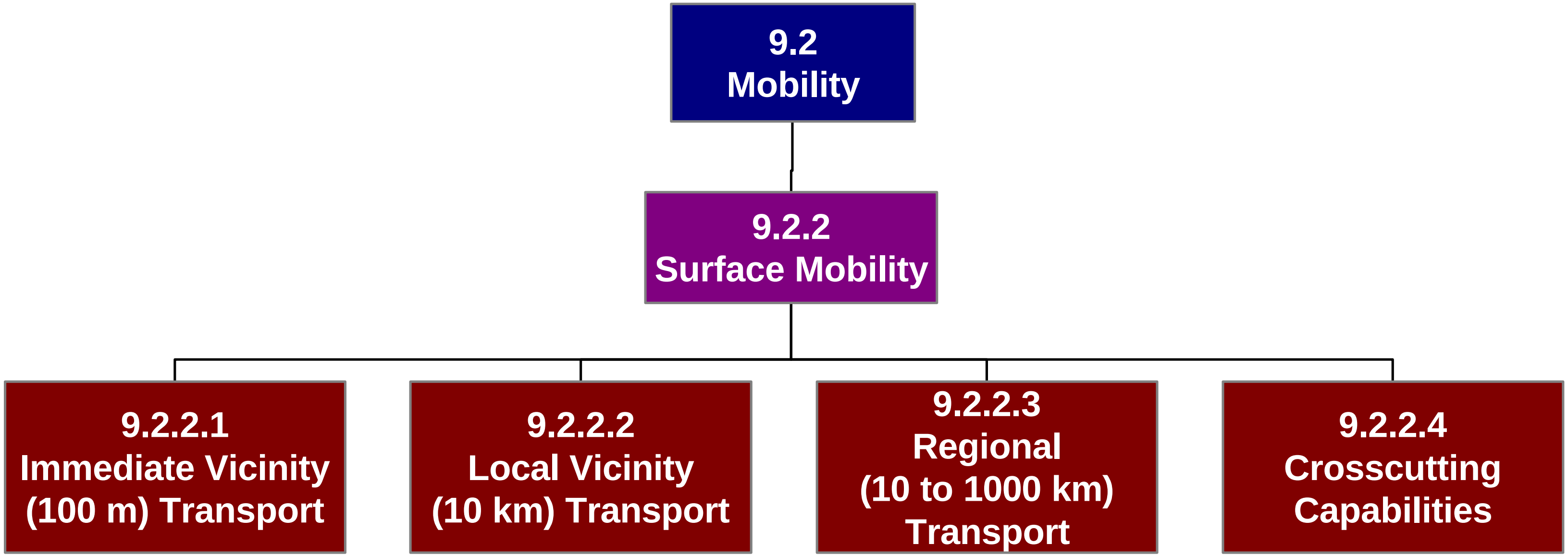
- Development of relative in-space navigation system to enable new systems to support operations
  - Free flying platforms (Camera, Tool Delivery,…)
  - Crew Maneuvering Unit
- Enhancement of in-space communications to provide:
  - EVA crew access to external video sources to enhance situational awareness
  - Command/control/video/data links between EVA crew and free flying platforms

Overall 9.2.1 Development Needed: low

9.2.1 In-Space Mobility Roadmap



Capability 9.2.2
Surface Mobility



9.2.2 Surface Mobility
Looking Back

- "We boarded Rover again and I floorboarded it, but almost immediately reduced my speed to a crawl over the thin dark mantle of lunar dirt covering the undulating plain around the lander. The route was pocked with craters of all sizes, from tiny to large, and large boulders frequently forced me to detour. All of the hazards were partially buried, making what should have been a routine trip a rather risky undertaking. ... The wire mesh wheels collected some impressive dents when I sideswiped a few boulders." [pp. 326-327]

- "We reached our first destination -- Hole in the Wall, at the foot of the South Massif -- by driving tilted along a steep slope, dodging craters and rocks, with the TV camera capturing the bouncing, rolling terrain. In one-sixth G, the Rover felt like it was about to roll over, so I made sure that Jack was always on the downslope side." [p. 331]

The Last Man on the Moon, by Eugene Cernan with Don Davis, 1999.

9.2.2 Surface Mobility
The Environments: Moon and Mars

Lunar Environment

- Far from a flat plain
- Fresh craters:
  - Interior slopes: 30-35 degrees
  - Steeper locally
- With erosion by impacts craters become wider and shallower, which makes undulating plains
- Surface material unconsolidated, fine-grained, gritty, and dusty
- Rock abundance: <1% of surface covered with rocks > 10 cm (except near fresh craters)
- Isotropic Geological Process - consistency across lunar surface

Martian Environment

- Far from a flat plain in many places
- Topography shaped by tectonics, impacts, water, and wind
- Surface material is highly variable (cemented dust, dust, sand dunes, rocky terrain)
- Improved knowledge of trafficability from Mars Exploration Rovers
  - Varied trafficability across planet

9.2.2 Surface Mobility Overview

- **Future Needs**
  - Future human missions (near-term) must allow crew to explore and harvest resources in the local and immediate areas (<10 km)
  - Systems must evolve/expand to allow humans to explore regional areas (up to 1000km)
  - Mobility “system of systems” must ensure safety of crew and maximize crew productivity
- **State of the Art**
  - Apollo Lunar Rover Vehicle
  - Mars Probes (Spirit, Opportunity, MSL)
  - Research activities

9.2.2 Surface Mobility
Capability Breakdown Structure

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- 9.2.2 Surface Mobility
  - 9.2.2.1 Immediate Vicinity (100 m) Transport
    - 9.2.2.1.1 Mobile Robotic Platforms
    - 9.2.2.1.2 Climbing Aids
    - 9.2.2.1.3 Crew Systems
  - 9.2.2.2 Local Vicinity (10 km) Transport
    - 9.2.2.2.1 Personal Transport
    - 9.2.2.2.2 Mobile Systems
    - 9.2.2.2.3 Crew Systems
  - 9.2.2.3 Regional (10 to 1000 km) Transport
    - 9.2.2.3.1 Rapid Transport
    - 9.2.2.3.2 Long-Duration Transport
    - 9.2.2.3.3 Crew Systems
  - 9.2.2.4 Crosscutting Capabilities
    - 9.2.2.4.1 Surface Navigation
    - 9.2.2.4.2 Local Worksite Communications
    - 9.2.2.4.3 Situational Awareness
    - 9.2.2.4.4 Autonomous Drive Operations
    - 9.2.2.4.5 Multi-Mobility System Cooperation

9.2.2 Surface Mobility Assessment and Needs

General Assessment

- Current SOA addresses only small area of needed capability
- Considerable research and engineering required to mature capability to meet future mission needs

Needs

- Fast, safe, long distance travel (Local and Regional Areas)
- Radiation and dust mitigation and countermeasures
- Autonomous, cooperative vehicle placement
- Surface navigation system
- Easy maintenance, long life
- Commonality between all surface system, including robotic
- Robust PLSS in-field recharge
- Order of magnitude improvement communications BW (Earth-based Communication SOA)

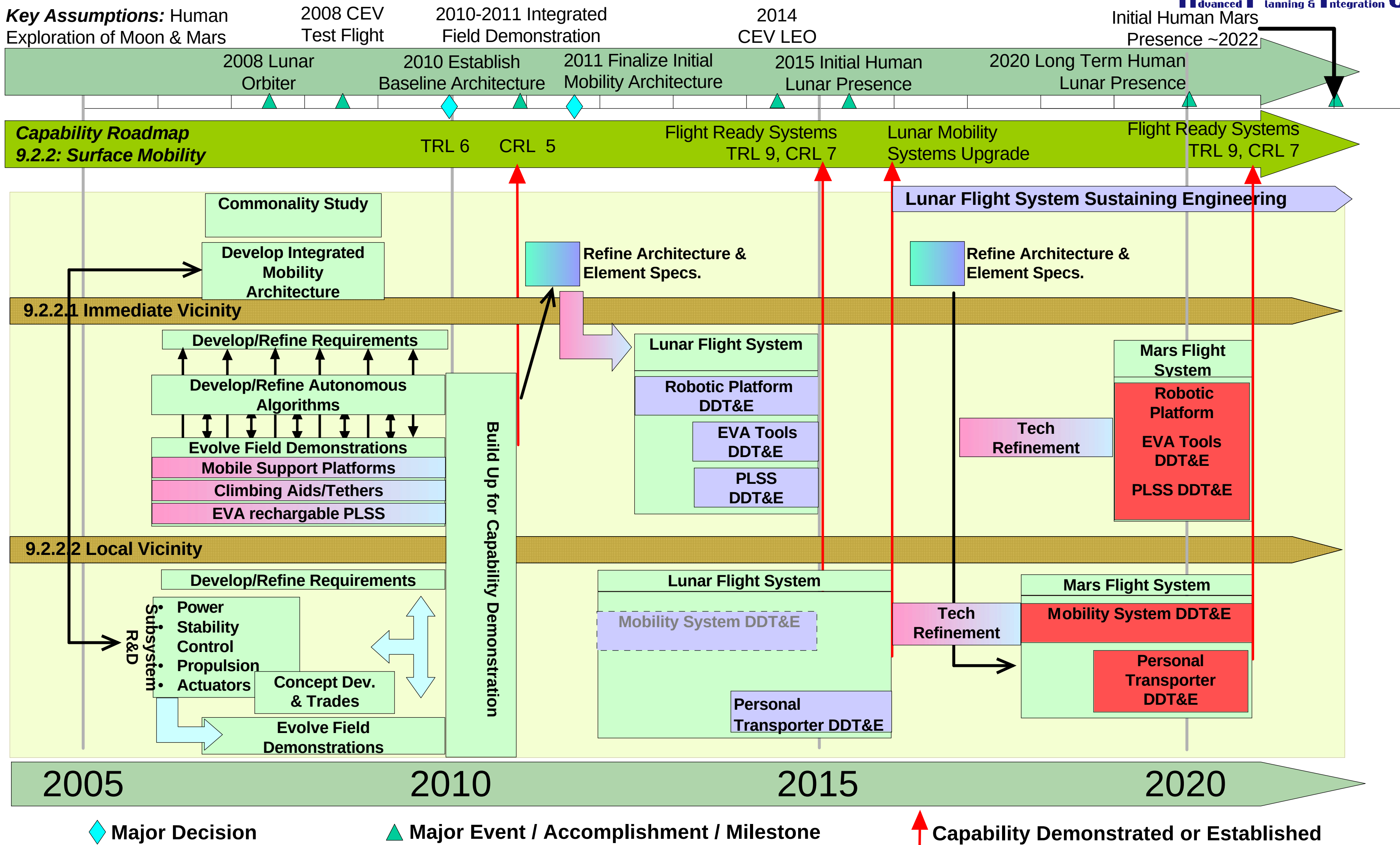
Capabilities with Development Needed HIGH

- Climbing Aids and Tethers
- Mobile Support Platforms
- Crew Systems
    - Robust PLSS in-field recharge
    - SPE Protection and Warning
- Personal Transport
- Rapid Transport
- Long Duration Transport
- Communications and Navigation
    - High Bandwidth Surface Beacons
- Autonomous Drive Operations
- Multi-Mobility System Cooperation

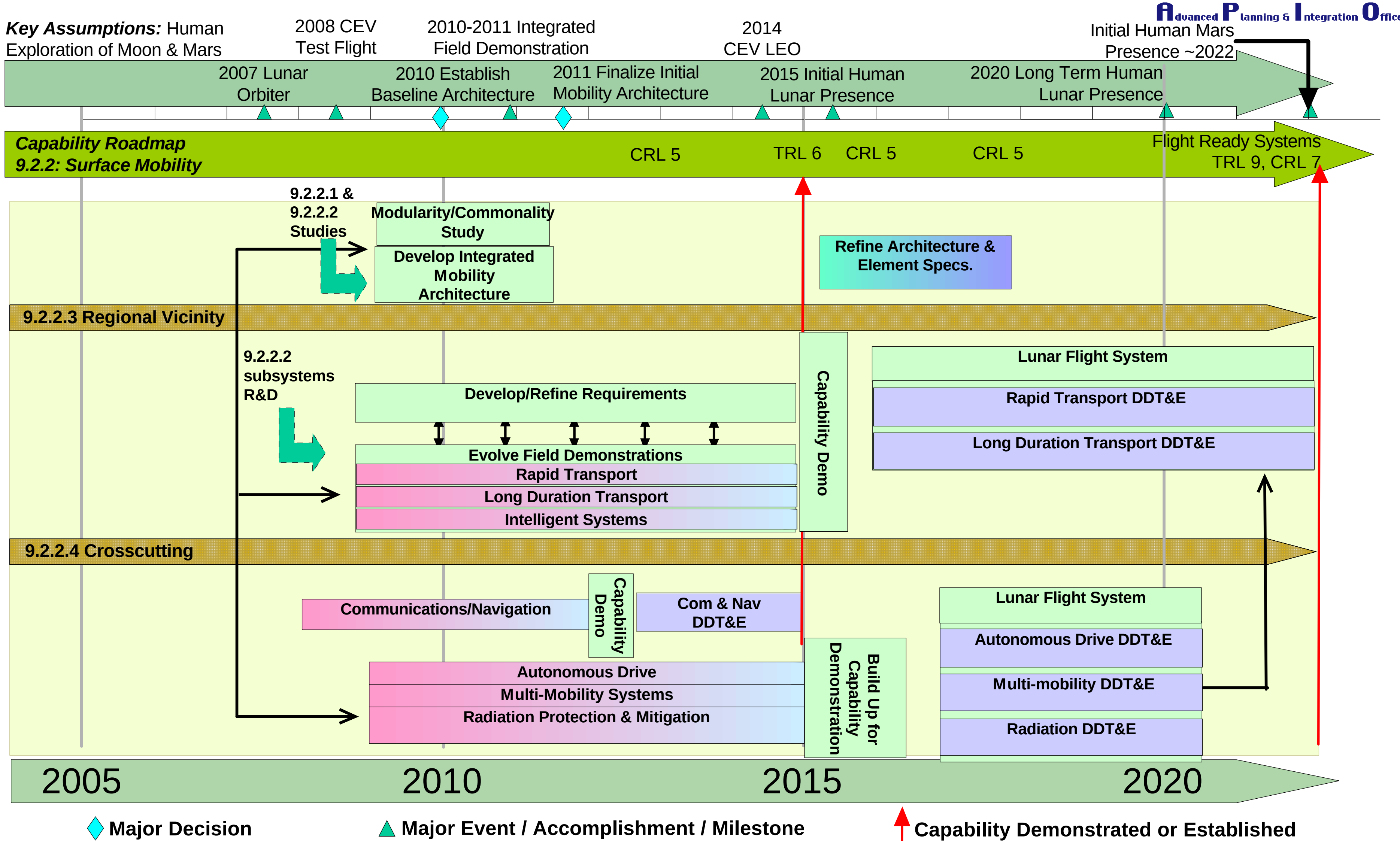
Capabilities with Development Needed HIGH

- Modular, reconfigurable Systems
- Intelligent Self Aware Systems
- Radiation and dust mitigation and countermeasures
- Easy maintenance, long life
- Commonality between all surface system, including robotic

9.2.2 Surface Mobility Roadmap

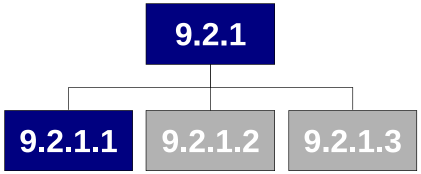


9.2.2 Surface Mobility Roadmap



Additional Detail 9.2 Mobility

Capability 9.2.1.1
Local In Space Mobility



9.2.1.1 Local In-Space Mobility

Description

– Efficiently and safely transport payloads (crew, robots, and equipment) between local worksites in space and deploy items within the new worksite

Sub-Capabilities

9.2.1.1.1 Plan and Monitor In-Space Movement **(low)**

9.2.1.1.2 Transport Payload Between Worksites **(Medium)**

9.2.1.1.3 Position Payload Within Worksite **(Medium)**

9.2.1.1.4 Align Payload to Worksite Interface **(low)**

Primary Benefit

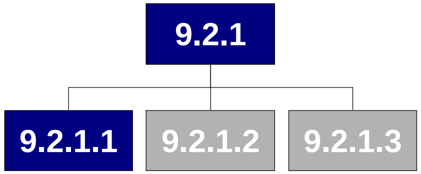
– Enables the assembly, operation, and maintenance of large scale on-orbit facilities

General Assessment

– New systems will need to be evolved from current SOA to provide more operationally efficient (faster) and more flexible on-orbit operations

– Collision avoidance

Development Needed : low to Medium



Capability 9.2.1.1
Plan and Monitor In-Space Movement

Description

- Plan and monitor in-space movements of payloads using varying levels of autonomy ranging from fully autonomous operations to direct planning/control of the movement by a crew member
- Examples: Autonomous path planner, collision avoidance planner, kinematics simulator, proximity sensors, camera platforms

Benefits

- Ensures the safety of payloads, worksites, and transport systems
- Ensures resources are capable of and available for performing the movement

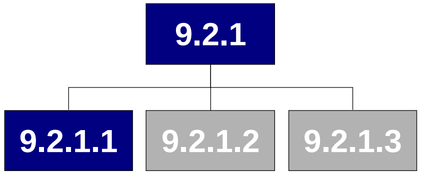
FOM

- Time to Plan, Memory/Processing Power, Crew Time, Impacts to Worksite, Impacts to Transfer System, Impacts to Payloads

General Assessment

- Components must be evolved and integrated with current elements to operate efficiently in changing worksites and unplanned environments

Development Needed low



Capability 9.2.1.1.2
Transport Payload Between Worksites

Description

- Transport payload (crew member, robotic system, or equipment) from one worksite area to another
- Examples/Components: Large Scale Robot, Powered Rail Cart, Walker, Free Flyer, Tow Line, Hand Rails, Body Restraint Tether

Benefits

- Enables on-orbit construction, operation, inspection, and maintenance of larger structures
- Provides flexibility in planning and staging for on-orbit assembly and maintenance

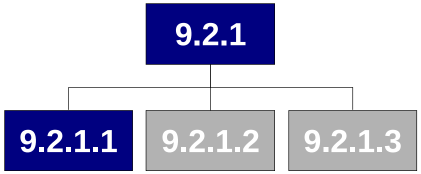
FOM

- Work Envelope/Mass, Time to Move, Power Consumption, Expandability, Impacts to Worksite/Spacecraft

General Assessment

- Current flight systems either are limited in Payload capacity (I.e. EVA crew member) or impose substantial penalties (mass, volume, limited access,…) to the worksites or spacecraft

Development Needed **Medium**



Capability 9.2.1.1.3
Position Payload within Worksite

Description

- Grossly position payload (crew member, robotic system, or equipment) within a worksite
- Examples/Components: Dexterous manipulator, EVA crew member, Powered Cart, Gross positioning robot manipulator

Benefits

- Provides flexibility in planning and staging for on-orbit assembly and maintenance
- Enables on-orbit construction and inspection of larger structures

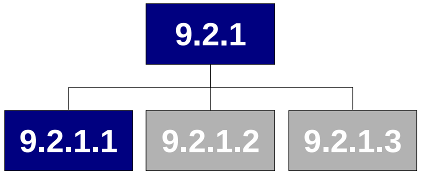
FOM

- Work Envelope/Mass, Time to Move, Power Consumption, Expandability, Worksite Impacts

General Assessment

- Current flight systems are effective at positioning payloads within a worksite but must be tailored to meet specific future mission needs and to reduce the mass, impacts to the worksite, and time to position a payload

Development Needed Medium



Capability 9.2.1.1.4
Align Payload w/ Worksite Interface

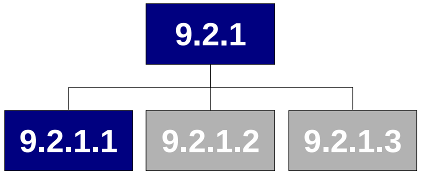
Description
- Accurately align payload to a mating interface within the worksite
- Examples/Components: Dexterous robot system, EVA crew member

Benefits
- Enables on-orbit construction and maintenance
- Use of robotic systems reduce safety risks to Crew

FOM
- Positional accuracy, access envelope, overhead to mobilize, required training and planning, availability

General Assessment
- Crew EVA capability well demonstrated
- Robotic capability demonstrated on ISS prior to exploration need
- Evolvement of systems required

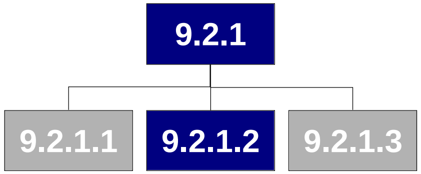
Development Needed low



Maturity Level – Technologies
9.2.1.1 Local In-Space Mobility

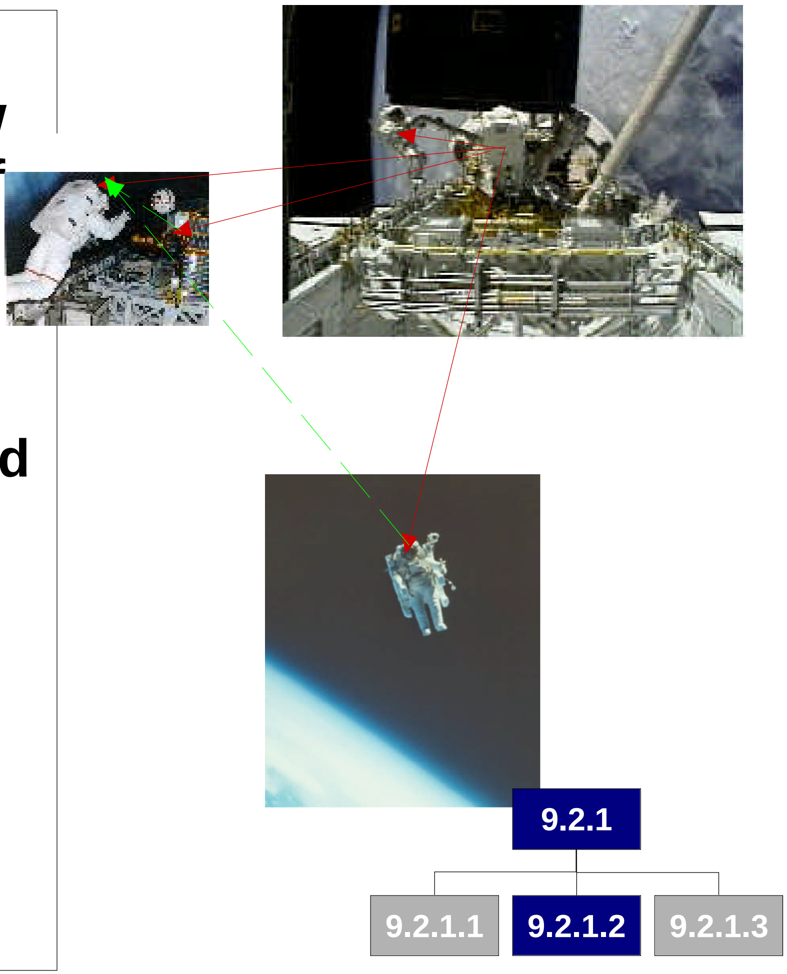
Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.2.1.1.1 Plan and Monitor In-Space Movement *Key: Prepare for ops near Mars w/ 40 min. delay*	Shuttle / ISS Simulation; Stationary camera with TDRSS Link	*5*	Autonomous planning of paths / collision avoidance; Free-flying camera platform	2010	2015	1-7
9.2.1.1.2 Transport Payload between Worksites *Key: Assembly of large payloads by robotic support systems*	ISS Mobile Transporter	*4*	Robotic crawler with structural interfaces; Eventual flying "Tug-boat"	2010	2015	1-7
9.2.1.1.3 Position Payload within Worksite *Key: Reduce worksite impacts & time to position PL*	ISS SPDM (Special Purpose Dextrous Manipulator)	*4*	Reduce mass, worksite impact, and time to position payload	2010	2015	1-7
9.2.1.1.4 Align Payload to Worksite Interface *Key: Minimize interface constraints*	ISS Work I/F MRMS End-Effector	*3*	Momentum-wheel attitude; Electromagnetic fine positioning	2010	2015	1-7

Capability 9.2.1.2
Local In Space Navigation



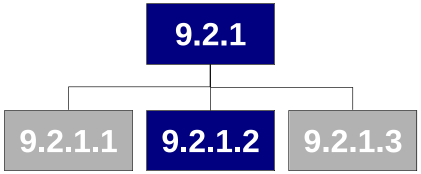
This capability provides relative navigation information for EVA crew personnel and equipment outside of a traversing spacecraft.

Techniques developed during previous U.S. space programs will be modified and expanded where needed to accomplish exploration EVA tasks.

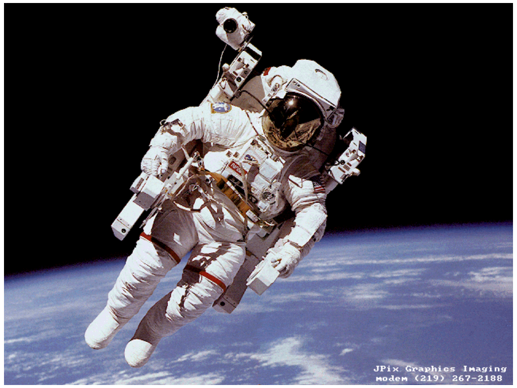


Description

- Provides relative navigation and attitude information for EVA crew personnel and detached equipment outside of a traversing spacecraft.
- Information provided includes attitude, relative position and velocity, relative range and range rate and any other needed relative navigation parameters.
- Navigation information is provided for:
  - EVA persons relative to the spacecraft
  - Detached and docking equipment relative to the spacecraft
  - Between an EVA crewperson and detached equipment
  - Among EVA crew personnel



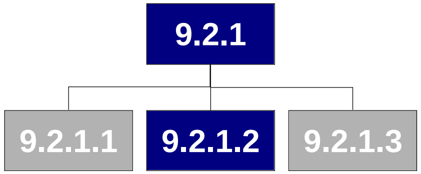
Benefits



•Allows EVA personnel to estimate traverse times

•Provides the needed elements to enable capture or rescue of crew or items that have are drifting away accidentally

•Enables automatic docking of co-orbiting equipment for examples, miniature flying camera systems, automated tool carts, equipment carriers, robotic crew assistants, etc.



FOM

- Required one sigma relative accuracies for EVA crew or non docking equipment:

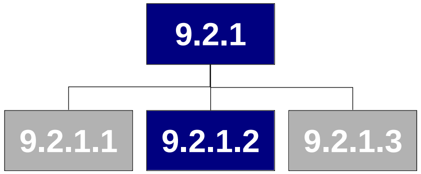
positions	2 meters
velocities	0.2 meters/sec
attitudes	1.5 degrees

- Typical one sigma relative accuracies for docking equipment:

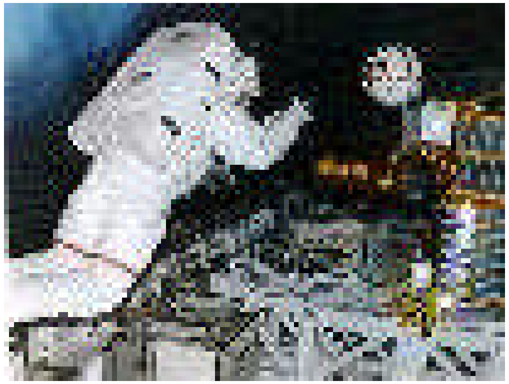
positions	2 centimeters
velocities	1 centimeter/sec
attitudes	1 degree

General Assessment : Though space relative navigation systems have not been developed for multiple users, the algorithms and navigation hardware changes are achievable.

Development Needed : Medium



Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Relative sensors						
Radar ranging	NSTS, GPS	9,8	less power, mass	2008	2010	5,5
Laser ranging	HTV rendezvous	4-5	space qualified	2006	2008	3
Optical LED tracking	Mini Aercam, ISS CBCS	6,9	adapt for specific docking vehicles	2008	2011	4,6
Optical shape/ color tracking	NSTS SVIS, JSC Scout	9,5	Explor.-focused space qualified	2009	2012	5,3
Relative navigation algorithms						
Single body	NSTS rendez.	9	CPU efficiency	2009	2008	6
2-body docking	ISS	9	CPU efficiency	2007	2009	6
n-body tracking	ICBM defense	7	Modify for explor.	2009	2012	4
Relative guidance algorithms	Closhesy-Wilshire equations	7	Modify for explor.	2008	2011	6



This capability provides communications for EVA crew personnel and equipment outside of a traversing spacecraft.

Current space methods need to be upgraded to use multi-point techniques and to provide expanded bandwidth to provide operational efficiencies.

Description

- Provides two-way voice, video and data communications while on EVA outside a traversing spacecraft:
    - Among EVA personnel
    - Between EVA personnel and the spacecraft
    - Between EVA personnel and detached or docking equipment
    - Between detached or docking equipment and the spacecraft

- Communications with surface bases with Earth are relayed through the spacecraft.

Benefits

- Provides situational awareness for EVA personnel

- EVA crew will be able to execute procedures using up-to-date textual and graphical data.

- Enables crew to monitor and control detached or docking equipment

- Spacecraft and ground/planetary personnel can monitor EVA procedures and operational status.

FOM Required total bandwidths (Megabits/sec) & Video Resolution

To \ From	EVA Person	Spacecraft	Robot	External Equipment
EVA Person	1 scalable	1 CHDTV	1 CHDTV	1 CHDTV
Spacecraft	1 CHDTV	n/a n/a	1 CHDTV	1 CHDTV
Robot	0.2 n/a	1 n/a	2 n/a	n/a n/a
External Equipment	0.2 n/a	1 n/a	n/a n/a	n/a n/a

General Assessment : Though space relative communication systems have not been developed for multiple users, the algorithms and new hardware changes are achievable.

Development Needed : Medium

Capability/ Technology	**SOA**	**TRL**	**Needs**	**Need TRL 6**	**Capability Date**	**CRL**
Low mass 3DHD cameras	surveillance personal cameras, Soni full concept 3DHD prototype	9 5	Add funding to full-concept 3DHD cameras	2009	2012	4
Crew/robot/Mobile transmitter/recv./ant.	surveillance personal rf devices	4	I MBPS, low mass, space qualify, 2 km range	2009	2012	2

Capability 9.2.2
Surface Mobility

Presenter:

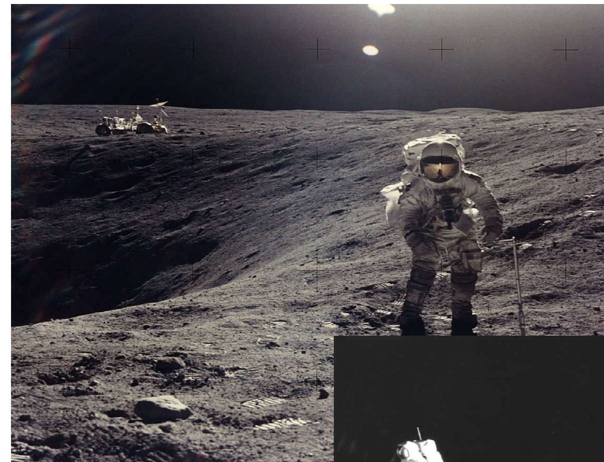
Team Lead

- "We boarded Rover again and I floorboarded it, but almost immediately reduced my speed to a crawl over the thin dark mantle of lunar dirt covering the undulating plain around the lander. The route was pocked with craters of all sizes, from tiny to large, and large boulders frequently forced me to detour. All of the hazards were partially buried, making what should have been a routine trip a rather risky undertaking. ... The wire mesh wheels collected some impressive dents when I sideswiped a few boulders." [pp. 326-327]

- "We reached our first destination -- Hole in the Wall, at the foot of the South Massif -- by driving tilted along a steep slope, dodging craters and rocks, with the TV camera capturing the bouncing, rolling terrain. In one-sixth G, the Rover felt like it was about to roll over, so I made sure that Jack was always on the downslope side." [p. 331]

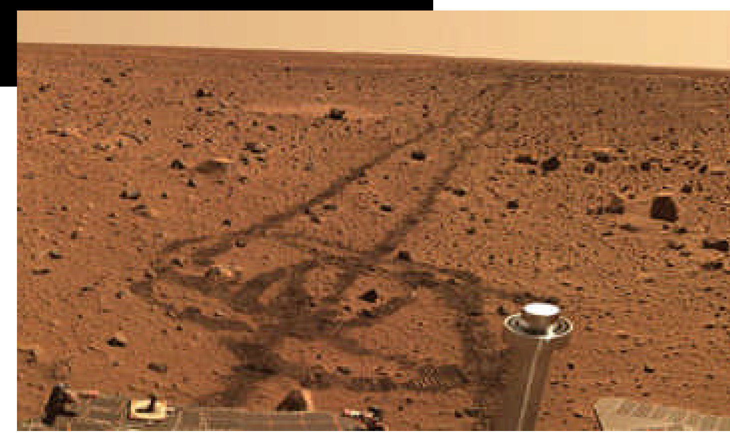
The Last Man on the Moon, **by Eugene Cernan with Don Davis, 1999.**

- Far from a flat plain
- Fresh craters:
  - interior slopes: 30-35 degrees
  - (steeper locally)
- With erosion by impacts craters become wider and shallower, which makes undulating plains
- Surface material is unconsolidated, fine-grained, gritty, and dusty
- Rock abundance: <1% of surface covered with rocks > 10 cm (except near fresh craters)
- Isotropic Geological Process - consistency across lunar surface



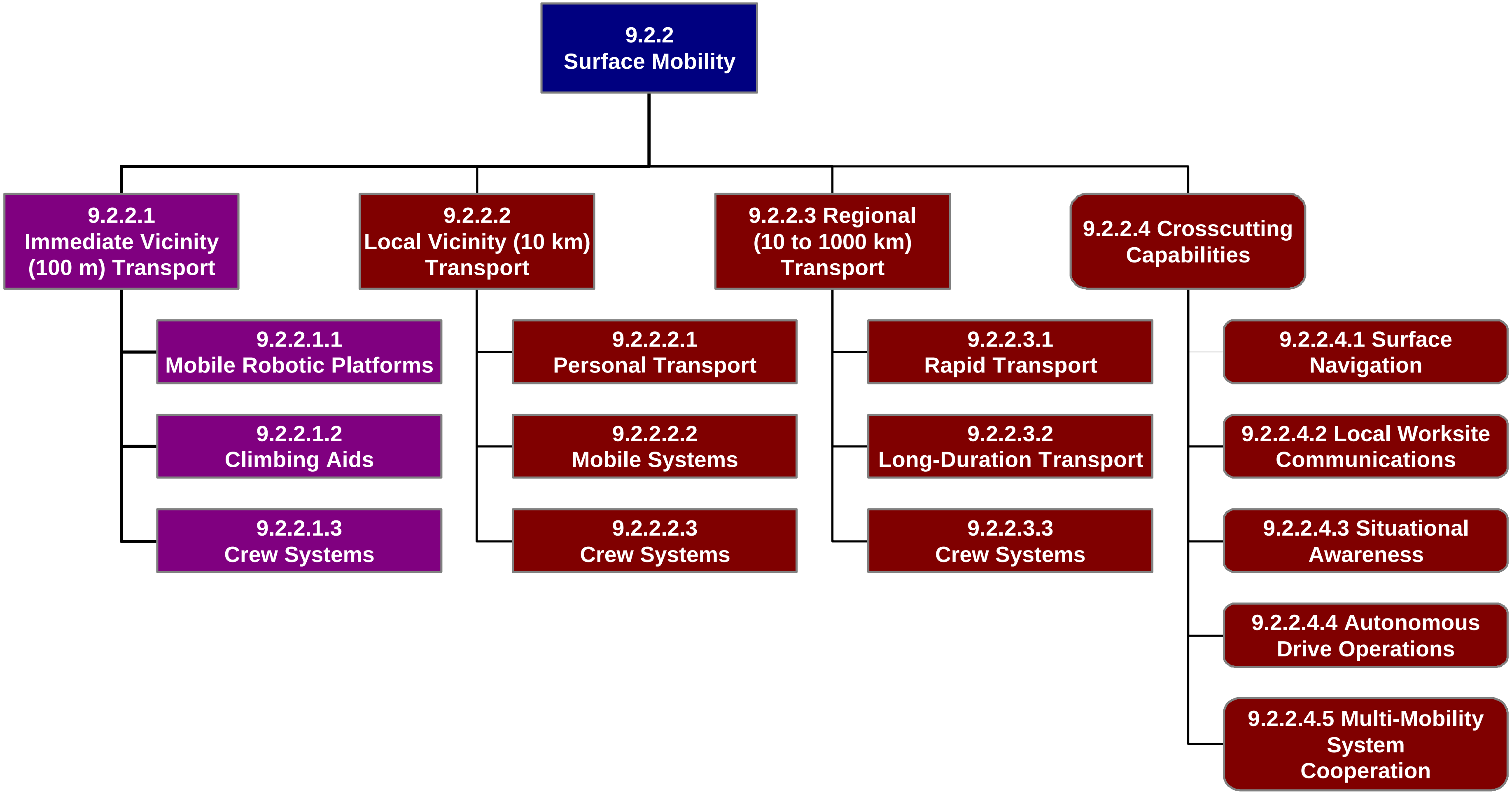
- Far from a flat plain in many places
- Topography shaped by tectonics, impacts, water, and wind
- Surface material is highly variable (cemented dust, dust, sand dunes, rocky terrain)
- Improved knowledge of trafficability from Mars Exploration Rovers
  - Varied trafficability across planet

Opportunity: Sandy route from Eagle crater



Spirit: Long traverse

- **Fast, Safe, Long distance travel**
- **Autonomous, cooperative vehicle placement**
- **Order of magnitude improvement BW for communications (Earth-based Communication SOA). Enables heads up display**
- **Surface Navigation System**
- **Robust PLSS recharge**
- **Radiation and Dust Mitigation and Countermeasures**
- **Easy maintenance, long life**



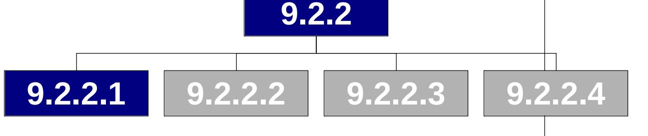
9.2.2 Surface Mobility
9.2.2.1 Immediate Vicinity (100 m) Transport
9.2.2.1.1 Mobile Robotic Platforms
9.2.2.1.2 Climbing Aids
9.2.2.1.3 Crew Systems
9.2.2.2 Local Vicinity (10 km) Transport
9.2.2.2.1 Personal Transport
9.2.2.2.2 Mobile Systems
9.2.2.2.3 Crew Systems
9.2.2.3 Regional (10 to 1000 km) Transport
9.2.2.3.1 Rapid Transport
9.2.2.3.2 Long-Duration Transport
9.2.2.3.3 Crew Systems
9.2.2.4 Crosscutting Capabilities
9.2.2.4.1 Surface Navigation
9.2.2.4.2 Local Worksite Communications
9.2.2.4.3 Situational Awareness
9.2.2.4.4 Autonomous Drive Operations
9.2.2.4.5 Multi-Mobility System Cooperation

Description: Support human surface operations in immediate vicinity (on the order of 100 meters) of landing vehicles, habitation areas, and regions reached by larger scale, longer distance surface mobility systems (9.2.2.2 and 9.2.2.3). Major systems are the following:

9.2.2.1.1 Mobile Support Platforms
9.2.2.1.2 Climbing Aids/Tethers
9.2.2.1.3 Crew Systems

Benefits: Improves Astronaut safety and provides for efficient explorations

General Assessment: Earth terrestrial Climbing Aids/Tethers models evolved for space exploration. Technology development and system engineering required.



Development Needed: **Medium**

9.2.2.1.1 Mobile Support Platforms

Description: Mobile Platforms perform direct operated/teleoperated/autonomous operations supporting astronauts during immediate vicinity EVAs, including equipment/cargo mass handling. Examples of such platforms include:

- Sensor Platform/ Data Relay Station
- Equipment Carriers (Carts, Sleds, lifts)
- Resource Carts

Benefits:

- Mobile Data Relay Stations will allow communications without a direct line-of-sight, essential for exploration of deep craters and rilles
- Equipment carriers/sleds reduce astronaut exertion, and mitigate the chance of damaging equipment by dropping it from height or in a fall
- Resource Carts carry large reserves of power and human consumables
- Improved crew productivity

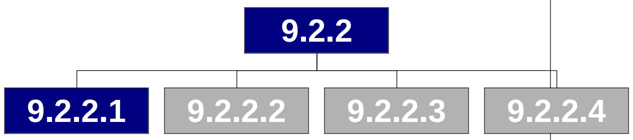
Figures of Merit

- Power, Dual utility, EVA efficiency, Ease of repair, access, use

General Assessment

- Current SOA is from Apollo (Modular Equipment Transport), Spirit/Opportunity sensor platform, EVA Robotic Assistant (TRL 6)

Development Needed: **Medium**



9.2.2.1.2 Walking and Climbing Aids

Description: Equipment to improve access to exploration targets

- Flat Terrain: Walking aid (e.g., “walking stick” for balance, stability, get-up)
- Unstable/Dark Areas: “Snowshoes” or “Skiis” / Power Umbilical or Lamp
- Steep Slope: “Ice Axe”, Ladder, Crampons, Shovel, “Ski” Poles, Rope
- Rope Interfaces: Harness, Carabineer, Belay/Arrest/Ascend Device, Reel, Knife
- Ground Interfaces: Piton, “Ice Screw”, Grapple, “Anchor”; Load Equalization
- Container/ Carriers: Rope Bag, Gear Clip, Tent/Bivouac sack, Hammock

Benefits:

- Flat Terrain: Improved safety, walking speed and fall recovery
- Unstable/Dark Area: Access permanently shadowed areas with unique regolith
- Steep Slope: Access lunar rilles and mountains, Allow rapid, safe motion
- Rope Interfaces: Access extreme terrain safely (cliff outcropping, lava tube, ...)
- Ground Interfaces: Safe anchoring in extreme environments, prevent fatal falls
- Container/ Carriers: Minimize dust effects on equipment, allow easy access

Figures of Merit

- Stowed volume, Dual utility, Ease of repair, Ease of use, Safety

General Assessment

- Neglected during Apollo missions, Earth analogue applicable

Development Needed: **Medium to HIGH**

9.2.2

9.2.2.1 | 9.2.2.2 | 9.2.2.3 | 9.2.2.4

9.2.2.1.3 Crew Systems

Description: Equipment carried by astronauts. Examples:

- Emergency Life Support Systems
  - Integration of fuel cell consumables with human consumables
  - Ensure ability to walk home after loss of larger scale surface mobility
  - Share power/life support
- Knapsacks/tool belt carry consumables, tools, and cargo (e.g., rocks)
- Hand/foot interfaces to improve habitation ingress and egress

Benefits

- Life support: Potential life saver in contingency
- Knapsack/tool belt: Allow Astronaut to work with free hands and tools at ready
- Hand/foot I/F Example: Magnetic doormat can remove dust before entry

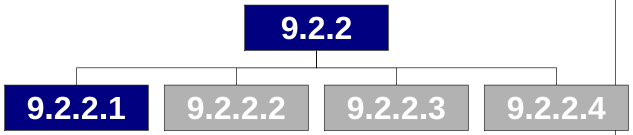
Figures of Merit

- Health, Safety, Volume, Lifetime, Dual use, Easy use,

General Assessment

- Longevity, reusability, serviceability (replenishing and repairing) are key technology challenges

Development Needed: **Medium for life support**



Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.2.2.1.1 Mobile Support Platforms *Key: Assist local crew mobility and safety*	Apollo experience	*5*	Mobile Data Relay Station, Carriers for Equipment & Resources	2010	2015	1-7
9.2.2.1.2 Walking and Climbing Aids *Key: Improve safety and enable access to important, presently unexplorable areas*	Apollo flat Terrain; Mountain Climbing tools on the Earth	*4*	Interfaces for Flat Terrain, Unstable / Dark Areas, Steep Slopes, Rope, Ground Anchors, and Containers	2010	2015	1-7
9.2.2.1.3 Crew Systems *Key: Assist local crew safety and utility*	Apollo experience with some gains from ISS	*3*	Contingency Life Support systems, Backpacks, and Hand/Foot I/Fs (magnet doormat)	2010	2015	1-7

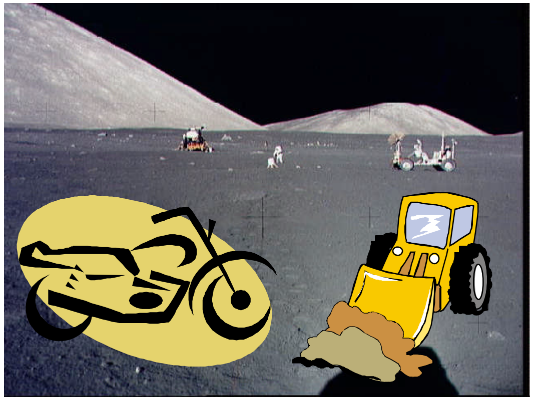
Capability 9.2.2.2
Surface Mobility: Local Vicinity Transport

Presenter:

Team Lead

Description

- Efficiently transport crew, supplies, and equipment to desired locations that are up to approximately 10 km from a habitat or other pressurized, protective shelter, and ensure the crew's safe return to their starting point



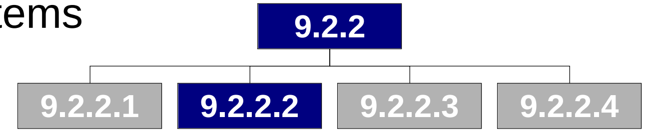
- **Sub-Capabilities**
  - 9.2.2.2.1 Personal Transport
  - 9.2.2.2.2 Mobility System
  - 9.2.2.2.3 Crew Systems
  - 9.2.2.2.4 Mobile Construction Systems

Primary Benefit

- Enables the assembly, operation, and maintenance of large scale facilities and increase reach for science and facilitates ISRU

General Assessment

- The Lunar Roving Vehicle represented the Apollo SOA and will generally suffice for upcoming missions. Durability and commonality across architectural elements need to be addressed.
- Technology development and a significant amount of systems engineering is required



9.2.2.2.1 Personal Transport Overview

Description

- Transport single crew member with very limited equipment to a remote worksite and/or back to a habitat or other pressurized, protective shelter that is up to approximately 10 km away
- Examples: All Terrain Vehicle, Sled, Motorcycle, Gyrostabilized Wheeled Vehicle “Segway”, Jet Pack, Mechanical Hopper, Exoskeleton

Benefits

- Increases EVA efficiency by providing quick transport to a pre-setup or remote site
- Preserves EVA consumables
- Reduces crew fatigue
- Increases flexibility in planning exploration excursions
- Improves crew safety by providing return to habitat or protective shelter
  - Contingency return for long duration transport

FOM

- Transit time, range, resource usage (Power, Propellant…), lifetime, maintenance, payload capacity, environmental (T, dust, daylight, radiation…), portability, EVA consumable savings, metabolic rate and crew fatigue reduction, safety redundancy

General Assessment

- Component technologies need to be developed and integrated to meet mission constraints and provide the mobility required to traverse the terrain

Development Needed HIGH

9.2.2.2.2 Mobile Systems Overview

Description

- Transport crew (2-4 people) and/or various size paylods, up to 1000 kg and TBD m3, to remote worksites that are up to approximately 10 km away from a primary habitat or base camp using various levels of autonomy (direct piloted to fully autonomous)
- Examples: Wheeled system (car), Tracked system (tank), Walker, Mechanical hopper, Propulsive hopper, Rail based train, Rocket plane

Benefits

- Allows further separation of support infrastructure (I.e. Habitat, power station, landing areas, etc.) to increase mission safety
- Preserves EVA consumables
- Reduces crew fatigue
- Increases carrying capacity
- Increases surface area for exploration (ISRU, science research, etc.)
- Increases available staging area for storage and construction

FOM

- Transit Time, Payload Capacity/System Mass, Range, Power, Terrain Agility, infrastructure requirements, lifetime, maintenance, environmental, EVA consumable savings, metabolic rate and crew fatigue reduction, safety redundancy

General Assessment

- Some component technologies need to be optimized (e.g. motors) while others need substantial development work
- Substantial system engineering and integration is required to architect a useful system that is applicable to a wide range of tasks

Development Needed Medium

9.2.2.2.3 Crew Systems Overview

Description

- Enable the crew to interact and control the mobility system effectively
- Supplement a crew member's Portable Life Support System (PLSS)
- Examples: Deployable Crew Aides, EVA Compatible Crew Controls, PLSS Resupply System, PLSS Consumable ORUs,

Benefits

- Enabling capability for crewed mobility systems (Option within Subcapability 9.2.2.2.2)
- Increases EVA duration
- Reduces mass required for PLSS thereby reducing crew fatigue during EVA

FOM

- EVA duration, EVA efficiency, EVA suit and PLSS weight, environmental

General Assessment

- Crew interface requirements and associated support systems (hand rails, displays,…) are well understood
- Ability to resupply a PLSS is highly dependent on the PLSS architecture but this issue has been studied by the advanced EVA community and demonstrated in a variety of environments/conditions (In flight, prototype testing, field testing, …)
- Advances need to develop robust connectors to reduce environmental contamination

Development Needed **Low**

9.2.2.2.4 Construction Systems Overview

Description

- Enable the capability to transport large items (e.g. habitat modules), shape the environment and mine for in-situ resources (ISRU)
- Examples: Dump truck, mobile crane, bull dozer, back hoe, tractor

Benefits

- Allows construction of support infrastructure (I.e. Habitat, power station)
  - Prepare roadways
  - Flatten landing areas
  - Move payloads from lander to other site
- Increase mission safety by providing distance separation between Lander and base
- Radiation shielding via excavating and covering modules with regolith, meters in thickness
- Supports ISRU

FOM

- Common components/subsystems, Reliability in lunar environment, Power consumption, Ease of use/Required training, maintenance, payload capacity, towing capacity

General Assessment

- Capability has not been demonstrated in the target environment
- Key issue will be how this system relates to other mobility systems and will thus require significant SE&I effort to develop an optimal mission approach
- Capability lacking

Development Needed **HIGH**

Capability 9.2.2.3
Surface Mobility: Regional Transport Transport

Presenter:

Team Lead

Description:

- This capability provides for the development of systems that enable regional transport* of Crew, Supplies and Equipment. Regional Transport is required for extended (Spiral 2) and permanent presence (Spiral 3) on Moon, surface area of 38 Million km^2 and for exploration of Mars, surface area of 144 Million km^2.

Major Sub-Capabilities:

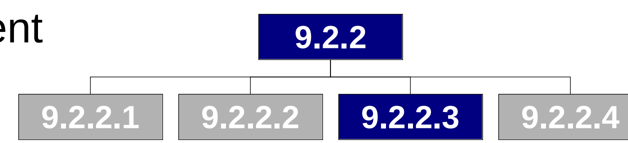
- 9.2.2.3.1 Rapid Transport
- 9.2.2.3.2 Long Duration Transport
- 9.2.2.3.3 Crew Systems

Benefits:

- Provides Crew Safety and enables exploration, and extended and permanent presence on Moon and Mars

General Assessment: Only current deployed system is the Lunar Roving Vehicle which does not meet long duration, long traverse, extreme terrain, rapid transport requirements. Needs significant development

Development Needed: HIGH



Drivers:

•Unimproved Surface Conditions regulate maximum speed for wheeled vehicles of 15 km/hr

Assumptions:

•Environmental protection of Crew criticality 1

•Mission must maximize crew productivity – minimal traverse time a priority

•.Missions will include regional distances traversed (500-1000km)

•Sufficient fuel is available for propulsion potentially In-Situ Propellant Production

•Improved surfaces (i.e. roads, railed systems) for travel not within roadmap timeframe

Capability for suborbital mobility or CEV precision landing to pre-identify location required for crew safety and productivity

Description: Capability to quickly transport Crew back to safe haven or base

Examples: Ballistic Hopper, Motorcycle, Improved surface rovers,…

Benefits:

- Safety of Crew
  - Emergency return to safe haven
  - Reduced exposure time to radiation flux
- Increases Crew Productivity

FOM: Transport time <1 hour up to days with advanced SPE warning, Traverse distances of 10km to 1000km; load capacity (Volume, weight, crew size), Size (Volume, weight), Environment Protection

General Assessment: Apollo 17, record of 17 km/hr driving downhill during return trip to the lunar module. Average of 7 km/hr. Non-rechargeable, power system designed maximum traverse of 92km.

Development Needed: **HIGH**

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Need Date	CRL
9.2.2.3.1 Rapid Transport					**2016**	**1**
Active Stability Control	None	1 - 2	1) Gyroscopic stability control 2) Stored energy/rocket braking 3) Enhancement of existing thruster controls 4) Architecture	2014		
Highly reliable throttleable, restartable, refuelable, high energy density green, bi-propellent propulsion system	Concepts developed, minor component testing	2	1) Selection of propellant type that minimizes weight penalty 2) Propellant storage/creation 3) Refuelling technologies 4) IVHM (Automated/Rapid Launch Sequence)	2013		
Real-Time landing site detection	None	1 - 2	1) Long range terrain definition 2) Automated landing site planning	2016		
Mars Flying Machine	Concepts	1	Propulsion/Aerodynamic system		2030	1

Drivers:

•Unimproved Surface Conditions regulate maximum speed for wheeled vehicles of 15 km/hr

Assumptions:

•Environmental protection of Crew criticality 1

•Mission must maximize crew productivity – minimal traverse time a priority

•.Missions will include regional distances traversed (500-1000km)

•Improved surfaces (i.e. roads, railed systems) for travel not within roadmap timeframe

Capability for robust, autonomous mobility systems required to deploy and preposition safe-havens for crew safety and productivity

Description: Capability to efficiently transport Supplies, Equipment, and possibly Crew

- Examples: Tractor, "RV", Trains……

Benefits: Enables Exploration and Reduces Lander requirements

FOM: Long life, rechargeable systems, 10:1 carrying capacity (payload mass/empty mass), load capacity (Volume, weight), Size (Volume, weight)

General Assessment: The Lunokhod had a life of 3 lunar days (3 earth months) and total mass of 840kg. The LRV had a life of 4 days, and an empty mass of 210 kg and a payload capacity of 490 kg.

Development Needed: **HIGH**

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Long Duration Transport					2022	2
Modular, Reconfigurable, rechargeable, long life power systems	LRV: Two non-rechargable independent battery systems; Primary 36 volt, 23 cell, silver-zinc using potassium hydroxide; 0.75 kW; 0.08 Watt-hrs/km-kg for wheeled motion STS: Non-rechargable Fuel Cells; Extended Duration Orbiter with crew use of water;	2	40kW -100kW hybrid, rechargable power system Modular, Plug and Play Architecture and components with common interfaces to allow for spiral growth Cross-Subsystem Synergy - use of reactants for water as a resource and for radiation protection	Architecture - 2010 Components 2015		

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Long Duration Transport					2022	2
Thermal Management				2015		
Radiation Protection				2015		
Noise Abatement	Terrestrial standards	2	Improved energy efficient components Noise conscious designs and materials	2015		
Integrated Wireless Network Systems			Virtual Presence Increased capacity	2015		
Compact, low power, digital mixed media devices		2	Devises with the ability to process data and retrieve information during IVAs and EVAs	2015		

Description: Capabilities to safely and reliably support human life for mission duration and Effectively perform IVA and EVA operations

Examples: Self-Contained ECLSS, Limited vs. Full radiation protection, …

Benefits: Safety of Crew and Ability for extended operations and permanent presence

FOM: Replenishable resources for 5-6 Crew, X REM over X days

General Assessment:

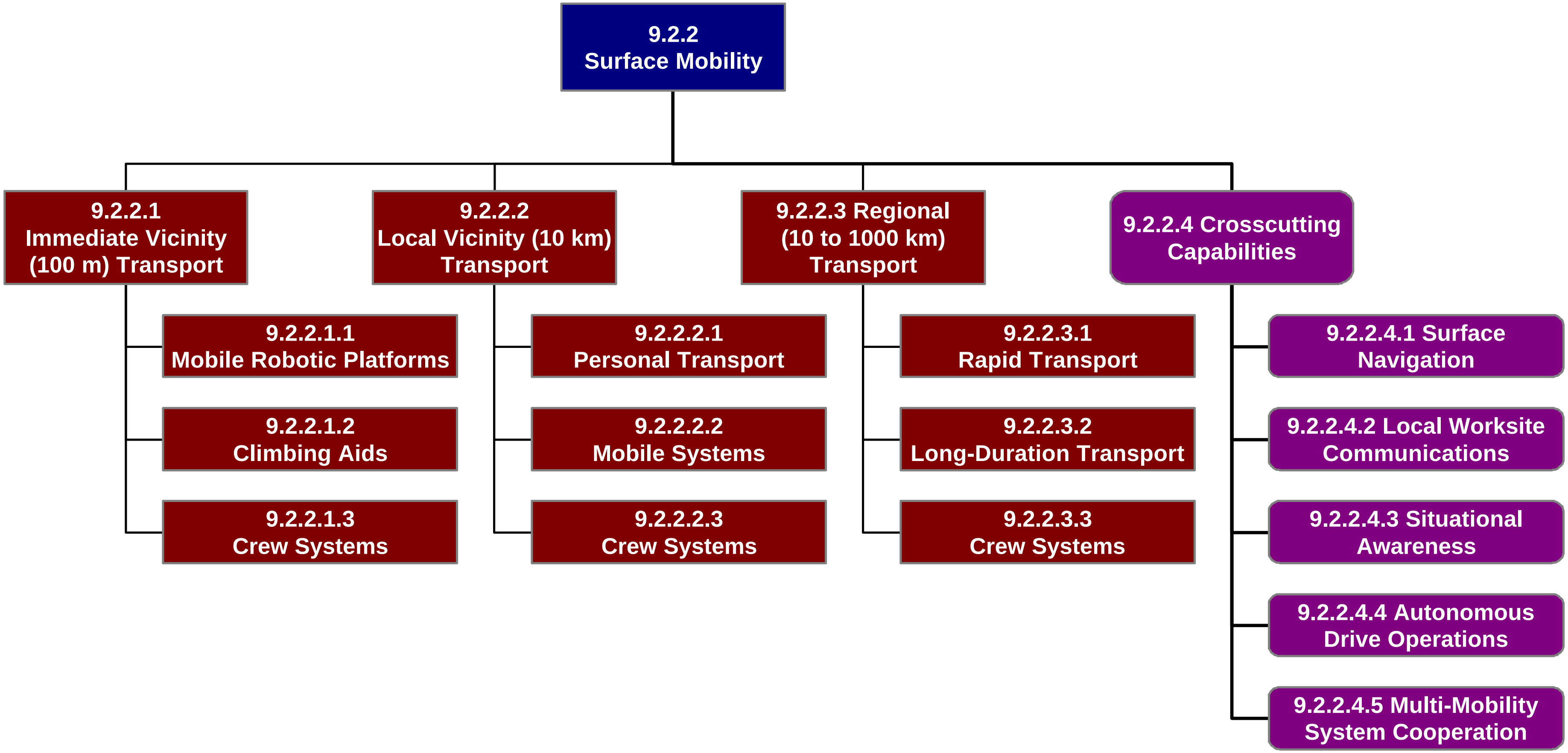
Development Needed: **HIGH**

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Crew Systems					2020	2
Robust Consumable EVA Interfaces			Advanced environmentally robust connections Fast re-supply	2015		
SEP Protection	None	2	24 hour response protection Advanced warning system	2015		
Noise Abatement	Terrestrial standards	2	Improved energy efficient components Noise conscious designs and materials	2016		
Integrated Wireless Network Systems			Virtual Presence Increased capacity	2016		
Compact, low power, digital mixed media devices		2	Devises with the ability to process data and retrieve information during IVAs and EVAs	2015		

Capability 9.2.2.4
Surface Mobility: Crosscutting Capabilities

Presenter:

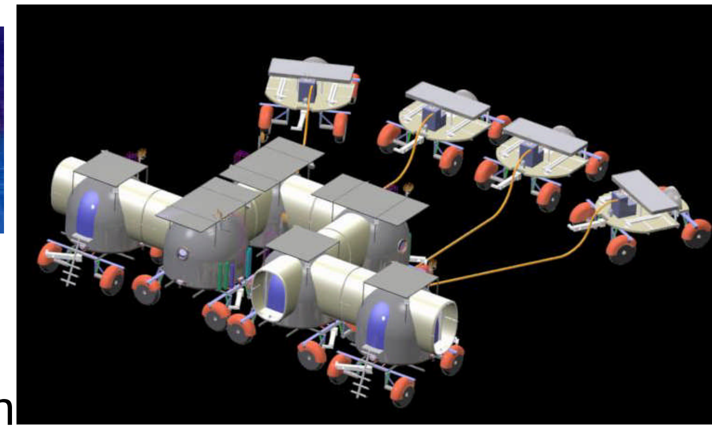
Team Lead


9.2.2
Surface Mobility
9.2.2.1
Immediate Vicinity
(100 m) Transport
9.2.2.2
Local Vicinity (10 km)
Transport
9.2.2.3 Regional
(10 to 1000 km)
Transport
9.2.2.4 Crosscutting
Capabilities
9.2.2.1.1
Mobile Robotic Platforms
9.2.2.1.2
Climbing Aids
9.2.2.1.3
Crew Systems
9.2.2.2.1
Personal Transport
9.2.2.2.2
Mobile Systems
9.2.2.2.3
Crew Systems
9.2.2.3.1
Rapid Transport
9.2.2.3.2
Long-Duration Transport
9.2.2.3.3
Crew Systems
9.2.2.4.1 Surface
Navigation
9.2.2.4.2 Local Worksite
Communications
9.2.2.4.3 Situational
Awareness
9.2.2.4.4 Autonomous
Drive Operations
9.2.2.4.5 Multi-Mobility
System Cooperation

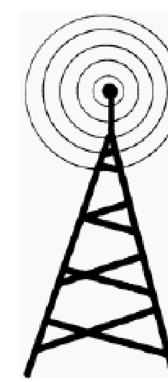
Description: Capabilities that are required to enable successful mission operations across all of the surface mobility elements. Capabilities required do not vary significantly between elements.

Major Sub-Capabilities:

- 9.2.2.4.1 Surface Navigation
- 9.2.2.4.2 Surface Communications
- 9.2.2.4.3 Situational Awareness
- 9.2.2.4.4 Autonomous Drive Operations
- 9.2.2.4.5 Multi-Mobility Systems Cooperation

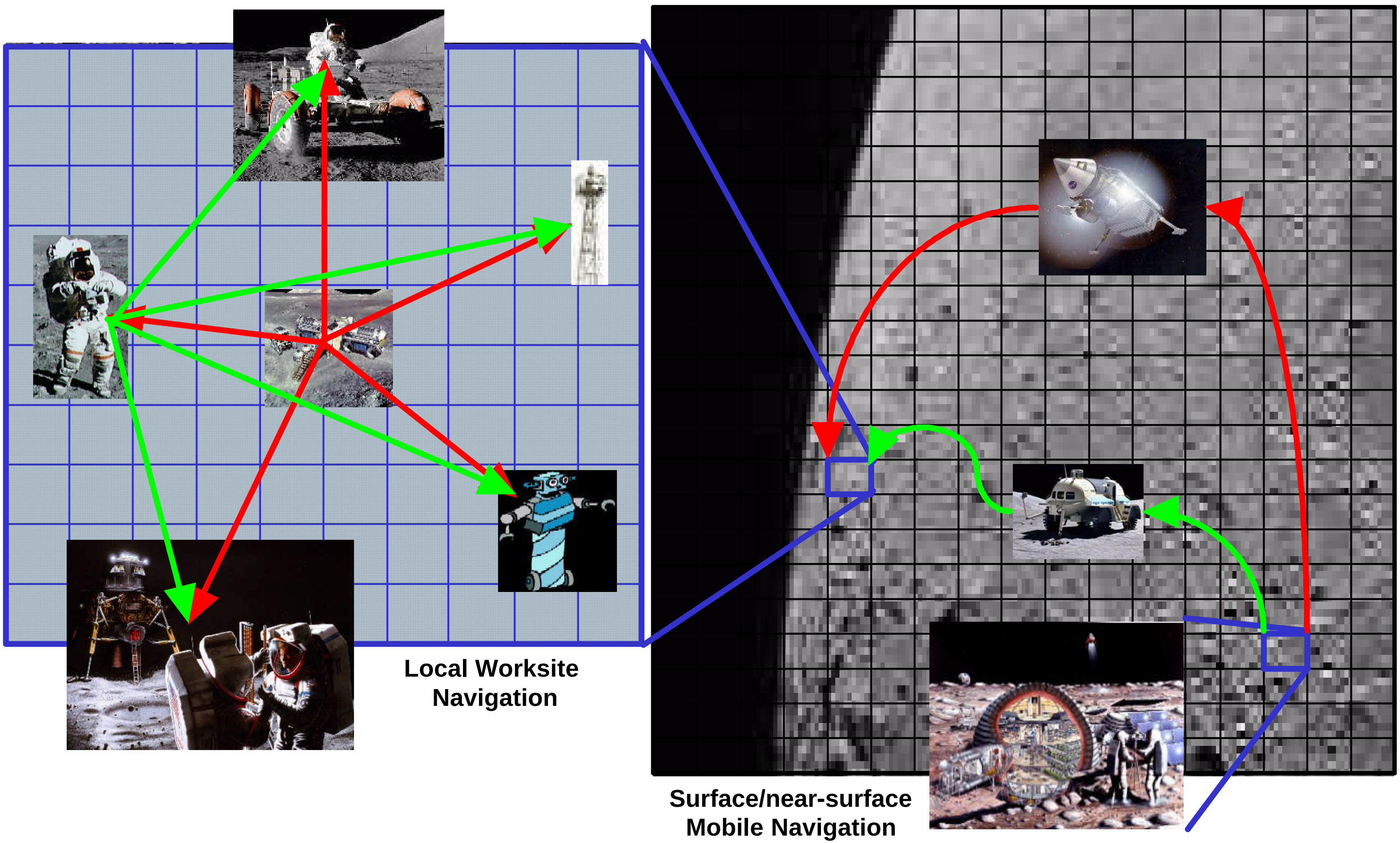


Modular Roving Planetary Habitat, Laboratory, and Base (MORPHLAB) *(2004, University of Maryland)*



Benefits: Provides Crew Safety and Enables Exploration and Extended Presence on Moon and Mars

Development Needed: HIGH


Local Worksite
Navigation
Surface/near-surface
Mobile Navigation

Description

- **Provides relative navigational information for personnel and equipment on the surface of the moon (or Mars/other similar body)**

- **Local work site area defined as a range of approximately 1 kilometer from the center of the work site or permanent base**

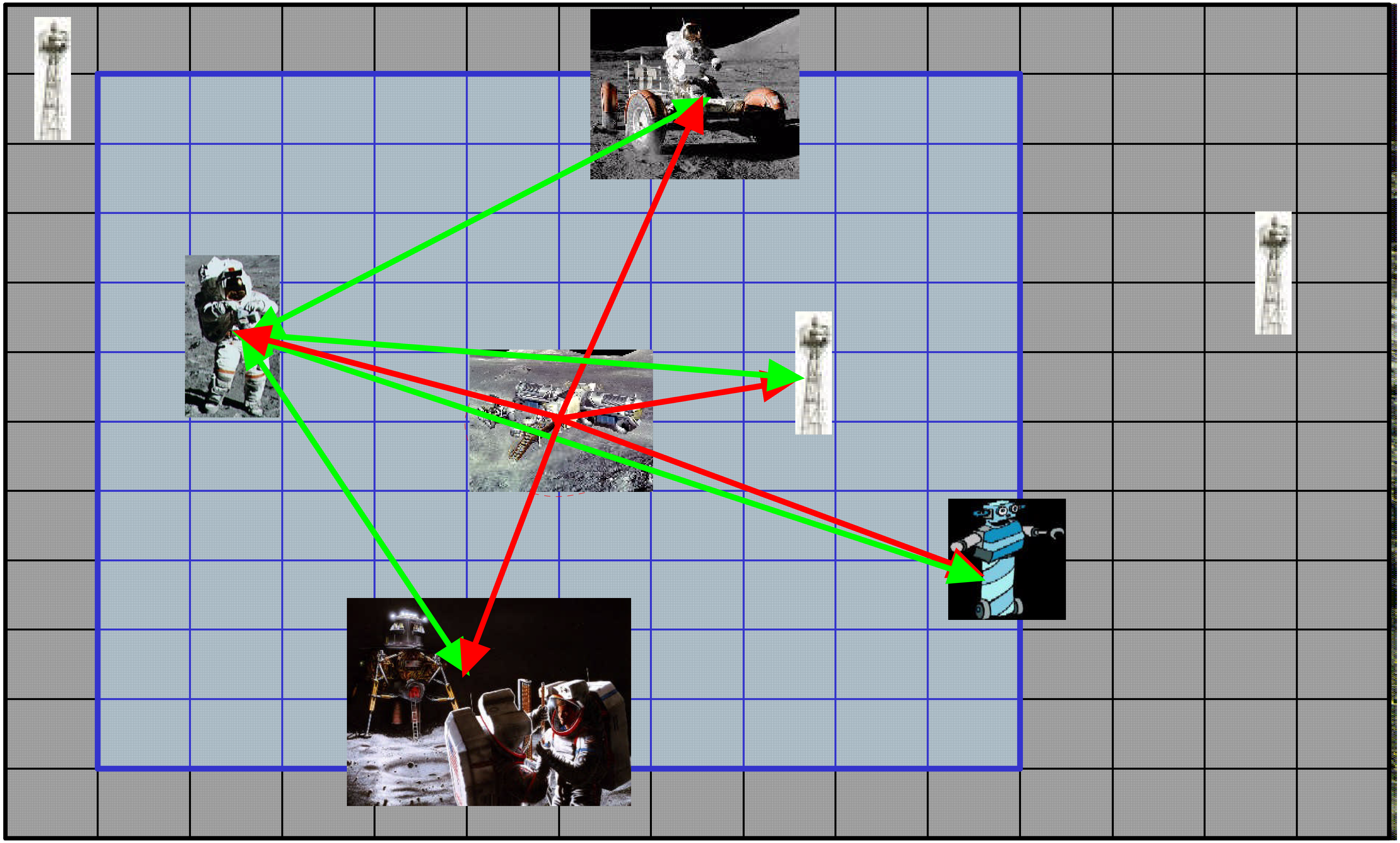
- **Work site personnel and equipment include, but are not limited to, EVA personnel, robots, rovers, surveyed navigational beacons or landmarks, fixed equipment, specimen locations, and local transports.**

- **Provides position, velocity, bearing, and other navigational parameters relative to a local rectangular or similar site grid.**

Lunar or Planetary surface navigation is composed of navigation tasks performed:

- **at local surface worksites (9.2.2.4.1.1),**
- **on vehicles moving along the surface (9.2.2.4.1.2),**
- **on suborbital transports (9.2.2.4.1.2), and**
- **on overhead reconnaissance vehicles (9.2.2.4.1.2).**

Techniques developed during Apollo, Martian, and more recent lunar programs along with current advances in terrestrial hardware and software are a starting point for the required moderate development of surface and near-surface exploration navigation systems.



Benefits

-

•Enables situational awareness for the personnel and autonomous equipment

•Provides the location of the other equipment or personnel with respect to each other and to the work site or the permanent base

•Ensures a degree of safety and mission success

•For example, EVA personnel or robots can return to the location where a previous specimen was taken for a second sample, or choose a new unexplored specimen location.

FOM

•Required one sigma position accuracies, relative to the local grid :

A) position of fixed equipment, such as recharging stations - 10 meters

B) position of mobile equipment and personnel - 20 meters

C) position of specimen locations, excavation sites and navigation beacons - 5 centimeters

•D) The local site grid must be matched to local overhead photography within 3 meters (1 sigma).

•E) The local site grid must be tied to an inertial coordinate system within an accuracy of 100 meters (1 sigma).

General Assessment : Existing Earth- and Apollo lunar-surface mapping and nav techniques are a good starting point for development of exploration algorithms. Surface beacons or equivalent need to be developed.

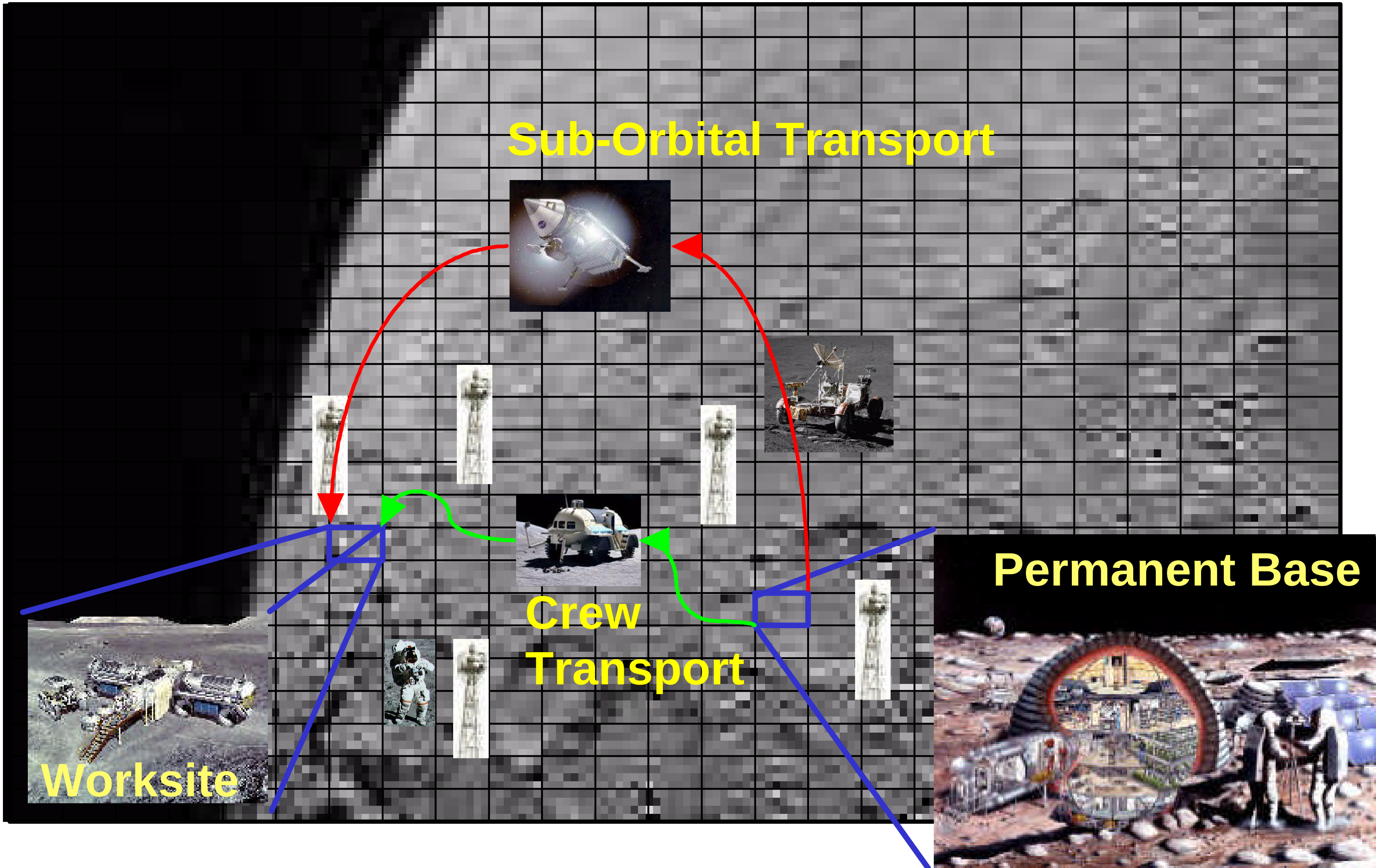
Development Needed : algorithms – A,B, & E Medium; C & D High

hardware – surface beacons High; small nav sets Medium

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capab. Date	CRL
Range-bearing Nav/comm beacons or equivalent	TACAN	4	space qualify, combine with comm, less power	2009	2012	2
Fixed equipment relative location system (A)	laser transit	5	space qualify	2008	2010	4
Mobile equipment/crew relative location system (B)	Opt. POSE laser,range from 2-way comm. link	5 5	space qualified, lighter weight, less power	2009	2012	2
Navigation beacon/sample site location system (C)	same as for **(B)**	5 5	same as for **(B)**	2008	2010	2
Calibration of local grid to overhead photography (D)	planetary photometry	7	Explor.-focused space qualified	-	2012	5
Calibration of local grid to inertial coordinates (E)	DSN	8	strong planetary site transmitter	-	2010	5
Surface satellite navigation system	TDRSS, GPS	7	combine with comm. sat., lunar/other qualify	-	2012	5

Description

- Provides both relative and inertial navigational information for personnel and equipment traversing the surface of the moon (or Mars/other similar body)
- The range of operation extends outward from the surface base to distances defined by remote work sites (eventually on the order of several thousand kilometers).
- Personnel and vehicles include but are not limited to pressurized crew transports, unpressurized equipment movers, suborbital transports, aerial reconnaissance vehicles, mobile rovers and robots, and EVA personnel.
- Provides relative position, velocity, bearing, and other navigation parameters with respect to a planet-wide surface grid.
- Provides absolute position, velocity, and other navigation parameters in an inertial coordinate system.



Sub-Orbital Transport
Crew
Transport
Permanent Base
Worksite

Benefits

-

- **Traversing relative navigation enables personnel and surface mobile equipment to traverse to find their way to remote work sites and to return to a permanent base using some of the same equipment and techniques used for local worksite navigation.**

- **Both the traversing inertial navigational system and the relative navigational systems enable suborbital or other transports to land close enough to designated sites to accomplish mission objectives safely.**

- **The inertial navigation allows overflight vehicles to perform required overhead surveys of remote worksites.**

FOM

- **Required one sigma position accuracies, of in-transit surface moving vehicles and personnel are:**
  - **100 meters with respect to the planetary surface grid (relative nav)**
  - **350 meters with respect to an inertial coordinate frame (inertial nav)**
- **For sub-orbital transports landing at a surface site and for overhead reconnaissance vehicles, the accuracies one sigma must be:**

  C) 100 meters in position with respect to the site surface grid (relative nav)

  D) 350 meters in position and .35 meters/sec in velocity inertially.

General Assessment : Realtime lunar inertial navigation is challenging due to the anomalous gravity field and the need to develop inertial nav sensors not dependent upon earth-based equipment. Satellites, beacons, and optical sensors are good technical candidates.

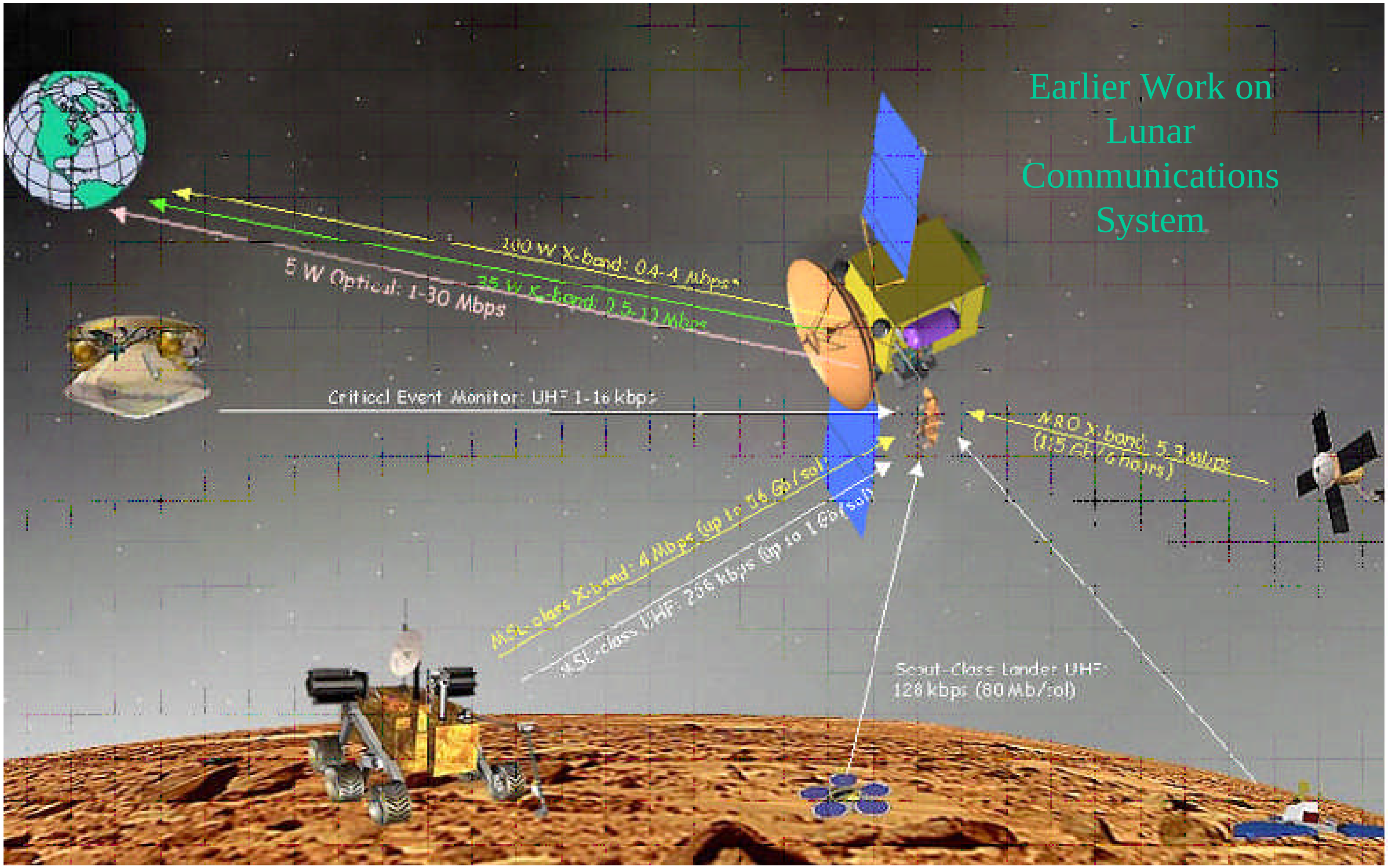
Development Needed : algorithms – A,B,C, & D Medium;

hardware – surface beacons and optical sensors High; satellites & inertial platforms Medium

In work

Capability/ Technology	**SOA**	**TRL**	**Needs**	**Need TRL 6**	**Capability Date**	**CRL**
Range-bearing Nav/comm beacons or equivalent	TACAN	4	space qualify, combine with comm., less power	2009	2012	2
Surface/near-surface beacon relative navigation system	TDRSS, GPS	7	combine with comm. sat., lunar/other qualify	-	2012	5
Surface vehicle inertial platform	In work				2015	
Near-surface inertial navigation system	NSTS onboard navigation	6	Adapt for lunar sub-orbiters, etc.	-	2015	4
Backup surface vehicle nav system	Photometry, wheel-turn counts	5	Near-complete replacement	2012	2015	4
Multi-beacon relative surface navigation algorithms	NSTS TACAN	6	Adapt for expl. vehicles	-	2015	4

Earlier Work on Lunar Communications System



Lunar or Planetary surface communications are composed of communications tasks performed :

- **among elements at local surface worksites, surface bases (9.2.2.4.2.1), and home planet facilities**
- **among vehicles moving along the surface, vehicles in suborbital transport or reconnaissance, surface elements, and home planet facilities (9.2.2.4.2.2).**

Modern operational concepts require significant bandwidths and multipoint communication capabilities.

When practical, communications and navigation can share common equipment.

- The exploration communications architecture has requirements for:
  - an adaptable, high-rate communication backbone infrastructure,
  - access links to space and ground networks,
  - inter-spacecraft communication links, and
  - close range wireless proximity links
- Human and robotic endeavors will require a communication infrastructure that:
  - can support bi-directional, multiple video, voice, and Internet-like data transfers
  - will enable simultaneous communications among local work site personnel and equipment, a planetary base, orbiting facilities and Earth-based control centers.
- When feasible, planetary orbital satellites will be deployed to aid in both communications and navigation.

Description

- Provides voice, video and data communications among personnel and equipment at a worksite on surface of the moon (or Mars/other similar body)

- Local work site area defined as a range of approximately 1 kilometer from the center of the work site or permanent base.

- Work site personnel and equipment include, but are not limited to, EVA personnel, robots, rovers, fixed equipment, local transports, and habitats.

- Provides communications between worksite elements, surface bases, and home planet facilities

Description, continued

- **Provides two-way voice and live high-resolution, compressible video (CHDTV) between each EVA crew person and the surface base**

- **Provides two-way voice and live video among EVA personnel**

- **Provides live high-resolution video from each crew person and robot to the surface base and to Earth (can be relayed through surface base)**

- **Provides bandwidth of sufficient width to send instructional photographs, data/command, and videos from the surface base to each EVA person**

- **Provide substantial two-way data/command transfer among EVA personnel and local robots**

Benefits

- **EVA crew will able to execute procedures using up-to-date textual and visual information sent by elements external to the site.**

- **Enables local crew to perform coordinated tasks via exchange information exchange with each other.**

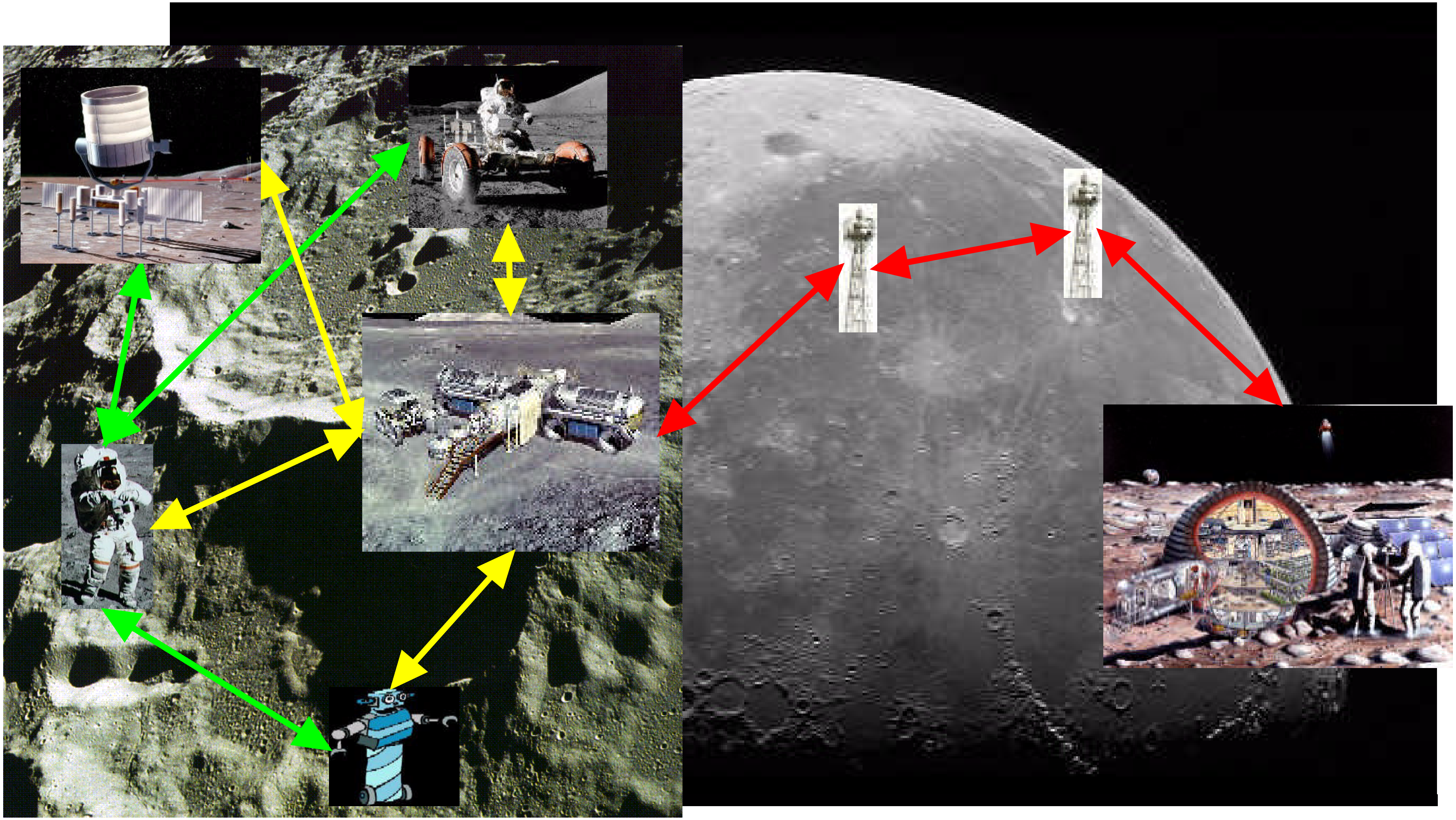
- **EVA time is saved using information retrieval and interchange.**

- **Enables crew to monitor and control robotic rovers and platforms**

- **Surface-based and Earth-based based personnel will able to provide operations support as needed.**

- **Improves crew morale through family email connectivity, etc.**

- **Ensures a degree of safety and mission success**



FOM Required total bandwidths (Megabits/sec) & Video Resolution

From / To	EVA Person	Site Base & Remote Base	Robot	Fixed Equipment	Surface Vehicles	Earth
EVA Person	1 scalable	10 CHDTV	1 CHDTV	0.2 scalable	1 CHDTV	n/a
Site Base & Remote Base	10 CHDTV	10 CHDTV	10 CHDTV	10 CHDTV	1 CHDTV	100 CHDTV
Robot	0.2 n/a	1 n/a	2 n/a	n/a n/a	0.2 n/a	10 n/a
Fixed Equipment	0.2 n/a	10 n/a	n/a n/a	n/a n/a	0.2 n/a	0.2 n/a
Surface Vehicles	1 scalable	1 CHDTV	1 CHDTV	1 scalable	1 CHDTV	1 CHDTV
Earth	n/a	100 CHDTV	1 CHDTV	n/a	1 CHDTV	n/a n/a

FOM (continued): **Communications among local worksite elements must not require line-of-sight clearance.**

General Assessment : In the 40 years since Apollo, communications technologies have improved dramatically. The ability to transfer megabits of information on Earth is near trivial. The greatest challenge on the lunar surface will be to communications over the horizon and to develop space-qualified equipment.

For more challenges, see assessment under 9.2.2.4.2.2.

Development Needed :

hardware – surface beacons High; satellites & other Medium

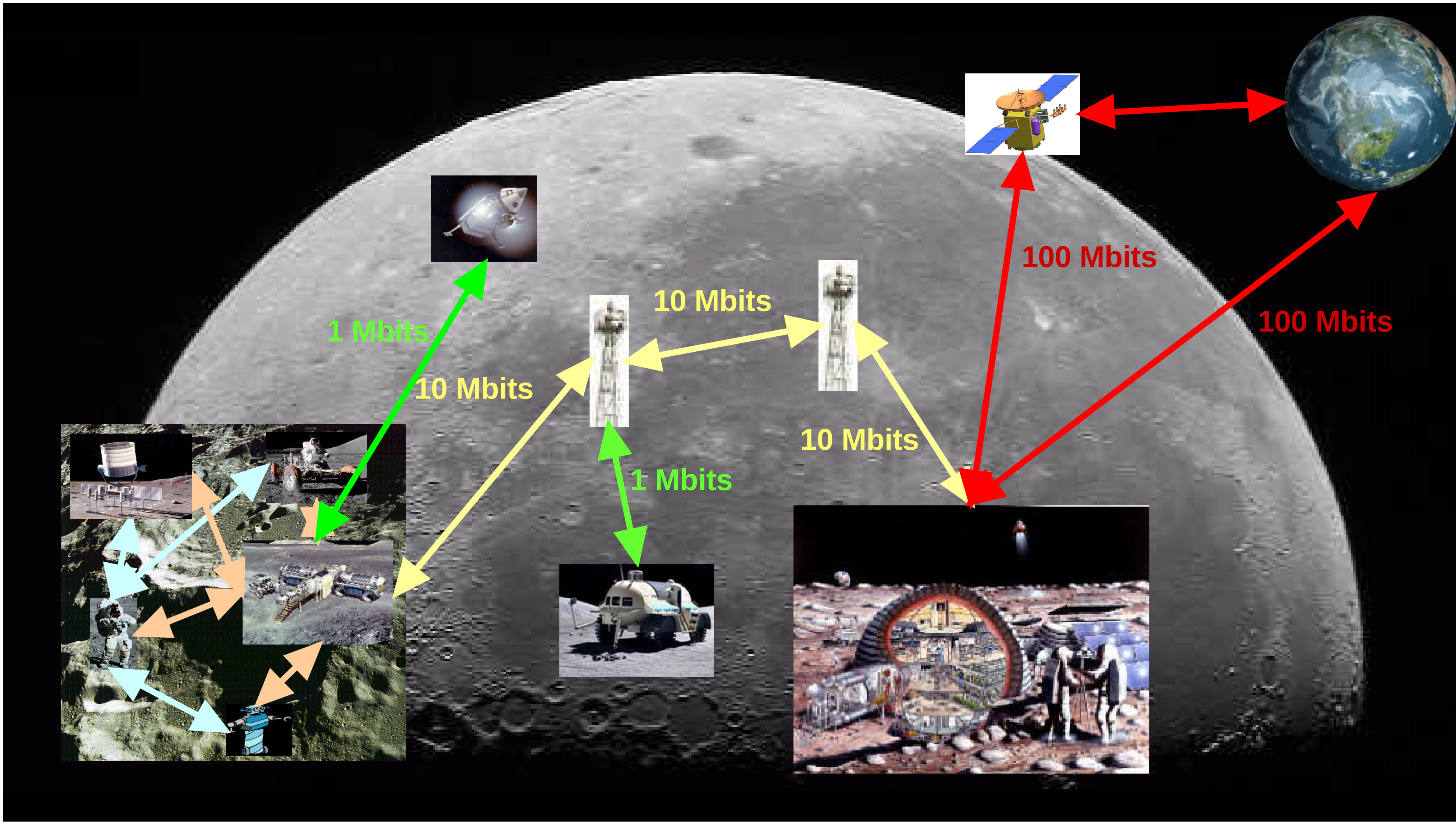
Description

Provides voice, video and data communications among vehicles moving along the surface, vehicles in suborbital transport or reconnaissance, surface elements, and home planet facilities

Benefits

Enables traversing vehicles and crew to:

- **receive procedures, maps, systems' data from surface bases and home planet facilities,**
- **perform coordinated tasks via exchange information exchange with each other, and**
- **have full command and control of robotic rovers, platforms, and stationary equipment.**


1 Mbits
10 Mbits
10 Mbits
1 Mbits
10 Mbits
100 Mbits
100 Mbits

FOM Required total bandwidths (Megabits/sec) & Video Resolution

From / To	Surface Vehicles	Sub-orbital Transports	Mobile Robots	Site Base, Remote Base, & Earth	Reconnaissance Vehicles	Fixed Equipment
Surface Vehicles	1 CHDTV	1 CHDTV	1 CHDTV	1 CHDTV	1 CHDTV	1 scalable
Sub-orbital Transports	0.2 low	0.2 n/a	1 CHDTV	1 CHDTV	n/a n/a	0.2 low
Mobile Robots	0.2 n/a	n/a n/a	2 n/a	2 n/a	n/a n/a	n/a n/a
Site Base, Remote Base, & Earth	1 CHDTV	1 CHDTV	1 CHDTV	100 CHDTV	10 CHDTV	10 CHDTV
Reconnaissance Vehicles	0.2 n/a	n/a n/a	n/a n/a	0.2 n/a	n/a n/a	n/a n/a
Fixed Equipment	0.2 n/a	0.2 n/a	n/a n/a	0.2 n/a	n/a n/a	n/a n/a

<u>General Assessment</u> :

- **Significant communication capabilities between the moon and the moon must be replaced.**

- **Past-used equipment is:**
  - **old,**
  - **doesn't use current protocols,**
  - **Is not web –compatible, and**
  - **mostly inoperative.**

<u>Development Needed</u> :

hardware – surface beacons High; satellites & other Medium

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Cap. date	CRL
Combined nav. & communications 10MBPS surface beacons	currently separate: A) TACAN, B) 300 kbps cell phone relays	3	Development of dual-use deployable low surface beacons	2011	2014	2
Low mass 3DHD cameras	surveillance personal cameras, Soni full concept 3DHD prototype	9 5	Add funding to full-concept 3DHD cameras	2009	2012	4
Crew/robot/Mobile transmitter/recv./ant.	surveillance personal rf devices	4	I MBPS, low mass, space qualify, 2 km range	2009	2012	2
100 MPBS bandwidth transmitter/recv.	1MBS DSN	2	space qualify	2012	2015	2
100 MPBS antenna	1MBS	2	Surface deployable, space qualify	2012	2015	2
Dual use Navigation & Communications Planetary Satellite	TDRSS, GPS, military laser based relays, JAXA laser satellite system in development	5	Development of dual use easily deployable satellite	2013	2016	4

Description: Capability to accurately and efficiently identify surrounding environment

- Examples: Illumination, Visualization,…

Benefits: Safety of Crew, reliable operations and mission success

FOM: X Lumens/watt, X feature identification, X bandwidth

General Assessment: LRV utilized visuals by astronauts to anchor position, Nav system accurate to 100 m

Development Need: low

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Situational Awareness						2021
Advanced Display Mediums		2-4	1)HMDs 2)Projectors 3) 3-D models 4)Holodecks	2019		
Advanced Processors		3	1) Graphics and CPU Intensive 2) Low Processing and graphics	2019		
High Smart Efficient Lighting	Fluorescent:91 Lumens/watt LED: 2700 Lumens/watt	4	1)Long life, low power, high lumens/watt lighting 2) Intelligent Lighting Control	2020		
Advanced Sensors		3	IR	2020		
Visualizing surrounding environement	HTDV, low power button cameras	2-3	Advanced Cameras 2) Synthetic Vision RT 3D modeling Ladar based systems Stereo based vision systems	2018		

Description: Capability to autonomously navigate and move the mobility system to mission destination. Capability includes override and hybrid drive options.

- Examples: Direct Control….Complete Autonomy

Benefits: Increased Crew Productivity, equipment reuse, decrease program costs, potential safety uses

FOM: Average of 2km/hr during autonomous drive operation, Autonomous navigation for X km, X roughness, X depth

General Assessment: Current SOA includes tele-operated systems. The Lunokhod traveled 11 km over 10 months and 37 km over 4 months. Mars exploration rovers are semi-autonomous operated. Full autonomy currently unavailable.

Development Need: **HIGH**

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Autonomous Drive Operations					2022	1
Automated Local Terrain detections	LRV: Human Visual System	2	Long and short range imaging and processing	2016		
Collision Avoidance	Manual spaced-based systems automated terrestrial-based systems	3	Long and short range imaging and processing Ability to alert and take steps to safe	2015		
Point to Point Navigation	1km/command; 1km/hour	2	GPS-like system for the moon	2015		
Automated Path Planning	Currently performed by humans	2	Sufficient mapping from surveillance	2015		

Description: Capability to have separate mobility systems that can combine and share resources and loads at and between mission destinations.

- Examples: Hierarchical Control, Shared/Learned Control, Shared resources & spares,…

Benefits: Allows "System of Mobility Systems" to be optimized to reduce mass, increase safety, and increase scientific returns.

FOM: % commonality, Position tolerance of X given surface level of x and X size obstacles

General Assessment: No automated mobility system-system cooperation. Deep Space Network has a complex schedule process to share its utilization among the 28 spacecraft

Development Need: **HIGH**

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Multi-mobility System Cooperation					2022	1
Common System Architecture	Avionics and diagnostic packages for FCF	6	1) Ability to plug and play components 2) Standard Interface connections	2014		
Resource sharing	Within system hardware redundancy	2	Ability to intelligently share resources across mobility systems and elements	2015		
Autonomous Control of docking and hookup	None for space, Terrestrial	1	Ability to mate mobility elements autonomously. Automated resource connections and verification of connection	2015		

Capability 9.3
Assembly and Deployment

Presenter:

John Dorsey

Assembly and Deployment Description

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- Large space systems are required for a range of operational, commercial and scientific missions objectives—however, current launch vehicle capacities substantially limit the size of space systems (on-orbit or planetary)
- **Assembly & Deployment** is the process of constructing a spacecraft or system from modules which may in turn have been constructed from sub-modules in a hierarchical fashion.
- In-situ assembly of space exploration vehicles and systems will require a broad range of operational capabilities, including:
  - Component transfer and storage, fluid handling, construction and assembly, test and verification
- Efficient execution of these functions will require supporting infrastructure, that can:
  - Receive, store and protect (materials, components, etc.); hold and secure; position, align and control; deploy; connect/disconnect; construct; join; assemble/disassemble; dock/undock; and mate/de-mate.

An Example Scenario for Assembly & Deployment

First launch: a crew habitat

Second launch: **Staging** and **Storage** of a payload container, after it rendezvous with & *docks* to the habitat; it contains truss segments, a power system, a *robot* assistant & a *crane*

Preparation For Assembly is completed & the truss is **Constructed** out from the habitat using the robot assistant; the crane is installed, including a mobile base that allows **Local Transport** along the truss, & then used for **Positioning and Alignment** of the power system, enabling it to be **Joined** to the truss

The third launch, with additional truss segments, is **berthed** to the truss using the crane & the truss is extended to provide space for additional storage & the spacecraft under construction

Subsequent launches bring storage containers with parts/modules/etc for the spacecraft that is under construction & are **berthed** to the truss

When assembly of the spacecraft is complete, **Verification** is performed, the spacecraft is undocked & transported to its operating location leaving the facility, including it's agents and infrastructure, available to assemble the next spacecraft.

Benefits of Assembly and Deployment

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- The ability to construct, assemble, deploy components to create a larger device/instrument/structure will enable much more complex missions
  - Allows the construction of large spacecraft without requiring a single launch vehicle that is large enough for the complete system.
  - Allows the construction of spacecraft so large that deployment after launch is not practical.
- In-situ assembly and deployment will allow more ambitious science activities
- Enables affordability through modularity & standardization of spacecraft components, interfaces, agent operations & capabilities & infrastructure.
- Systems designed for in-situ assembly and deployment using a modular system approach are likely to be more easily maintained and serviced
- A versatile Assembly & Deployment infrastructure can be applied to many missions & spacecraft, increasing affordability of Exploration.
- Reduced spacecraft mass - designed for space, not launch environments.

Drivers & Assumptions for Assembly and Deployment

Advanced Planning & Integration Office

Payload size and mass will not significantly change over the next 20 – 25 years. In other words, we won't have a 100 metric ton lift vehicle with significantly larger shroud size than today's launch options.

This will lead to the need to assemble larger, more complex systems in-situ

- Spacecraft designed for efficient, in-space construction & servicing. Assume design for modularity, assembly and maintenance will be used and standards developed for broad application and commonality
- Long life systems; years to 10's of years
- Location of assembly facility may vary depending on the choice of missions, but would be at a location from which the spacecraft can "easily move" to its "operating location"
  - For a Mars exploration spacecraft, assembly would be done either in LEO or at the Earth-Moon L1 point
  - For a large telescope, assembly would be done at the Earth-Moon L1 point
  - For surface assembly, it would be local to human exploration activities, a central site where human sorties originate

Capability Breakdown Structure
9.3 Assembly and Deployment

Advanced Planning & Integration Office

9.3.1 Staging (capture, docking & berthing)

9.3.2 Storage (environmental protection, just-in-time component availability)

9.3.3 Preparation for Assembly (unpack, inventory, prepare worksite & worksystem)

9.3.4 Construction (erect, inflate, fabricate)

9.3.5 Local Transport (ref. 9.2.0)

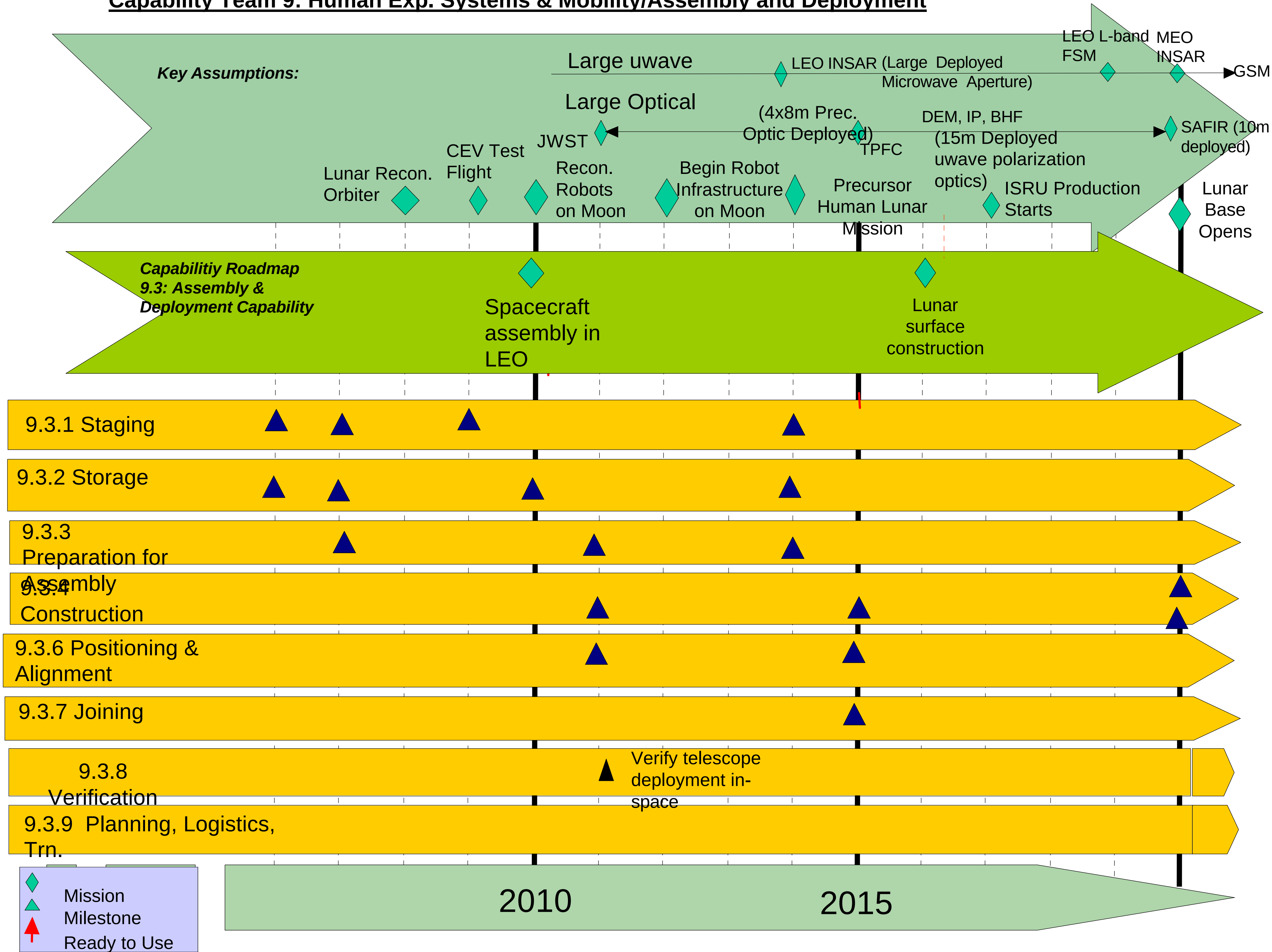
9.3.6 Positioning and Alignment (final assembly)

9.3.7 Joining

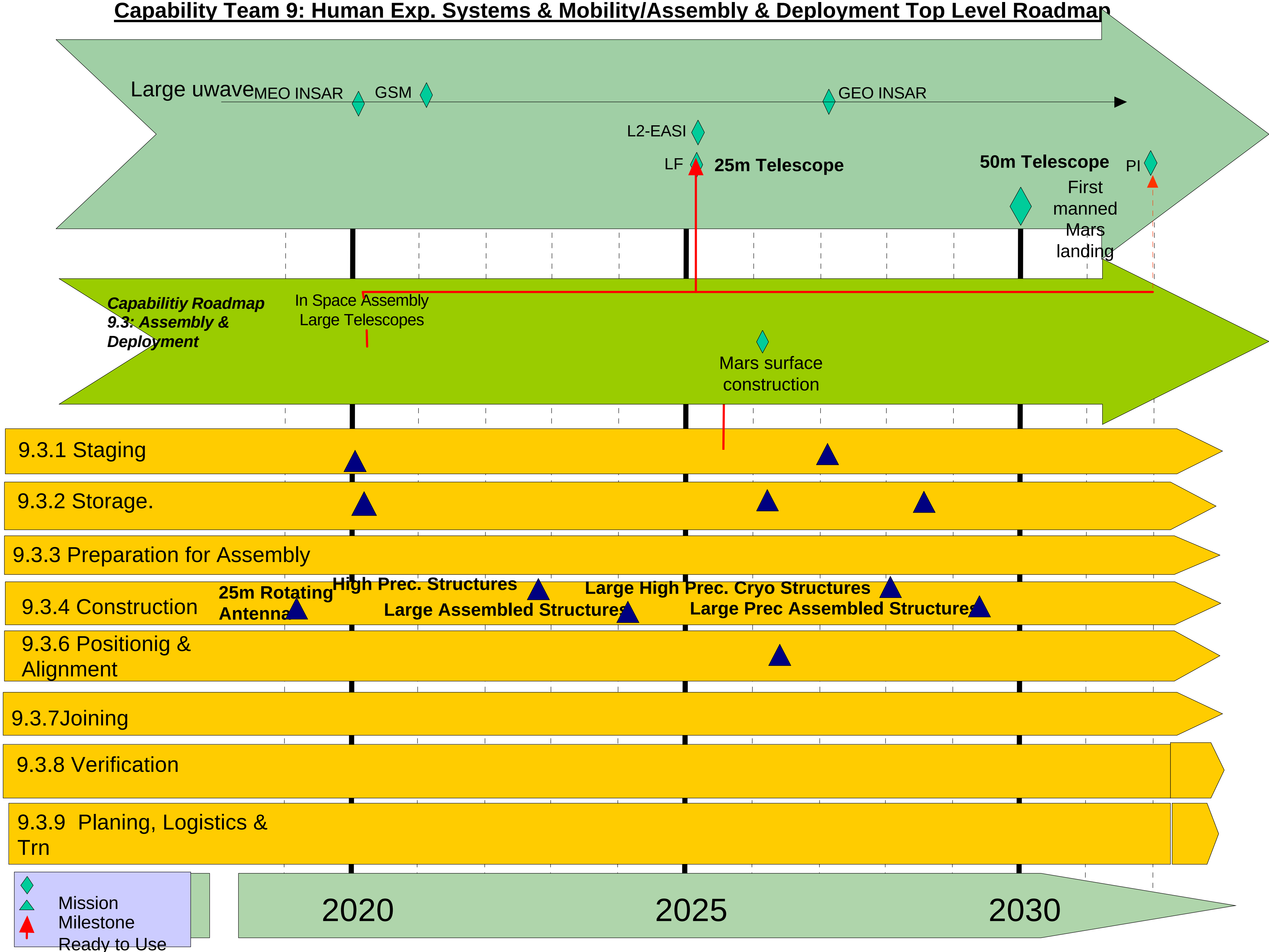
9.3.8 Verification (inspect, test, as-built documentation)

9.3.9 Planning, Logistics, Training, etc. (common across all the above)

Capability Team 9: Human Exp. Systems & Mobility/Assembly and Deployment



Capability Team 9: Human Exp. Systems & Mobility/Assembly & Deployment Top Level Roadmap



9.3 Assembly and Deployment Critical Gaps

- System level verification of large spacecraft assembled / deployed in-space
- Skill training for human / robot teams who will assemble / deploy large spacecraft in-space
- In-space assembly / deployment that supports the precision required of large telescopes
- Architectures & components that provide standard interfaces & modularity
- Fluid transfer technology

Appendix with SOA details by WBS

Capability 9.3.1
Staging

Contributor:

Wendell Chun

Capability 9.3.1 Staging

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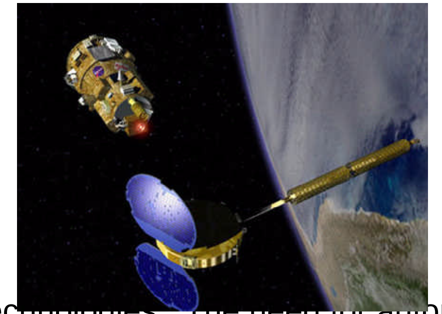
Description: Staging is the first step in assembly, having two or more vehicles working in close proximity to each other\attaching two vehicles together to establish a common coordinate frame. This also includes a payload from a launch vehicle that rendezvous & docks at an assembly facility that represents a permanent in-space infrastructure. In addition to proximity operations, the joining of two platforms includes capture, docking / berthing in 6 DOF for in-space & 3 DOF for surface operations. Staging continues with logistics, unpacking, & inventory planning, leading to storage.

Benefits: By joining two platforms together, a common reference frame is established to enable work to be accomplished, such as manipulation from one vehicle to the other. The remainder of the capabilities are required sequentially to proceed into storage. This capability is necessary for all assembly, servicing, and maintenance operations.

Figure of Merit:

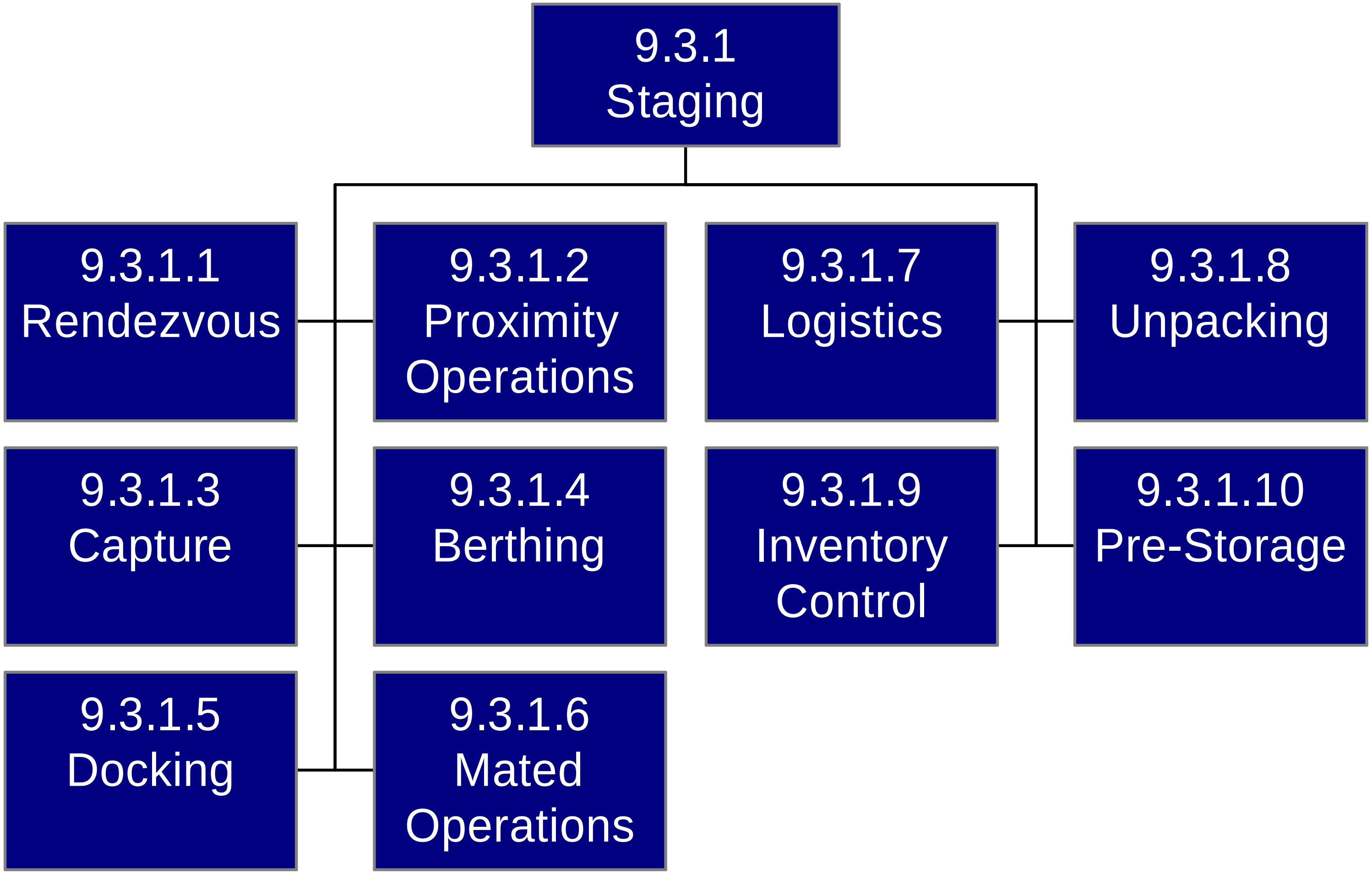
- Zero collisions when multiple vehicles are operating in close proximity
- Pass/Fail criteria for berthing or docking
- Maneuverability & pose sensing to satisfy the capture specifications of the attaching mechanism
- Capability to counteract moments & forces imparted
- Stiffness of attachment interface
- Efficient Logistics Plan (minimum number of steps)
- Minimum lost time in the schedule
- Unpacking efficiency (based on time)
- Number of human inputs into the inventory control system
- Space utilization (in preparation for storage)



General Assessment: Rendezvous and Proximity Operations are mature technologies. The need for automated berthing is driven by communication latencies bandwidth limitations, if the assembly facility is entirely robotic; otherwise, it is an efficiency for the crew who could contnue construction when a new cargo vehicle arrives. This capability requires major development & demonstration. While there is some experience with logistics, unpacking, inventory control, & pre-storage in space, the construction of large telescopes will use many more parts than have been used in Shuttle experiments or ISS construction & servicing.

Development Needed: **High (Soft Docking not demonstrated by NASA) and staging initiates entire capability.**

Capability Breakdown Structure
9.3.1 Staging



State-of-the-Art/Maturity Level / Sub - Capabilities for 9.3.1 Staging

Advanced Planning & Integration Office

Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Rendezvous						7
• Ground Control	Apollo, Soyuz	9	-	-	-	
• Automated	Shuttle	8	-	-	-	
• Proximity Operations						6
• Situation Awareness	Visual Cues	5	Efficient Info Disp.	2007	2012	
• Teaming	Laboratory – ground	4	Rel. Env.	2010	2012	
• Capture						5
• Cooperative	ETS-VII	7	No targets	2007	2010	
• Un-cooperative	Hubble Servicing	3	Pose Est.	2007	2010	
• Tumbling	Hubble Servicing	2	3-Axis	2007	2012	
• Berthing						5
• Formation Control	Station Keep	8	-	2007	2012	
• Grappling	Shuttle RMS	7	-	2007	2012	
• Docking						5
• Hard	Probe & Cone/KURS	9	-	-	2012	
• Soft	ETS-VII latches & towel bars	7	Lidar	2007	2010	
• Mated Operations						6
• Master Active/Slave Passive	Shuttle-active/ISS-passive	8	-	-	-	
• Shared	Not demonstrated	2	Impedance	2010	2012	

State-of-the-Art/Maturity Level / Sub - Capabilities for 9.3.1 Staging

Advanced Planning & Integration Office

Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Logistics						5
• Planning	Apollo, Soyuz, ISS	9	-	-	-	
• Just-in-time	Shuttle	8	-	-	-	
• Unpacking						3
• Pre-assembly Preparation	ISS	5	Robotic	2012	2012	
• Opening	EVA-ISS	6	Robotic .	2012	2012	
• Sorting	EVA-ISS	6	Robotic	2012	2012	
• Inventory Control						6
• Identification	Electronic Tags	4	Rel. Env.	2012	2012	
• Checkout	Electronic Checklist	6	Short. Slev	2010	2010	
• Grouping	Re-Palleting	4	Robotic	2012	2012	
• Pre-storage						4
• Staging	Mobility to Storage Facility	6	Smaller	2012	2012	

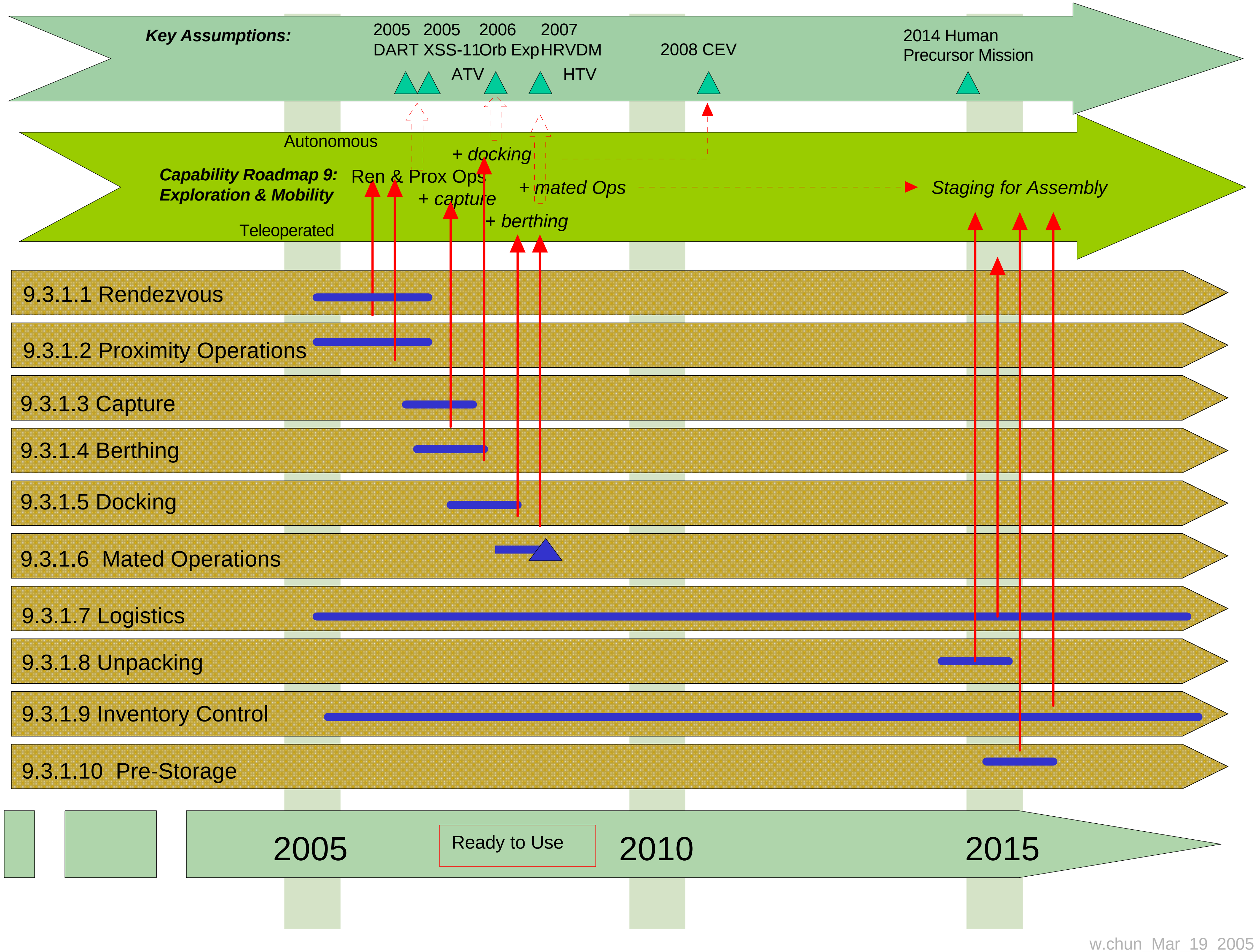
State-of-the-Art/Maturity Level / Technologies for 9.3.1 Staging

Technologies	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
9.3.1.1 Rendezvous						7
• Hills Equations	Apollo, Soyuz, Shuttle	9	-	-	2012	
• Clohsey-Wilshire	Shuttle	9	-	-	2012	
9.3.1.2 Proximity Operations						6
• Collision Avoidance	Range Sensing	5	Real-time 3D Model	2010	2012	
• Circumnavigation	Football Orbits	5	3D	2010	2012	
• Collaborative Planning	Swarm Behaviors	4	Rel. Env.	2010	2012	
9.3.1.3 Capture						5
• RMS Snare EE	Shuttle, SRMS	9	No Grapple	2008	2007	
• Latches	ETS-VII, TPDM	3	Stiffness	2006	2007	
• Magnetic EE	STS-62	2	EMI	2008	2012	
9.3.1.4 Berthing						5
• Auto Manipulation	Factory	7	Closed L	2012	-	
• Auto Tracking	Vision, Sensor Fusion	6	Obscur.	2008	2012	
• Teleoperation	HST, Spartan Retrieval	9	Backup	-	2012	
9.3.1.5 Docking						5
• Sensors	RF, Machine Vision, Lidar	7	Full Range	-	2012	
• Algorithms	RPOP, DART	7	All Axes	2008	2012	
9.3.1.6 Mated Operations						6
• Control Authority	Shuttle-active/ISS-passive	9	-	-	2012	
• Shared Control	Laboratory Demo (JPL)	2	Rel. Environ	2010	2010	

State-of-the-Art/Maturity Level / Technologies for 9.3.1 Staging

Technologies	State-of-the-Art	TRL	Needs	TRL 6 Date	Need Capability Date	CRL
• Logistics						5
• Planning	Auto. Planning Software	7	-	2010	2012	
• Just-in-time	Scheduling Software	7	-	2010	2012	
• Unpacking						4
• Pre-assembly Preparation	Centralized	5	A Priori	2010	2012	
	Distributed	4	Coordin	2010	2012	
• Opening	EVA	7	Re-usable.	2010	2012	
	Robotic	3	Tools	2010	2012	
• Sorting/Palletizing	Access Experiment	7	-	2010	2012	
	Robotic	3	I/F	2010	2012	
• Waste Disposal	Waste Container (in-space)	7	-	2010	2012	
	In-situ Stacking	4				
• Inventory Control						6
• Electronic Tags	RFID	6	Sp Qual	2008	2010	
• Electronic Checklist	Electronic Checklist	7	Reconfig	2007	2009	
• Grouping	Pick & Place Manipulation	6	Mob Man	2010	2012	
• Pre-storage						
• Mobility to Storage Facility	See Construction & Assembly section for Details					

9.3.1 Staging Top Level Capability Roadmap



Capability 9.3.2
Storage

Contributor:

Kenneth Baker

Capability 9.3.2 Storage

Advanced Planning & Integration Office

Description:

- The process of storing in-space, until preparation for assembly begins, the "parts" needed to build modules/complete spacecraft
  - Storage pre-berthing as launch packages floating nearby or controlled/sustained by upper stage
  - Storage post-berthing is for items unpacked & prepped, awaiting use, in need of keep-alive & protection
- Provide *environmental protection*, including keep-alive utilities, from launch until the parts reach the *assembly point*; say, LEO for a Mars spacecraft or an Earth-Moon libration point for a large telescope..

Benefits

- Removes the size/weight limit that a single launch imposes, enablng larger spacecraft.
- Uncouples assembly & launch, allowing them to proceed at different rates by providing a buffer on-orbit
- Provides environmental protection for parts until preparation for assembly begins.
- Provides access to equipment in the order needed for construction

Figures of Merit

- Probability that equipment will be in *working order* at the start of assembly
- Maximum *number of storage containers* needed on-orbit at one time for assembly
- Maximum *keep-alive power* required at one time.

General Assessment

- Required technology exists, need to integrate it into a standard set of launch package utilities, such as: truss to rendezvous & dock/berth parts containers with, as-shipped parts inventory, crew/robots to unpack, inventory & re-store/assemble as needed, parts marked (barcode?) to enable recording the as-built configuration of the spacecraft, .

Development Needed: Low

Capability Breakdown Structure
9.3.2 Storage

9.3.2.1 **Rendezvous & Docking/Berthing** (see 9.3.1) will be required to attach each launch package to the assembly facility

9.3.2.2 **Utility Joining** (see 9.3.7) will be required to connect utilities, such as power, fluid & communication lines to the launch package after it is attached to the assembly facility

9.3.2.3 **Inventory Control** (see 9.3.9) will be required to keep track of the parts as-shipped in each launch package & to create an al-build record of where each part was used in the assembly process. Bar-coding of parts could facilitate this process.

9.3.2.4 **Assembly Planning** (see 9.3.9) will be required to:

- Determine the overall spacecraft assembly sequence
- Select the parts to be included in each launch package & determine their arrangement so as to provide parts in the order needed for assembly, consistent with protection from the launch environment

Capability 9.3.3
Preparation for Assembly

Contributor:

Jud Hedgecock

Capability 9.3.3 Preparation for Assembly

Description:

Preparation for Assembly entails checking that all the *antecedents* for the planned assembly have been completed, such as:

Preparing the *work-site*; if a sub-assembly is to be constructed and added to a previous one as part of a module, is there room for both & is the assembly location convenient to the parts supply.

Preparing the *work-system*; are the agents (*robot & human*) that will do the work on-hand & ready, are their tools in working order and conveniently located for the job

Preparing the *components* to be assembled; have they *arrived*, are they *in good condition* & *conveniently located* with respect to the work-site.

Benefits:

Efficiency, since the work-site has been temporarily optimized for the new subassembly task while still allowing construction of the complete spacecraft.

Figures of Merit:

Number of agent moves required to get the components being assembled & the tools needed

General Assessment:

This task combines a number of the sub-capabilities needed in other areas, such as: inspection of parts & work-site; unpacking & inventorying parts as needed; re-arranging the worksite, for example, moving a completed module to its final location if it was not built there; checking to be sure that all the antecedents of the current assembly task are complete is part of planning.

- **Development Needed**: **Low??**

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Capability 9.3.4
Construction

Contributor:
John Dorsey

Capability 9.3.4 Construction

Description:

- The process of positioning, holding and joining small to intermediate elements to build a larger spacecraft sub-module or module. Also includes in-space fabrication and manufacturing.
- Will involve many more (smaller, less massive) parts than assembly, & a larger number of repetitive operations.
- For truss structures, examples include: erection, mechanical deployment & inflation deployment.

Benefits

- Increased payload mass & volume efficiency for transportation to orbit; choice of launch vehicles.
- Assembled sub-modules are designed for in-space loads, not launch or 1-g loads.
- Construction capability naturally lends itself to servicing.

Figures of Merit

- For construction agents: reach, stiffness, stability, mass capability, positioning accuracy, contamination.
- Construction operations: time/speed, complexity, versatility, adaptability, autonomy.
- Hardware: modularity, commonality, reconfigurability. standardization.

General Assessment

- EVA is well developed capability, construction robots being developed in ground laboratories. Hardware limited to erectable and mechanical deployable trusses, some operations & infrastructure.

Development Needed: **Medium**

Capability Breakdown Structure
9.3.4 Construction

- 9.3.4 Construction
  - 9.3.4.1 Positioning
    - 9.3.4.1.1 Humans - EVA
    - 9.3.4.1.2 Humans - IVA
    - 9.3.4.1.3 Robotic Manipulators
    - 9.3.4.1.4 Turntables
  - 9.3.4.2 Holding and Aligning
    - 9.3.4.2.1 Holding Fixture
    - 9.3.4.2.2 Alignment Jig
    - 9.3.4.2.3 Robotic end Effectors
    - 9.3.4.2.4 Tools (clamps, etc.)
  - 9.3.4.3 Modular Hardware
    - 9.3.4.3.1 Erectable Trusses
    - 9.3.4.3.2 Mechanical Deploy. Trusses
    - 9.3.4.3.3 Inflation Deploy. Trusses
    - 9.3.4.3.4 Pressure vessels
    - 9.3.4.3.5 Other Functional Elements
  - 9.3.4.4 Scenarios, Sequencing

Maturity Level – Technologies for Capability 9.3.4 Construction

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.1 Positioning						3
9.3.4.1.1 Humans - EVA	HST Repair/Service ISS Construction Ops.	9 9	Reduced contamination levels	2010	2013	
9.3.4.1.2 Humans - IVA (Teleoperate)	Shuttle ISS	9 9				
9.3.4.1.3 Robotic Manipulators	Robonaut Ranger Industrial type arms	4 5 5	Increased autonomy compatability with space & planetary surface environs.	2010	2013	
9.3.4.1.5 Turntable	ACCESS - manually operated	9	Modularity, versatility, reconfigurability	2010	2013	
9.3.4.2 Holding and Aligning						3
9.3.4.2.1 Holding Fixtures	LaRC SSF, PSR construction experiments	5	Modularity, versatile, adaptable, Reconfigurable	2010	2013	

Maturity Level – Technologies for Capability 9.3.4 Construction (Continued)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.2.2 Alignment Jigs	LaRC SSF, PSR construction experiments	5	Modularity, versatile, adaptable, Reconfigurable	2010	2013	
9.3.4.2.3 Robotic End Effectors	LaRC ASAL truss & hex-panels	5	Versatile, adaptable	2010	2013	
9.3.4.2.4 Tools (Clamps, supports, ..)	HST Servicing	9	Commonality, versatility, standardization	2010	2013	
9.3.4.2.5 Robotic & Astronaut Teaming	1-g test with robonaut, suited astronaut	4	Robot speed, versatility, adapt-ability, autonomy	2010	2013	
9.3.4.3 Modular Hardware						3
9.3.4.3.1 Erectable Trusses	LaRC Erectable SSF, PSR trusses	5	Modularity wrt. Sub-system integration	2010	2013	
9.3.4.3.2 Mechanical Deployable Trusses	Astromasts, ABLEmasts, Stem, Bi-Stem, etc	9	Load, modularity, damping, stiffness reconfigurability	2010	2013	

Maturity Level – Technologies for Capability 9.3.4 Construction (Concluded)

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Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.3.3 Inflation Deployable Trusses	LaRC/DARPA - Watson, et. al.	3	Load, modularity, damping, stiffness reconfigurability	2020	2023	
9.3.4.3.4 Pressure Vessels	Shuttle, ISS	9	Modularity, commonality, reconfigurability	2010	2013	
9.3.4.3.5 Other ISS Functional Elements	Solar arrays Other Items	9	Modularity, commonality, reconfigurability	2010	2013	3
9.3.4.3.6 Telescope Mirror Segments	Keck - Grnd. Based JWST - Space	9 6	Modularity, commonality	2010	2013	
9.3.4.4 Scenarios, Sequencing						4
9.3.4.4 Scenarios, sequencing	LaRC SSF, PSR LaRC ASAL LaRC ACCESS ISS HST Servicing	6 6 9 9 9	Reduced time and complexity	2010	2013	

Capability 9.3.6
Positioning and Alignment

Contributor:
John Dorsey

Capability 9.3.6 Positioning and Alignment

Advanced Planning & Integration Office

Description:

- Positioning and alignment are two critical capabilities enabling assembly, where assembly pertains to building the final spacecraft or system from large modules.
- Individual modules must be positioned, aligned and then moved relative to each other so that they can be joined.
- Requires infrastructure hardware to transport, slew, manipulate, hold and position modules.

Benefits

- Allows assembly of modular spacecraft, which will enable affordable and sustainable exploration architectures.
- Versatile, reusable and standardized infrastructure reduces cost and development time for space systems.
- Reduces the cost and complexity of spacecraft modules and sub-modules: capabilities reside in infrastructure and agents.

Figures of Merit

- For all infrastructure and devices (platforms, scaffolding, jigs, etc.): adaptable geometry, scalability, reconfigurability, versatility, low maintenance.
- For arms/cranes: stiffness, damping, mass capability, slew rates, controllability, work volume, accuracy.
- For operations: assembly time, assembly complexity, induced contamination, standardization.

General Assessment

- Arms (SRMS, SSRMS) are in service but are limited to 0-g, limited in: rates, reach, damping. Crane concepts, that are modular, and can be configured for surface operations, have limited development.

Development Needed: **Medium**

Capability Breakdown Structure
9.3.6 Positioning and Alignment

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- 9.3.6 Positioning & Alignment
  - 9.3.6.1 Grab, Attach, manipulate
    - 9.3.6.1.1 Manipulators
    - 9.3.6.1.2 End Effectors
    - 9.3.6.1.3 Grippers
  - 9.3.6.2 Slewing (large disp. & angles
    - 9.3.6.2.1 Large Arms
    - 9.3.6.2.2 Space Cranes
    - 9.3.6.2.3 ISS Devices
  - 9.3.6.3 Translation
    - 9.3.6.3.1 Transporters
    - 9.3.6.3.2 Mobile Bases
  - 9.3.6.4 Holding & Aligning
    - 9.3.6.4.1 Platforms & Scaffolding
    - 9.3.6.4.2 Holding Fixtures
    - 9.3.6.4.3 Alignment Jigs

Maturity Level – Technologies for Capability 9.3.6 Positioning & Alignment

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Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.6.1 Grab, Attach, Manipulate						2
9.3.6.1.1 Manipulators	Robonaut Ranger Industrial type arms SPDM	4 5 5 5	Increased autonomy compatibility with space & planetary surface environs.	2010	2013	
9.3.6.1.2 End Effectors	SRMS/SSRMS - snares.	9	Mass capability, stiffness	2010	2013	
9.3.6.1.3 Grippers	Robonaut (hands) Ranger (parallel jaw) SPDM (parallel jaw)	4 5 5	Low maintenance, space and planetary surface qualification	2010	2013	
9.3.6.2 Slewing - Large Displacement, Angles						2
9.3.6.2.1 Large Arms	SRMS, SSRMS	9	Adaptable, damping, reconfigurability, stiffness, mass capability, work volume, slew rate	2010	2013	

Maturity Level – Technologies for Capability 9.3. 6 Positioning & Alignment (Continued)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.6.2.2 Space Cranes	LaRC Erectable crane	4	Engineering development	2010	2013	
9.3.6.2.3 ISS Devices	ORU Transfer Device, Strella	9	Mass capability, work volume, adaptable geometry, reconfigurability			
9.3.6.3 Translation						2
9.3.6.3.1 Transporters	ISS - CETA cart Spiderbots	9 3	Mass capability, versatility, work volume, adaptable geometry	2010	2013	
9.3.6.3.2 Mobile Bases	LaRC Mobile Transporter - SSF	5	Adaptable geometry scalability	2010	2013	
9.3.6.4 Holding and Aligning						3
9.3.6.4.1 Platforms and Scaffolding	LaRC Erectable Truss	5	Modularity wrt. Sub-system integ.	2010	2013	

Maturity Level – Technologies for Capability 9.3. 6 Positioning & Alignment (Concluded)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.6.4.2 Holding Fixtures	HST Servicing	9	Scalability, versatility, reconfigurability	2010	2013	
9.3.6.4.3 Alignment Jigs	HST Servicing	9	Scalability, versatility, reconfigurability	2010	2013	

Capability 9.3.7
Joining

Contributor:

John Dorsey

Capability 9.3.7 Joining

Description:

- Joining (and unjoining) is used during operations that perform assembly, construction, replacement, repair & refurbishment. Processes include mechanical connection, welding & bonding.
- Types of potential joining operations include single-point discrete, multi-point discrete & continuous (line-type), & can be either permanent or reversible.
- Completed joints must provide a variety of functions including:load transfer, maintaining structural stiffness & linearity, & transferring utilities (power, data, fluids, etc.).

Benefits

- Enables construction & assembly of systems on orbit or on planetary surfaces.
- Enables reconfiguration, replacement, servicing & repair of systems on orbit or on planetary surfaces.
- Standardization will significantly reduce spacecraft development time, cost & risk.

Figures of Merit

- Degree of standardization, time to join, complexity of joining process & operations, type & complexity of supporting infrastructure required, compatibility with standard agents.

General Assessment

- Limited development of mechanical fastening/joining, electrical, fluid & data connectors for ISS & HST (servicing & repair). Orbital Express developing some capability for servicing (fluid) connections. Limited development of processes that apply to in-space welding (electron beam, laser). Little standardization that applies across missions.

Development Needed: **Medium**

Capability Breakdown Structure
9.3.7 Joining

- 9.3.7 Joining
  - 9.3.7.1 Structural Joining
    - 9.3.7.1.1 Mechanical
    - 9.3.7.1.2 Welded
    - 9.3.7.1.3 Bonded
  - 9.3.7.2 Utility Joining
    - 9.3.7.2.1 Power
    - 9.3.7.2.2 Fluids
    - 9.3.7.2.3 Thermal
    - 9.3.7.2.4 Data and Other
  - 9.3.7.3 Specialized Tools, End Effect
    - 9.3.7.3.1 Mechanical Joining
    - 9.3.7.3.2 Welded Joining
    - 9.3.7.3.3 Bonded Joining
  - 9.3.7.4 Fixtures and Jigs
    - 9.3.7.4.1 Alignment
    - 9.3.7.4.2 Holding
    - 9.3.7.4.3 Positioning

Maturity Level – Technologies for Capability 9.3.7 Joining

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.7.1 Structural Joining						3
9.3.7.1.1 Mechanical	ISS: latches, bolts HST: over-center clamps LaRC: erectable truss joints	9 9 5	Standardization, reduced time to join, agent compatibility Robot agent compatibility	2010	2013	
9.3.7.1.2 Welded	Terrestrial-based only?	4 - 5	Standardization, process develop., supporting infrastr.	2012	2015	
9.3.7.1.3 Bonded	Terrestrial-based only?	4 - 5	Standardization, process develop., supporting infrastr.	2015	2018	
9.3.7.2 Utility Joining						6
9.3.7.2.1 Power	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2013	

Maturity Level – Technologies for Capability 9.3.7 Joining (Continued)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.7.2.2 Fluids	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2012	
9.3.7.2.3 Thermal	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2012	
9.3.7.2.4 Data and Other	ISS	9	Standardization, agent compatibility, reduced time and complexity	2010	2012	
9.3.7.3 Specialized tools and end effectors						2
9.3.7.3.1 Mechanical Joining	EVA: ISS, HST Robotic: Robonaut, Ranger	9 4 - 5	Standardization, agent compatibility	2010	2012	

Maturity Level – Technologies for Capability 9.3.4 Construction (Concluded)

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.4.3.2 Welded Joining	Terrestrial based only?	4 - 5	Standardization, agent compatibility	2012	2015	
9.3.7.3.4 Bonded Joining	Terrestrial based only?	4 - 5	Standardization, agent compatibility	2015	2018	
9.3.7.4 Fixtures and Jigs						3
9.3.7.4.1 Alignment	ISS, HST Servicing	9	Standardization, agent compatibility, reduced set-up time & complexity	2010	2013	
9.3.7.4.2 Holding	ISS, HST Servicing	9	Standardization, agent compatibility, reduced set-up time & complexity	2010	2013	
9.3.7.4.3 Positioning	ISS, HST Servicing	9	Standardization, agent compatibility, reduced set-up time & complexity	2010	2013	

Capability 9.3.8
Verification

Contributor:
Chris Culbert

Capability 9.3.8 Verification

Description:

- The process of determining that an assembled (or serviced) item/component is working properly or is in the right configuration or is assembled correctly.
- Usually involves applying active stimulation, lighting, irradiation, mechanical pinging, loading pressurizing, followed by data collection & analysis for characterization
- Frequently, this activity will be closely coordinated with the ground.

Benefits

- Verifying a system prior to use greatly increases the probability of mission success and helps to ensure mission safety.
- Verification allows developers and users to understand any limitations of a system.
- Reuse of equipment unloads customer, accumulated capability at facility

Figures of Merit

- Number of corrected faults, amount of specialized test equipment, time to conduct verification tests, amount of human involvement, raw materials required

General Assessment

- Current SOA is fairly effective, but does not find a high enough percentage of failures during testing and requires too much overhead.

Development Needed: Low

Capability Breakdown Structure
9.3.8 Verification

- 9.3.8 Verification
  - 9.3.8.1 Visual Inspection
    - 9.3.8.1.1 Alignment Markers
    - 9.3.8.1.2 Close Out Photos
  - 9.3.8.2 Pressure Testing
    - 9.3.8.2.1 Leak Checks
    - 9.3.8.2.2 Pressure Cycling
  - 9.3.8.3 Functional Testing
    - 9.3.8.3.1 Checklists
    - 9.3.8.3.2 Built in Architecture Testing
  - 9.3.8.4 Continuity Testing
    - 9.3.8.4.1 Indicator Lights
    - 9.3.8.4.2 Voltage/Curerrent Levels
    - 9.3.8.4.3 Fluid Flow Monitors
  - 9.3.8.5 Structural Integrity
    - 9.3.8.4.1 Metrology
    - 9.3.8.4.2 Vibration Analysis
    - 9.3.8.4.3 Latching Mechanisms
    - 9.3.8.4.4 Welding Bond Certification
    - 9.3.8.4.5 Joint Bond Certification

Maturity Level – Technologies for Capability 9.3.8 Verification

Capability/Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.8.1 Visual Inspection						7
9.3.8.1.1 Alignment Markers	Permanent marks, lines, indicators placed on components prior to flight	9		-	2012	
9.3.8.1.2 Close-out photos	Digital close-out photos routinely used on-orbit	9	In-situ access	-	2012	
9.3.8.2 Pressure Testing						5
9.3.8.2.1 Leak checks	External sniffers, pressure sensors	7?	Mobile, external devices that can sense a variety of gasses	2010	2012	
9.3.8.2.2 Pressure Cycles	Cycling pressure higher and lower	8?	Embedded, autonomous systems	2010	2012	

Maturity Level – Technologies for Capability 9.3.8 Verification

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.8.3 Functional Testing						7
9.3.8.3.1 Checklists	Electronic checklists in routine use	9	Integrate with fault management tools	2010	2012	
9.3.8.3.2 Built-in test architecture	ISS uses multiple test subsystems	9	Integrate with monitoring and diagnosis tools	2012	2015	
9.3.8.4 Continuity testing						6
9.3.8.4.1 Indicator lights	Routine use in all systems	9		-	2008	
9.3.8.4.2 Voltage or current levels	Routine use in all systems	9		-	2008	
9.3.8.4.3 Fluid flow monitors	Routine use in all systems	7	Improvements for use in low gravity and micro gravity	2010	2012	

Maturity Level – Technologies for Capability 9.3.8 Verification

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.3.8.5 Structural Integrity						4
9.3.8.5.1 Metrology	Laser alignment systems	6?	Space qualification?	2015	2020	
9.3.8.5.2 Vibration analysis	Space Station	5?	Space qualification, small packaging	2010	2012	
9.3.8.5.3 Latching mechanisms	Space Station	9		-	2012	
9.3.8.5.4 Welding bond certification	X-ray for ground based	3	Space qualification, small packaging	2010	2012	
9.3.8.5.5 Joint bond certification	X-ray for ground based	5	Space qualification	2010	2012	

Capability 9.3.9
Planning, Logistics, Training, etc.

Contributor:

Wendell Chun

Capability 9.3.9 Planning, Logistics, & Training

Description: These are broad capabilities that span the entire assembly sequence. Planning is defined as the ordering of steps required to complete a task or maneuver. It includes time estimates, resource management & decision reiteria. Logistics is all of the support & movement planning of assemblies, parts, tools, equipment & supplies necessary to meet the objectives of the task. Training uses documentation, models & simulators to teach / practice a skill or maneuver so as to be able to perform it as expected.

Benefits: Planning, logistics, & training are integral to each other & necessary to complete assembly & deployment. Pre-planning & contingencies will increase the probability of success of the assembly operations. Logistics determines the whereabouts & timing of all the sub-assemblies & parts required. Training is necessary to insure that the task of assembly & deployment will occur as planned. A key benefit is reduced cost & time to perform construction, assembly and joining operations. This will increase the probability of success of the assembly operations, *thus reducing risk to mission success.*

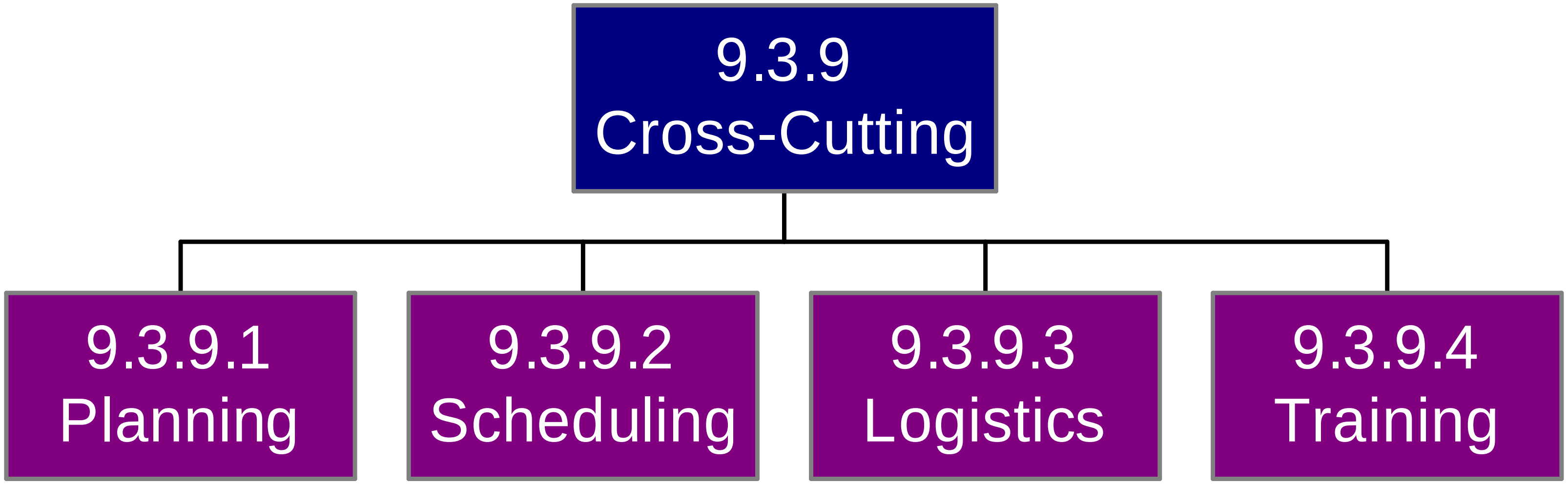
Metrics:

- Number of steps in the plan
- Completeness of plan, including acceptable contingencies
- Percentage of Distributed vs. Centralized Operations
- Timeline for logistics
- Transport Manifest
- Skills, *as opposed to task specific,* training
- Training Plan, competency test & number of skills in training
- Realistic Simulation based on update rate, fractal & polygon count, field-of-view
- Versatility & adaptability of methods

General Assessment: Planning, Logistics, & Training are common today in NASA missions, typically in a manual mode with some automated tools. Fully automated planning tools exist, but with less maturity at the mission level. Logistic tools are mature & verified through comprehensive checklists. Training exist, but could benefit from better tools & technologies to insure a higher level of preparedness.

Development Need: **Low**, with room for technological improvements as available, except for **human-robot training where the need is high.**

Capability Breakdown Structure
9.3.9 Planning, Logistics, & Training



State-of-the-Art/Maturity Level/Capabilities for 9.3.9 Planning, Logistics, & Training

Capabilities	State-of-the-Art	TRL	Needs	TRL 6 Date	Need Date	Capability CRL
• Planning						6
• Mission Planning	Apollo, Soyuz, Shuttle	6	Auto	-	2010	
• Strategic Planning	Shuttle	7	Auto	-	2010	
• Vehicle Planning	Shuttle	8	Integ.	-	2010	
• Trajectory Planning	Shuttle, Soyuz	9	Auto	-	2010	
• Collision Avoidance	Manual Visualization	3	Dev.	2006	2008	
• Dynamic Replanning	XSS-11	4	Real-Time	2006	2008	
• Scheduling						7
• Automated	Shuttle	6	Real-Time	2010	2012	
• Logistics						6
• Logistics Planning	Shuttle PIC	9	Auto	-	2010	
• Resource Allocation	New Millennium	6	Auto	2008	2010	
• Automated Tracking	Shuttle GSE	8	Common	-	2010	
• Inventory Control	NASA Pre-Flight	8	Implement	-	2010	
• Training						6
• Competency Program	Astronaut Program	9	Update	2008	2012	
• Skill-based	Astronaut Program	9	w/ robot	2008	2012	
• Knowledge-Based	Astronaut Program	4	experts	2006	2008	
• Simulation	Shuttle Training	6	hi-res	2006	2008	
• Immersion	Laboratory	4	mature	2008	2012	
• Testing & Checkout	Conventional	9	Auto	-	2012	

State-of-the-Art/Maturity Level/Sub-Capabilities for 9.3.9 Planning, Logistics, & Training

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Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Planning						6
• Auto Mission Planner	Apollo, Soyuz , Shuttle	5	Auto	2008	2008	
• Auto Strategic Planning 2008	Shuttle	7	-	-		
• Auto Vehicle Planning	Shuttle	8	-.	-	2008	
• Smooth Trajectory	Shuttle, Soyuz	9	-	-	2008	
• Auto Col. Avoid System	Manual Visualization	3	Dev.	2006	2008	
• Auto Replanning	XSS-11	4	Real-Time	2006	2008	
• Scheduling						7
• Ground	Shuttle	8	-	-	2008	
• On-board	Shuttle	6	Real-Time	2008	2010	
• Logistics						6
• Real-time Log. Planning	Shuttle PIC	5	Auto	2008	2010	
• Off board Log. Plan	Shuttle	9	-	-	2008	
• Resource Allocation	New Millennium	6	Auto	2008	2010	
• Real-time Tracking	Shuttle GSE	8	Common	-	2008	
• Auto Inventory Mgt	NASA Pre-Flight	8	Implement	-	2008	
• Real-Time traffic model	Shuttle	8	Auto	-	2008	
• Spares Planning	ISS	9	-	-	2008	

State-of-the-Art/Maturity Level/Sub-Capabilities for 9.3.9 Planning, Logistics, & Training

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Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Training					6	
• General Comprehension	Astronaut Program	9	Update	-	2008	
• Situation-based	Military	6	infusion	-	2010	
• Skill-based	Astronaut Program	9	w/ robot	-	2012	
• Knowledge-Based	Astronaut Program	4	experts	2008	2010	
• Computer Sims.	Shuttle Training	6	hi-res	2008	2010	
• Hardware-In-Loop Sim	Ground	4	custom	2008	2010	
• Immersion Room	Laboratory	4	facility	2010	2012	
• Immersion Desk	Laboratory	4	models	2010	2012	
• Testing & Checkout	Conventional	9	Auto	-	2008	

State-of-the-Art/Maturity Level/ Technologies for 9.3.9 Planning, Logistics, & Training

Advanced Planning & Integration Office

Technologies	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Planning						6
• Auto Mission Software	COTS-Grease	6	Auto	2010	2012	
• Auto Strategic Software	4D-RCS, Mapgen	7	Auto	2010	2012	
• Auto Vehicle Software	Remote Agent	8	Integ.	2008	2010	
• Trajectory Algorithm	A*, D*	9	Auto	-	2008	
• Col. Avoid Sensor	Manual Visualization	3	Dev.	2006	2008	
• Col. Avoid Behavior	Potential Field, Occupancy-Grid	4	Mature	2006	2008	
• Auto Replanning	State Machine Re-Planning	4	Real-Time	2006	2008	
• Scheduling						7
• Ground	COTS	9	-	-	2005	
• On-board	Remote Agent	6	Optimization	2008	2010	
• Logistics						6
• Real-time Log. Planning	Shuttle PIC	9	Auto	-	2010	
• Off board Log. Plan	COTS	9	-	-	2005	
• Resource Allocation	New Millennium	6	Auto	2008	2010	
• Real-time Tracking	Shuttle GSE	8	Common	-	2010	
• Auto Inventory Mgt	NASA Pre-Flight	8	Implement	-	2010	
• Real-Time traffic model	COTS	9	Contingency	-	2005	
• Spares Planning	NASA Std	9	Contingency	-	2005	

State-of-the-Art/Maturity Level/ Technologies for 9.3.9 Planning, Logistics, & Training

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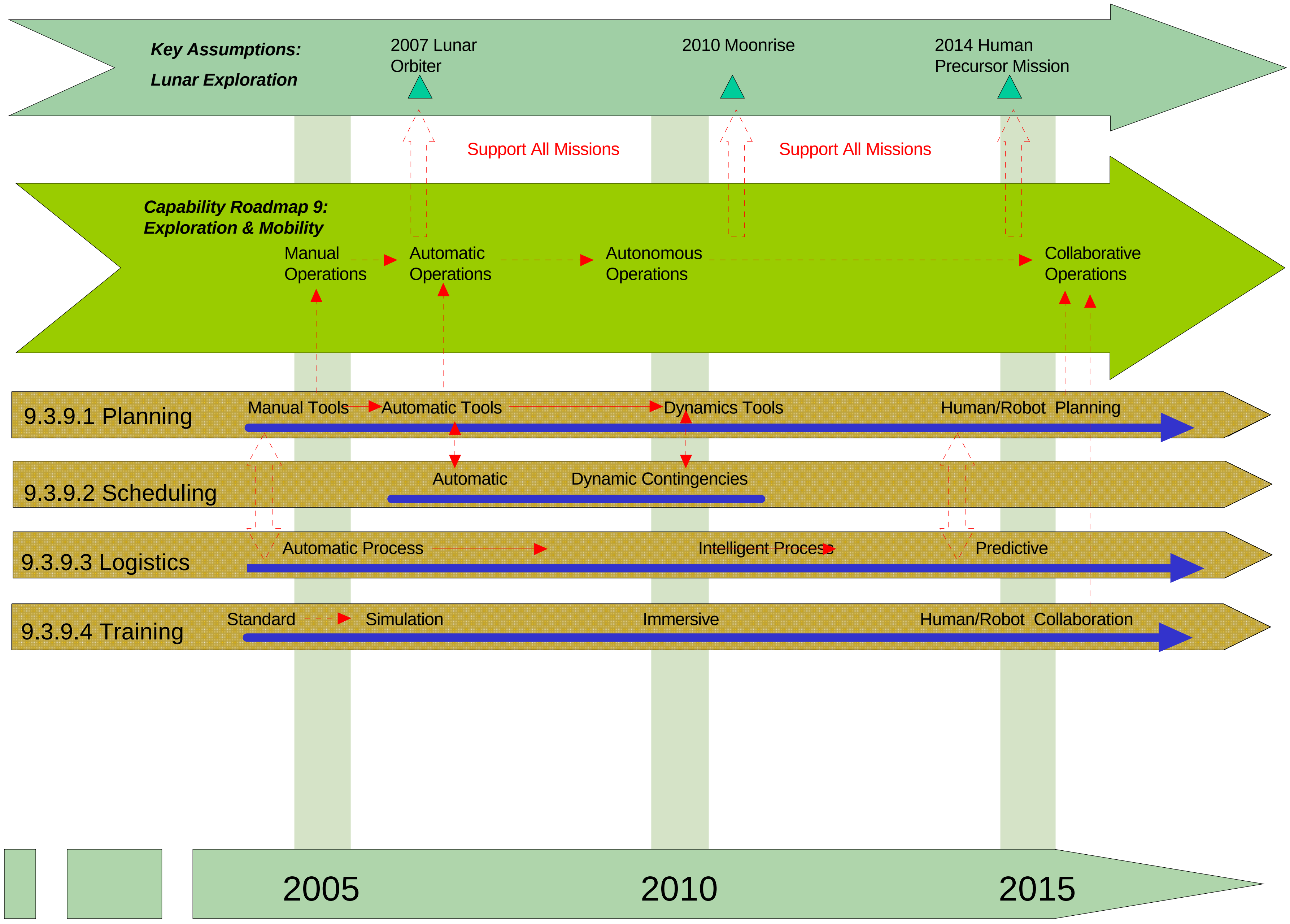
Sub-Capabilities	State-of-the-Art	TRL	Needs TRL 6	Need Date	Capability	CRL
• Training					6	
• Tops Down Training	Scenario Role Playing	6	Update	2008	2010	
• Bottoms Up Training	Human-skills Development	9	-	-	2010	
• Hi-Res Comp. Sim.	Sony, Boston-Dyn, Evans-Suth.	4	Cost	2006	2010	
• Low-Res Comp. Sim	COTS	8	-	-	2006	
• Pc_based Comp. Sim	COTS	8	-	-	2006	
• Man-In-the-Loop Sim.	Univ. Washington, Media Lab	6	Human Fac	2008	2010	
• Motion Base	NRL, MSFC, JSC	6	Full Scale	2008	2010	
• Virtual Reality	ARC, NC State, Media Lab	3	Maturity	2010	2012	
• CAVE-based Virtual	U. of Illinois, U. of Colo.	4	Dev.	2008	2010	
• Augmented Reality	HRL, Microsoft, Media Lab	4	Dev.	2008	2010	
• Gestures, Gaze	CMU, GM	2	Research	2010	2012	
• Human/Robot Training	Commercial Robot Manufac.	2	Dev.	2010	2012	

Human-Robot Training is a Gap that requires filling.

9.3.9 Assembly & Deployment Cross-Cutting Top Level Capability Roadmap



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Human Exploration Systems and Mobility Capability Roadmap Progress Review

Chris Culbert, NASA Chair

Jeff Taylor, External Chair

March 29, 2005

Agenda

- Capability Roadmap Team
- Capability Description and Capability Breakdown Structure
- Benefits of the Human Systems and Mobility Capability
- Roadmap Process and Approach
- Drivers and Assumptions for the whole team
  - Current State-of-the-Art, Assumptions and Requirements will be covered in the appropriate sections
- Capability Presentations by Leads under Roadmap (Repeated for each capability under roadmap)
  - Capability Description, Benefits, Current State-of-the-Art
  - Capability Requirements and Assumptions
  - Roadmap for Capability
  - Capability Readiness Level
  - Technology Readiness Level
  - Figures of Merit
- Summary of Top Level Capability
- Significant Technical Challenges
- Summary and Forward Work

Human Exploration Systems and Mobility Capability Roadmap Team

Co-Chairs

- NASA: Chris Culbert, NASA/JSC
- External: Jeff Taylor, University of Hawaii

Team Members

– Government

Ken Baker, NASA/JSC
John Dorsey, NASA/LaRC
Rick Eckelkamp, NASA/JSC
David Kohrsmeyer, NASA/ARC
Dennis Lawler, NASA/JSC
Wendell Mendell, NASA/JSC
Rud Moe, NASA/GSFC
Jeff Patrick, NASA/JSC
June Zakrajsek, NASA/GRC
Wayne Zimmerman, NASA/JPL

– Academia/Industry

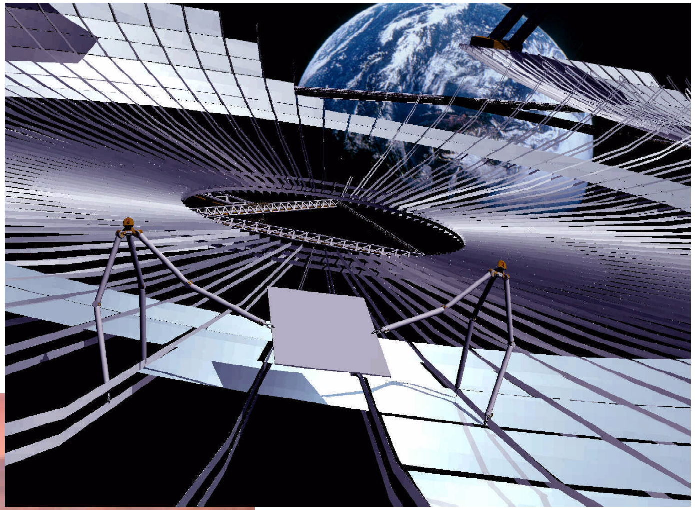
David Adlis, Aerospace Corp.
Jim Blacic, Los Alamos Labs
David Carrier, Bromwell & Carrier
Wendell Chun, Lockheed Martin
Mark Henley, Boeing
Jud Heddgecock, Oceaneering
Larry Taylor, Univ. of Tennessee
Robert Yowell, Aerospace Corp.

Coordinators

Directorate: Betsy Park and Doug Craig, NASA/HQ/ESMD
APIO: Tom Inman, NASA/MSFC

9.0 Capability Description

Supports human exploration activities in space and on planetary surfaces. Includes a wide range of capabilities to allow scientific observations, instrument deployment, and resource exploration. Divided into four major categories:



9.1 Exploration Activities

9.2 Mobility

9.3 Assembly and Deployment

9.4 Servicing

Capability Breakdown Structure

9.0
Human Systems and Mobility
Chair: Chris Culbert, JSC
Co-chair: Jeff Taylor, U. Hawaii

- **9.1 Exploration Activities**
  Coordinator:
  Rick Eckelkamp, JSC
  - 9.1.1 Access to Exploration Targets
  - 9.1.2 Observation
  - 9.1.3 Analyze
  - 9.1.4 Operate
  - 9.1.5 Command and Control and Information
- **9.2 Mobility**
  Coordinator:
  Jeff Taylor, U. Hawaii
  June Zakrasjek, NASA/Glenn
  - 9.2.1 In Space Mobility
  - 9.2.2 Surface Mobility
- **9.3 Assembly and Deployment**
  Coordinator:
  Ken Baker, JSC
  - 9.3.1 Staging
  - 9.3.2 Storage
  - 9.3.3 Preparation for Assembly
  - 9.3.4 Construction
  - 9.3.5 Local Transport
  - 9.3.6 Positioning and Alignment
  - 9.3.7 Joining
  - 9.3.8 Verification
  - 3.9 Planning, Logistics, Nav, Comm, etc.
- **9.4 Servicing**
  Coordinator:
  Dennis Lawler, JSC
  - 9.4.1 Inspection and surveying
  - 9.4.2 Detect&Isolate Faults
  - 9.4.3 Perform Planned Maintenance
  - 9.4.4 Perform Unplanned Repair
  - 9.4.5 Install Upgrades
  - 9.4.6 Planning, Logistics, Nav Comm, etc.

Benefits of Human Systems and Mobility

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Human Exploration systems are required to:

- Support human presence for long-duration spaceflight or missions to planetary surfaces
- Allow deployment of complex scientific instrumentation in space, such as large interferometric telescopes
- Allow installation of instrumentation and sophisticated scientific facilities on planetary surfaces
- Enhance human access to scientific targets on planetary surfaces
- Provide global access on the Moon, Mars, and other planetary bodies
- Enhance human-robot partnerships to make the most efficient and effective use of each

Roadmap Process and Approach

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- **Team members chosen to represent wide range of expertise and experience (including Apollo experience) for this broad topic**
- **Devise CBS and choose working groups through a series of telecons, email exchanges, and meetings**
- **Details of subcapabilities fleshed out by working groups, vetted by entire team**
  - Define capabilities and appropriate levels of subcapabilities, their benefits, figures of merit, and estimate of the amount of development needed
  - Assessment of technologies required and when they will be needed
- **Working groups use the above to devise roadmap for each capability, with review by whole team**
- **Presentation to NRC**
- **Revise plan based on comments**
- **Write detailed capability document**

Requirements /Assumptions for Human Exploration Systems and Mobility

General drivers

- Long duration (> 180 day) human presence on the Lunar surface
- Short duration (< 180 day) human presence on the Mars surface
- Assume reliable access to all ‘useful’ points in the Earth – Mars area
- Gateway type facility on-orbit for Moon (assembly, refueling, staging, etc.)
- Infrastructure rich locations on the surface with ‘sorties’ going out from them
- Power readily available (100s of KW available to bases)
- Thermal control, heat rejection technologies considered by other teams
- Communications – very high bandwidth will be provided at least locally
- Human safety considerations are critical; systems will be fault tolerant
- Human productivity/efficiency considerations – no more than 25% of human time spent on routine maintenance & housekeeping
- Systems are capable of at least supervised autonomy

General drivers (cont'd)

- Radiation shielding provided for normal environment & solar flares. Environment protection also provided for:
  - Dust
  - Meteorites/orbital debris
  - Secondary ejecta
  - Electric fields on the moon
- Locally information rich and information accessible
- Local science analysis capability is necessary and some sample return is still necessary
- Assume design for modularity, assembly and maintenance will be used and standards developed for broad application and commonality
- Payload size and mass will not significantly change over the next 20 – 25 years. In other words, we won't have a 100 metric ton lift vehicle with significantly larger shroud size than today's launch options.

Assumptions on Dates

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Date Assumptions

- In the absence of specific mission definitions, the team reviewed existing material on the Vision for Space Exploration and the Spiral development models and defined a rough outline of dates (below) for development needs.

	Beyond LEO	Moon	Mars
Initial Presence			
Robotic Precursors	2008-2015	2008-2015	2012-2022
Initial Human Presence		2015-2020	2022-2030
Infrastructure Operational Deployment			
In Space	2015-2025		
Surface		2012-2020	2020-2025
Long Duration Human Presence			
Exploration Sorties		2015-2030	
ISRU Production	2020-2030	2017-2030	2020-2030
Facility Operation and Maintenance	2020-2030	2020-2030	

Key technical challenges:

- We will summarize the most significant technical challenges, across all of the technical areas.

Do the Capability Roadmaps have connection points to each other when appropriate?

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– **Have not done much work in this area yet, and won't really address until after the NRC discussion.**

Summary/ Forward Work

- Make changes to roadmaps based on verbal feedback from NRC review
- Consider overlap with other Capability Roadmap teams and eliminate duplication
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for Human Exploration Systems
- Make changes to Human Exploration Systems roadmaps to ensure consistency with Strategic Roadmaps requirements
- Develop rough order of magnitude cost estimates for the Human Exploration Systems Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Autonomous Systems, Robotics, and Computing Systems Capability Roadmap

NRC Dialogue

NASA Chair: Steve Zornetzer, ARC
External Chair: Douglas Gage, DARPA (ret.)

March 30, 2005

Overview

- **Introduction (Steve Zornetzer)**
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- Computing Systems (Mike Lowry)
- Conclusion

Capability Roadmap Teams

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Team

Co-Chairs
NASA: Steve Zornetzer, NASA/Ames Research Center
External: Douglas Gage , DARPA (ret.)
NASA Deputy: James Crawford , NASA/Ames Research Center
NASA Deputy: Paul Schenker, JPL

NASA
Steve Chien, JPL
Michael Lowry, ARC
Ron Diftler, JSC
Dave Lavery, NASA HQ
Illah Nourbakhsh, ARC
Julia Loftis, GSFC
Michel Ingham, JPL
Serdar Uckun, ARC

Industry
Chris Leslie, USA
Dan Clancy, Google (ex-NASA)
Additional reviews underway:
- Barry Fox, Boeing
- Kerry Fisherkeller, NG

Academia
Dave Akin, Univ. of Maryland
Red Whittaker, CMU
Reid Simmons, CMU
Bob Full, UC Berkeley
Brian Williams, MIT
James Allen, IHMC
Michael Evangelist, CMU

Coordinators
Directorate: Harley Thronson, SMD
APIO: Jan Aikins, ARC

Capability Description

- **The Autonomous Systems, Robotics, and Computing Systems (AR&C) capability roadmap details the information technology and robust hardware and computing technology required for NASA spacecraft, robots, and human/robotic teams to explore harsh dynamic environments safely and affordably.**

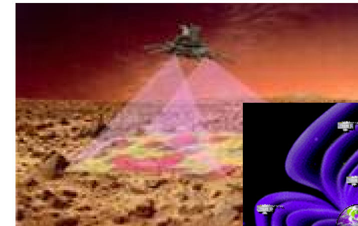
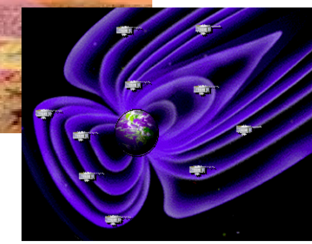
- AR&C capabilities include:
  - 10.1 Autonomous Operations
  - 10.2 Integrated Systems Health Management
  - 10.3 Vehicle Control
  - 10.4 Process Control
  - 10.5 Robotics for Solar System Exp.
  - 10.6 Robotics for Lunar and Planetary Hab.
  - 10.7 Robotics for In-Space Operations
  - 10.8 Software Validation and Verification
  - 10.9 Avionic Systems (incomplete)

- AR&C does NOT include (by charge from APIO):
  - Supercomputing
  - Data archiving and analysis
  - Computer networks and grid computing
  - Robotic hardware (except as required to develop and benchmark software)
  - Much of “classic” Computer Science – compilers, programming languages, databases, etc. (except in limited cases as driven by the capabilities above)

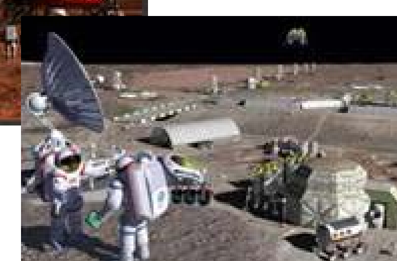
Driving Requirements

- Exploration is a contact sport. To understand our universe and to search for life, NASA robots and spacecraft will be:
  - On and under the surface of Mars, on cliffs and in caves
  - On asteroids and taking samples on comets
  - On the surface and in the clouds of Venus
  - Under the clouds of Titan, and under the ice on Europa
  - On the moon searching for resources and preparing for a long-term human presence

- NASA manned and unmanned missions will be carrying out increasingly challenging tasks far from Earth:
  - Habitat construction and long term habitation
  - In-space construction of spacecraft and observatories
  - Mining and in-situ resource utilization
  - Deep drilling (lunar, Mars, Europa, etc.)
  - Spacecraft constellations (interferometry, gravity wave detection, Earth-Sun connection, etc.)
  - Scientific laboratory tests currently done only on earth
  - Biological and habitability analysis





These missions create pacing NASA challenges in Autonomy, Robotics, and Computing

Capability Breakdown Structure

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10.0 Autonomous Systems, Robotics, and Computing Systems

Co-Chair: Steve Zornetzer, NASA/ARC
Co-Chair: Douglas Gage, DARPA (ret.)
Deputy: James Crawford, NASA/ARC
Deputy: Paul Schenker, JPL

10.1 Crew-Centered and Remote Operations
Chair: Julia Loftis / GSFC
- 10.1.1 Crew-Centered Planning
- 10.1.2 Autonomous Mission Operations
- 10.1.3 Multi-System Coordination & Collaboration
- 10.1.4 Human-Automation Interaction
- 10.1.5 Multi-Modal Interfaces for Collaborative Execution

10.2 Integrated Systems Health Management
Chair: Serdar Uckun / ARC
Co-Chair: Brian Williams / MIT
- 10.2.1 Design of Health Management Systems
- 10.2.2 Real-Time System Health Management
- 10.2.3 Informed Logistics

10.3 Autonomous Vehicle Control
Chair: Michel Ingham / JPL
Co-Chair: Lorraine Fesq / JPL
- 10.3.1 Rendezvous and Docking
- 10.3.2 Orbit Insertion
- 10.3.3 Entry, Descent, and Landing
- 10.3.4 Launch Systems
- 10.3.5 UAV Control

10.4 Autonomous Process Control
Chair: James Crawford / ARC
- 10.4.1 Life Support
- 10.4.2 ISRU Process Control
- 10.4.3 Nuclear Reactors
- 10.4.4 Deep Drilling
- 10.4.5 Plug & Play Controllers
- 10.4.6 Smart Systems

10.5 Robotics for Solar System Exploration
Chair: Reid Simmons / CMU
Co-Chair: Doug Gage / DARPA (ret.)
- 10.5.1 Mobility and Access
- 10.5.2 Instrument Deployment
- 10.5.3 Onboard Autonomous Science
- 10.5.4 Human-Robotic Field Science
- 10.5.5 Human-Robot Interaction

10.6 Robotics for Lunar and Planetary Habitation
Chair: Illah Nourbakhsh / ARC
- 10.6.1 Site Development
- 10.6.2 Site Maintenance
- 10.6.3 ISRU
- 10.6.4 Field Logistics and Support
- 10.6.5 Human-Robot Interaction

10.7 Robotics for In-Space Operations
Chair: Ron Diftler / JSC
- 10.7.1 Assembly
- 10.7.2 Inspection
- 10.7.3 Maintenance
- 10.7.4 Human-Robot Interaction

10.8 Computing Systems
Chair: Mike Lowry / ARC
Co-Chair: Mike Evangelist / CMU
- 10.8.1 Automated Testing
- 10.8.2 Analytic Assurance
- 10.8.3 Fault tolerance
- 10.8.4 Certified, automated SW generation
- 10.8.3 Maintainability & Reusability

Autonomy | Robotics | Computing

Overview

- Introduction (Steve Zornetzer)
- **Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)**
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- Computing Systems (Mike Lowry)
- Conclusion

Approach and Process

- Roadmapping has been based on a series of workshops with presentations by experts on mission classes and by technologists, and a series of follow-up meetings between workshops (process detailed below).

- The capability sub-teams have also studied the relevant NASA-level, directorate-level, and theme-level strategic plans (and other documents detailed below).

- The primary output of the process is a set of deliverables
  - 5-8 per sub-capability
  - Each deliverable linked to one or more mission drivers
  - Sub-Capability deliverables will be prioritized by the degree to which they enable missions and mission classes, and by the degree to which the enhance missions and mission classes (as measured increased science return and decreased cost).
  - This prioritization has been done only roughly since it requires further input from the Strategic Roadmaps.

Top Level Assumptions

- Autonomy, Robotics, and Computing requirements will be driven primarily by the following mission sets:
  - Exploration Mission Directorate
    - The Exploration Initiative Mission Spirals
    - Robotic Lunar Exploration (RLEP)
  - Science Mission Directorate
    - Mars Exploration
    - Solar System Exploration
    - Earth Science
    - Structure and Evolution, and Origins
    - Sun-Earth Connection
  - Aeronautics
    - High Altitude Long Endurance Remotely Operated Aircraft (HALE ROA)
- Timelines for these mission classes will be available in April from the Strategic Roadmap Teams. For this package we have used available information and, where necessary, made assumptions about mission dates.
- Roadmap deliverables are shown on the timeline ~5 years before mission launch.
- NASA's investments will focus on NASA pacing challenges. NASA will avoid investing in capabilities that will be independently developed by industry. NASA will pursue partnerships with DARPA, and other federal agencies, where priorities align.
- Since this is a strategic exercise (not program formulation), the following is out of scope:
  - Where R&D will be done (industry, academics, NASA centers)
  - How R&D will be managed to maximize mission impact (integration frameworks, partnerships, etc.)
  - Scope, budgets, and time lines for programs

Roadmapping Process

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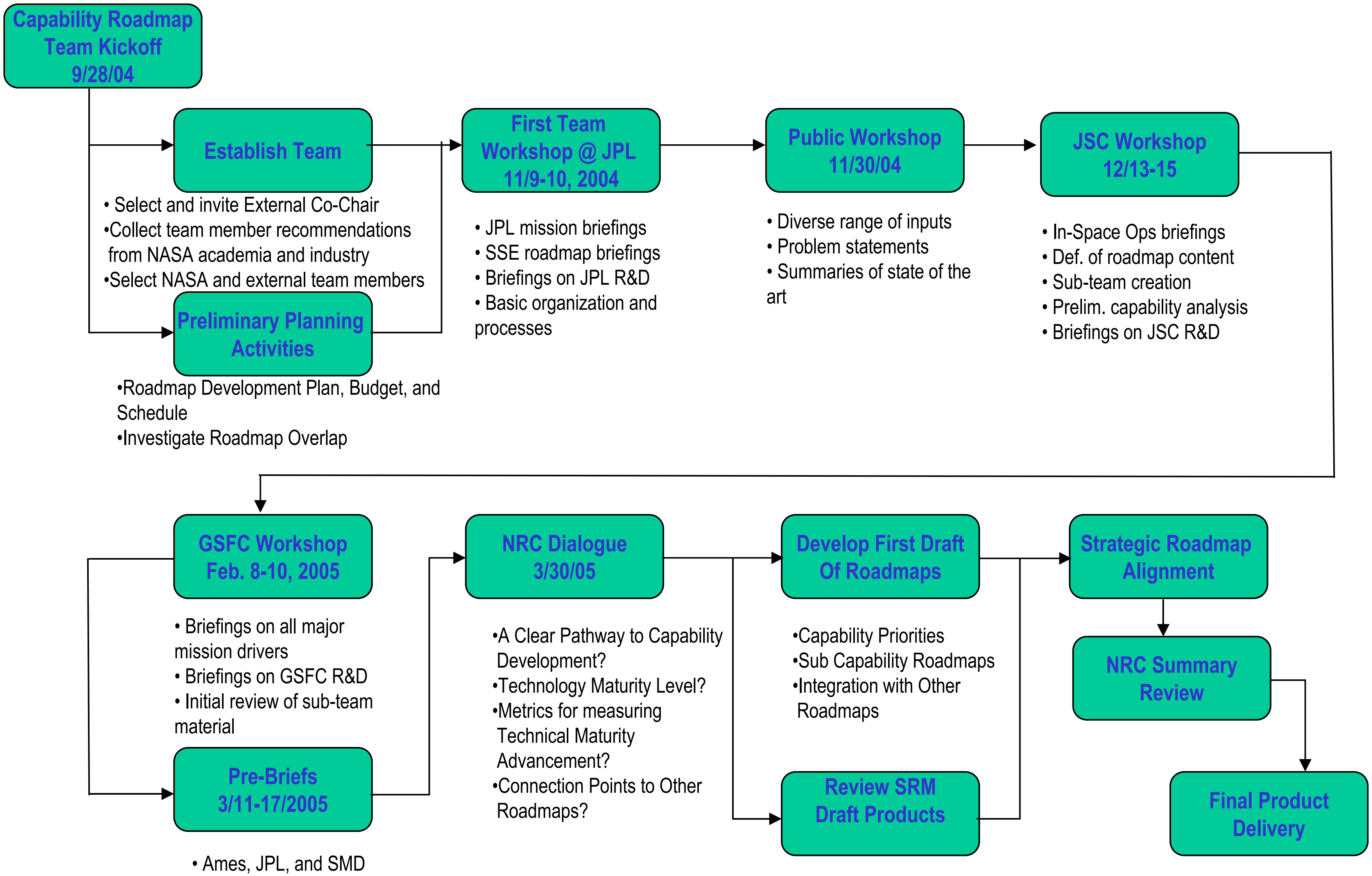
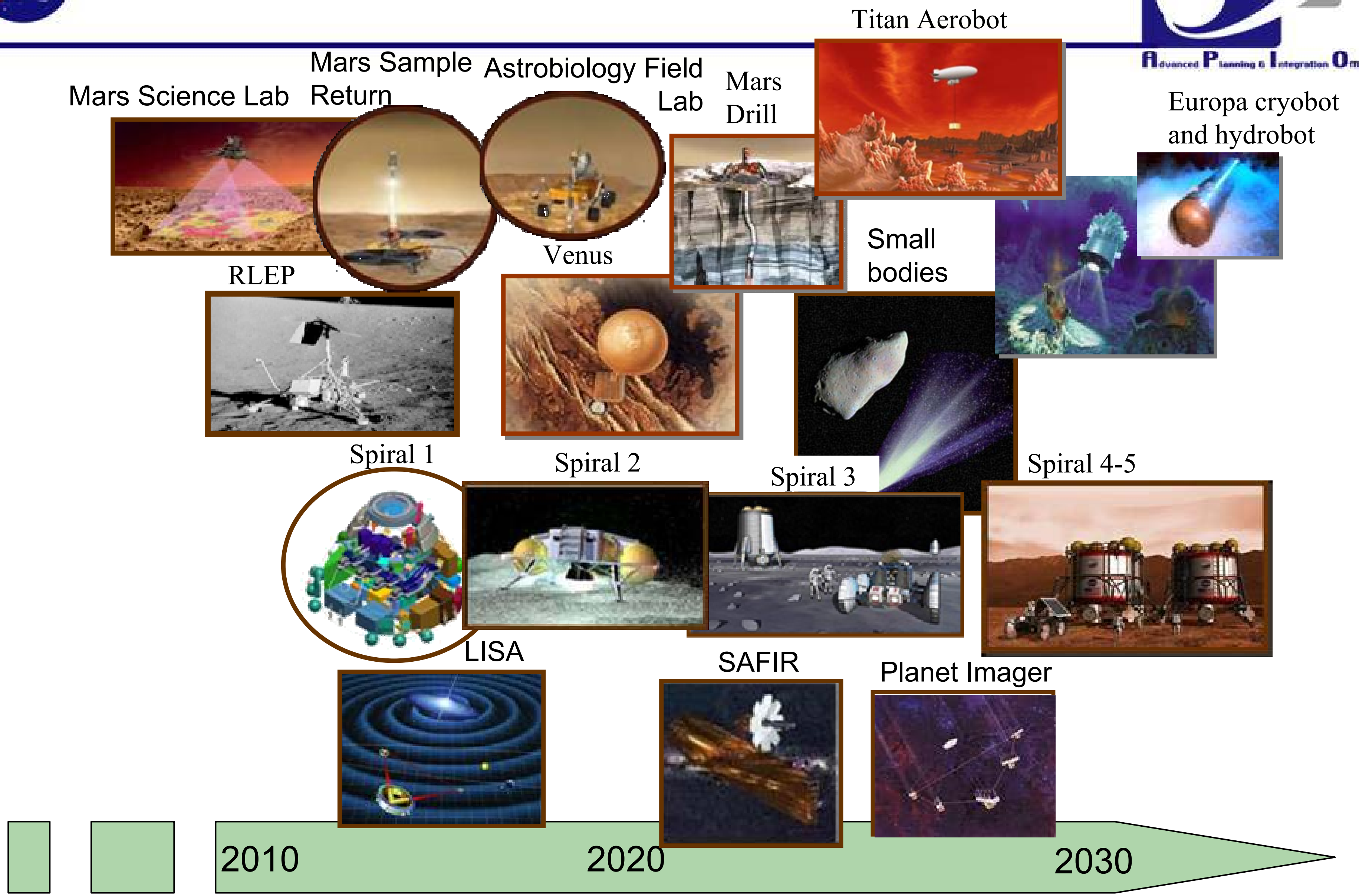


Mission Drivers



MEP: A Strategy of Exploration & Discovery

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A science-driven effort to characterize and understand Mars as a dynamic system, including its present and past environment, climate cycles, geology, and biological potential.

"Following the Water"

This decade we set the context for the Search for Life as we characterize and understand Mars and its environments.

"Following the Carbon"

Towards the end of the decade, the search focus' on "Following the Carbon", the basic building blocks of life, and life itself.

"Robots, to Human Precursors, to Humans"

The knowledge and understanding being developed today paves the way…

Mars Potential Next-Decade Pathways

Pathway	Lines of Scientific Inquiry
Search for Evidence of Past Life	**Science from First Decade missions plus early next-decade missions confirms ancient Mars was wet and warm** • **Locating and analyzing water-lain sedimentary rock is primary goal.** • **Pathway includes search for evidence of past life.**
Explore Hydrothermal Habitats	**Exploration in First Decade discovers hydrothermal deposits (active or fossil)** • **Probability of hydrothermal regions being discovered is potentially high.** • **Hydrothermal habitats are focus of second decade of Mars exploration.** • **Potential for discovery of evidence of past and present life is greatly improved.**
Search for Present Life	**Commits to search for present life at sites determined to be modern habitats by First Decade missions** • **Search for life at active hydrothermal deposits or polar margins.** • **Path would be taken only following a discovery that revolutionizes our understanding of the potential of Mars to harbor present life.** • **MSR with mobility is included as the most reliable, validatible means of detecting life.**
Explore Evolution of Mars	**Science of First Decade of Mars exploration does not find evidence of past or present liquid water environments** • **Determine the loss mechanisms and sinks for water and CO_2 over time.** • **Determine why the terrestrial planets evolved differently, much more so than we had thought.** • **Determining whether the initial conditions on Venus, Earth and Mars were similar or very different.**

Mars Exploration & Agency Roadmaps

1. Undertake robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations. (Agency Objective 4)

2. **Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (Obj 5)**

   Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions, and after successfully demonstrating sustained human exploration missions to the Moon. (Obj 6)

3. Conduct robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration. (Obj 7)

4. Search for Earth-like planets and habitable environments around other stars. (Obj 8)

5. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. (Obj 10)

6. Focus research and use of the International Space Station on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (Obj 12)

7. Return the Space Shuttle to flight, complete assembly of the International Space Station, and transition from the Space Shuttle to a new exploration-focused transportation system. (Obj 11)

8. Explore our Universe to understand its origin, structure, evolution, and destiny. (Obj 9)

9. … rstand … quences … for life

10. … nd the … tem, and … ill be experienced by human explorers. (Obj 2)

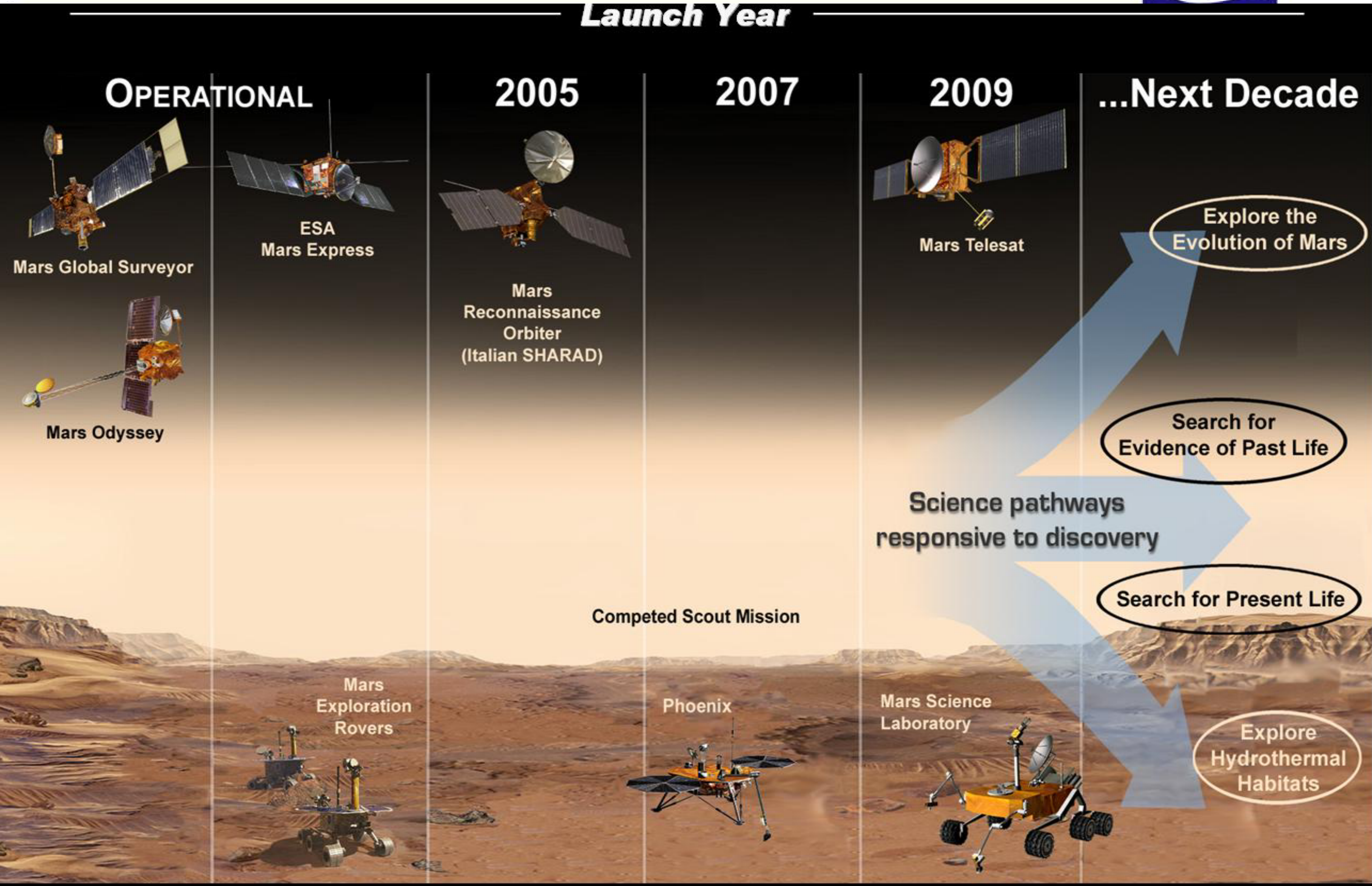
Mars Robotic *and* Human Exploration Requirements

11. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (Obj 3)

12. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (Obj 14)

13. Develop a comprehensive national plan for utilization of nuclear systems for the advancement of space science and exploration. (No Agency Obj)

This Decade's Discoveries Leads to the Next Decade's Pathway



...and Potential Pathway Mission Sequences

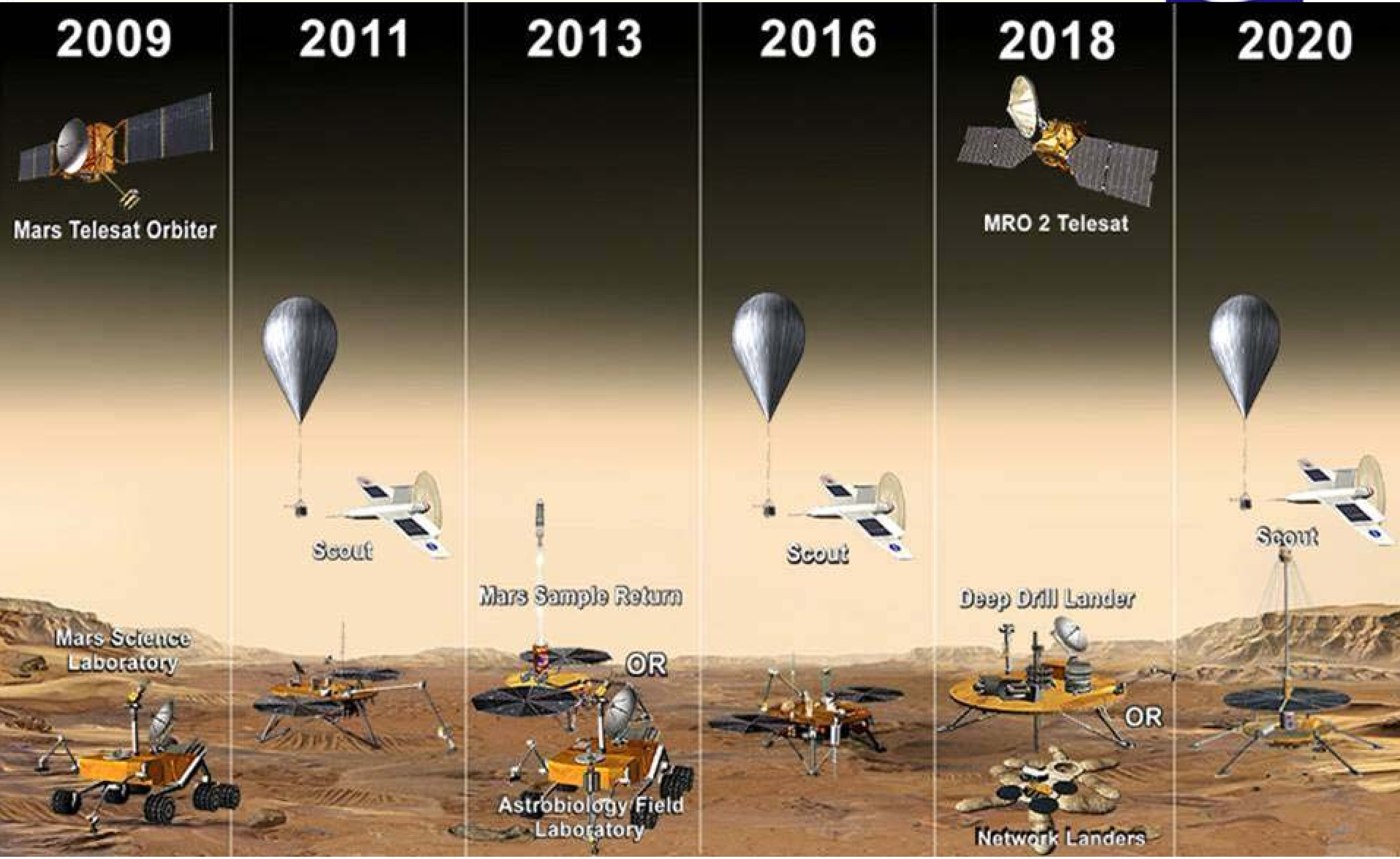
Pathway	2009	2011	2013	2016	2018	2020	Notes
Search for Evidence of Past Life	MSL to Moderate Latitude	Scout	MSR	Scout	Astrobiology Field Lab or Deep Drill	Scout	Missions to high-probability past habitat. Mission in '18 influenced by MSL results.
Explore Hydrothermal Habitats	MSL to Hydrothermal Deposit	Scout	Astrobiology Field Laboratory	Scout	Deep Drill	Scout	All core missions sent to active or extinct hydrothermal deposits.
Search for Present Life	MSL to High Latitude or Active Vent	Scout	Scout	MSR	Scout	Deep Drill	Missions to modern habitat. Path has highest risk.
Explore Evolution of Mars	MSL to Moderate Latitude	Scout	MSR	Aeronomy	Network	Scout	Path rests on proof that Mars was never wet.

2005 President's Budget Augmentation		Scout & Mars Testbed		Mars Testbed		Mars Testbed	

MTO → Replacement Telecom* →

Note: The pathway followed will depend on knowledge and technologies developed this decade.

“Search for Past Life” Pathway Example



*Mars Testbeds are human exploration pathfinders

Candidate Solar System Exploration Missions

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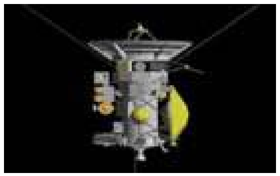
2010

Cassini Huygens

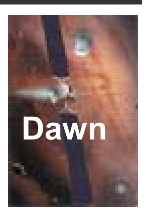


New Frontiers

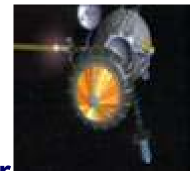
Moonrise

Juno

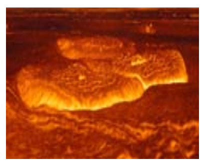
Discovery



Europa Orbiter Or Titan Explorer



New Frontiers Candidates



Venus SAGE

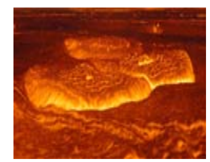
Comet Clipper

2015

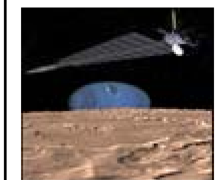
Prometheus Enabled Missions

New Frontiers Candidates

Venus Geophysical Network or rover



2020



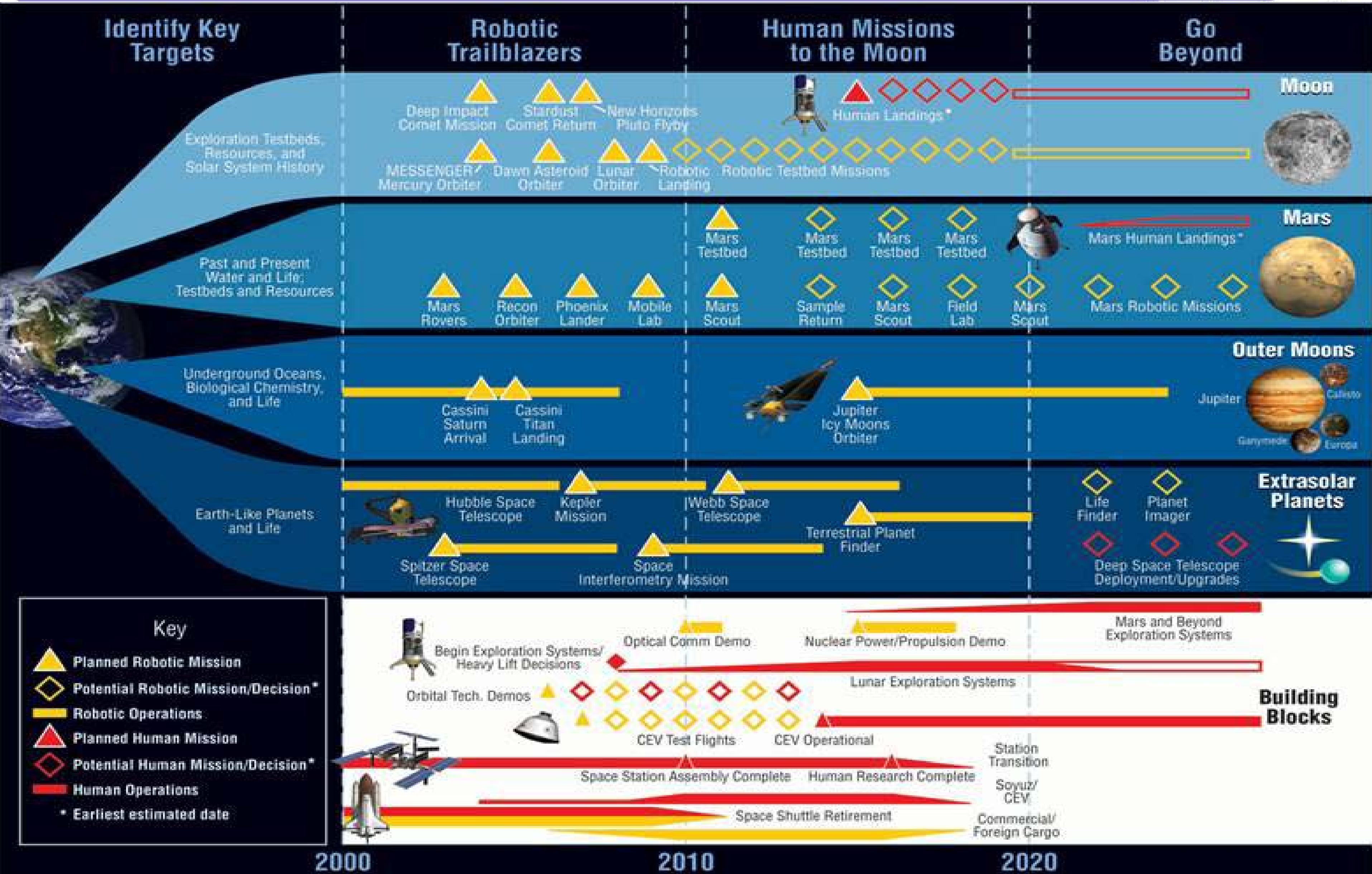
Neptune Triton Orbital Tour

New Frontiers

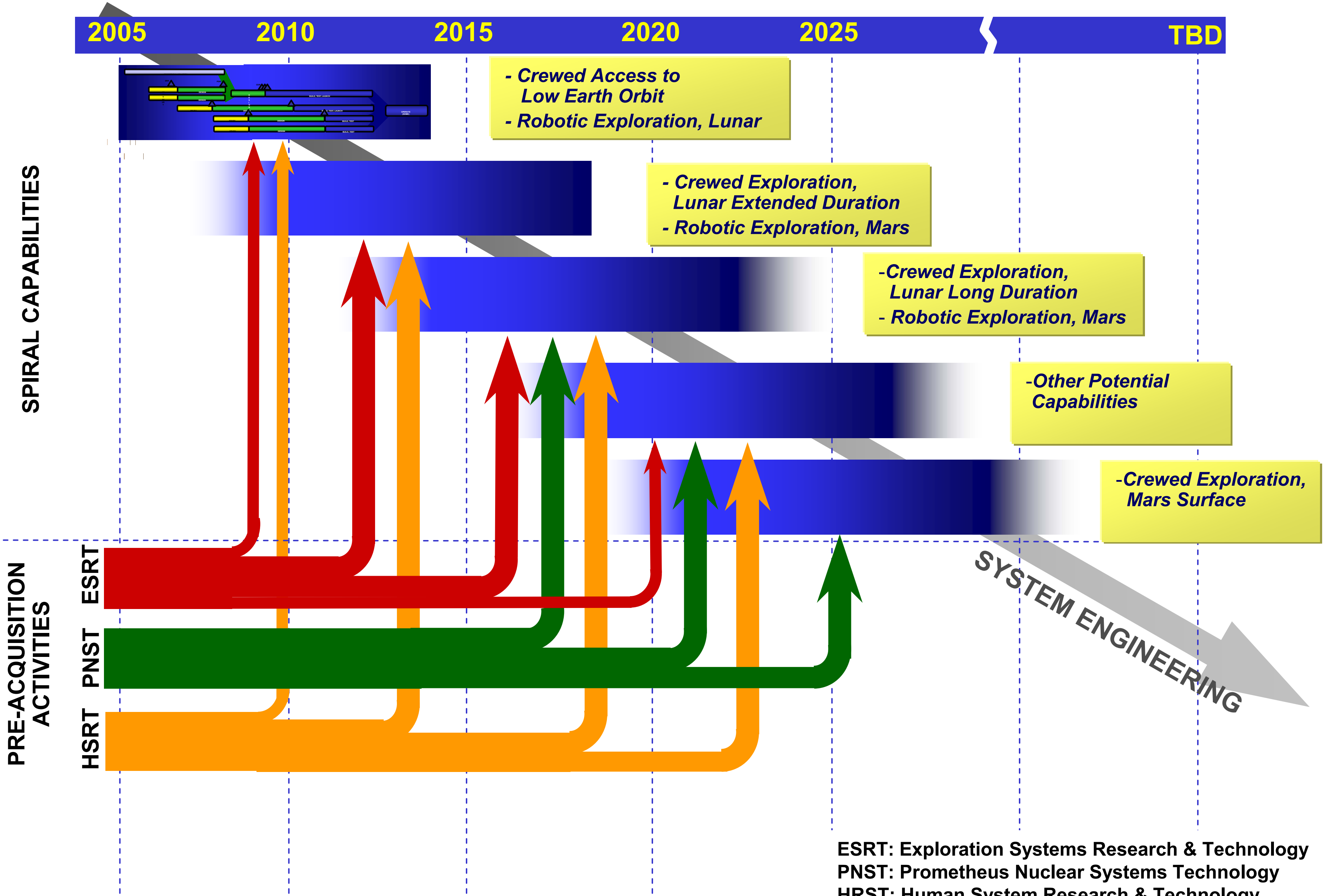
Comet Cryogenic sample return

Pre-Decisional Draft: Illustrative Only

Exploration Roadmap



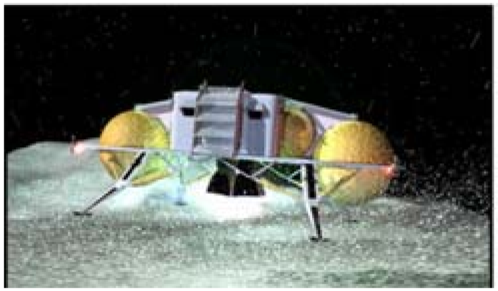
Constellation Spirals

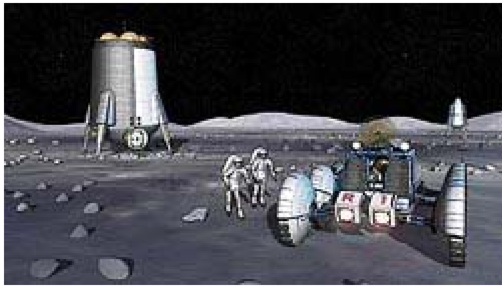


ESRT: Exploration Systems Research & Technology
PNST: Prometheus Nuclear Systems Technology
HRST: Human System Research & Technology

Spirals Definition

- **Spiral 1: 4-6 crew to Low Earth Orbit (2014)**
  - Crew Exploration Vehicle (CEV)
    - Launch environment
    - LEO environment
    - Earth entry, water (or land) recovery
- **Spiral 2: 4-6 crew to lunar surface for extended-duration stay (2015-2020)**
  - Crew Exploration Vehicle (CEV)
    - Earth-moon cruise - 4 days
    - Low lunar orbit (LLO) operations – 1 day
    - Untended Lunar Orbit operations – 4-14 days
    - Low lunar orbit operations – 1 day
    - Moon-Earth cruise – 4 days
  - Lunar Lander
    - Surface operations with EVA 4-14 days
- **Spiral 3: 4-6 crew to lunar surface for long-duration stay (2020-TBD)**
  - Lunar habitat
    - Lunar surface operations 60-90 days
- **Spiral 4: Crew to Mars vicinity (2025+)**
  - Transit vehicle
    - Earth-Mars cruise – 6-9 months
    - Mars vicinity operations – 30-90 days
    - Mars-Earth cruise – 9-12 months
- **Spiral 5: Crew to Mars surface (2030+)**
  - Surface habitat and exploration





Requirements and Deliverables: Observations

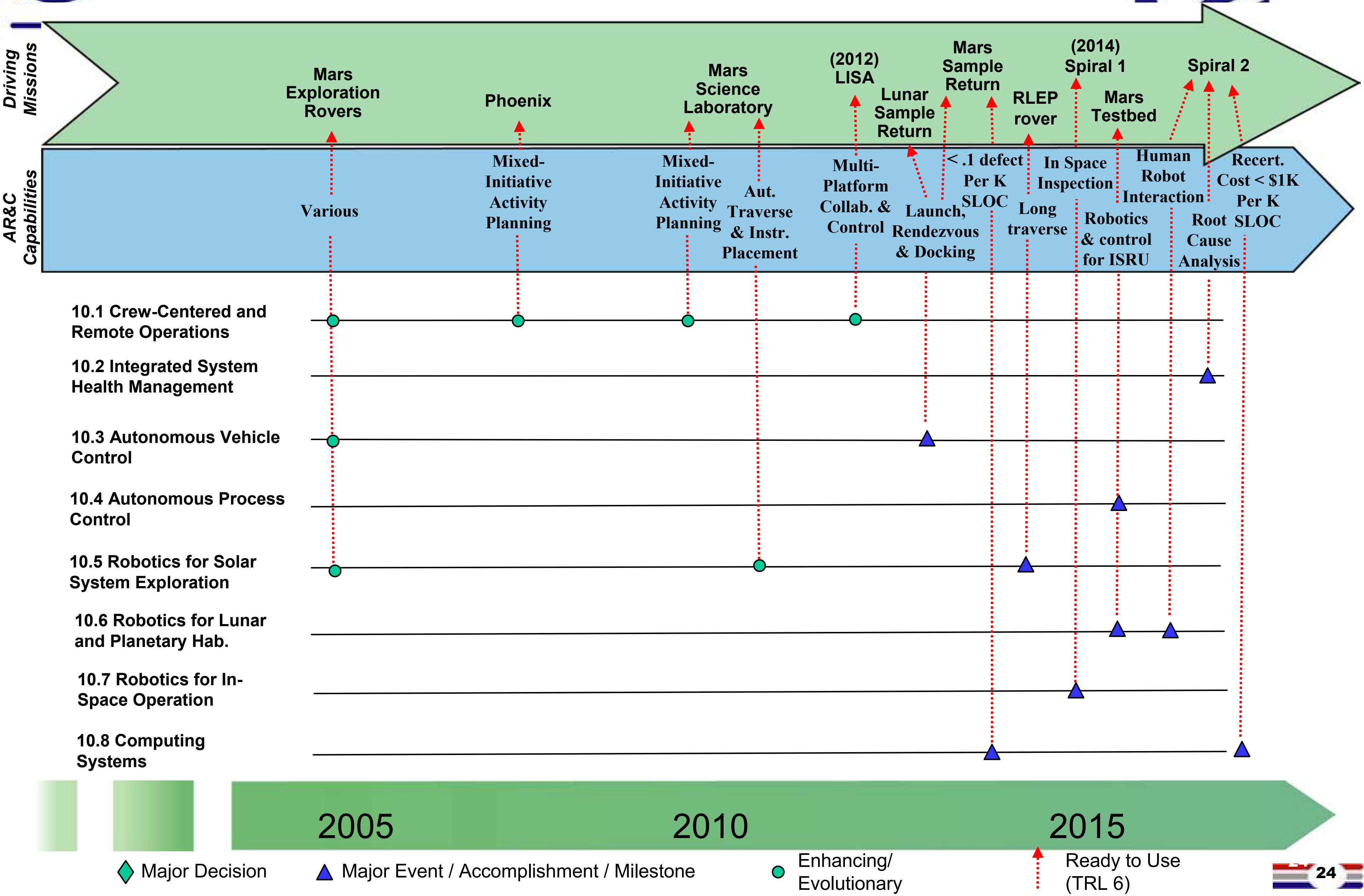
1. AR&C is heavily cross-cutting. Most capabilities are relevant to multiple missions and mission classes. For purposes of the roadmap we have listed the first major driver.

2. In many cases AR&C is providing control and execution software for hardware developed by other capability roadmaps (e.g., drilling, EDL, nuclear reactors, life support, etc.). Conversations with these capability roadmap teams have begun and will increase once all teams have full packages.

3. Numerous AR&C capabilities have applications in superficially very different missions (e.g., control and execution software shared between rovers, drilling, life support, and interferometry). Such sharing can reduce costs, shorten schedules, and reduce risks. This is an important lesson of agency-level analysis.

4. Common themes:
   1. Communication latencies create pacing NASA challenges
   2. Surface exploration drives autonomy and robotics
   3. The other driver is challenging manipulative tasks (construction, drilling, ISRU, constellations, science experiments, etc.)

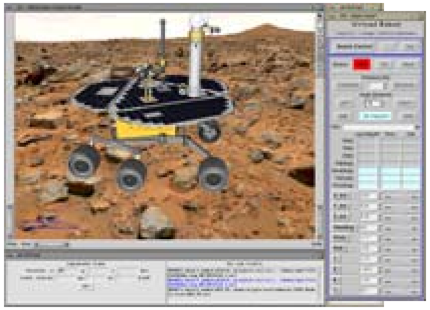
Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



MER Capabilities (10.1)

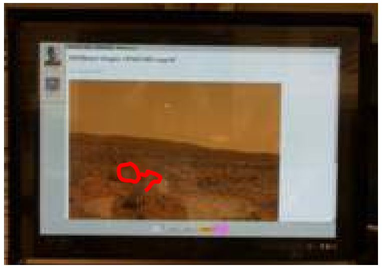
MAPGEN: Activity plan development and analysis

MER science and uplink team members have estimated that overall science return increased by 20 to 50%.



Viz: High fidelity terrain modeling and analysis

CIP: Customizable data navigation, search, and information management



MERBoard: Collaborative information analysis and sharing

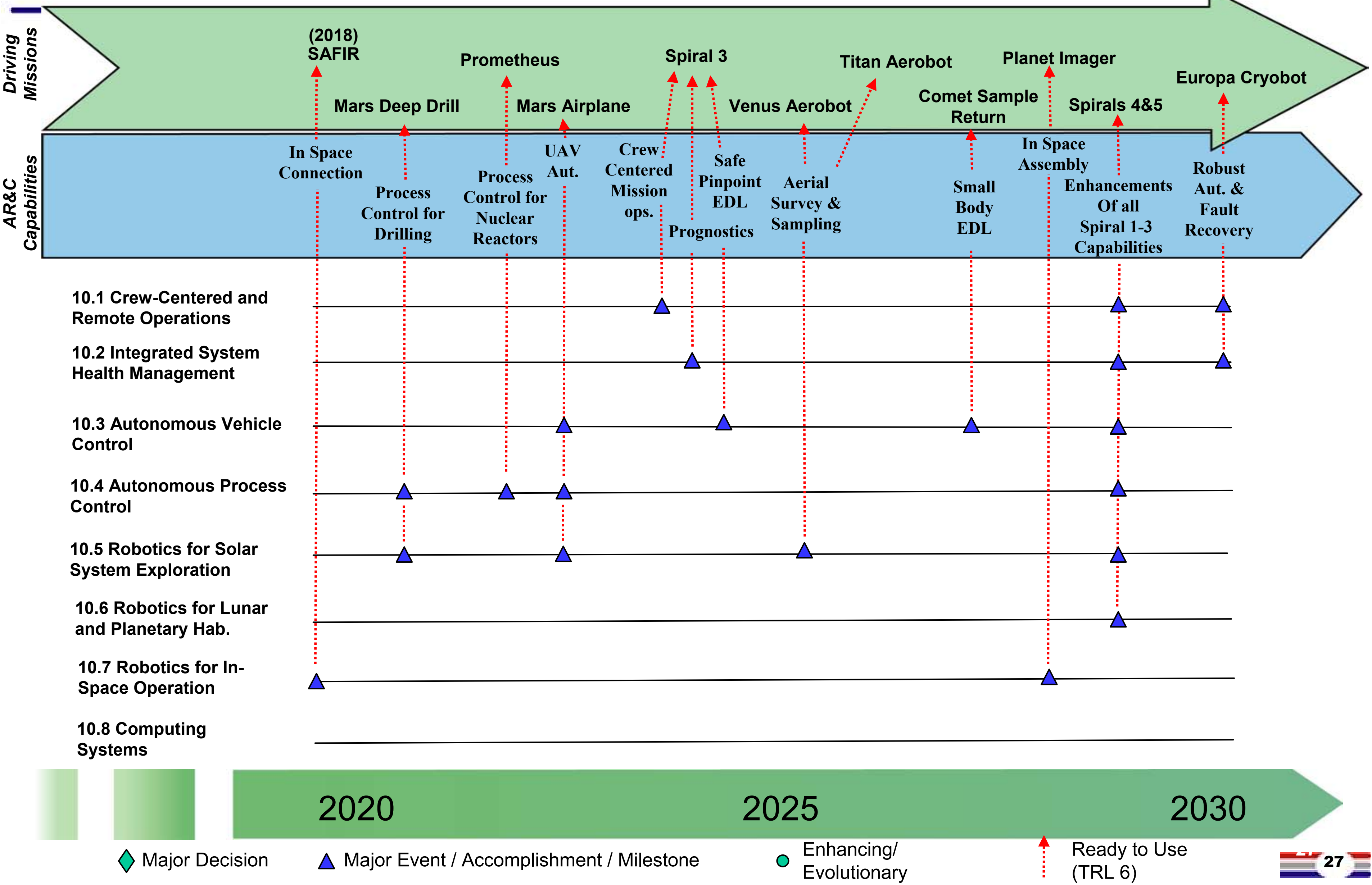
HCC & Fatigue Countermeasures: Improved data understanding and Enhanced situational awareness

MER Capabilities (10.3, & 10.5)

Advanced Planning & Integration Office

	Technology	Funding Source	Description	PI/Technologist
1	Long Range Science Rover	NASA (Code R and MTP)	Provides increased traverse range of rover operations, improved traverse acuracy, landerless and distributed ground operations with a large reduction in mass	Samad Hayati Richard Volpe
2	Science Activity Planner	NASA (Code R and MTP)	Provides downlink data visualization, science activity planning, merging of science plans from multiple scientists	Paul Backes Jeff Norris
3	FIDO: Field Integrated Design and Operations Rover	NASA (MTP)	Developed TRL 4-6 rover system designs, advancing NASA capabilities for Mars exploration; demonstrated this in full-scale terrestrial field trials, Integrated/operated miniaturized science payloads of mission interest, coupling terrestrial field trials to	Paul Schenker Eric Baumgartner
4	Manipulator Collision Prevention Software	NASA (MTP)	Computationally efficient algorithm for predicting and preventing collisions between manipulator and rover/terrain.	Eric Baumgartner Chris Leger
5	Descent Image Motion Estimation System (DIMES)	NASA (Code R and MTP)	Software and hardware system for measuring horizontal velocity during descent, Algorithm combines image feature correlation with gyroscope attitude and radar altitude measurements.	Andrew Johnson Yang Cheng et al.
6	Parallel Telemetry Processor (PTeP)	NASA (Code R and MTP)	Data cataloging system from PTeP is used in the MER mission to catalog database files for the Science Activity Planner science operations tool	Mark Powell Paul Backes
7	Visual Odometry	NASA (MTP)	Onboard rover motion estimation by feature tracking with stereo imagery, enables rover motion estimation with error < 2% of distance traveled	Larry Matthies Yang Cheng
8	Rover Localization and Mapping	NASA (MTP)	An image network is formed by finding correspondences within and between stereo image pairs, then bundle adjustment (a geometrical optimization technique) is used to determine camera and landmark positions, resulting in localization accuracy good for trav	Ron Li Clark Olson et. al.
9	Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT)	NASA (Code R and MTP)	Performs traversability analysis on 3-D range data to predict vehicle safety at all nearby locations; robust to partial sensor data and imprecise position estimation. Configurable for avoiding obstacle during long traverse or for driving toward rocks for	Mark Maimone

Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Summary of Key Deliverables

Advanced Planning & Integration Office

SMD: Mars – Sun-Earth; ESMD: Spiral 1 – Spiral 3

	Mars	Solar Sys.	Lunar	Obs.	Earth Sci.	Sun-Earth	Spiral 1	Spiral 2	Spiral 3
10.1 Autonomous mission ops	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enabling, First driver	Enhancing	Enhancing	Enabling, First driver
10.1 Multi-platform collaboration				Enabling, First driver	Enabling	Enabling, First driver		Enhancing	Enhancing
10.2 Root-cause analysis	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling, First driver
10.2 Prognostics	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling, First driver
10.3 Rendezvous and Docking	Enabling, First driver		Enhancing	Enhancing				Enhancing	Enabling
10.3 Entry, descent, & landing	Enabling, First driver	Enhancing	Enhancing					Enhancing	Enabling
10.4 Nuclear reactor control		Enabling, First driver	Enhancing						Enabling, First driver
10.4 Sub-surface drilling	Enabling, First driver	Enabling	Enabling, First driver		Enhancing			Enhancing	Enhancing
10.5 Long traverse	Enabling, First driver	Enhancing	Enabling, First driver		Enhancing			Enhancing	Enhancing
10.5 Aerial survey and sampling	Enhancing	Enabling, First driver			Enabling				Enhancing
10.6 Human-robot interaction					Enhancing			Enhancing	Enabling, First driver
10.6 ISRU	Enabling, First driver		Enabling, First driver					Enhancing	Enabling
10.7 In-space inspection				Enhancing	Enhancing		Enhancing	Enhancing	Enabling, First driver
10.7 In-space connecting				Enabling, First driver				Enhancing	Enabling, First driver
10.8 <.1 defect per K SLOC	Enabling, First driver	Enabling	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling
10.8 Recert. < $1K per K SLOC	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling, First driver	Enabling

Legend: ✸ First driver; ■ Enabling (red); ■ Enhancing (yellow)

Notes:

- Spiral 4 is similar to spiral 3.
- In most case AR&C is developing software to control hardware developed by other capabilities.

Breakthrough Capability Rollup

Advanced Planning & Integration Office

Capability

- Autonomy and control for deep drilling (10.4, 10.3, 10.5, and 10.2)
- Dependable, and affordable robotic in-orbit maintenance (10.7 and 10.3)
- Dependable and affordable robotic in-orbit assembly (10.7 and 10.3)
- Dependable autonomy for aerobots and sub-surface (10.4, 10.1, and 10.5)
- Surface mobility to cliffs and other current inaccessible sites (10.5).
- Largely automated CEV and habitat operations (10.1 and 10.2)
- Autonomous robotic surface construction and ISRU (10.6 and 10.4). Safe, dependable, pinpoint landing (10.3).

Enables

- Sub-surface search for evidence of life on Mars and Europa
- Instrument change-out and long term operation of observatories
- Large aperture telescopes, affordable human exploration beyond earth-moon neighborhood.
- Aerial Mars survey. Surface access on Titan. Search for evidence of life on Europa.
- Search for evidence of life on Mars in areas showing possible recent fluid flow
- Human exploration of Mars.
- Affordable human habitation on Moon and Mars. Robotic site preparation in advance of manned surface missions

Exploration/Science Traceability

- AR&C requirements can be traced back to the following documentation:
  - Major recent vision documents:
    - “The Vision for Space Exploration”, 2004, (Doc NP-2004-01-334-HQ)
    - “Exploration Systems Interim Strategy”, 2004
    - “A Journey to Inspire, Innovate, and Discover”, President’s Commission Report
    - “The New Age of Exploration: NASA’s Direction for 2005 and Beyond”
  - NASA Enterprise Strategy Documents
    - “The Future of Solar System Exploration, 2003-2013”, NRC Planetary Decadal Report, 2002
    - “Assessment of Mars Science and Mission Priorities”, National Research Council, 2003
    - “Scientific Goals, Objectives, Investigations, and Priorities” – MEPAG report on priorities for Mars exploration
    - “Mars Exploration Strategy”, Mars Science Program Synthesis Group, 2003
    - Solar System Exploration Roadmap, 2003, (Doc JPL 400-1077 5/03)
  - Design Reference Missions
    - Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities (NASA/TP 2003-212053)
    - The Mars Surface Reference Missions: A Description of Human and Robotic Surface Activities (NASA/TP 2001-209271)
    - Solar System <update from Cutts>
  - ESMD preliminary requirements documents: ESS Technology Requirements RevB, CTS Spirals 1-3 RevB, RLEP Requirements (Sept ’04), CEV ConOps (Sept ’04)

- Sub-team materials include tracing from each deliverable to the first driving mission (and our assumptions about the timing of that mission)

Interfaces: Leveraging non-NASA Robotic Developments

- Other players
  - DOD, DOE: well-defined relevant development thrusts (next slides)
  - Industrial: principally manipulators (pick and place, painting, etc)
  - Commercial/consumer: hard to predict, especially the future
    - Roomba vacuum, Aibo dog
  - Diversity of national focus
    - USA: UAVs, UGVs, military
    - Japan: humanoids, care for aging ("silver society")
    - Korea: robotic workers
- Commonality of technologies limited by diversity of applications
  - Perception, navigation, behaviors, planning, HRI
  - Different tasks, environments require different knowledge bases
    - Sensors, effectors must be appropriate to each application
    - May require qualitatively different software approaches
- Space-based computational resources extremely limited
  - Need for rad-hard operation precludes effective exploitation of Moore's law price/performance gains

DoD Robotics Efforts

- DoD Robotics/UXV Service Thrust Areas
  - Army: Future Combat System (FCS): UGVs, UAVs, crew enhancement
  - Navy: UUVs, UAVs
  - Air Force: UAVs
- DARPA Office Robotics-related Themes
  - TTO: UGVs & UAVs (system level), innovative mobility
  - IPTO: software (perception, behavior, learning, HRI)
  - DSO: biological inspired approaches
  - MTO: sensors, actuators, "micro-robots"
  - IXO: sensor systems
  - ATO: ad hoc communications networks
- DARPA Grand Challenge
  - On-road/trail, following dense GPS waypoints, with perception-based corrections for obstacle negotiation
  - Has successfully generated awareness, enthusiasm, and constituency for attacking the autonomous UGV navigation problem
- NASA Participation in IPTO MARS Program
  - Mobile Autonomous Robot Software (1999-2004)
  - JSC (R. Ambrose): perception-based autonomous manipulation and mobility base for Robonaut
  - JPL (L. Matthies): perception for UGV navigation

Comparison—Inter-Agency Robotics Requirements

	NASA	DoD	DoE
Robot Physical Characteristics	**Light, Mass & Volume Constrained**	**Sturdier; Re-Usable; Can Resist Wear and Tear**	**Sturdier; Re-Usable; Can Resist Wear and Tear**
Robot Environment	**Unexplored Terrain; Extreme Cold/Heat**	**Earth Terrain; On-Road & Off-Road**	**Radiation Rich Sites**
Distance from Control and Command Station	**Up to Millions of Kilometers**	**Few Kilometers**	**Up to 1 Kilometer**
Robot Level of Autonomy	**Semi-Autonomous (long time-delay)**	**Teleoperation/Semi-Autonomous (short time delay)**	**Teleoperation/Semi-Autonomous (short time delay)**
Robot Manipulators	**Pick-Up and Handle Small Objects (e.g. rocks); Low-Gravity Manipulation of Human-Made Objects**	**Lift and Handle Heavy Loads**	**Lift and Handle Heavy Loads**
Robot Vision	**Discover Interesting Science Samples; Detect Natural Hazards**	**Detect & Track Human Objects (walking soldier; moving lead vehicle)**	**Inspect Hazardous Sites; Cluttered Environment**

Leveraging non-NASA Robotic Developments

- NASA is well aware of non-NASA efforts
  - Some joint work with non-NASA sponsors
- Commonalities in technology needs are limited by:
  - Differences in application requirements
    - Differences in environments (e.g., no vegetation)
    - Differences in tasks to be performed
  - Differences in resources available
    - Communications latency and bandwidth
    - Limited opportunity to exploit human support
    - Limited computing power and memory due to rad-hard requirement
- Bottom Line: we can't wait for someone else to do what we need to have done

Capability Roadmap Crosswalk

	Capability Roadmap	Crosswalk Status to Date
(yellow)	2. High-energy power and propulsion	
(yellow)	3. In-space transportation	Initial discussion with leads. Exchange of material. Results incorporated.
(yellow)	4. Advanced telescopes and observatories	Exchange of material.
(yellow)	5.Communication & Navigation	Exchange of material.
(red)	6. Robotic access to planetary surfaces	Presentations to team workshops. Exchange of materials and multiple ongoing discussions.
(yellow)	7. Human planetary landing systems	Discussions with team. Attendance at workshop.
(yellow)	8. Human health and support systems	Initial discussions with leads.
(red)	9. Human exploration systems and mobility	Close working relationship with lead.
(green)	11. Transformational spaceport/range technologies	
(yellow)	12. Sensors and instruments	Minimal discussions. Have draft of material.
(yellow)	13. *In situ* resource utilization	
(green)	14. Advanced modeling, simulation, analysis	
(green)	15. Systems engineering cost/risk analysis	
(green)	16. Nanotechnology	

(green)	Limited relationship (or relationship at sub-capability level)
(red)	Critical Relationship
(yellow)	Moderate Relationship

Strategic Roadmap Crosswalk

	Strategic Roadmap	Crosswalk Status to Date
	1. Lunar: Robotic and Human Exploration	Jim Watzin presentation at workshop.
	2. Mars: Robotic and Human Exploration	Dave Lavery representing Mars program.
	3. Solar System Exploration	Design Reference Missions and strategic guidance documentation. Discussions with Jim Cutts and Scott Hubbard.
	4. Search for Earth-Like Planets	Design Reference Missions and strategic guidance documentation.
	6. International Space Station	
	7. Space Shuttle	
	8. Universe Exploration	Design Reference Missions and strategic guidance documentation.
	9. Earth Science and Applications from Space	Design Reference Missions and strategic guidance documentation.
	10. Sun-Solar System Connection	Design Reference Missions and strategic guidance documentation.
	11. Aeronautical Technologies	
	12. Education	
	13. Nuclear Systems	
	Limited Relationship	
	Critical Relationship	
	Moderate Relationship	

Capability Readiness Levels

Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

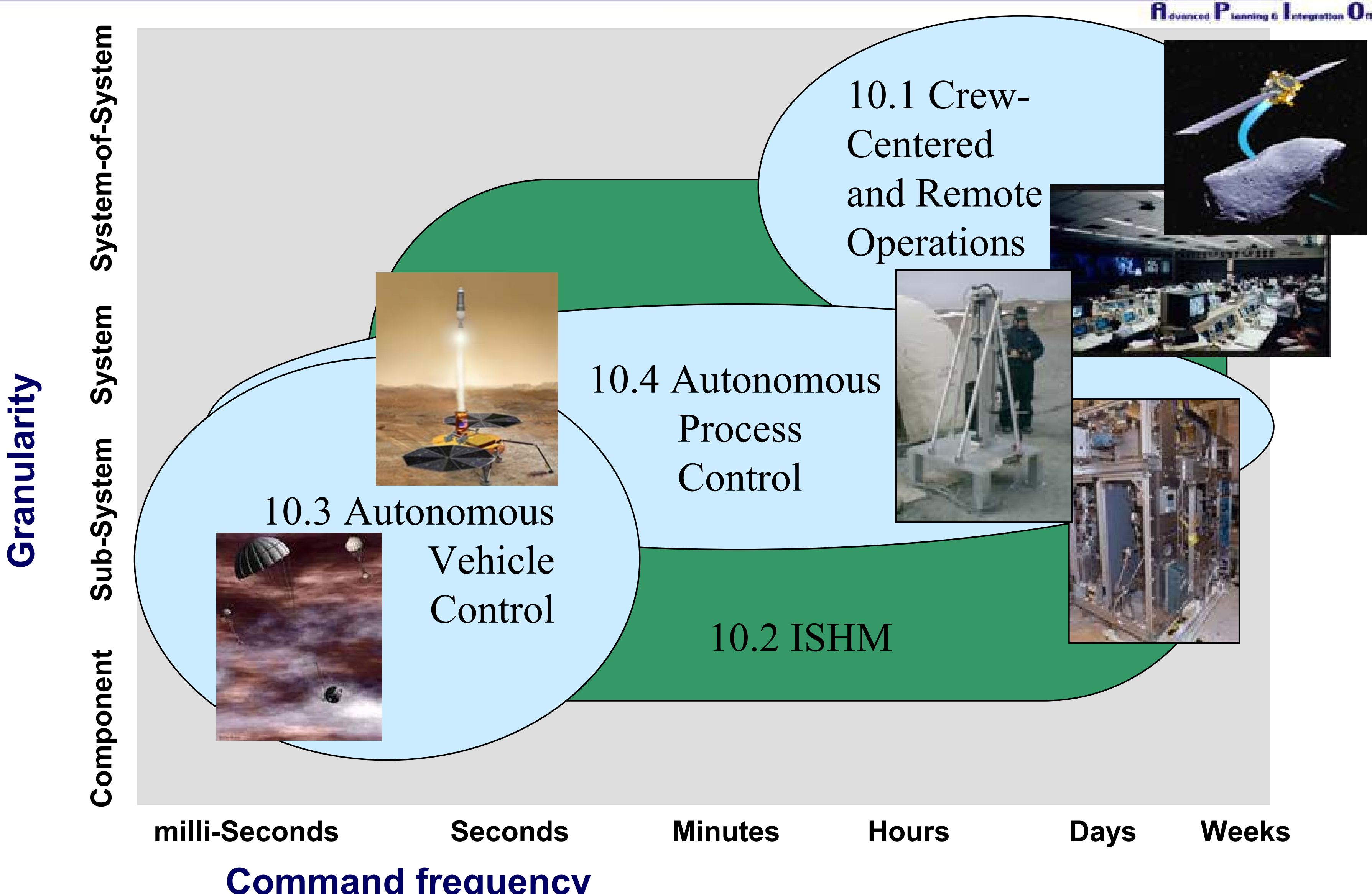
The Four Questions (again)

1. Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?
2. Are technology maturity levels accurately conveyed and used?
3. Are proper metrics for measuring advancement of technical maturity included?
4. Do the Capability Roadmaps have connection points to each other when appropriate?

Overview

- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- **Autonomy (James Crawford)**
  - **Crew-Centered and Remote Operations**
  - **Integrated Systems Health Management**
  - **Autonomous Vehicle Control**
  - **Autonomous Process Control**
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- Computing Systems (Mike Lowry)
- Conclusion

Autonomous Systems – 10.1-10.4



Capability 10.1
Crew-Centered and Autonomous Operations

Sub-Team Chair: Julia Loftis, NASA/GSFC
Presenter: James Crawford, NASA/ARC

Capability 10.1
Crew-Centered and Autonomous Operations

- **This capability area defines the evolution of command and control for both manned and unmanned science and exploration missions. This includes:**
  - Crew-Centered Planning (activity sequences created by crew rather than ground personnel)
  - Autonomous Mission Operations
    - Health and Safety Monitoring, Analysis and Anomaly Recovery
    - Science Analysis and Optimization
    - Dynamic Planning
    - Onboard Robust Execution
    - Logistics and Inventory
  - Multi-system Coordination and Collaboration
  - Human Automation Interaction
  - Multi-modal Interfaces for Collaborative Execution

Benefits of Capability 10.1
Crew-Centered and Autonomous Operations

- **Crew-centered** operation is *enabling* for Martian exploration due to both the latency of light speed communication, and the potential loss of communication.
- **Autonomous** operation is *enabling* for some classes of planetary surface exploration and remote in-situ science.
- Additional benefits
  - Reduced operations costs
  - Ability to react to unforeseen circumstances without reliance on ground → increased safety
  - Ability to take advantage of schedule gaps → increased efficiency

Summary Status for Capability 10.1 Crew-Centered and Autonomous Operations

- Operation of crewed missions (Station and Shuttle) is presently a manually intensive process:
  - Station flight controllers uplink ~500,000 individual commands per year to fly and maintain the craft
  - A team of 50 Station mission planners manually develops a timeline for each crew member, which takes 2 weeks for each day's activities; safety and feasibility constraint checking is not automated, but is handled through the knowledge of these experts
  - The Russians (who do not have constant communication via TDRSS as we do) upload some automated procedures.

- Operation of unmanned vehicles is done via ground based sequence generation with some low level task automation and automated constraint checking; onboard automated safety procedures are routinely implemented

- The state of the art in this area includes technology demonstrations for autonomous operation
  - EO-1 ('03-'05): technology demonstration of autonomous tracking of science events, onboard mission planning, smart task execution, and model-based diagnosis; autonomous formation maneuver planning and execution
  - DS-1 ('99): technology experiment demonstrating autonomous planning, diagnosis, and execution

Detailed Status for Capability 10.1 Crew-Centered and Autonomous Operations

- Crew Centered Planning
  - Constraint-based activity planning (MER)
  - Ground-based automated scheduling (Shuttle ground processing)

- Autonomous Mission Operations
  - Health and Safety Monitoring, Analysis & Anomaly Recovery
    - NASA: largely manual (except critical onboard sequences)
    - Fail-operational autonomous on-board control (DS-1)
    - On-board model-based diagnosis (EO-1/DS-1)
    - DOD/DARPA? External? (JSF,777)
  - Science Analysis and Optimization
    - Autonomous tracking and reaction to science events (EO-1)
  - Dynamic Planning
    - DS-1 and EO-1 technology demonstrations cited above
    - MER (MAPGEN ground planner)
  - Onboard Robust Execution
    - DS-1/ESL, EO-1/SCL
    - Terrestrial robotic demonstrations (LITA, PSA, K-9)
  - Logistics and Inventory
    - NASA: time-consuming, manual process to maintain database
    - External: barcode, RFID (powered & passive)

Current Status for Capability 10.1 Crew-Centered and Autonomous Operations

- Multi-platform Coordination and Collaboration
  - "String of pearls" constellation control (Terra,Aqua,Aura,EO-1)
  - Technology demonstration of cooperation between two spacecraft: leading spacecraft perceives a phenomena and trailing spacecraft reacts to it. (EO-1)
- Human Automation Interaction
  - Tele-operation with sequential command, execution; during execution, some subtasks (such as alignment) are automated
  - Mixed initiative activity planning used for MER (MAPGEN)
- Multi-modal Interfaces for Collaborative Execution
  - In-situ Crew Training
    - Written procedure list; simple assistance for problem diagnosis
    - Task demonstration as human simulation
    - Free-Flying Mobile Robot with LCD/Pointer/Sensors (PSA)
  - EVA Support
    - Basic informational displays within helmet
    - AERCam in testing
  - Voice-based intelligent procedure access (Clarissa)

Summary of Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

Advanced Planning & Integration Office

- Human Automation Interaction: Rapid Situational Awareness, Data Analysis, and Decision Support Tools
  - ESMD: Spiral 1 : TRL 6 by 2009

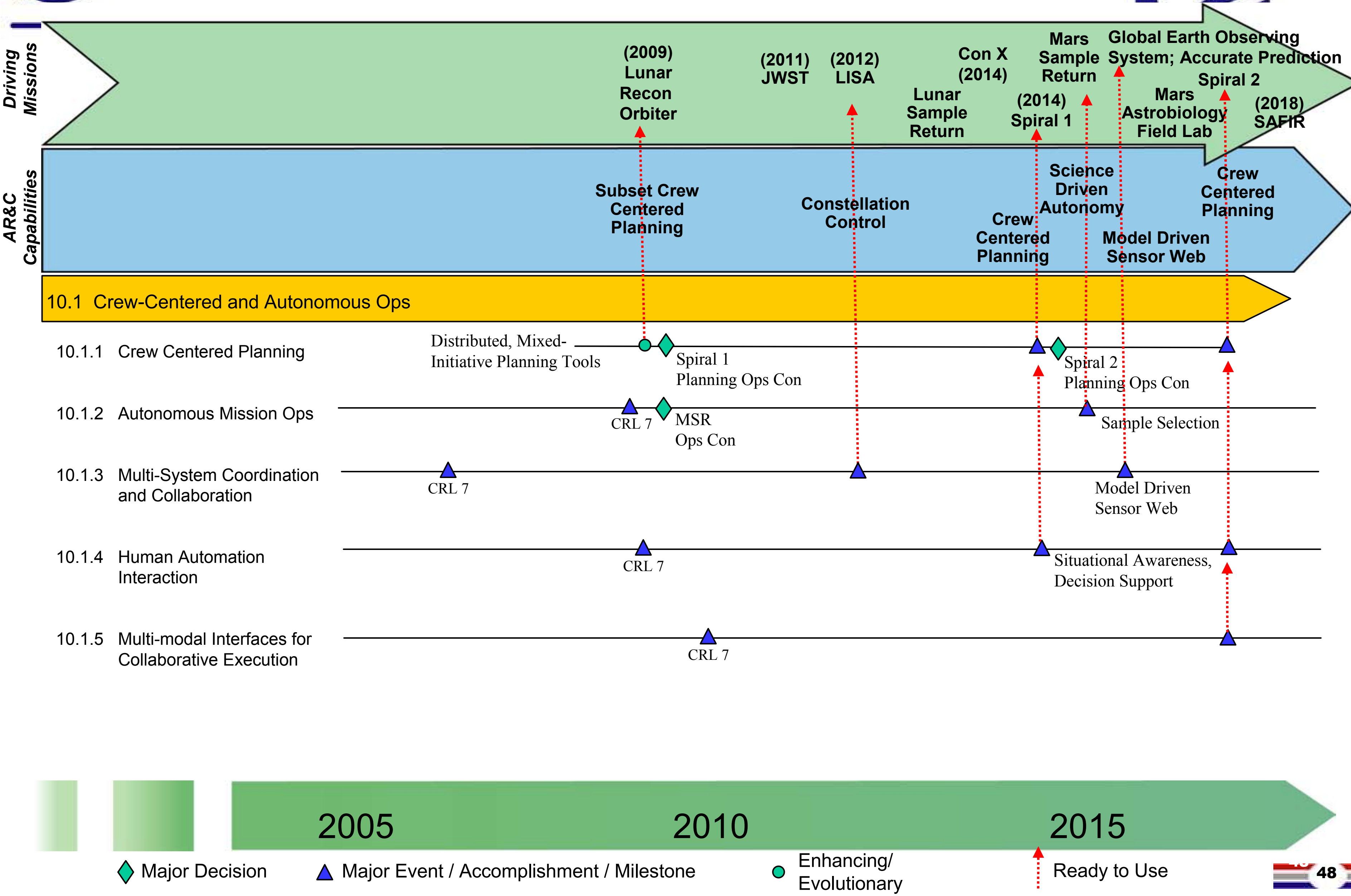
- Crew Centered Planning: Distributed, Constraint-based, Mixed-initiative, Mission Ops Planning Tools
  - ESMD: Spiral 2: TRL 6 by 2010

- Multi-modal Interfaces for Collaborative Execution (e.g., voice for EVA)
  - ESMD: Spiral 2: TRL 6 by 2010

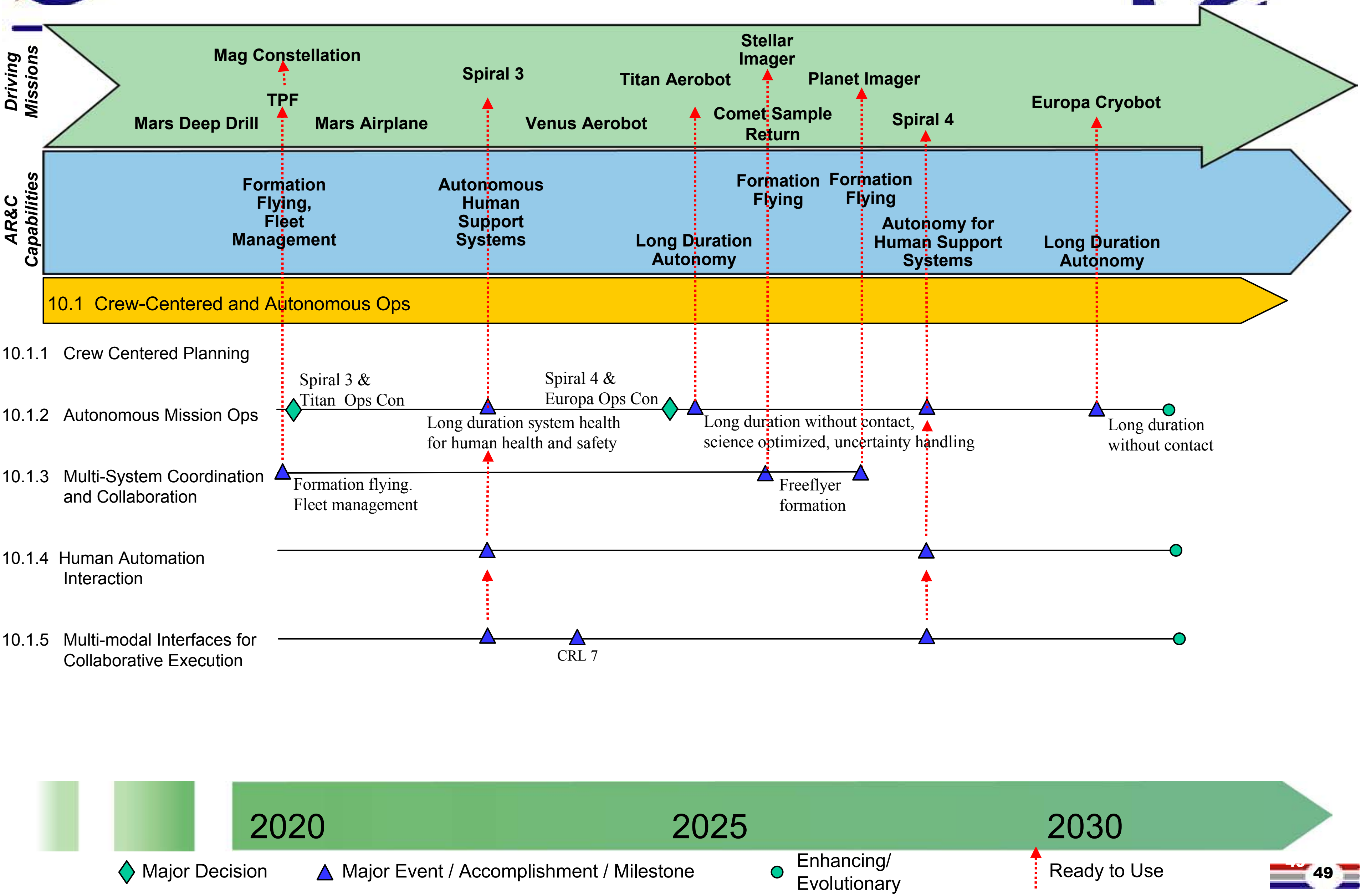
- Multi-platform Coordination and Collaboration
  - SMD: LISA-3, MMS-4, GEC-4, MagCon-50 2012-2014, Stellar Imager-25 2015, Black Hole Imager Pathfinder-several 2018, Earth Science Sensor Web
  - ESMD: Spiral 2: TRL 6 by 2010

- Autonomous Mission Operations: Health and Safety Monitoring, Analysis & Anomaly Recovery; Science Analysis and Optimization; Dynamic Planning; Logistics and Inventory
  - SMD: MSL 2009, MSR 2013, Earth Science Sensor Web, Titan / Europa missions (weeks out of contact), LISA 2012
  - ESMD: Spiral 3: TRL 6 by 2015

Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

- Human Automation Interaction: Rapid Situational Awareness, Data Analysis, and Decision Support Tools
  - ESMD Driver: Spiral 1, CEV (2014)
  - TRL 6 date: 2009
  - Interfaces: HESM
  - Decision points: Technology demonstrations

- Crew Centered Planning: Distributed, Constraint-based, Mixed-initiative, Mission Ops Planning Tools
  - ESMD Driver: Spiral 2, lunar surface habitat (2015)
  - TRL 6 date: 2010
  - Interfaces: HESM
  - Decision points: Technology demonstrations in spirals 1 & 2

Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

- Multi-modal Interfaces for Collaborative Execution: Voice interfaces between flight crew and automated tools and robots, mixed GUI-voice interfaces for ground crew. (Some risk)
  - ESMD Driver: Spiral 2, surface ops with EVA (2015)
  - TRL 6 date: 2010
  - Interfaces: HESM, HHS
  - Decision points: Technology demonstrations in spirals 1 & 2

- Multi-platform Coordination and Collaboration: Command and control for coordinated observation, sensor web, interferometery, etc.
  - ESMD Driver: Spiral 2, CEV and Lunar Lander (2015)
  - SMD Drivers: LISA-3 (2012), MMS-4 (2012), GEC-4 (2014), MagCon-50 (2013), Stellar Imager-25 2015, Black Hole Imager Pathfinder-several (2018), Earth Science Sensor Web
  - TRL 6 date: 2007
  - Interfaces: HESM. SIS, ATO
  - Decision points: Technology demonstrations in spirals 1 & 2

Deliverables for Capability 10.1 Crew-Centered and Autonomous Operations

Advanced Planning & Integration Office

- Autonomous Mission Operations: Health and Safety Monitoring, Analysis & Anomaly Recovery; Science Analysis and Optimization; Dynamic Planning; Logistics and Inventory
  - ESMD Driver: Spiral 3, lunar surface habitat (2020)
  - SMD Drivers: MSR sample selection (2013), Earth Science Sensor Web, Titan / Europa missions (weeks out of contact), LISA (2012)
  - TRL 6 date: 2004
  - Interfaces: HESM, SIS, AMSA
  - Decision points: Technology demonstrations in spirals 1 & 2

Maturity Level – Capabilities for 10.1 Crew-Centered and Autonomous Operations

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Crew Centered Planning	Distributed, mixed-initiative constraint-based planning tools (ground and onboard)	2 (crewed missions)	6	ESMD Spiral2	2010
	Graphical interfaces to support plan creation and modification	2 (crewed missions)	6	ESMD Spiral2	2010
Autonomous Health & Safety Monitoring, Analysis and Anomaly Resolution	On-board tools to support diagnosis and recovery by crew	2	6	ESMD Spiral2	2010
	Automated uncertainty handling – autonomous information gathering for resolution	2	6	SMD MSR ESMD Spiral3	2008 2015
	Rapid creation of ad-hoc teams	2?	6	ESMD Spiral1	2009

Maturity Level – Capabilities for 10.1 Crew-Centered and Autonomous Operations

Advanced Planning & Integration Office

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Autonomous Science Analysis, Predictive Modeling, and Optimization	Science goal driven autonomous systems	2	6	SMD LISA, MSR	2007
Autonomous, Dynamic Planning	Embedded, continuous planning integrated with execution decision theoretic planning	2	6	SMD Titan Aerobot, Europa Cryobot	2010
Onboard, Robust Execution	Reactive task decomposition, health management with goal-achieving recovery	4	6	LISA, MSR	2007
Automated Logistics and Inventory	Inventory / supply chain management	2	6	ESMD Spiral2	2010
Multi-Platform Coordination and Collaboration	Formation flying	2	6	SMD LISA, MMS	2007
	Inter-satellite communication and networking	2	6	TBD	
	Fleet Management (centralized and decentralized)	2	6	SMD MagCon	2008
	Model-driven sensor web	2	6	SMD ES Sensor Web	?

Maturity Level – Capabilities for 10.1 Crew-Centered and Autonomous Operations

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Human Automation Interaction	Rapid situational awareness (visualization of complex information and actions of autonomous systems)	2	6	ESMD Spiral1	2009
	Decision support systems	2	6	ESMD Spiral1	2009
	Trusted autonomy	2	6	SMD MSR ESMD Spiral3	2008 2015
Multi-modal Interfaces for Collaborative Execution	Multi-media interfaces (presentation and reception)	2	6	ESMD Spiral2	2010
	Crew observation, analysis, and assistance	2	6	ESMD Spiral2	2010

Maturity Level – Technologies for 10.1 Crew-Centered and Autonomous Operations

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Distributed, mixed-initiative constraint-based planning tools (ground and onboard)	Planning engine and logic; prioritization scheme	MAPGEN, ASPEN, PASSAT	7	Crew centered mission planning and control	2010
Graphical interfaces to support plan creation and modification	Plan presentation, editing, and explanation of automation	MAPGEN, SAP	7		2010
On-board tools to support diagnosis and recovery by crew	Presentation of fault diagnosis and supporting information	SERS	3	Advanced approaches to communication of complex context, history information	2008
Automated spacecraft health management with uncertainty handling	Probabilistic fault diagnosis and resolution; autonomous information gathering for resolution	PSA Agent, DAPRA Prognosis Program, Army F135 engine health management			
Rapid creation of ad-hoc teams with critical skills for anomaly resolution		SERS	3		2009

Maturity Level – Technologies for 10.1 Crew-Centered and Autonomous Operations

Advanced Planning & Integration Office

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Science goal driven autonomous systems	Goal Capture, Real-time Data and Information Fusion and Analysis	SGM, Domain specific algorithms and models, SWIFT TOO and FOM	6	Performance of key algorithms; data interoperability	2007
Embedded, continuous planning integrated with execution decision theoretic planning	Constraint network, heuristic set, goal set, uncertainty specs	ASPEN / CASPER, Livingstone, EUROPA	6	Performance, verification	2010
Robust Execution Technology	State estimation, task decomposition, goal assessment, recovery, adjustable autonomy	Remote Agent, IDEA, 3T/RAPS, APEX, ESL, TDL, SCL	7 5 6 6	Verification	2007
Inventory / supply chain management	Tag (RFID/Barcode), detector	Autonomous Detector (PSA)	5	Currently manual.	2010
Formation Flying	Formation Control, Relative Navigation	SPHERES, PSA Agent, Autocon, Decentralized Formation Control	5	Operational infusion	2007
Inter-satellite communication and networking		API Crosslink Transceivers (CLT)			

Maturity Level – Technologies for 10.1 Crew-Centered and Autonomous Operations

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Fleet Management (centralized and decentralized)	Path planning and optimization, collision avoidance, collaboration, distributed architectures	ASF	4	Spacecraft application	2008
Model driven sensor web	Data fusion, realtime analysis, sensor collaboration		4	Performance, interoperability	2007
Rapid situational awareness	Visualization of complex information and actions of autonomous systems		3	Communicatio n of complex information	2009
Decision support systems	Knowledge management and presentation		4		2009
Trusted autonomy			4	Reliability, predictability	2008
Multi-media interfaces	Presentation and perception	Clarissa	4	Ease of use	2010
Crew support	Observation, analysis, and assistance		3	Ease of use	2010

Metrics for 10.1
Crew-Centered and Autonomous Operations

Advanced Planning & Integration Office

Metric	Technology / Sub-Capability	Current Value	Target Value*	Need Date
Number of CEV (or other major) system commands issued weekly by ground crew	Crew centered operations	10,000	1000 100	Spiral 2 (2018) Spiral 3 (2023)
Hours per week of flight crew time required for spacecraft operations	Onboard automation	1 (done by ground)	10	Spiral 3 (2023)
Planned and actual average percent of days of onboard autonomous operation	Onboard automation	0 (except for DS1, EO1)	90%	TBD
Size of ground crew for regular and extended missions. Percent of ground crew that must be physically co-located.	Autonomous mission operations	Varies by mission	Cut by 75%	TBD
Percent of science decisions (e.g., target selection, download prioritization, etc.) that can be done onboard	Autonomous science analysis and optimization	0% (except EO1)	75%	TBD
Hours per week of flight and ground crew time spent tracking inventory (for CEV, lunar base or other facility)	Automated logistics and inventory	TBD	Cut by 90%	TBD
Size of ground team required for coordinated operation of spacecraft fleets	Multi-platform coordination and collaboration	TBD	Cut by 75%	TBD
Minutes required for human ground crew to understand status of remote autonomous craft they were not previously monitoring	Situational Awareness	NA (no current craft are autonomous)	10 min.	TBD

*Target values are an educated guess until mission requirements are finalized.

Technology Candidates

APEX - Architecture for Procedure Execution (ARC)
ASF – Adaptive Sensor Fleet (GSFC)
ASPEN - Automated Scheduling and Planning ENvironment (JPL)
Autocon – Automated On-board Maneuver Planning (GSFC)
CASPER - Continuous Activity Scheduling Planning Execution and Replanning (JPL)
Clarissa – Spoken-Language Dialogue System (ARC)
CLT – Crosslink Transcievers (APL)
ESL – Execution Support Language (JPL)
EUROPA – Extensible Universal Remote Operations Planning Architecture (ARC)
Livingstone – (ARC)
IDEA – Intelligent Distributed Execution Architecture (ARC)
MAPGEN - Mixed-Initiative Activity Planning GENerator (ARC/JPL)
PSA Agent- Personal Satellite Assistant Agent (ARC)
Remote Agent – (ARC)
SAP – Science Activity Planner (JPL)
SHAC – Shared Hierarchical Activity Coordination (SHAC)
SCL – Spacecraft Command Language (ICS)
SGM – Science Goal Monitor (GSFC)
SPHERES - Synchronized Position Hold Engage and Reorient Experimental Satellites (MIT/ARC)
TDL – Task Description Language (CMU)
3T/RAPS – Three-tier Agent/Reactive Action Packages (JSC)

Capability 10.2
Integrated Systems Health Management (ISHM)

Sub-Team Chair: Serdar Uckun, NASA/ARC

Sub-Team Co-Chair: Brian Williams, MIT

Presenter: Serdar Uckun, NASA/ARC

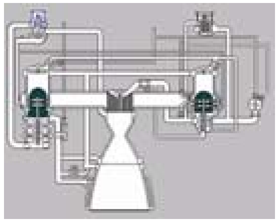
Summary for Capability 10. 2
Integrated Systems Health Management

- Today's state-of-the-art in spacecraft health is fault detection, isolation, and recovery (FDIR).
  - Based on fixed detection/isolation logic and recovery procedures.
  - Verified and validated using exhaustive testing.
  - Fragile (limited modeling of interactions with outside world or across subsystems, anomalous behavior depending on rule orderings).
  - Not scalable (verification and validation complexity increases dramatically with number of inputs/outputs/state variables).
- ISHM is the next frontier in systems health.
  - Highly desirable for complex exploration missions in ill-understood environments.
  - Based on scalable, flexible, model-based detection, isolation, and recovery methods.
  - Integrated into spacecraft at design stage and not as an afterthought.
  - Critical investment for safety, reliability, and mission assurance.

Capability 10.2
Integrated Systems Health Management

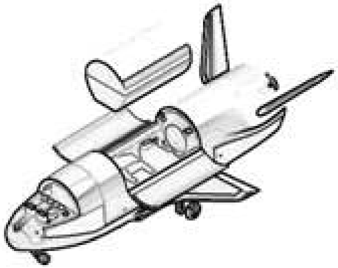
This capability area defines capabilities for robust mission operations throughout the system lifecycle.

- **Design of Health Management Systems**
  - Testability
  - Maintainability
  - Recoverability
  - Verification and validation of ISHM capabilities
  - Verification and validation of software under failure



- **Real-Time Systems Health Management**
  - Distributed sensing for structural health
  - Fault detection, isolation, and recovery
  - Failure prediction and mitigation
  - Robust control under failure
  - Crew and operator interfaces

- **Informed Logistics**
  - Modeling of failure mechanisms
  - Prognostics
  - Troubleshooting assistance
  - Maintenance planning
  - End-of-life decisions



Benefits of Capability 10. 2
Integrated Systems Health Management

- **ISHM *enables*:**
  - Mitigation of failures with short time to criticality,
  - Robust execution of critical maneuvers,
  - Self-sufficient, crew-centered operations, and
  - Missions in harsh environments.
- **ISHM *enhances*:**
  - Long duration missions, and
  - Ground operations (e.g., logistics).
- **Additional benefits:**
  - Increased crew and payload safety,
  - Reduced maintenance costs through adoption of condition-based maintenance policies, and
  - Faster turnaround of reusable systems.

State-of-the-Art for Capability 10. 2 Integrated Systems Health Management

- **Design of Health Management Systems:**
  - ISHM functions often designed *after* initial design of the system.
  - Joint Strike Fighter incorporated prognostics requirements into design.
  - Qualitative failure analysis methods commonly used by NASA (FMEA).
  - Quantitative criticality assessment methods favored by DoD (FMECA).
- **Real-Time Systems Health Management:**
  - Limited sensing capability (weight and power concerns).
  - Caution and warning events require human expertise to resolve.
  - Inflexible recovery schemes (typically scripted failover to backups).
  - Model-based diagnosis and recovery demonstrated on two NASA spacecraft, EO-1 and DS-1.
- **Informed Logistics:**
  - Limited built-in troubleshooting aids in components and subsystems.
  - Trends in industry beyond fixed scheduled maintenance (e.g., condition-based and informed maintenance practices).
  - Prognostics becoming a key driver for systems health (notably JSF and Boeing 777).

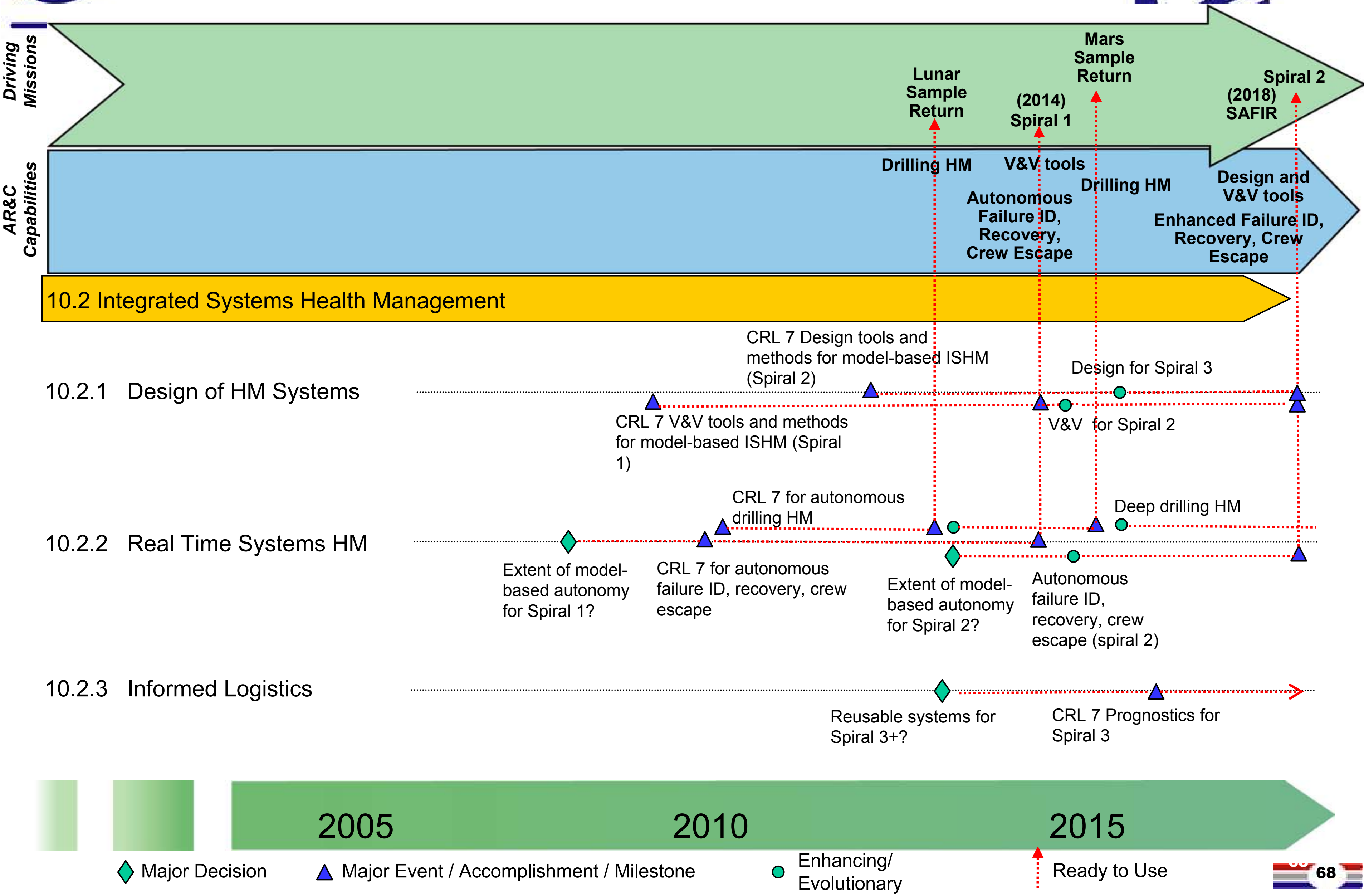
Requirements /Assumptions for Capability 10. 2 Integrated Systems Health Management

- **Crewed Missions**
  - Spiral 1: 2014 Crew Transportation System (CTS) (per ESMD-RQ-0011)
    - *Detection and annunciation of conditions which could result in loss of human life, loss of vehicle, loss of mission, or significantly impact mission capability.*
    - *Autonomous (preferably automated) isolation and recovery from conditions which could result in loss of human life or loss of vehicle.*
    - *Anytime autonomous (preferably automated) abort and crew escape capability.*
    - *Autonomous (preferably automated) rendezvous and docking capability.*
  - Spiral 2: 2015-2020 CTS and extended-duration lunar surface ops
    - *Technology demonstration of ISHM for life support subsystems (anticipated).*
  - Spiral 3: 2020+ Long-duration lunar surface missions
    - *Prognostics and remaining life estimation for critical subsystems and components.*
  - Spiral 4: 2025 Mars transit and vicinity ops
    - *Robust, automated process control and ISHM of all major subsystems on the CTS.*
  - Spiral 5: 2030+ Martian surface habitat and exploration
    - *Above plus ISHM of all major subsystems on the Mars habitat.*

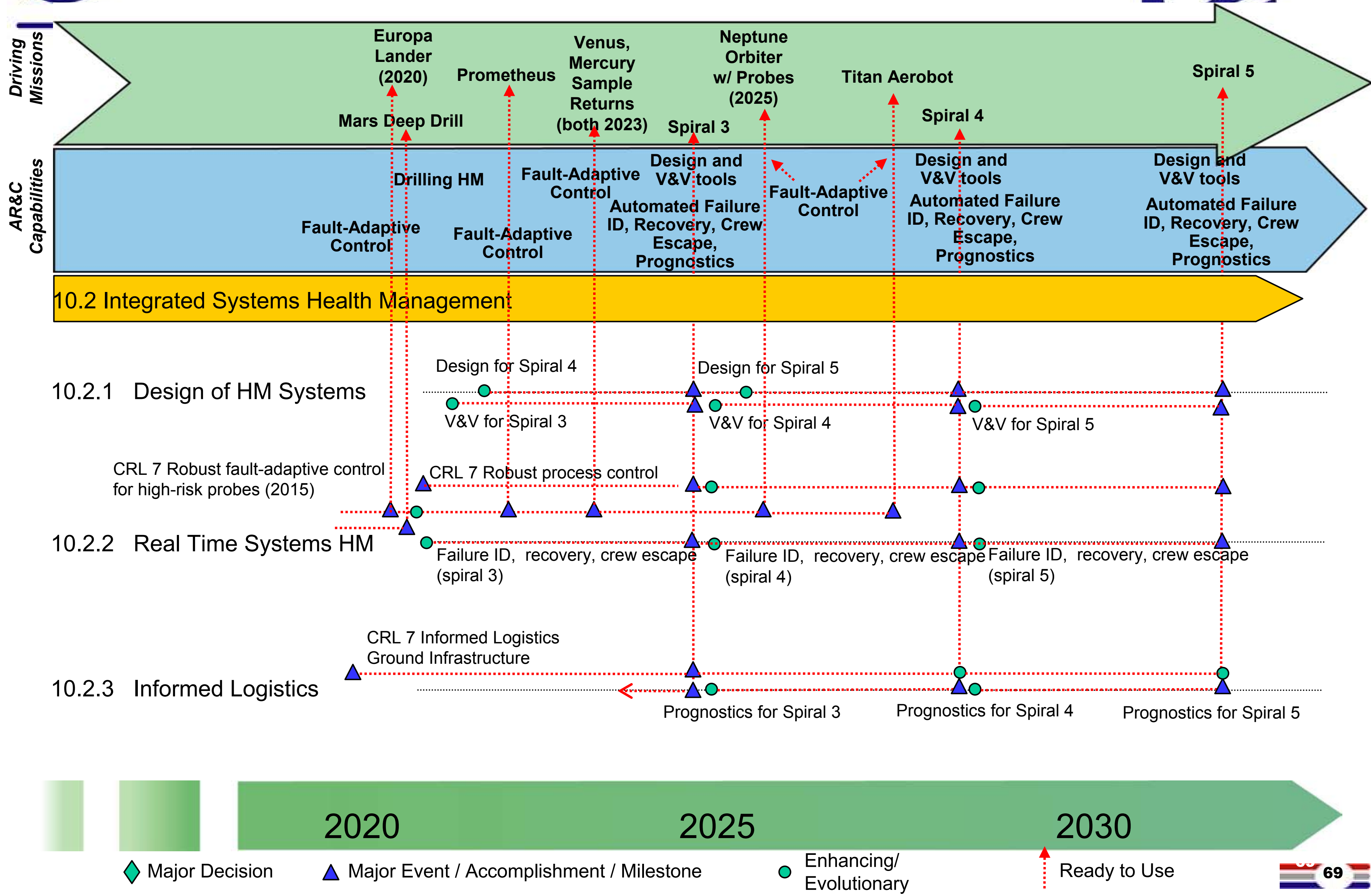
Requirements /Assumptions for Capability 10. 2 Integrated Systems Health Management

- **Robotic Exploration and Science Missions**
  - Robotic Lunar Exploration Program (2009+)
    - *Automated, robust control and recovery of sensor systems during long-duration reconnaissance missions.*
    - *ISHM and recovery for surface ops (ISRU, drilling).*
  - Mars (2011+)
    - *Evolutionary enhancements to increase efficiency and science return, e.g., fault-adaptive control for surface ops (ISRU, drilling, rover mobility).*
  - Solar System (2014+)
    - *Robust, fault-adaptive control for nuclear reactors.*
    - *Robust, fault-adaptive control for autonomous high-risk expeditions (Venus surface, Titan, Europa, etc.).*
  - Observatories (2020+)
    - *Robust coordination of multi-spacecraft constellations (e.g., interferometers).*

Capability Roadmap for Capability 10. 2 Integrated Systems Health Management



Capability Roadmap for Capability 10. 2
Integrated Systems Health Management



Deliverables for Capability 10. 2 Integrated Systems Health Management

- Verification and validation methods for model-based ISHM (some risk)
  - Driver: ESMD Spiral 1
  - CRL 7: 2009+
  - Interfaces: System Engineering Cost/Risk Analysis CRT
- Autonomous failure identification and recovery for CTS (some risk)
  - Driver: ESMD Spiral 1
  - CRL 7: 2009
  - Interfaces: In-Space Transportation CRT; System Engineering Cost/Risk Analysis CRT
- Autonomous anytime abort and crew escape decision capabilities for CTS (some risk)
  - Driver: ESMD Spiral 1
  - CRL 7: 2009
  - Interfaces: In-Space Transportation CRT; System Engineering Cost/Risk Analysis CRT
- ISHM for ISRU, remote drilling, surface mobility, and surface assembly tasks
  - Driver: RLEP, MTP, ESMD Spiral 3
  - CRL 7: 2011
  - Interfaces: Robotic Access to Planetary Surfaces CRT; ISRU CRT

Deliverables for Capability 10. 2 Integrated Systems Health Management

- Tools and methods for codesign of function and ISHM
  - Driver: ESMD Spiral 2
  - CRL 7: 2012
  - Interfaces: System Engineering Cost/Risk Analysis CRT
- Robust autonomous monitoring, control, and recovery for life support and other subsystems (some risk)
  - Driver: ESMD Spiral 2
  - CRL 7: 2012+
  - Interfaces: In-Space Transportation CRT; Human Health and Support Systems CRT
- Robust fault-adaptive control for autonomous probes in harsh environments
  - Driver: SMD Solar System Exploration, Prometheus
  - CRL 7: 2012+
  - Interfaces: High Energy Power & Propulsion CRT
- Prognostics for spacecraft and habitation systems
  - Driver: ESMD Spiral 3
  - CRL 7: 2016+
  - Interfaces: In-Space Transportation CRT; Human Health and Support Systems CRT
- Informed Logistics ground infrastructure
  - Driver: ESMD Spiral 3 (assuming reusable systems)
  - CRL 7: 2020
  - Interfaces: Transformational Spaceport CRT; Exploration Transportation System SRT

Maturity Level – Technologies for Design of Health Management Systems

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Tools/methods for testability	Function and Behavior Modeling Standards	RMPL, TEAMS, FACT Modelica	6-7 3-5 6-7	Established standards No failure models	2009
	Model-based diagnosis and recovery engines	Livingstone, Titan, HyDE, TEAMS, BEAM FACT	5-7 3-5	Certification of engines; V&V methods for models; engine scalability	2009
Function-based failure analysis and design methods	Component function models and failure libraries Function-based reasoning engines	FFDT	3-4	Comprehensive failure datasets	2012
Systems analysis and optimization for ISHM	Sensor placement optimization Figures-of-merit tradeoff analyses Sensor selection	TEAMS DTOOL	6-7 4-5	Cost/benefit trade studies for spacecraft sensor systems Limited to causal diagnosis	2008

Maturity Level – Technologies for Real-Time Systems Health Management

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Distributed sensing	Misc. physical and chemical sensors	Misc.	6-7	Sensor durability and reliability	All missions
	Sensor power and data communications	Wired (multiple architectures) or wireless sensor networks	9 (wired); 5-6 (wireless data); 3-4 (wireless power)	Long-term power for wireless sensors; scalable wired architectures	2008+
Situational awareness tools	Data mining and data fusion tools	Misc. commercial and R&D tools (e.g., BEAM, IMS)	3-7	Visualization of very large data sets; effective data reduction	2018
	Integrated vehicle capability and impact assessment	N/A	2	No current investment	2012
Diagnosis and Recovery	Model-based diagnosis	Titan, Livingstone, HyDE, HME, CME, etc.	5-7	V&V; response time; HW/SW and subsystem interactions; hybrid systems; model acquisition	2009
	Model-based recovery	Titan, Livingstone	4-5	V&V; flight validation; coverage of continuous problem domains	2009
	Rule- or dependency-based diagnosis	SHINE, TEAMS, etc.	9	N/A	Available today
ISHM User Interfaces	Displays for crew and ground	Misc.	4-9	Multimodal interfaces	2009
	Recovery procedures	Computer-based procedure manuals	9 (written); 6 (computer-based)	On-demand procedure generation and verification	2009

Maturity Level – Technologies for Informed Logistics

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Prognostic models	Life remaining estimates	Custom models	3-4	Gold standard datasets and testbeds	2015+
	Short-term predictions of functional degradation and failure	Custom models	3-4	Modeling and analysis of across-subsystem interactions	2009
Physics of failure models	Mechanical systems; propulsion systems; structures; electronics	Custom models	3-4	Understanding and quantifying effects of operational environments	2015+
Maintenance Informatics	Planning and scheduling tools	CMMD (USC/ISI, VU/ISIS and DARPA); Autonomic Logistics (JSF)	4-5	Condition-based and informed maintenance practices	2015
	Distributed logistics databases and data analysis tools	Autonomic Logistics (JSF)	4-5	Conflict between access and data security needs	2015
	Integrated logistics architectures	Boeing Sustainment Data System	6-7		2015

Metrics for Design of Health Management Systems

Metric	Technology / Sub-Capability	Target Value	Need Date
% testability of critical failures on a Critical Items List (CIL)	*Tools/methods for testability; System Analysis and Optimization*	100%	2009
Sensor redundancy (alternative means of confirming the validity of data from a particular sensor)	*System Analysis and Optimization*	>2	2009

Metrics for Real-Time Systems Health Management

Metric	Technology / Sub-Capability	Target Value	Need Date
Ambiguity group size	*Diagnosis*	1 for CIL items; 2 for non-critical items	2009
Latency	*Diagnosis and Recovery*	< 2 plant time constants	2009
Sensitivity (% false negatives)	*Diagnosis and Recovery*	Low-very low (tradeoff on the ROC curve with specificity)	2009
Specificity (% false positives)	*Diagnosis and Recovery*	Low-very low (tradeoff on the ROC curve with sensitivity)	2009
Sensor durability (years)	*Sensors*	Order of magnitude longer than the nominal mission	2015
Sensor power consumption (watt/hours)	*Sensors; Sensor Networks*	Low or none (e.g., energy harvesting)	2015
Caution-warning information access (milliseconds)	*User interfaces*	<500 msec.	2009

Metrics for Informed Logistics

Metric	Technology / Sub-Capability	Target Value	Need Date
Prognostic accuracy (+/- % estimated life remaining)	*Prognostics*	+/- 10% for CIL items	2015
Predictive lead time (seconds-hours)	*Prognostics and Prediction*	At least one order of magnitude longer than plant time constant	2009
Short-term predictive sensitivity (% false negatives for failure predictions)	*Prognostics and Prediction*	Low-very low (tradeoff on the ROC curve with specificity)	2009
Short-term predictive specificity (% false positives for failure predictions)	*Prognostics and Prediction*	Low-very low (tradeoff on the ROC curve with sensitivity)	2009
Turnaround time improvements for reusable assets	*Maintenance*	> 30% time savings	2015

Acronyms for Capability 10. 2 Integrated Systems Health Management

- BEAM: Beacon-Based Exception Analysis for Multimissions (NASA JPL product)
- CIL: Critical Items List
- CME: Compiled Mode Estimation (MIT product)
- CMMD: Coordinated Multisource Maintenance on Demand (USC/ISI, NASA ARC, Vanderbilt University product)
- CRL: Capability Readiness Level
- CRT: Capability Roadmap Team
- DARPA: Defense Advanced Research Projects Agency
- DoD: Department of Defense
- DS-1: Deep Space One
- DTOOL: Diagnosability Analysis Tool (Vanderbilt University product)
- EO-1: Earth Observing One
- ESMD: (NASA) Exploration Systems Mission Directorate
- FFDT: Function-Failure Design Tool
- FMEA: Failure Modes and Effects Analysis
- FMECA: Failure Modes, Effects, and Criticality Analysis
- HME: Hybrid Mode Estimation (MIT product)
- HyDE: Hybrid Diagnosis Engine (NASA ARC product)
- IMS: Inductive Monitoring System (NASA ARC product)
- ISRU: In-Situ Resource Utilization
- JSF: Joint Strike Fighter
- RMPL: Reactive Model-Based Programming Language (MIT product)
- ROC: Receiver Operating Characteristics
- RQ: (NASA ESMD) Requirements Division
- SHINE: Spacecraft Healt Inference Engine (NASA JPL product)
- TEAMS: Testability and Engineering Maintenance System (QSI, Inc. product)
- USC/ISI: University of Southern California/Information Sciences Institute
- VU/ISIS: Vanderbilt University/Institute for Software Integrated Systems
- V&V: Verification and validation

Capability 10.3
Autonomous Vehicle Control

Sub-Team Lead: Michel Ingham, JPL

Sub-Team co-Lead: Lorraine Fesq, JPL

Presenter: Michel Ingham, JPL

Capability 10.3
Autonomous Vehicle Control

Advanced Planning & Integration Office

- Autonomous vehicle control capabilities are necessary to perform critical mission activities where time-sequenced or ground-in-the-loop control is impossible or impractical.
- Specific sub-capabilities include:
  - Autonomous Rendezvous and Docking
  - Autonomous Orbital Insertion, Maintenance and Modification
  - Autonomous Entry Descent and Landing
  - Autonomous Launch Systems
  - Autonomous Control of Unmanned Air Vehicles

NOTE: we adopt the ESMD definition of "autonomy", i.e., activities performed by manned or unmanned vehicles without Earth-based operators in-the-loop. That is, "autonomous" implies "remote closed-loop", but does not necessarily imply "fully-automated".

Benefits of Capability 10.3
Autonomous Vehicle Control

- **Autonomous Rendezvous and Docking:**
  - Mating of separate spacecraft (manned or unmanned) is *enabled* in remote orbits (e.g., at Mars, Lagrange points, in deep space).
  - Return to Earth of samples collected on remote planetary surfaces is *enabled* (assuming no direct-to-Earth transfer of sample from surface).
  - Human safety and operational efficiency is *enhanced* by allowing autonomous (but human-supervised) mating of separate spacecraft in Earth or lunar orbit.
- **Autonomous Orbital Insertion, Maintenance and Modification:**
  - Robust delivery of manned and unmanned spacecraft into orbit around other bodies is *enabled* (for the purposes of remote sensing and/or eventual delivery to the surface).
  - Delivery of manned and unmanned spacecraft into orbit around the Earth or the Moon is *enhanced* through autonomous (but human-supervised) control of the insertion maneuver.
  - Operations are *enhanced* (and operations costs are reduced) through autonomous orbit maintenance and modification.
- **Autonomous Entry, Descent and Landing:**
  - Robust delivery of robotic vehicles and cargo from orbital trajectories down to remote planetary surfaces is *enabled*.
  - Safe transportation of humans from orbital trajectories down to remote planetary surfaces is *enabled* by high-precision autonomous entry, descent and landing.
  - Robust/safe transportation of robotic vehicles, cargo and humans from Earth orbit back to Earth, and from lunar orbit down to the lunar surface, is *enhanced*.
- **Autonomous Launch Systems:**
  - Safe return of humans and samples from remote planetary surfaces back to Earth is *enabled*.
  - Safe return of humans and samples from the lunar surface back to Earth is *enhanced*, by reducing the complexity of, or even the need for, ground-in-the-loop involvement in launches from the lunar surface.
- **Autonomous Control of Unmanned Air Vehicles:**
  - Control of agile vehicles with aerodynamics and highly dynamic flight paths is *enabled.*
  - Control of aerobot vehicles in extreme environments is *enabled*.

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.1: Autonomous Rendezvous and Docking

- Significant ground demonstrations and simulations
- On-orbit, unmanned:
  - Visual acquisition and tracking (AFRL XSS-10)
  - Proximity operations, manipulator-assisted docking, relative GPS (Japanese NASDA ETS-VII RV&D technology demonstration mission)
  - Autonomous RV&D with ground planning (Progress re-supply of ISS)
  - Under development: Autonomous proximity operations, collision avoidance (NASA DART, ~5m), docking (DARPA Orbital Express), onboard planning & resource management (AFRL XSS-11), identification and capture of non-participatory/tumbling s/c (Hubble Robotic Servicing and Deorbit Mission)
- On-orbit, manned:
  - Manned control for final docking (Gemini, Apollo)
  - Significant ground supervision (Soyuz/Progress/Shuttle with MIR/ISS)
  - Shuttle payload operations (Hubble Space Telescope, SPAS, etc)
- Other related or relevant capabilities:
  - Optical-based autonav (DS-1, Deep Impact's Impactor spacecraft)

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.2: Autonomous Orbital Insertion, Maintenance and Modification

- Orbital insertion demonstrated with unmanned vehicles:
  - Onboard GNC computations based on delta-energy (not delta-V) for optimal arc trajectory burn; event-driven, statechart-based fault protection with burn restart capability (Cassini at Saturn)
  - Small-body orbit insertion (NEAR at Asteroid Eros)
  - State-of-the-art in unmanned orbital insertion control has not advanced significantly since early lunar, Mars & Venus missions
- Lunar orbit insertion demonstrated with manned vehicles in Apollo Program
- Aerobraking for orbit modification of unmanned spacecraft with ground-in-the-loop (Magellan at Venus, Mars Odyssey, Mars Global Surveyor, ESA Mars Express)
- Aerocapture demonstrated in ground simulations (LaRC, JSC/Draper, NASA ST-9 concept study)

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

Sub-capability 10.3.3: Autonomous Entry, Descent and Landing

- Approach navigation: ground-in-the-loop navigation updates (MER)
- Entry: aeroentry control from Mars orbit (Viking 1 & 2); direct entry control (Pioneer 2 Multiprobes at Venus, Mars Pathfinder, MER); guided entry control (Apollo at Earth); X-38 Crew Return Vehicle demonstrator autonomous landing tests
- Parachute descent: unguided for all space applications to date; Earth-based guided parachute systems (Sherpa, Precision Air Drop System, etc)
- Terminal descent: powered, guided gravity turn maneuver control (Viking 1 & 2 at Mars); feature tracking, lateral velocity estimation based on descent images (MER DIMES); pilot-in-the-loop hazard avoidance (Apollo at Moon)
- System capabilities: precision landing (MER landing ellipse ~80km x 25km); event-driven sequencing (MER, Huygens, etc)

Summary State-of-the-Art for Capability 10.3
Autonomous Vehicle Control

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Sub-capability 10.3.4: Autonomous Launch Systems

- Launches currently require significant ground-in-the-loop preparation & process control
- EELV lower-cost, simplified launch operations (Boeing Delta IV, Lockheed-Martin Atlas V)
- Astronaut-in-the-loop launch sequencing (Apollo lunar ascent module)
- Ballistic missiles, ICBMs (e.g., submarine-launched Trident missile)
- "Fire and forget" autonomous missile guidance
- Autonomous launch preparation, planning, initiation, and abort determination not yet demonstrated

Summary State-of-the-Art for Capability 10.3 Autonomous Vehicle Control

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Sub-capability 10.3.5: Autonomous Control of Unmanned Air Vehicles

- Remotely piloted with auto-pilot for nominal flight paths: Predator (General Atomics Aero. Systems), Global Hawk (Northrop-Grumman)
- Ground-based coordination of multiple UAVs: J-UCAS (Boeing X-45 & Northrop-Grumman X-47), other UCAV programs
- NASA- & DARPA-funded aeronautics research:
  - High Altitude Long Endurance aircraft (DFRC remotely-piloted Helios)
  - Reconfigurable flight controls research (accommodation of control surface failures – DFRC Intelligent Flight Control System)
  - Adaptive/morphing wing control research (DFRC Active Aeroelastic Wing, DARPA Morphing Aircraft Structures program)
  - Earth-based flight demonstrations of single and multiple UAV/rotorcraft autonomy, micro UAVs (DFRC, Berkeley, MIT, Stanford, etc)
- Simulations & Earth-based demos for Mars Airplane (ARES, KittyHawk, MATADOR, MAGE, etc)
- Aerobot autonomy research (JPL): vehicle management system for failure detection/recovery, GPS-assisted horizontal flight control, Image-based vehicle motion estimation

Requirements/Assumptions for Capability 10.3
Autonomous Vehicle Control

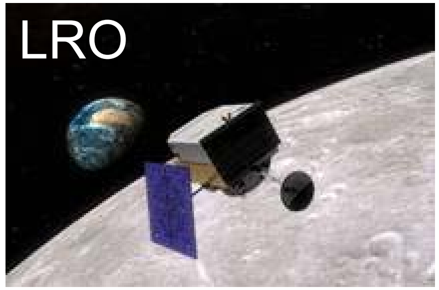
Manned Missions

- **Spiral 1: 2008-2015**
  - Routine Earth entry, descent & landing
- **Spiral 2: 2015-2020**
  - Routine orbital insertion of manned & unmanned lunar orbiting spacecraft
  - High-precision delivery of manned & unmanned lunar landers
  - Ascent from lunar surface, rendezvous & docking in lunar orbit of manned & unmanned spacecraft
  - Routine delivery of robotic precursor Mars orbiters and landers
- **Spiral 3: 2020-2025**
  - High-precision delivery of massive manned & unmanned lunar landers
- **Spiral 4: 2025+**
  - Mars transit and orbital insertion of manned spacecraft
- **Spiral 5: 2030+**
  - Safe pinpoint delivery of manned & unmanned Mars landers
  - Ascent from Mars surface, rendezvous & docking in Mars orbit of manned & unmanned spacecraft

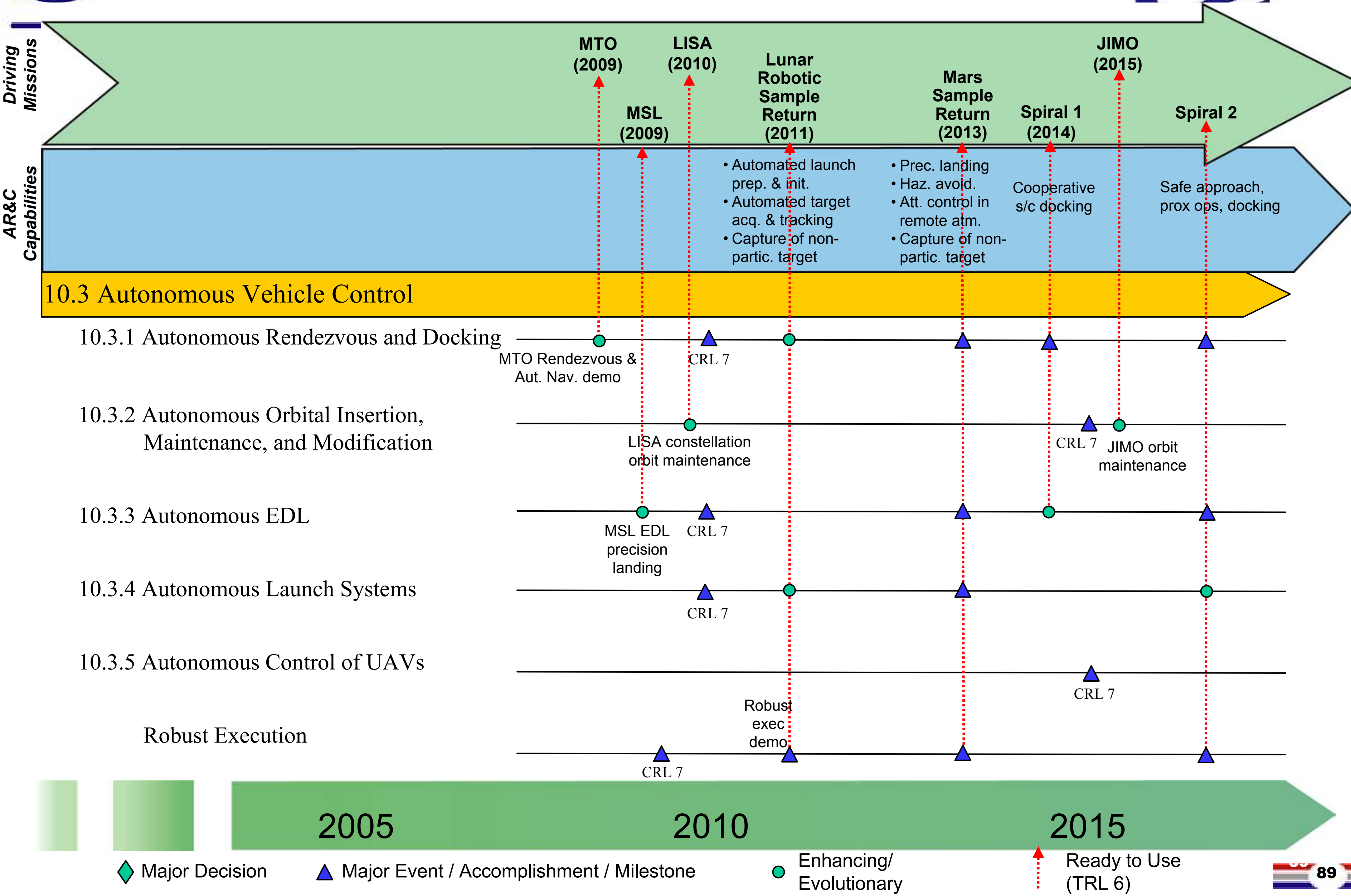
Requirements/Assumptions for Capability 10.3
Autonomous Vehicle Control

Un-manned Missions

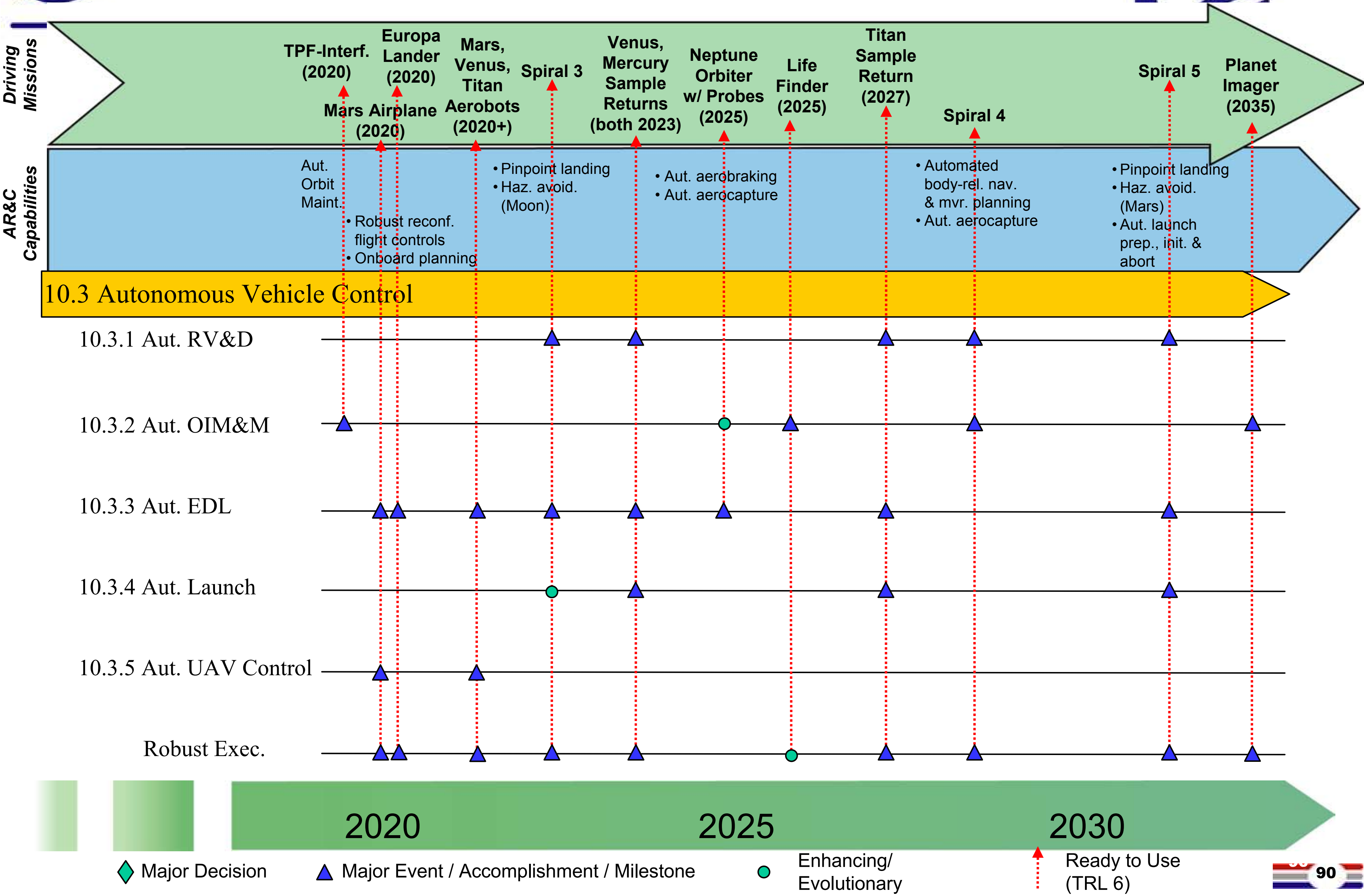
- Orbital Express advanced technology demonstration 2006
- Hubble Robotic Vehicle Deorbit Module ~2008
- Lunar Reconnaissance Orbiter (LRO) 2008
- HALE Remotely Operated Aircraft in the National Air Space 2008
- Mars Science Lab 2009 or 2011
- Lunar robotic sample return ~2011
- Mars Sample Return (MSR) ~2013
- Jupiter Icy Moons Orbiter ~2015
- Terrestrial Planet Finder Interferometer ~2020
- Mars airplane ~2020
- Europa astrobiology lander ~2020
- Mars, Venus, Titan aerobots ~2020+
- Mercury sample return ~2023
- Venus sample return ~2023
- Neptune orbiter with probes ~2025
- Titan sample return ~2027



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Deliverables for Capability 10.3
Autonomous Vehicle Control

- **Autonomous Rendezvous and Docking: automated target acquisition, target orbit/trajectory determination, target approach, safe proximity operations, docking of cooperative spacecraft, capture of non-participating targets (Moderate risk)**
  - Drivers: Mars Sample Return, ~2013; Spiral 1, CEV docking, ~2014; Spiral 2, Crewed Lunar surface missions, ~2015+
  - CRL 7 date: 2010
  - Interfaces: 9: HES&M, 10.8: AR&C/CS, 12: SI&S, 14: AMSA
- **Autonomous Orbital Insertion, Maintenance and Modification: automated body-relative navigation & maneuver planning, aerobraking & aerocapture (Significant risk for aerocapture)**
  - Drivers: Terrestrial Planet Finder, ~2020; Spiral 4, Crewed Mars orbital missions, ~2025
  - CRL 7 date: 2015
  - Interfaces: 10.8: AR&C/CS, 14: AMSA
- **Autonomous Entry, Descent and Landing: pinpoint landing with <100m (3 sigma) accuracy, hazard avoidance (Significant risk)**
  - Drivers: Mars Sample Return, ~2013; Spiral 2, Crewed Lunar surface missions, ~2015+; Spiral 3, Long Duration Crewed Lunar surface missions, ~2020+; Spiral 5+, Crewed Mars surface missions, 2030+
  - CRL 7 date: 2010
  - Interfaces: 6.3: RAPS/EDL, 7: HPLS, 10.8: AR&C/CS, 12: SI&S, 14: AMSA

Deliverables for Capability 10.3
Autonomous Vehicle Control

- **Autonomous Launch Systems: automated launch preparation (fueling, ignition, etc), initiation and abort, attitude control in remote planetary atmosphere (Moderate risk)**
  - Drivers: Mars Sample Return, ~2013; Spiral 5+, Crewed Mars surface missions, 2030+
  - CRL 7 date: 2010
  - Interfaces: 13: ISRU, 2: HEPP, 10.8: AR&C/CS, 14: AMSA
- **Autonomous Control of UAVs: robust reconfigurable flight controls, onboard mission planning/replanning, coordination of multiple UAVs, adaptive/morphing wing control**
  - Drivers: HALE ROA in the NAS, 2008; Mars airplane, ~2020; Mars/Venus/Titan aerobots, ~2020+
  - CRL 7 date: 2015
  - Interfaces: 6.4: RAPS/AS, 10.8: AR&C/CS, 14: AMSA
- **Cross-cutting capability: robust execution**
  - Drivers: Lunar robotic sample return, 2011; all other complex science & exploration missions
  - CRL 7 date: 2009
  - Interfaces: 10.2: AR&C/ISHM, 10.4: AR&C/APC&EA, 10.8: AR&C/CS, 15: SECRA

Breakthrough Capabilities for 10.3 Autonomous Vehicle Control

Safe, autonomous, pinpoint landing

- To enable a sustained exploration campaign, teams of humans, robots and their supplies must be delivered with tremendously high precision and reliability to the surface of the Moon, Mars, and other remote planetary bodies. The current state-of-the-art atmospheric entry, descent and landing system (e.g., MER) provides sub-100km landing ellipse with a "rough" airbag landing. A capability breakthrough is needed in order to achieve two orders of magnitude improvement in landing precision, while improving reliability to meet safety-critical standards. This will require a return to the propulsive terminal descent control systems of the types used for the Apollo lunar landings and the Viking Mars landers, coupled with significant advanced autonomy technology to assure the necessary reliability and robustness for safe human exploration. In particular, this capability will require advances in robust execution, autonomous GN&C algorithms, sensor fusion, machine vision, and feature recognition/classification.

Autonomous rendezvous and orbital maintenance

- Launch mass/cost constraints will drive the development of breakthrough robotic in-orbit maintenance and assembly capabilities, including autonomous vehicle control for rendezvous and docking. These capabilities will require significant technological advances including robust execution, autonomous GN&C algorithms, and maneuver planning.
- Similar technological advancements will enable successful and affordable operation of future space-based observatories and remote planetary networks consisting of multiple coordinated spacecraft. A breakthrough in autonomous control will be required in order to operate such systems with reasonably-sized ground operations teams and to address the complex coordination and resource management challenges associated with such missions.

Maturity Level – Capability 10.3 Autonomous Vehicle Control

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Autonomous Rendezvous and Docking	• Automated target acquisition & tracking algorithms, • GNC algorithms for safe approach, proximity ops, and capture of cooperative and non-participating spacecraft	4	6-7	MSR, Crewed Lunar Surface Missions	~2010
Autonomous Orbital Insertion, Maintenance & Modification	• Automated body-relative nav & maneuver planning, • Algorithms for automated aerobraking & aerocapture • Libration halo orbit maintenance	3-4	7	Crewed Mars Orbital Missions, Large Space Telescopes	~2015
Autonomous EDL	• Nav algorithms for pinpoint landing, • Guided entry control algorithms, • Optimal-fuel guidance algorithms, • Feature tracking, hazard recognition & avoidance algorithms	3-4 (100m accuracy, 1m haz)	6-7	MSR, Crewed Mars Surface Missions	~2010

Maturity Level – Capability 10.3 Autonomous Vehicle Control

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Autonomous Launch Systems	• Automated launch preparation (fueling, ignition, etc) & initiation, • Attitude control in remote planetary atmosphere	3	6	MSR	~2010
Autonomous Control of UAVs	• Robust reconfigurable flight control algorithms, • Onboard mission activity and path planning, • Algorithms for coordination of multiple UAVs, • Adaptive/morphing wing control algorithms	3-4	6	Mars Airplane	~2015
All	Robust execution	3-4	6	Lunar Robotic Sample Return	~2009

Maturity Level – Technologies for Capability 10.3
Autonomous Vehicle Control

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Robust execution software	State/model-based execution with integral fault management, procedural & rule-based execution	MDS (JPL), RMPL (MIT), TDL (CMU), ESL (JPL/ARC), SCL (ICS)	4-5 7 8	Large-scale system demo	2009
Automated target acquisition & tracking algorithms, feature tracking algorithms	Vision-based target/feature recognition, target/feature tracking	Extensions to Deep Impact impactor targeting & guidance, machine vision research	6	Demo in space application	2010
GNC algorithms for safe approach, proximity ops, and capture of cooperative and non-participating spacecraft	Manipulator-assisted docking, Trajectory planning	ETS-VII, SSRMS Kirk-MILP (MIT, etc), D* (CMU etc), RRT (U of I), RL (Stanford, etc.)	6 5	Fully-automated end-to-end demo in space application	2010

Maturity Level – Technologies for Capability 10.3 Autonomous Vehicle Control

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Automated body-relative nav & maneuver planning		Evolution of DS-1 Autonav, Deep Impact impactor guidance	4	Autonav-maneuver control loop closure	2009
Algorithms for automated aerobraking & aerocapture		Automation of current aerobraking ops process, ST-9 aerocapture study	3	Robust fault protection (deflection maneuver execution)	2015
Navigation algorithms for pinpoint landing	Relative GPS-based nav	Evolution of MSL EDL GN&C	4	Sufficient accuracy & precision	2010
Guided entry control algorithms, optimal-fuel guidance algorithms		Modified Apollo Guided Entry, Evolution of MSL Entry GN&C	5	Algorithm speed (computation speed)	2010
Hazard recognition & avoidance algorithms	Vision-based target/feature recognition, classification	Modified MER DIMES algorithm, machine vision research	2	Hazard recognition from descent images	2010

Maturity Level – Technologies for Capability 10.3 Autonomous Vehicle Control

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Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Automated launch preparation (fueling, ignition, etc) & initiation		Modified ELV, missile launch process control	3	Adequate observability into process, sensor fusion	2010
Attitude control in remote planetary atmosphere		Modified ELV, missile control systems	3	Atmospheric model fidelity	2010
Robust reconfigurable flight controls		Research for X-33, X-36	4	Flight demo	2018
Onboard mission planning/replanning	Deliberative goal-based planning	CASPER, MDS (JPL), PLASMA (ARC), Kirk (MIT)	7-8	Large-scale system demo, algorithm speed	2018
Coordination of multiple UAVs	Distributed planning	Kirk-MILP (MIT), Maneuver automata (U of I, MIT, Stanford)	3	Large-scale system demo, algorithm speed	2018

Metrics for Capability 10.3
Autonomous Vehicle Control

Advanced Planning & Integration Office

Metric	Technology / Sub-Capability	Target Value Fig of Merit	Need Date
Time to react to events and faults	Robust execution, Onboard mission replanning (for UAVs)	O(microsecs) for execution, O(seconds) for replanning	2011 for execution, 2020 for replanning
Cost of critical sequence development & validation	Autonomous RV&D, OI, EDL, Launch	Factor of 10 improvement	2015
Error in target trajectory estimate	Autonomous Rendezvous & Docking	3-sigma < X meters	2013
Likelihood of successful docking	Autonomous Rendezvous & Docking	99.99%	2015
Error in achieved orbit	Autonomous Orbital Insertion	3-sigma error < X for each orbital param.	2015
Cost of operations	Autonomous Orbital Maintenance, Autonomous Control of UAVs	Factor of 10 improvement	2015
Pinpoint landing accuracy	Autonomous EDL	3-sigma error < 100m	2015
Likelihood of hazard-free touchdown	Autonomous EDL	99.99%	2030
Mean error in launch trajectory vs. intended profile	Autonomous Launch	3-sigma < X meters	2013

Capability 10.4 Autonomous Process Control and Embedded Autonomy

Presenter: James Crawford, NASA/ARC

Team Lead: James Crawford, NASA/ARC

Capability 10.4 Process Control and Embedded Autonomy

- **Autonomous process control encompasses the automation of mission-critical systems that, in terrestrial analog applications, require continuous human monitoring and intervention.**

- **Example applications include:**
  - **Process control for closed-loop life support**
  - **Process control for ISRU**
  - **Process control for nuclear reactors**
  - **Process control for deep drilling**
  - **System-level automation and intelligence for power, propulsion, thermal, communication, GN&C (guidance, navigation, and control), C&DH (command and data handling), and other systems**

Benefits of 10.4 Process Control and Embedded Autonomy

- Increased system robustness
- Rapid reaction to off-nominal events
- Increased crew autonomy (for manned missions)
- Decreased operations costs
- Enables complex remote operations (e.g., closed-loop life support, ISRU, Brayton-cycle nuclear reactors, deep drilling, etc.)
- Reduction in (material) buffers (and thus mass) through more effective control

Current State-of-the-Art for 10.4 Process Control and Embedded Autonomy

- The Space Station is manually controlled from earth. Ground controllers issue roughly 500,000 commands per year.
  - Flight crew can, at least in theory, handle emergencies without ground support (for some period of time)
- For unmanned missions, some critical sequences (e.g., entry, descent, and landing) are automated but most systems are monitored and controlled from earth
  - Outside of critical sequences, the state of the art is for the craft to go into a quiescent “safe” mode
- Limited technology demonstrations (e.g., DS1 and EO1) of onboard autonomy have been performed.
- No full demonstrations of automated process control for closed-loop life support, nuclear reactors, ISRU, or other systems.

Requirements /Assumptions for Capability 10.4 Process Control and Embedded Autonomy

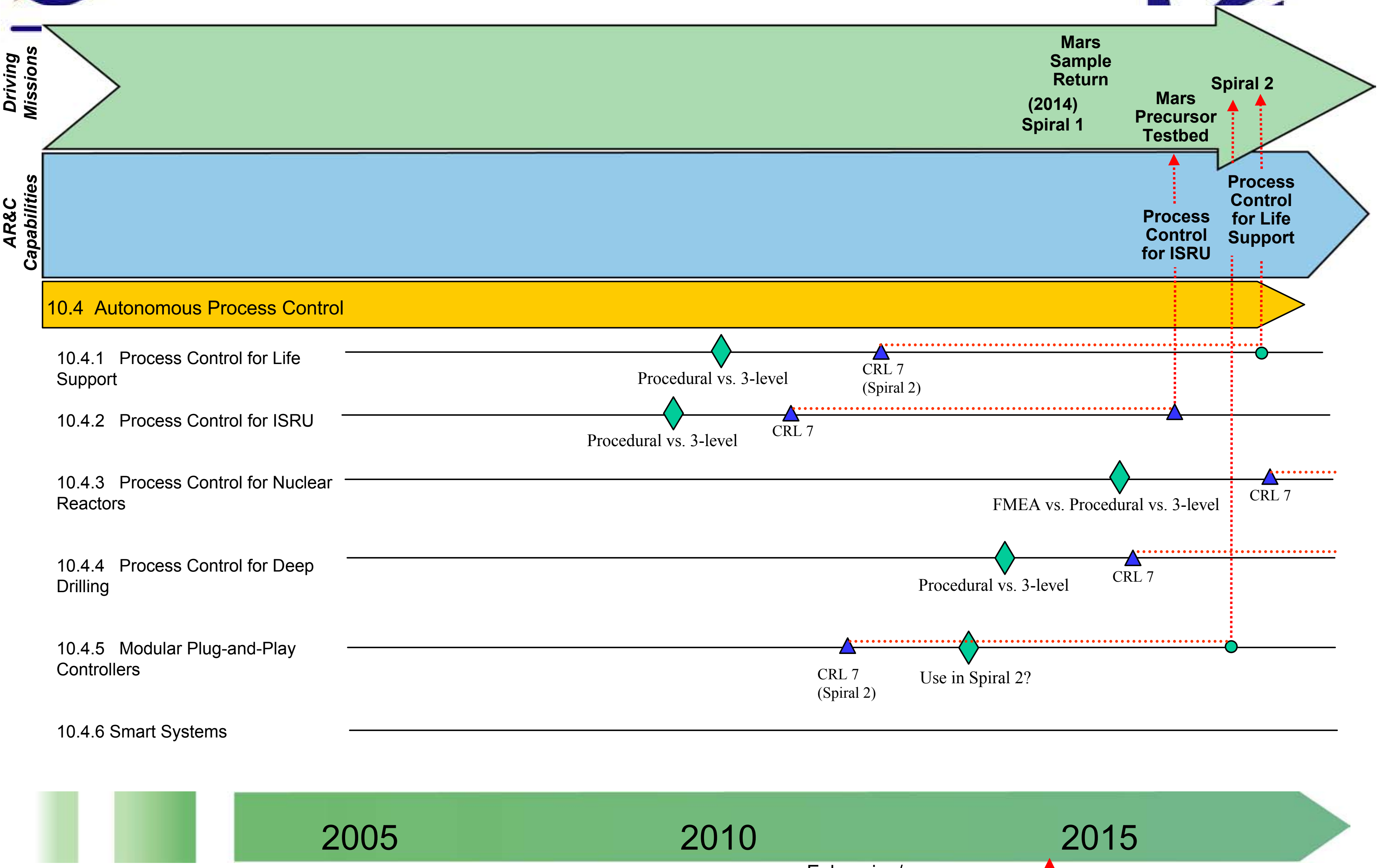
Manned Missions

- Spiral 1: 2014 CEV LEO
- Spiral 2: 2015-2020 CEV LLO and EVA lunar surface ops
  - Technology demonstration of process control for life support
- Spiral 3: 2020 Lunar surface habitat
  - Automated process control of all major systems (CEV, habitat, and vehicles) during nominal operations (under Mars latency). Process control for nuclear reactors?
- Spiral 4: 2025 Mars transit and vicinity ops
  - Automated process control of all major systems during nominal operations and fault recovery, ground as advisor
- Spiral 5: 2030+ Martian surface habitat and exploration
  - Above plus process control for ISRU and surface vehicles

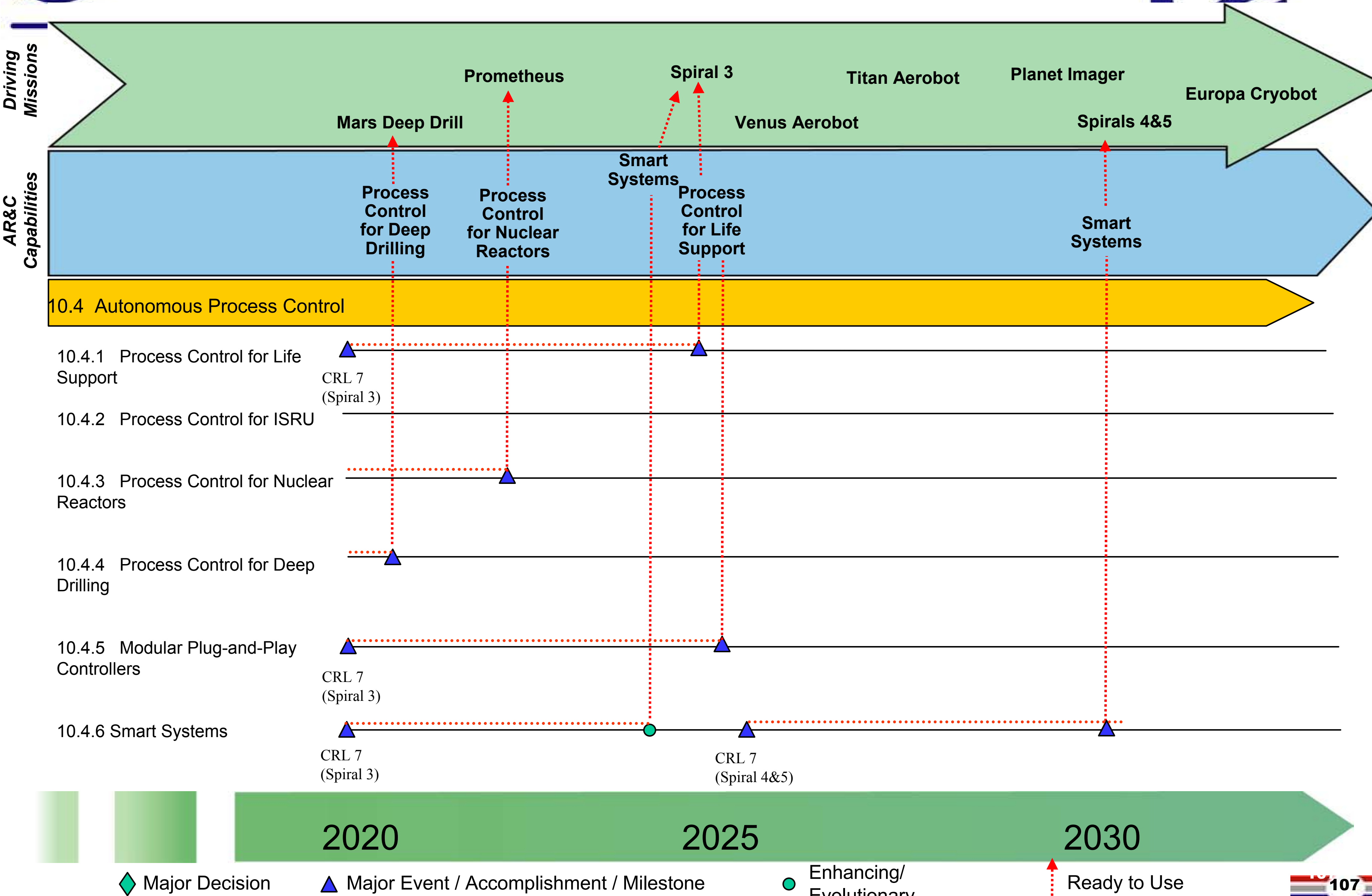
Requirements /Assumptions for Capability 10.4
Process Control and Embedded Autonomy

- Un-manned Missions
  - Mars
    - Process control for ISRU
    - Process control for drilling and sample handling
    - Process control for complex in-situ scientific analysis
  - Planetary
    - Process control for nuclear reactors
    - Process control for complex in-situ scientific analysis
    - Autonomous systems for cases where communications is limited (Venus surface, Titan, Europa, etc.)
  - Observatories
    - Control for interferometry
  - Lunar
    - Process control for ISRU
    - Process control for drilling
    - Process control for in-situ science,
    - Process control for nuclear reactors?

Autonomous Process Control: Capability Roadmap



Autonomous Process Control: Capability Roadmap



Deliverables for Capability 10.4 Process Control and Embedded Autonomy

- Process control for life support: management of material buffers, automation of routine operations, management of system consisting of multiple chemical and biological life support devices, monitoring and fault recovery (joint with ISHM) (Some risk for fault recovery)
  - Driver: ESMD spirals 2-3
  - CRL 7: 2015
  - Interfaces: human environment capability team
- Process control for ISRU: management of flows and processes, automation of routine operations, monitoring, and fault recovery (joint with ISHM) (Some risk)
  - Driver: Mars and lunar precursor missions
  - CRL 7: 2011
  - Interfaces: ISRU capability team
- Process control for nuclear reactors: management of flows and processes, automation of routine operations, monitoring and fault recovery (joint with ISHM) (Moderate risk)
  - Driver: Prometheus reactor deployment
  - CRL 7: 2015 (estimate)
  - Interfaces: HEPP (2.0), "Nuclear Systems" strategic roadmap
- Process control for drilling: management of drilling process, automation of routine operations, monitoring and fault recovery (joint with ISHM) (Some risk)
  - Driver: Mars and lunar programs
  - TRL 6: 10M in 2013, 100M in 2025
  - Interfaces: HESM (9.0), RAPS (6.0)

Maturity Level – Capabilities for 10.4. Process Control

Sub-Capability	Technologies	Current CRL	Required CRL	Driver	Need Date
Process Control for Life Support	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Multi-variant optimal control (including off-nominal) • Model estimation	2	6	ESMD spirals 2-3	2015
Process Control for In-Situ Resource Utilization	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Multi-variant optimal control (including off-nominal) • Model estimation	2	6	Mars and Lunar precursors	2011
Process Control for Nuclear Reactors	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Model estimation	1-2	6	Prometheus	2015?

Maturity Level – Capabilities for 10.4. Process Control

Sub-Capability	Technologies	Current CRL	Required CRL	Driver	Need Date
Process Control for Deep Drilling	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Model estimation	5 (2M) 1 (10M+)	6	Mars and Lunar programs	2013 (to 10M) 2025 (to 100M+)
Modular Plug-and-Play Controllers	• Process-control software architectures • Monitoring and state estimation • Multi-variant optimal control (including off-nominal) • Model estimation	2-3	6	ESMD spirals 1-2	2009
Smart systems (power, thermal, comm., C&DH, etc.)	• Process-control software architectures • Monitoring and state estimation • Robust execution • Planning and replanning (including fault recovery) • Multi-variant optimal control (including off-nominal) • Model estimation	1-5 (varies by sub-system)	6	ESMD spirals 1-2 Mars and SSE programs (enhancing)	2009 – 2020 (varies by sub-system)

Maturity Level – Technologies for 10.4. Process Control

Technology	Components	Candidates	Current TRL*	Key Gaps	Need Date
Process-control architectures		• Three-level architectures • Procedural systems	2-6	• Validation techniques for complex systems	2011 - 2025
Monitoring and state estimation		• Model-based monitoring • Statistical analysis • Expert systems	2-7	• Elimination of false-positives in complex hybrid systems	2011-2025
Robust execution		• Model-based execution • Procedural execution	2-9	• Recovery from unexpected anomalies • Validation	2011-2025
Planning and replanning		• Generative planning • Local repair	3-9	• Mixed-initiative planning • Validation of onboard planners	2011-2025
Multi-variant optimal control			2-6		2011-2025
Model estimation		• Inductive learning	2-4	• Validation	2011-2025

* For many of these technologies the TRL level varies widely by application domain. For example, robust execution for shallow drilling (~2M) is TRL 6 because demonstrations have been done in relevant environments. However, for process control of Nuclear Reactors the same technology is TRL 2 because demonstrations have not yet been attempted.

Metrics for 10.4

Metric	Technology / Sub-Capability	Target Value	Need Date
Flight crew hours per week required for process control of life support (assuming Mars-like communication with ground)	Process Control of Life Support	5	2015
Interventions per week by ground team to correct anomalies in ISRU plant	Process Control of ISRU	1 (none mission critical)	2011
Interventions per week by ground team to correct anomalies in Nuclear Reactor	Process Control for Nuclear Reactor	1 (none mission critical)	2010
Depth of autonomous drilling in a variety or rock types	Process Control for Drilling	10M 100M	2013 2025
Number of spacecraft systems that can be controlled by standard controller	Modular Plug-and-Play Controller	Most systems	2015
Flight crew hours per week required for control of major flight systems (assuming Mars-like communication with ground)	“Smart” systems	Less than 1 hour for most systems	2015

Overview

- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- **Robotics (Paul Schenker)**
  - **Robotics for Solar System Exploration**
  - **Robotics for Lunar and Planetary Habitation**
  - **Robotics for In-Space Operations**
- Computing Systems (Mike Lowry)
- Conclusion

Introduction to sub-capabilities 10.5-10.7

Robotics

Presenter: Paul Schenker, JPL

Robotic and Human-Robotic Systems

Exploration Systems:

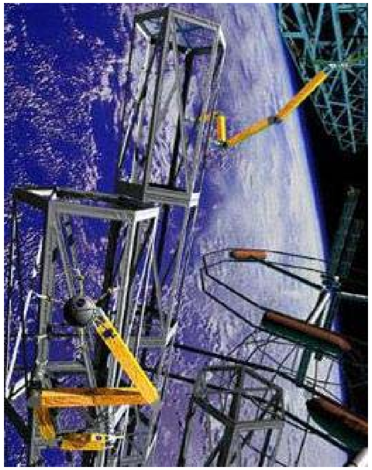
- **Expeditions on-or-near solar system bodies, including sustained robotic access to very rugged and adverse environments (lunar, planetary, and related small bodies). Robotic capabilities will evolve to human-robotic.**
- **In-space assembly, inspection, and maintenance of instruments or facilities, with extension to surface habitat development and servicing**

Required Capabilities:

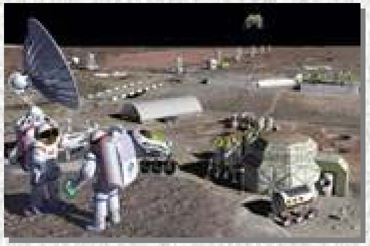
- **Dexterous human/robotic work systems; agile aerial, surface, and sub-surface autonomous explorers**

  … "*go where we currently can't—survive—do breakthrough science*"
- **Advanced mobility, manipulation, and on-board intelligence technologies, enabling efficient human/robotic task inter-actions and multi-robot cooperation for larger tasks**

  … "*autonomy—an integrative bridge for large scale systems*"

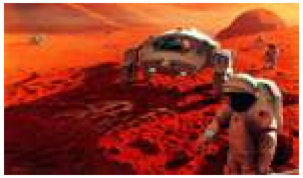


Diverse Mission Applications



Robotics Capability Breakdown

- **Robotics for Solar System Exploration (CRM 10.5)**



  - Autonomous mobility and access (surface, aerial, and sub-surface)
  - Autonomous instrument deployment (from landed and mobile platforms)
  - On-board autonomous science
  - Human-robotic field science (robotic scouts, assistants, telepresence, multi-robot cooperation)
  - Human-robot interaction (remote and on-site C^4I for mission planning, operations, monitoring)

- **Robotics for Lunar and Planetary Habitation (CRM 10.6)**

  - Site development (survey, excavation, initial construction, resource deployments)
  - Site maintenance (inspection, repair, assembly, materials transport & warehousing)
  - In situ resource production (robotic support to extraction, transport, manufacturing)
  - Field logistics and operations support (materials & equipment transport & warehousing)
  - Human-robot interaction (H/R task allocation, teleoperation, remote supervisory control, etc.

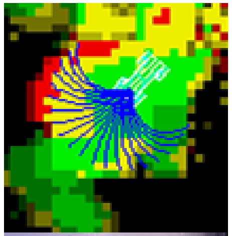
- **Robotics for In Space Operations (CRM 10.7)**

  - Assembly (manipulation, preparation, connecting, self-deployment)
  - Inspection (structural, access, component/system failure detection)
  - Maintenance (staging, H/R interface rated manipulation, grapple dexterity)
  - Human-robot interaction (multi-agent teams, communication of intent, time delay compensation)

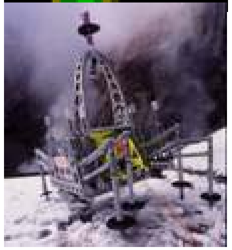
Science Exploration Examples & Requirements

(Reference: NExT Study on Space Robotic Capabilities)

Surface Mobility

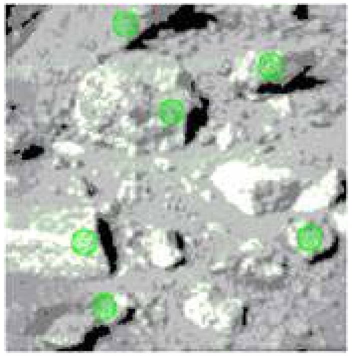


(Mobile Autonomy)
Terrain assessment, path planning, visual servoing



(Mobility Mechanization)
Extreme terrain access, energy efficiency

Science Perception, Planning & Execution



On-board and ground tools; data analysis, target selection, operations planning and execution

Human-Robot EVA Interactions

Tele-operation and human supervision of robotic explorers

Robotic work crews

Instrument Placement and Sample Manipulation

Position sensors, collect and process samples

May include sample containerization and return-rendezvous phases

In-Space Operation Examples & Requirements

(Reference: NExT Study on Space Robotic Capabilities)

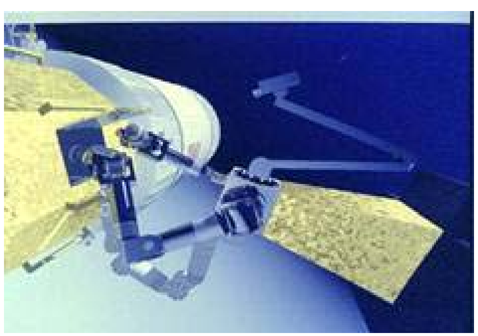
Assembly

Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

Inspection

Visual inspection of exterior spacecraft surfaces; path planning and coverage planning; automated anomaly detection

Maintenance



Change-out of components; accessing obstructed components; robotic refueling

Human EVA Interaction

Monitoring and documenting EVA tasks; preparing a worksite; interacting with astronauts; human-robot teaming

Mission Enablement & System Trends

(Space operations will grow in scale—robotic systems will grow in complexity)

Advanced Planning & Integration Office

SOLAR SYSTEM EXPLORATION

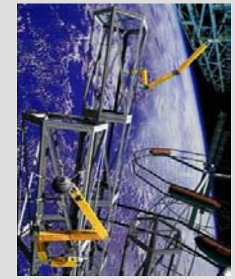
- Explore large aerial, surface, & sub-surface regions
- Precision instrument placement & deployment
- In-situ dig, drill, scoop, manipulate, and process
- Sustained autonomous operations & resource mgmt
- Cooperative robotic & human/robot task execution

ASSEMBLY, INSPECTION, MAINTENANCE

- Fast, structure-attached crawling
- Handling of small parts, flexible films
- Deploy & adjust delicate optical elements
- Heavy-duty work from unstable bases
- Material acquisition, transport, deployment

Robonaut

In-Space Assembly



Robot Work Crew

Titan Aerobot

Mars Drill

AERcam

SSRMS (2000)

MER (2003)

SRMS (1985)

SOJOURNER (1997)

Flight Operational Systems

Mobile / Manipulative Degrees of Freedom: 10, 100

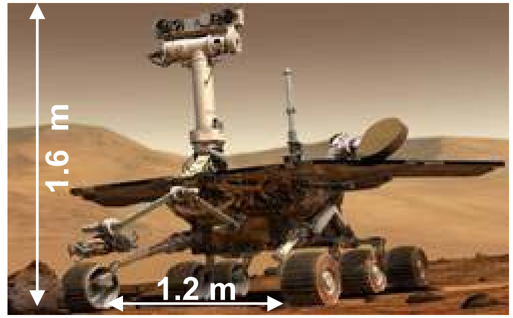
Robot Range or Operational Workspace (meters extent): 1, 10, 100, 1000

Inter-Agency Robotics Drivers

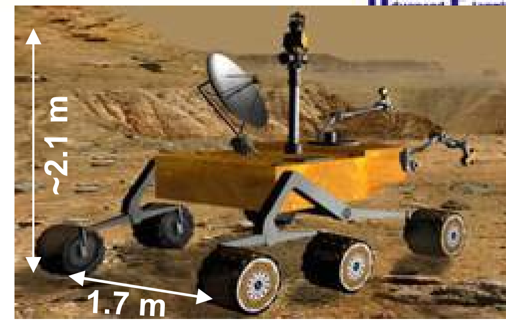
(space imposes unique requirements and constraints)

	NASA	DoD	DoE
Robot Physical Characteristics	Light, Mass & Volume Constrained	Sturdier; Re-Usable; Can Resist Wear and Tear	Sturdier; Re-Usable; Can Resist Wear and Tear
Robot Environment	Unexplored Terrain; Extreme Cold/Heat	Earth Terrain; On-Road & Off-Road	Radiation Rich Sites
Distance from Control and Command Station	Up to Millions of Kilometers	Few Kilometers	Up to 1 Kilometer
Robot Level of Autonomy	Semi-Autonomous (long time-delay)	Teleoperation/Semi-Autonomous (short time delay)	Teleoperation/Semi-Autonomous (short time delay)
Robot Manipulators	Pick-Up and Handle Small Objects (e.g. rocks); Low-Gravity Manipulation of Human-Made Objects	Lift and Handle Heavy Loads	Lift and Handle Heavy Loads
Robot Vision	Discover Interesting Science Samples; Detect Natural Hazards	Detect & Track Human Objects (walking soldier; moving lead vehicle)	Inspect Hazardous Sites; Cluttered Environment

Capability Benchmarks: From MER to MSL



Mars Exploration Rover



Mars Science Laboratory

	Mars Exploration Rover	Mars Science Laboratory
Landed Mass	**174 kg**	**~600 kg**
Designed Driving Distance	**600 m**	**5000-10,000 m**
Mission Duration	**90 sols**	**687 sols**
Power/Sol	**400 - 950 w/hr**	**~2400 w/hr**
Instruments (#/mass)	**7/5.44 kg**	**6-9/65 kg**
Data Return	**50-150 Mb/sol**	**100-400 Mb/sol** **500-1000 Mb/sol (with MTO)**
EDL	**Ballistic Entry**	**Guided/Precision Entry**

**images not to scale*

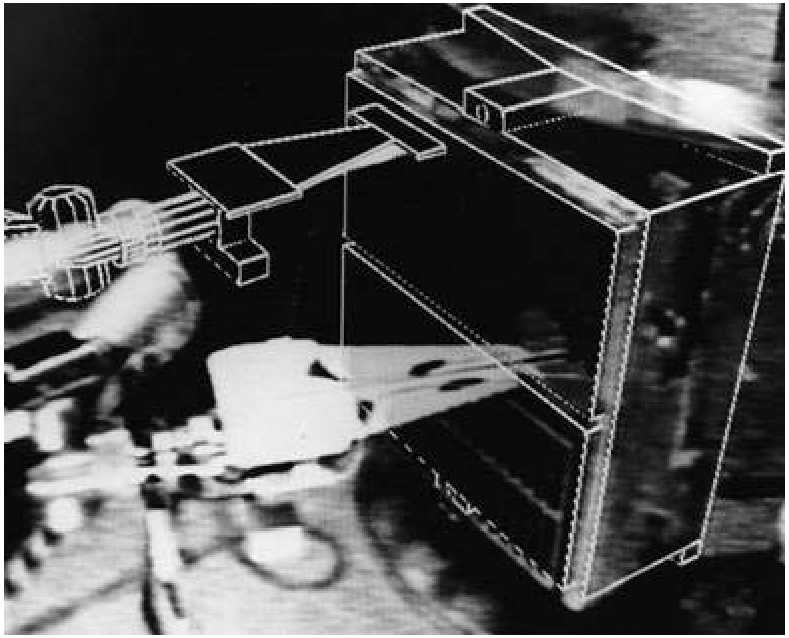
Two Fundamentally Different Approaches, or a Capability Convergence?

- **Teleoperation**
  - Structured, often well-modeled, sometimes cooperative environment
  - Low latency or none, but past 250 msec, a new operational regime
  - Global viewing is limited, can be obscured, low fidelity is an issue
  - Sensory feedback often multi-modal and non-intuitive to operator
  - Secondary workload is an issue, may require multiple operators
  - Dexterity, haptics, human-rated performance of interest (metrics?)
  - Evolution of teleoperation to *telerobotic* shared and traded control
  - Signal-Sign-Symbol, “Visually Servoed-Guided-Designated”, etc.

- **Supervised Autonomy**
  - Unstructured, partially-modeled, rarely a “cooperative” environment
  - High latency, structured planning/CDH, limited contingency handling
  - Limited mass, volume, power, and communication; compute bound
  - Localized perception and situational awareness primary to s/c safety
  - Mid-range localization/servoing and analog planning key to efficiency
  - Long range localization and global coordination a key to networking
  - Operator may enter planning, monitoring, and control at multiple levels

ORU Change-Out Task with Predictive Graphics and Compliance Control

JPL Operations Site

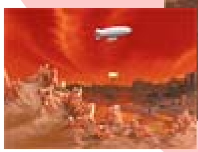


GSFC Servicing Site

← *6-to-15 seconds asynchronous communications delay* →

Robotic Sub-Capabilities (10.5-10.7)

Commonality of Architectures and Components



On-and-Near SSE Bodies

Enabling Technologies

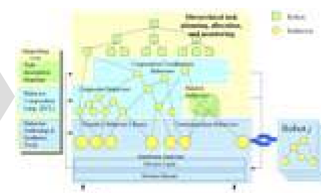
On-Board Intelligence
Manipulation
Mobility

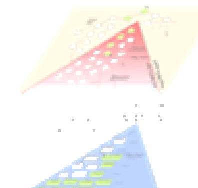
Human/Robot System Architectures

- Distributed & cooperative agents
- Reconfigurable, redeployable robots
- Telerobotic & teleprogrammed control
- Visualization & designation interfaces
- Sequencing & contingent planning
- Reactive, reflexive system GN&C
- Sensory fused global perception
- Multi-modal operations interfaces
- Teleoperation with latency

Unified Human/Robot Operations

- Cooperative H/R work on orbit and surfaces
- Surface preparations for human explorers
- Instrument deployments for mission crew
- Robot assistance to EVA exploration
- Robotic risk mitigation to spacecraft and crew safety (inspection & intervention)





Needed Capabilities

Manipulative instrument placement
Sample processing and handling
Navigational long range traverse
Rough terrain mobility & safety
Multi-sensory state estimation
Visual tracking, localization
Local area mobility planning
Cooperation of multiple robots
Activity sequencing / visualization

In-Space

Needed Capabilities

Manipulation of parts / assemblies
Traverse of large space structures
Grapple dexterity on trusses, etc.
Transport, docking, and deployment
Multi-sensor modeling / recognition
Visual tracking, localization
Local structure mobility planning
Cooperation of multiple robots
Activity sequencing / visualization

EXAMPLE: Capability Trends (1)

Required Capability	Current TRL	Now (TRL varies)	Figure of Merit In 2008 (TRL 6)	Long Term
Surface Mobility				
Command Cycles per Operation for Surface Mobile Exploration	3-9	Mobility: 10+ meters per command (MER) Manipulation: 3-4 sols per instrument placement (MER)	Mobility: 1 Kilometer per command Manipulation: 1 science measurement per command	Automated planning and sequencing of local area activities (science scripts, maintenance & logistics functions). Multi-target science sorties in one command.
Range of Operations (Planetary Surface)	3-9	> 1 kilometer linear path (MER)	>1000 Km^2 incl. use of aerial or multi-agent systems	Global coverage of science bodies through networked science assets
Access to Adverse and Rugged Terrain	4	VL 1 terrains, recent MER post-baseline ops on 30 deg. slopes	> VL2 terrains, vertical cliffs, cratered walls	Rove at will into densely featured and highly variable terrains at lunar and Mars gravity
Networked Robotic Systems (Surface)	2-4	Concept demos of shared payload transport (TRL 4)	Full scale terrestrial demo of power station / habitat deployment	Mix and match modularized hardware-software robotic assets for all basic surface H/R support and logistical functions
In-Space Mobile Dexterity				
Level of Dexterity	4-9	Teleoperatively Grapple Large (>1 m^3) ORUs (STS)	Human "bare hand" dexterity	Full body emulation of human assembly and repair skills by robotic anthropmorph
Range of Operations (In-Space Systems)	2-9	Fixed base (SRMS, SSRMS) operations; 100 meter linear track (MSS/SPDM)	1 Km^3 coverage by coordinated mobile manipulative systems	Robotically traverse complex space structures to perform planned and spontaneous inspection and servicing functions
Networked Robotic Systems (In-Space)	2-3	Cooperative transport and docking by free-flyers, air-table demo (TRL 3)	Dockable, modular multi-robot elements for assembly, servicing	Robots and crew freely and safely interact both physical-cooperative and symbolic command i/f levels

EXAMPLE: Capability Trends (2)

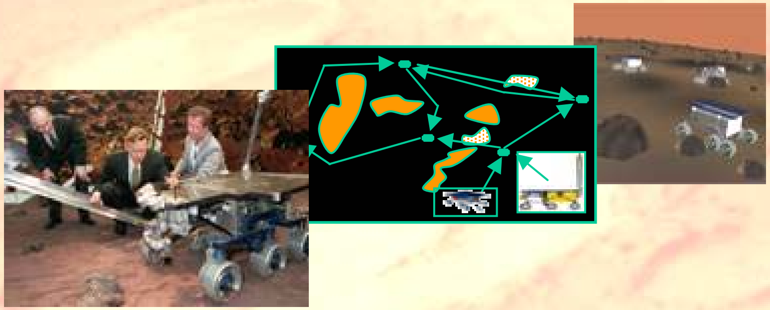
Subsurface & Aerial Access				
Autonomous Drilling/ Coring	3-6	Drilling 10-100's cm in penetrable rock, sand media; novel arm-mounted core extraction devices (TRL 3-4)	Drilling 10-20 meters in Mars analogs. Automated detection and mitigation of slip-stick conditions	Drilling 50-100 meters at Mars, drilling for resources as needed at Earth moon.
Icy Melt Exploration	2-5	Cryobotic access to uniform icy media (TRL 5)	Self powered and science instrumented cryobot earth analog experiment	Cryobotic exploration of Europan ice fields. Deep icy soil exploration of Mars high latitudes.
Aerial Access to Small Bodies	2-4	Powered aerobotic flight over terrain of interest (TRL 3-4)	Titan aerobot scenario demonstrated in full scale earth analog demo	Titan aerial exploration and possible drop-sonde and sampling.
Robotic Intelligence & H/R Interaction				
Planning & Monitoring Systems	3-5	Contingent Resources Planners; Local Spatial Planners (TRL 4-5)	Deliberative task planners for well structured assembly tasks; automated sequencing of basic science routines; integrated spatial-resource planners for long ranging traverse	Integrated planning and sequencing tools for ground operations of SSE robotic missions. High fidelity simulation of all aspects of planetary surface exploration.
Time Delay Control of Telerobotic Tasks (ground to orbit, from orbit to surface)	3-5	Teleoperative preview-predictive displays; shared compliance controls (TRL 3-5)	Teleprogrammed modes of remote control—the robot autonomously sequences local task behaviors / primitives	High dexterity operations over variable time delay from earth, orbit, and at field sites.

EXAMPLE: Field Trials and Analog Missions

Demonstrate New Capabilities and Provide Integrated V&V for Component Technologies

Testbed Use

- Component technology integration and test
- Intelligent Systems (IS) and other initiatives technology product infusion/leverage
- Development and verification of human/robot operation interfaces, planning/visualization
- Quantitative system-level performance evaluation & characterization
- Ground truth, field validation, and science community tie-ins for relevant experiments
- Advances in synergistic science operations and on-board science analysis



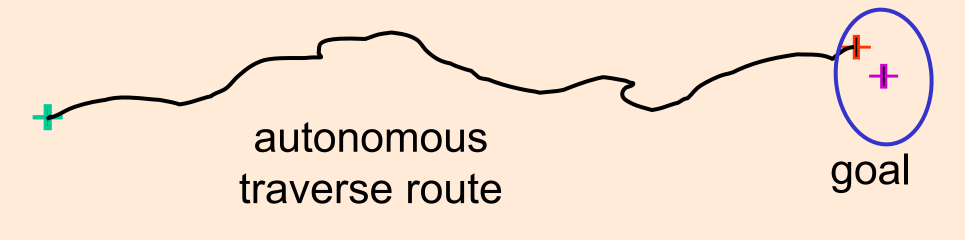
P. S. Schenker, et al., "Planetary Rover Developments Supporting Mars Exploration, Sample Return and Future Human-Robotic Colonization," ***Autonomous Robots*****, No. 2/3, March/May, Vol. 14, pp. 103-126, 2003 (Special Issue on Robots in Space)**

FIDO and K9 Rover Used in MER Analog Missions

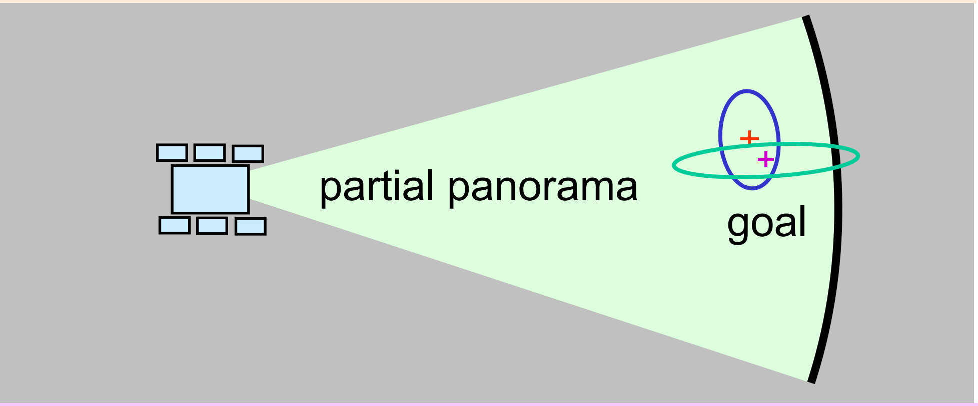
Supporting Technology Development

- Comprehensive control architectures for multiple, interacting, instrumented planetary and on-orbit robotic systems
- On-board intelligence for automated science sequence planning, error handling and recovery; visually referenced mobility and manipulation
- High-fidelity simulations for concept development
- End-to-end capability to emulate science-relevant remote operations, including critical program elements of human/robot interaction & cooperation

EXAMPLE: Challenges to Mobile Autonomy



AUTONOMOUS TRAVERSE:
Autonomous traverse, obstacle avoidance, and position estimation relative to the starting position.



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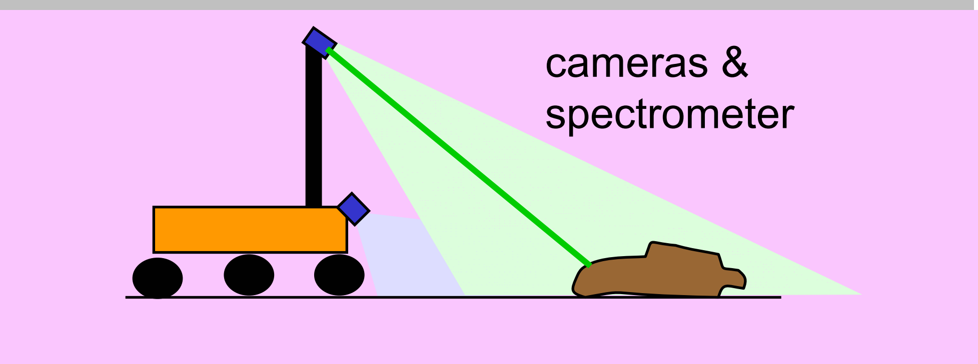

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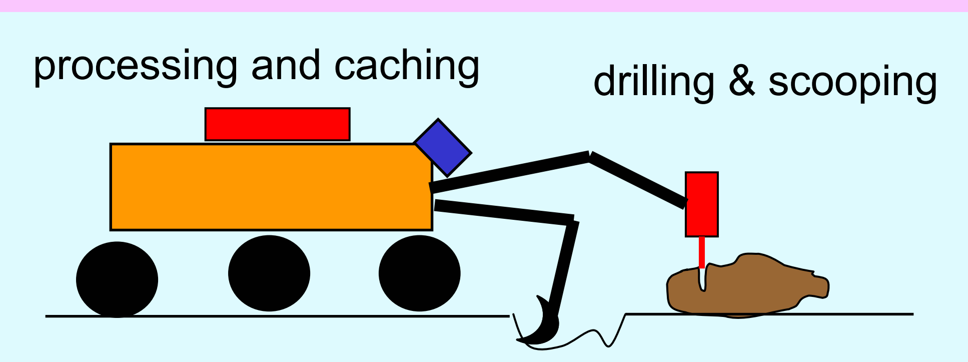

SAMPLING:
Sampling, sample processing, and sample caching through development of controls for new system components.

EXAMPLE: Technology Infusion to MER

(from Mars Technology Program and Predecessors)

Advanced Planning & Integration Office

	Technology	Funding Source	Description	PI/Technologist
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Capability 10.5
Robotics for Solar System Exploration

Sub-Team Chair: Reid Simmons, CMU

Presenter: Paul Schenker, JPL

Capability 10.5
Robotics for Solar System Exploration

- This capability area defines the robotic capabilities needed for both unmanned and manned science and exploration missions throughout the solar system. They include:
  - Autonomous mobility and access (surface, aerial, and sub-surface)
    - Exploration of large regions
    - Sub-surface access (shallow, deep, ice-melt probes)
    - Access to high-risk/high-payoff sites (cliffs, canyons, craters)
    - Navigation on small bodies
    - Aerial survey
  - Autonomous instrument deployment (from landed and mobile platforms)
    - Target selection
    - Precision instrument placement
    - Data collection and validation
  - On-board autonomous science
    - Perception
    - Analysis
    - Planning
    - Execution
  - Human-robotic field science
    - Site mapping/survey
    - Site characterization
    - Sample acquisition (digging, drilling, scooping, trenching, etc.)
    - Sample processing (grinding, crushing, etc.)
    - Sample handling (containment)
  - Human-robot interaction
    - Ground based teleoperation
    - Proximate telepresence
    - Shoulder-to-shoulder interaction
    - Robot assistants

Benefits of Capability 10.5
Robotics for Solar System Exploration

- Robotic mobility, instrument deployment, and sample access are ***enabling*** for unmanned planetary surface, aerial, and sub-surface exploration by providing access to places where human access is impossible, or would be too dangerous or expensive
  - ***go where we currently can't—survive—do breakthrough science***
- Robotics and on-board autonomous science capabilities are ***enabling*** for long-endurance remote in-situ science operations at multiple sites, permitting synoptic sampling and increasing science productivity
- Robotic scouts and astronaut assistants are ***enhancing*** for manned planetary surface exploration by replacing humans on some tasks and working with them on others
  - Reduction/elimination of "dirty, dull, and dangerous" tasks for humans
  - Reduction in the workloads of humans
  - Consequent reductions in mission manning levels and, therefore, in the resources required to support them

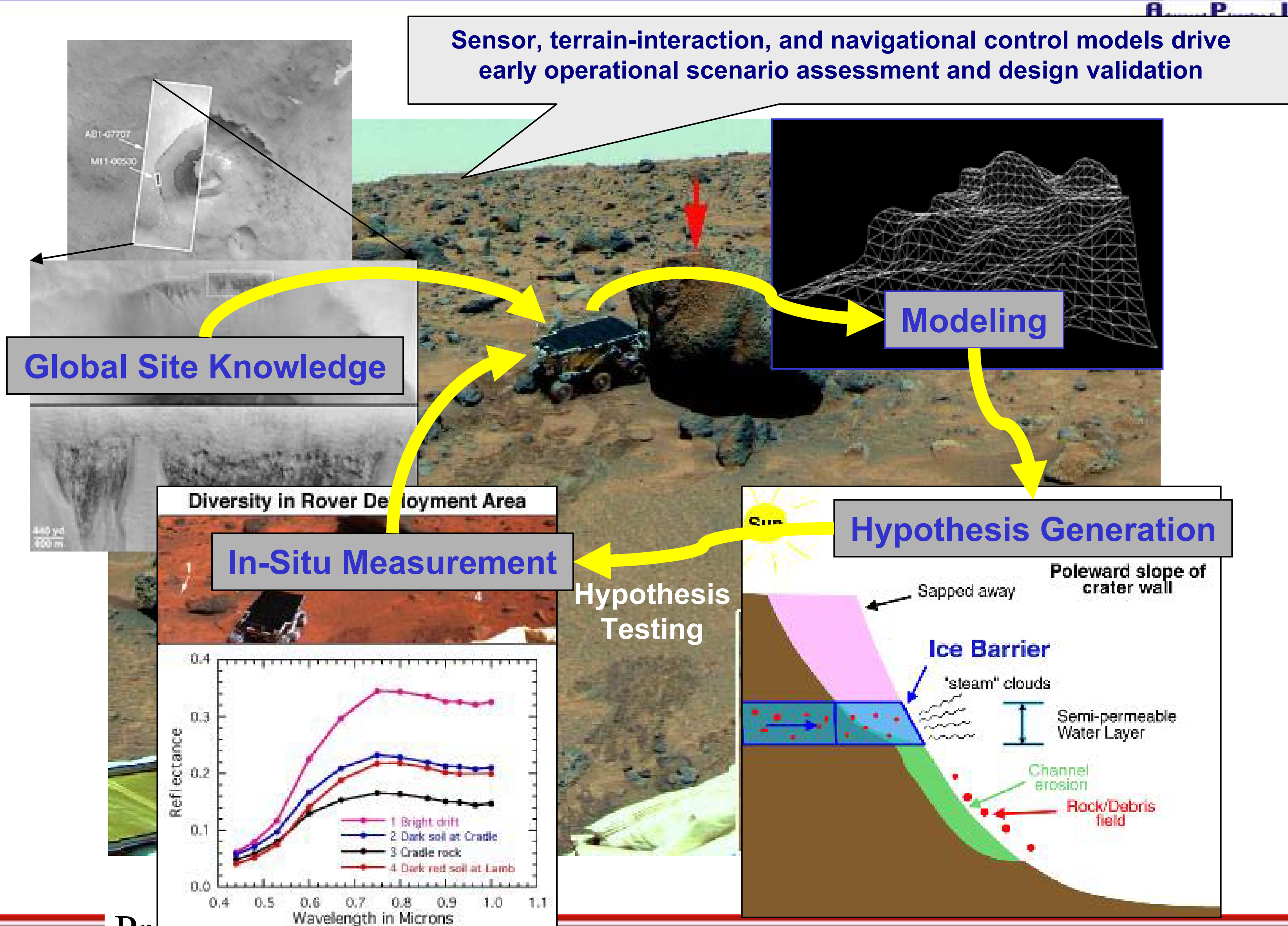
Current State-of-the-Art for Capability 10.5 Robotics for Solar System Exploration

- **Autonomous mobility and sample access**
  - MER mobility: 10-120 m/sol to commanded point with > 90% success, < 20 degree slopes, sparse obstacle field
  - MER visual odometry: ~2% accuracy over distance traveled
  - MER sample access: RAT, wheel scuffing of soil
  - Deep Space 2: Small, sub-surface micro probe, ~50cm access
- **Autonomous instrument deployment**
  - MPL arm: ~2 m reach, 4 DOF, operated from fixed platform
  - MER arm: 90 cm reach, 4 DOF, operated from mobile base
- **On-board autonomous science**
  - Human-commanded on per-sol basis
  - Fixed sequences
- **Human-robotic field science**
  - No operational experience
- **Human-robot interaction**
  - Sojourner/MER: Ground teleoperation
  - MER: Commanded on per-sol basis

=> *Laboratory, and some field, demonstrations of long-range navigation (< km per command cycle), 7DOF arms, meter-deep drilling, single instrument placement, autonomous science planning and execution, robotic assistants, etc.*

Robotic Autonomy, Science & Simulation

… and the potential of "on-board (autonomous) science" …



Requirements /Assumptions for Capability 10.5
Robotics for Solar System Exploration

Advanced Planning & Integration Office

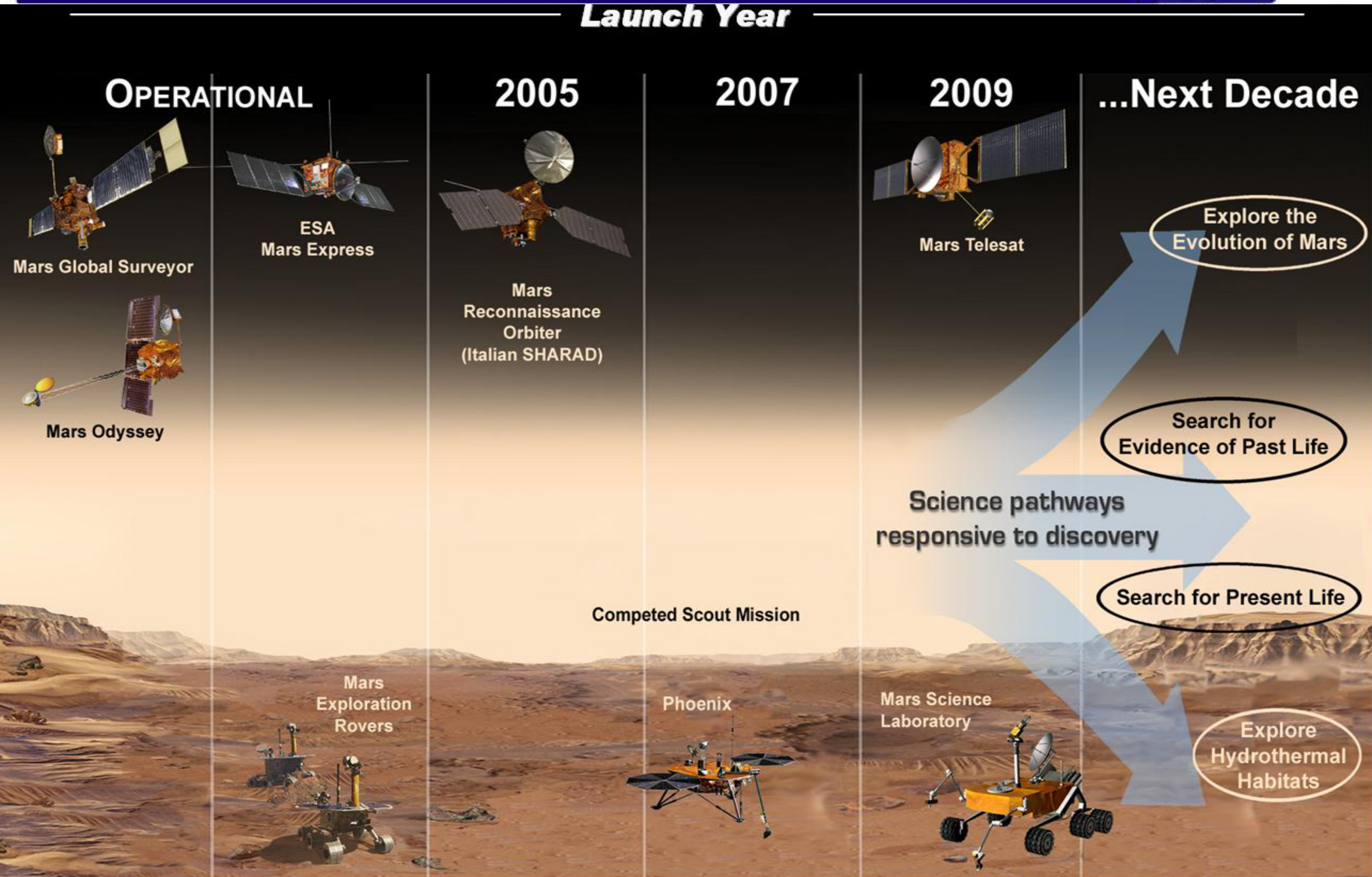
- **Robotics for Solar System Exploration in Support of Manned Missions**
  - **Spiral 1: 2014** Robotic Lunar Exploration
    - Ground-based teleoperation of rovers or landers
    - Exploration of large regions
  - **Spiral 2: 2015-2020** Lunar Surface Ops
    - Human-robot field science from Earth and Lunar surface
    - Sample acquisition and processing
    - Semi-autonomous site mapping / survey
  - **Spiral 3: 2020** Lunar Habitat and Mars Human Precursor
    - Proximate telepresence from lunar habitats
    - Sample acquisition, processing, and analysis
    - Autonomous site characterization
  - **Spiral 4: 2025** Mars Vicinity Ops
    - Human-robot field science from orbiting craft
    - Proximate telepresence from orbiting craft of multiple rovers and landers
  - **Spiral 5: 2030+** Martian Surface Exploration
    - Shoulder-to-shoulder interaction
    - Robot assistants for exploration

Requirements /Assumptions for Capability 10.5 Robotics for Solar System Exploration

- **Robotics for Solar System Exploration in Support of Unmanned Missions**
  - **Lunar Surface**
    - Moonrise
  - **Mars Surface**
    - Astrobiology Field Lab
    - Mars Science Lab
    - Mars Sample Return
  - **Non-Planetary Surface (small body)**
    - Comet Sample Return
    - Asteroid Rover Sample Return
  - **Mars Sub-Surface**
    - Deep Drill
  - **Planetary Sub-Surface**
    - Europa Astrobiology Lander
  - **Planetary Aerial**
    - Titan Explorer
    - Venus Mobile

Mars Exploration Program

This Decade's Discoveries Leads to the Next Decade's Pathway

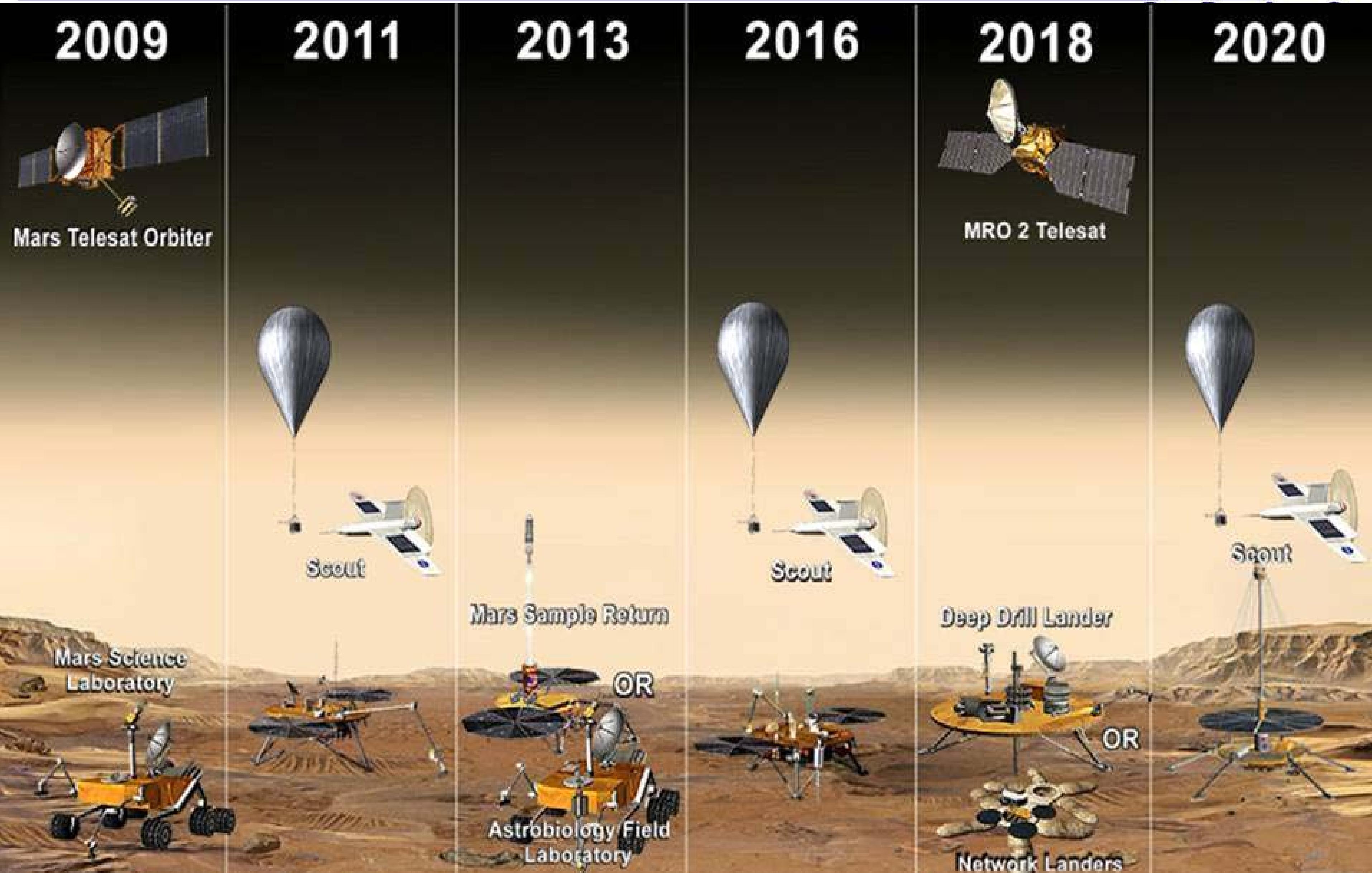


Potential Pathway Mission Sequences

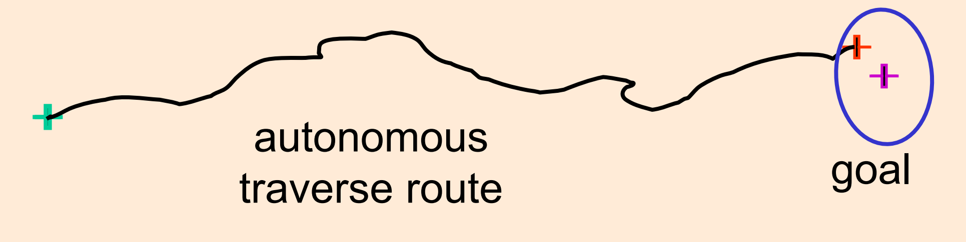
Pathway	2009	2011	2013	2016	2018	2020	Notes
Search for Evidence of Past Life	MSL to Moderate Latitude	Scout	MSR	Scout	Astrobiology Field Lab or Deep Drill	Scout	Missions to high-probability past habitat. Mission in '18 influenced by MSL results.
Explore Hydrothermal Habitats	MSL to Hydrothermal Deposit	Scout	Astrobiology Field Laboratory	Scout	Deep Drill	Scout	All core missions sent to active or extinct hydrothermal deposits.
Search for Present Life	MSL to High Latitude or Active Vent	Scout	Scout	MSR	Scout	Deep Drill	Missions to modern habitat. Path has highest risk.
Explore Evolution of Mars	MSL to Moderate Latitude	Scout	MSR	Aeronomy	Network	Scout	Path rests on proof that Mars was never wet.

2005 President's Budget Augmentation		Scout & Mars Testbed		Mars Testbed		Mars Testbed	
	MTO →	→	→	→	Replacement Telecom* →	→	

"Search for Past Life" Pathway Example



Challenges to Mobile Autonomy



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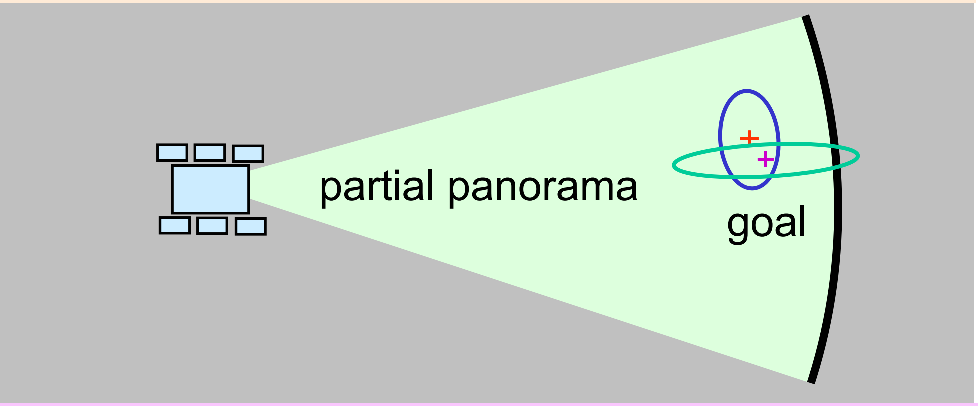

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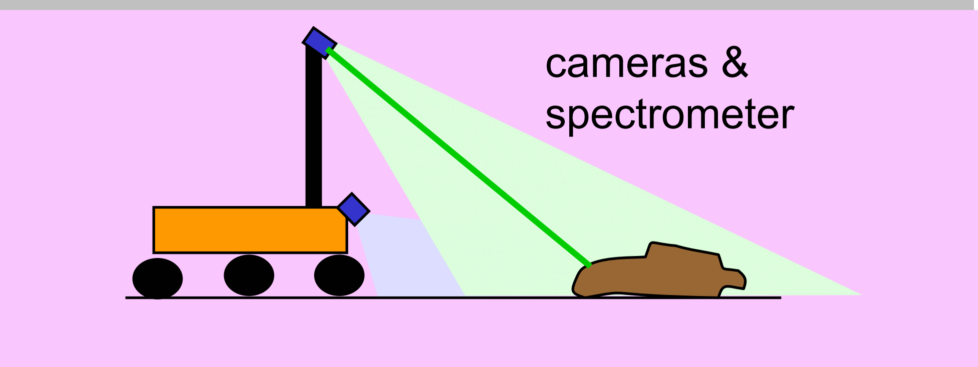

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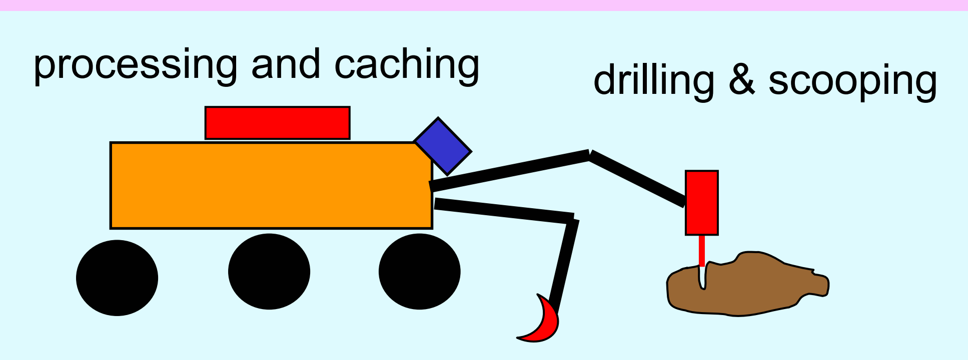

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SSE SRM: Design Reference Mission Set

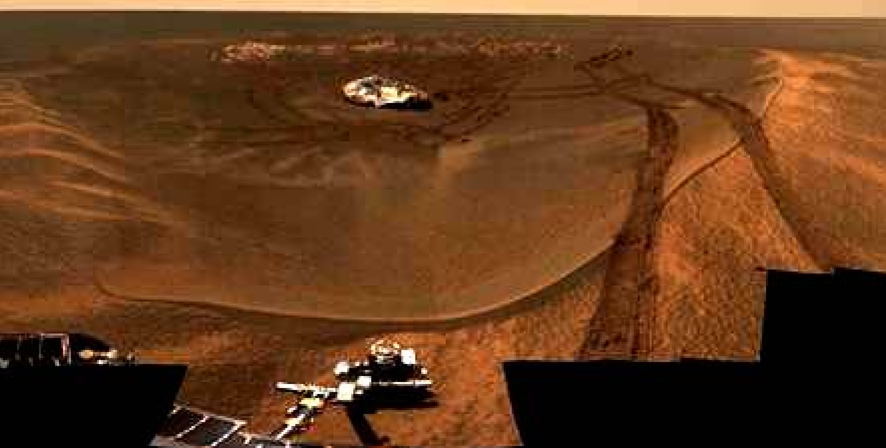
Mission Class	Time Frame	Small Missions Discovery Class	Medium Mission New Frontiers Class	Intermediate Mission Intermediate Class	Large Missions Flagship Class
Frequency		6 to 7 per decade	4 per decade	TBD per decade	1 per decade
FIRST DECADE	2003 to 2013	***Competitive All solar system targets except for Mars***	*Kuiper Belt- Pluto Explorer* *South Pole-Aitken Basin Sample Return* *Jupiter Polar Orbiter* ***with probes*** *Venus In Situ Explorer* ***- VSSR techval*** *Comet Surface Sample Return*		*Europa Geophysical Observer* ***Jupiter Icy Moons Orbiter(2015)***
SECOND DECADE	2014 to 2023	***Same***			
Primitive Bodies			*Asteroid Rover Sample Return* *Trojan Centaur Reconnaissance Flyby*		*Comet Cryogenic Sample Return*
Inner Solar System			***Geophysical Network -Venus*** →	***Geophysical Network Venus*** ***Venus Mobile Mission***	 *Venus Sample Return*
			Geophysical Network - Mercury		*Mercury Sample Return*
Giant Planets			***Neptune Flyby*** ←	***Neptune Flyby with Probes*** ←	*Neptune Orbiter with Probes*
				Neptune Triton Orbital Tour ←	*Neptune Orbiter/Triton Explorer*
			Uranus Flyby ←	***Uranus Flyby with Probes*** ←	*Uranus Orbiter with Probes*
				Saturn Flyby with Probes ←	*Saturn Ring Observer*
			Jupiter Flyby with probes		
Large Satellites			*Io Observer* *Ganymede Observer*	***Titan Explorer (no orbiter)***	*Europa Lander* *Titan Explorer (with Titan orbiter)*
Third Decade	2024 to 2035		*Overflow from Second Decade* *New science driven opportunities*		*Overflow from Second Decade* *New science driven opportunities*

Notes:

Missions in *black italics* are the Decadal Survey missions.

Missions in ***red bold italics*** **are Decadal Survey missions or parts of missions that are now known to be incompatible with this mission class**

Missions ***in blue bold italics*** **are New Missions that have been identified to address some of Major Mission objectives at affordable cost**



Planetary Mobility: Today

Mars

- Ability to traverse moderately rocky surfaces at <500m/sol
- Vulnerable to low bearing strength deposits (sand and dust, particularly on slopes.
- ***Many important science targets including craters and rock outcrops involve a significant risk of the rover getting immobilized .***

Titan

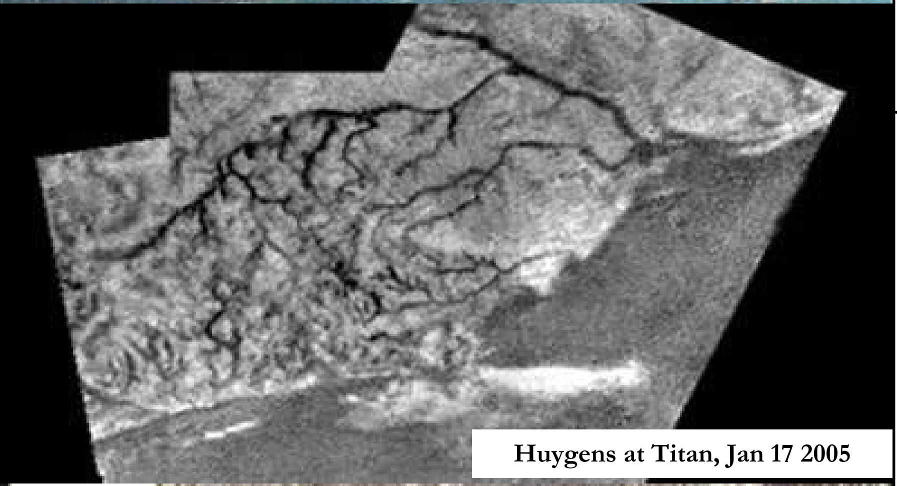
- Demonstration of key technologies to survive in the cold environment of Titan (FY03-05 R&TD).
- Initial test bed investigations of autonomy for Titan.
- ***Not yet at a point that NASA could commit to a Titan in situ mission.***

Venus

- Capability to circumnavigate Venus by high latitude balloon (e.g. JPL VALOR proposal to the 2004 Discovery call)
- Near surface metal bellows balloon demonstrated in R&TD topic proposal in 2004
- ***No other current NASA work on mobile near surface exploration of Venus.***

Endurance Crater's Dazzling Dunes (August 6 2004

Dunes were **too treacherous** for Opportunity to drive on



Huygens at Titan, Jan 17 2005

Venera 13, Mar 3, 1982

Planetary Mobility: Vision

Mars Surface Mobility

- ***Increase speed of travel*** by a factor of 20 and cover 100 km in three months
- **Reduce power** needed for locomotion by a factor of three.
- **Traverse** dunes, dust deposits, large boulders and steep slopes with equal facility
- ***Access rock outcrops above talus slopes at the angle of repose***.

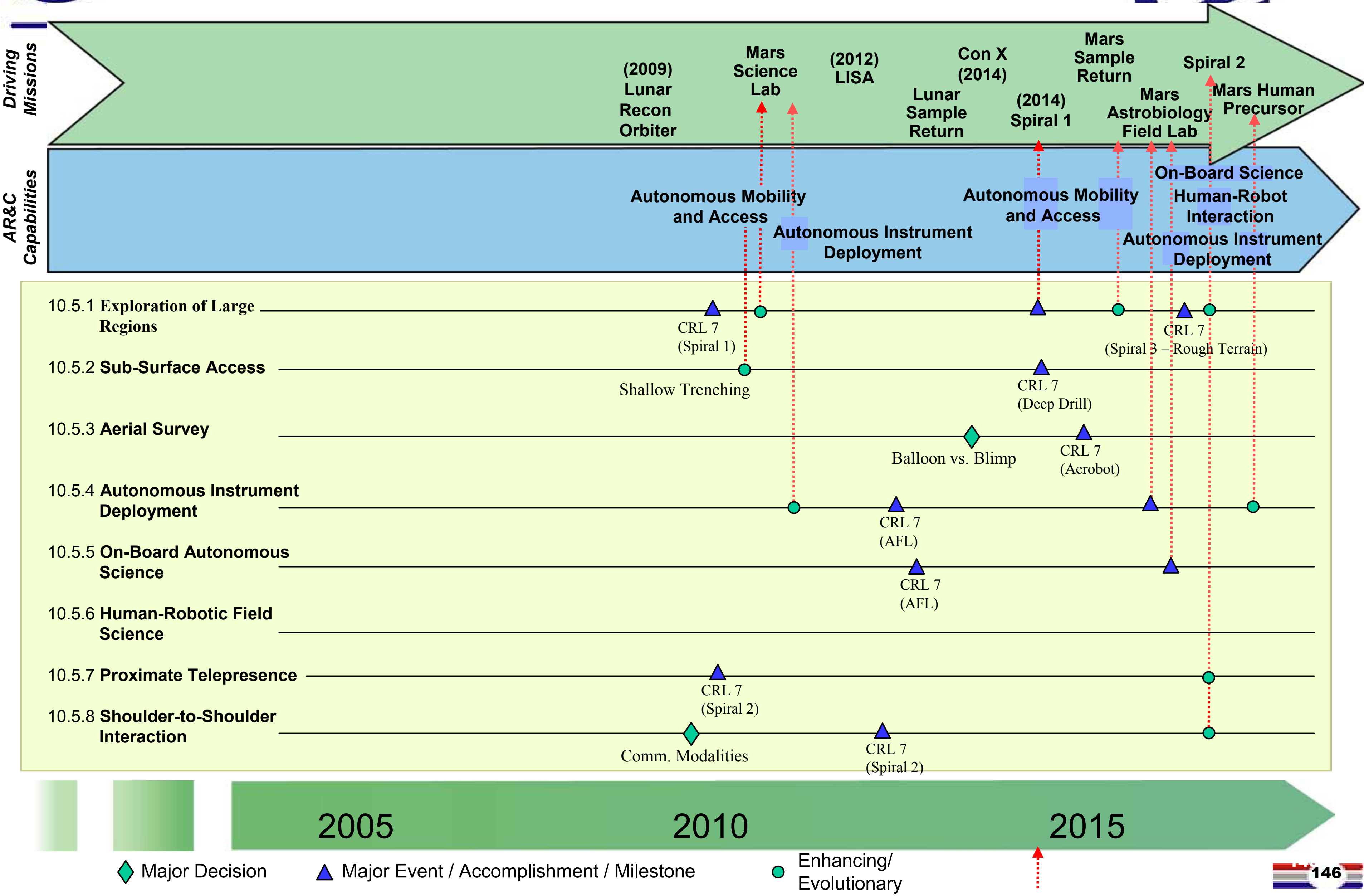
Titan Aerial Exploration

- ***Circumnavigate*** Titan and acquire 1000X the image data obtained by Huygens at high S/N
- ***Descend*** repeatedly to the surface of Titan to image fluvial and cryovolcanic features up close
- **Acquire touch and go samples** from selected targets on the Titan surface and perform in situ analysis.

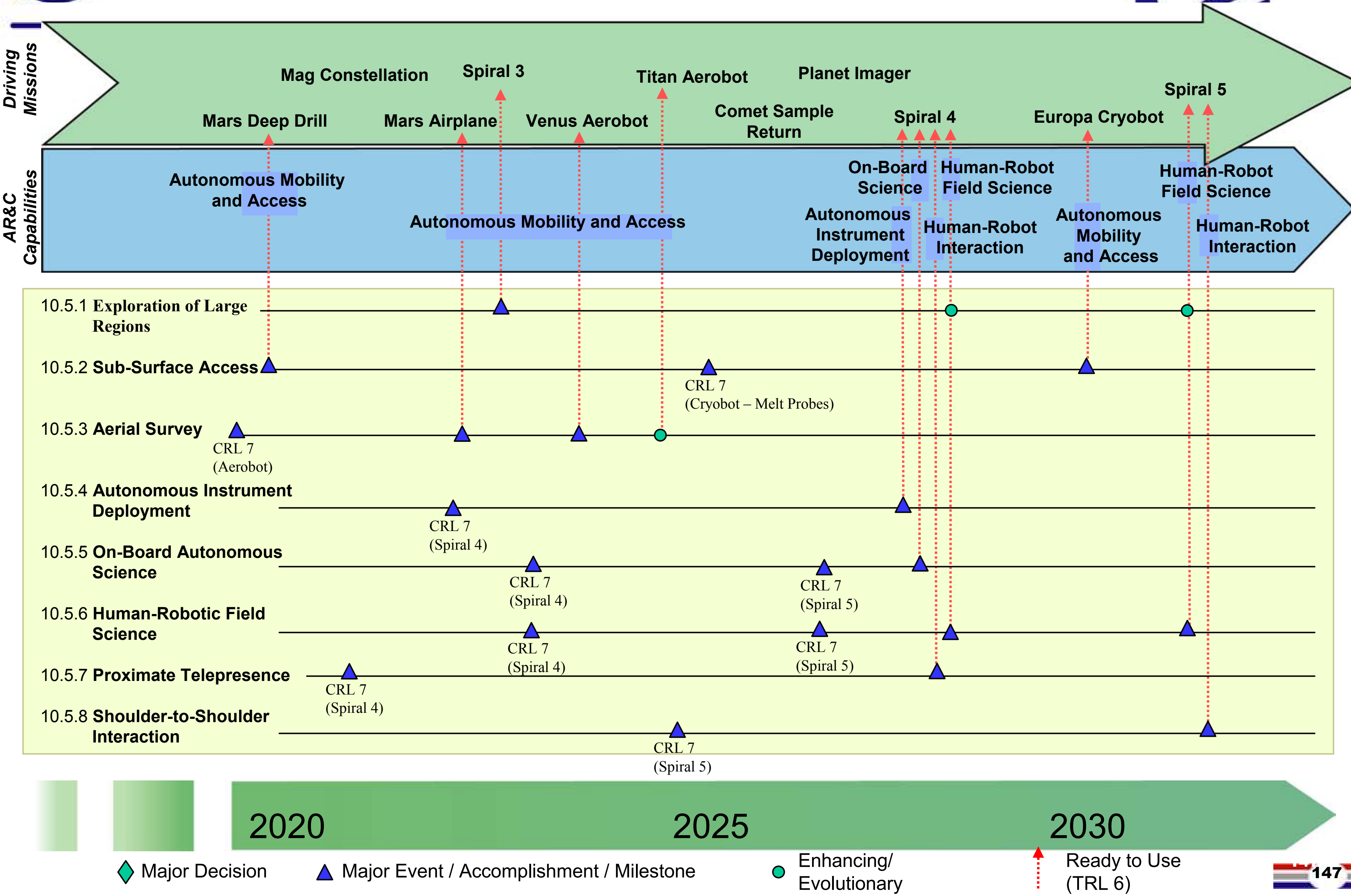
Venus Aerial Exploration

- ***Circumnavigate*** Venus and acquire 10,000 times the image data obtained by Venera 9-14
- ***Descend*** repeatedly to the surface of Venus and perform in situ analysis.
- ***Survive*** for several months in the Venus **near surface environment** .

Deliverables for Capability 10.5
Robotics for Solar System Exploration



Deliverables for Capability 10.5
Robotics for Solar System Exploration



Deliverables for Capability 10.5
Robotics for Solar System Exploration

- **Exploration of large regions**
  - Driver: Spiral 1 (Lunar); Spiral 3 (Mars)
  - CRL 7 date: 2009
  - Interfaces: 6-RAPS, 9-HESM
- **Sub-surface access**
  - Drivers: Deep Drill, Europa Astrobiology Lander
  - CRL 7 date: 2013
  - Interfaces: 6-RAPS
- **Aerial survey**
  - Drivers: Titan Explorer, Venus Mobile
  - CRL 7 date: 2015
  - Interfaces: RAPS
- **Autonomous instrument deployment**
  - Driver: Astrobiology Field Lab, Mars Human Precursor
  - SMD - TRL 6 - 2013
  - Interfaces: 12-SI/S

Deliverables for Capability 10.5
Robotics for Solar System Exploration

- **On-board autonomous science**
  - Driver: Astrobiology Field Lab
  - CRL 7 date: 2013
  - Interfaces: 12-SI/S, 6-RAPS
- **Human-robotic field science**
  - Driver: Spiral 4 and 5 (Mars)
  - CRL 7 date: 2020
  - Interfaces: 6-RAPS,12-SI/S, 9-HES&M
- **Proximate telepresence**
  - Driver: Spiral 2 (Lunar); Spiral 4 (Mars)
  - CRL 7 date: 2010
  - Interfaces: 9-HES&M, 8-HH&SS
- **Shoulder-to-shoulder interaction**
  - Driver: Spiral 5
  - CRL 7 date: 2025
  - Interfaces: 9-HESM, 8-HH&SS

Maturity Level – Capabilities for 10.5 Robotics for Solar System Exploration

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Exploration of Large Regions	Autonomous Navigation Localization Path Planning Rough-Terrain Navigation (hills, cliffs, craters, etc.)	3-5	6	Spiral 1 – Lunar Exploration Spiral 3 – Mars Exploration	2009
Sub-Surface Access	Shallow Trenching Deep Drilling Melt Probes	2-5	6	Deep Drill Europa Astrobiology Lander	2013
Aerial Survey	Real-Time Adaptive Control Real-Time Control in 3D Path Planning in 3D	2-4	6	Titan Explorer Venus Mobile	2015
Autonomous Instrument Deployment	Target Detection Precision Placement Dexterous Robotic Arms Data Collection & Validation	3-5	6	Astrobiology Field Lab Mars Human Precursor	2013

Maturity Level – Capabilities for 10.5 Robotics for Solar System Exploration

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
On-Board Autonomous Science	Target Detection On-Board Classification Robust State Estimation Task Planning	2-4	6	Astrobiology Field Lab	2013
Human-Robotic Field Science	Autonomous Navigation Target Detection On-Board Classification Sample Acquisition & Processing	2-4	6	Spirals 4 & 5 – Mars Exploration	2020
Proximate Telepresence	Remote Teleoperation Dexterous Robots Safeguarding Sliding Autonomy	3-5	6	Spiral 2 – Lunar Exploration Spiral 4 – Mars Exploration	2010
Shoulder-to-Shoulder Interaction	Multi-Modal Communication Behavior Recognition Safeguarding Task Management	2-3	6	Spiral 5 – Mars Exploration	2025

Maturity Level – Technologies for 10.5 Robotics for Solar System Exploration

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Autonomous Navigation	Long Range Navigation	Stereo-based local obstacle avoidance	6-9	Obstacle density	2009
	Localization	Visual odometry	6-9		
	Path Planning	Heuristic, resource-cognizant search	4-6	Computational complexity	
	Rough Terrain Navigation	Dynamics-based planning	2-4	Complexity, modeling	
Perception of Geologic Features	Target Detection	SIFT, PCA-SIFT	3-5	Robustness	2013
	On-Board Classification	Neural net, Bayesian classifier	2-4	Data volume, scalability	
Sample Acquisition	Precision Placement	Visual Servoing	5-7	Robustness	2013
	Dexterous Robotic Arms	Robonaut, Ranger	4-6	Reliability	
	Scooping	5 DOF Arm	6-9		
	Coring	?	4-7		
Sample Processing	Crushing	?	3-5	Power	2013
	Containment	?	2-3	Validation	

Maturity Level – Technologies for 10.5 Robotics for Solar System Exploration

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Real-Time Adaptive Control		Non-linear control Fuzzy control	3-6 3-4	Modeling	2015
Robust State Estimation		Kalman Filters Particle Filters	6-9 3-5	Accuracy, modeling	2013
Task Planning		Planning/scheduling Contingent planning Decision-theoretic planning	5-7 4-6 2-4	Complexity, modeling	2013
3D Planning and Control		Probabilistic roadmaps Non-linear control, fuzzy control, memory-based learning	3-5 3-6	Complexity, modeling	2015
Teleoperation		Direct teleop Teleop with local behaviors	6-9 5-6	Validation, scalability	2010
Behavior Recognition	Tracking Interpretation	SIFT, PCA-SIFT HMMs, Cognitive models	3-5 2-3	Robustness	2020
Task Management	Executive	Procedural decomposition Planning/scheduling	4-6 5-7	Validation Modeling	2020
Multi-Modal Communication	Speech Gesture	HMMs, Natural language HMMs	5-7 2-4	Robustness	2025

Breakthrough Capabilities for 10.5 Robotics for Solar System Exploration

All-Planetary Vehicle

- Current rovers are limited to exploring small sections of relatively benign terrain. However, the most interesting science sites lie in relatively inaccessible and inhospitable locations (on the sides of cliffs/craters, up in the mountains, in deep valleys). It would be a breakthrough in robotic exploration to have rovers that could go essentially anywhere on a planet that the scientists want to go. Besides the obvious need for advances in mobility, this capability would require significant advances in perception, planning, control, and monitoring and safeguarding.

Self-Aware, Self-Correcting Robots

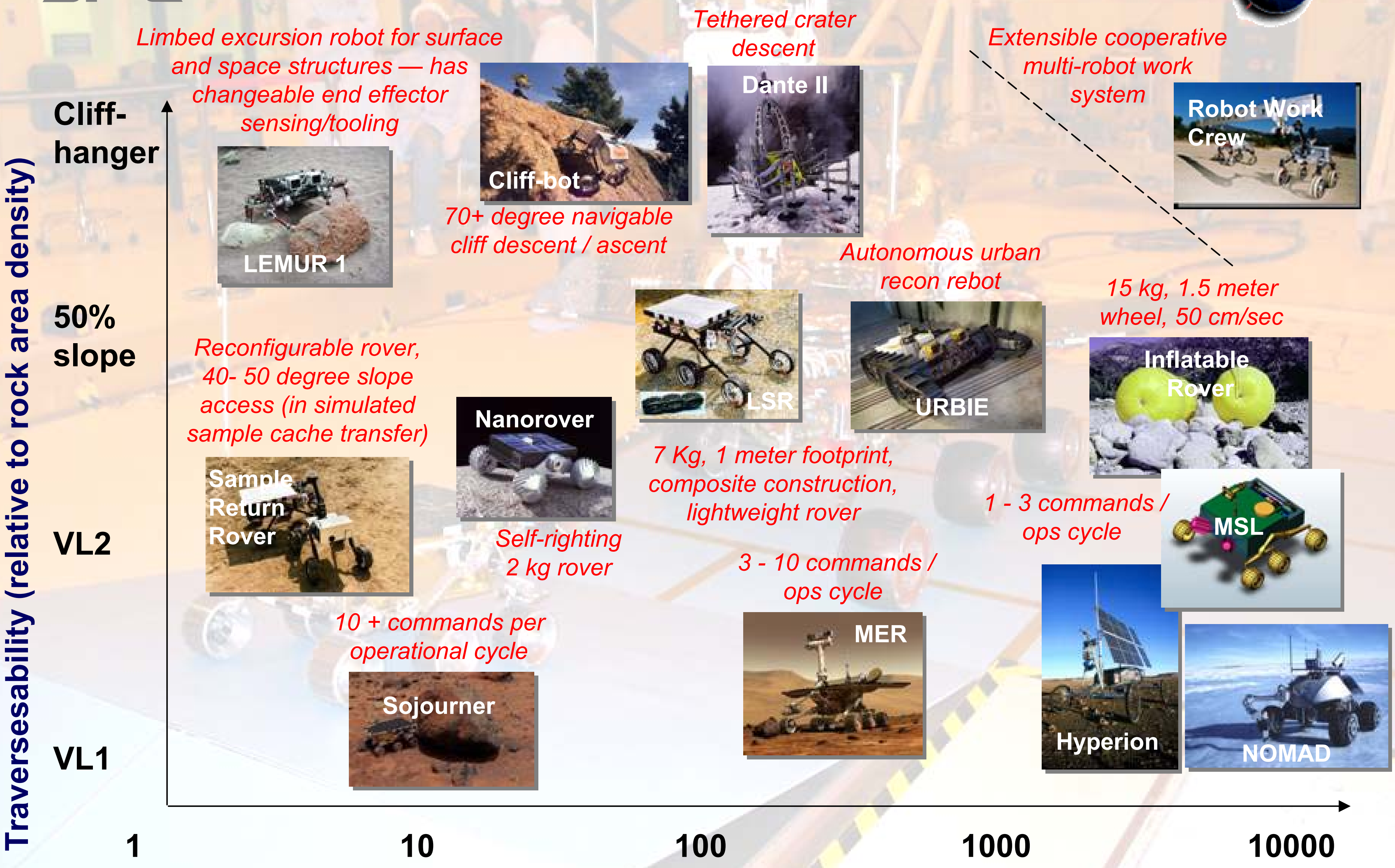
- By its very nature, exploration involves dealing with the unknown and unexpected. Current robots have limited capabilities for understanding when they are outside their limits and, if they are, how to get back to nominal mode of operations. This is especially apparent when things go wrong internal to the robot (such as sensors or actuators malfunctioning). It would be a breakthrough in robotic exploration to have a capability that monitors the robot at all times for these situations, recovers (or compensates for) such failures, and learns from past mistakes to avoid making them in the future.

Metrics for 10.5
Robotics for Solar System Exploration

Advanced Planning & Integration Office

Metric	Technology / Sub-Capability	SOA	Target Value	Need Date
Distance traveled per day	Autonomous Navigation Aerial Traverse	100m 1km	1km 10km	2009 2015
Difficulty of terrain that is accessible	Autonomous Navigation	VL1	>VL2, cliffs, craters	2015
Drilling depth	Sub-Surface Access	10's cms	10-20 ms	2013
Autonomously controlled manipulator degrees of freedom	Instrument Placement, Human-Robot Interaction	7	10's	2020
Command cycles per sample acquired	Instrument Placement, Field Science	3-6	1	2009
Command cycles per sample processed	Field Science	Dozens	1-2	2013
Command cycles to survey/characterize site	Field Science	>100	<20	2020
Percent of interactions interpreted correctly by robot	Multi-modal communication Behavior tracking	80% 70%	95% 95%	2020
# robots supervised per human	Human-Robot Field Science Co-located Interaction	<<1	3-5	2020

EXAMPLE: Rover System Capability Metrics



Background image: MER 2 with Sojourner model

Backup slides follow

Deliverable Descriptions for Capability 10.5 Robotics for Solar System Exploration

Exploration of Large Regions

- Effective robotic exploration will require autonomous navigation over wide areas (10's of kms) with diverse features (hills, craters, dense obstacles). Rover plans to distant goals, executes those plans, and keeps itself safe by knowing where it can, and cannot, go. (Some risk in rough terrain)

Sub-Surface Access

- Direct evidence of water and past life is likely to be found beneath the surface. Access and sample acquisition will be required at shallow depths (10's of cms), deep depths (10's of ms) and through thick ice layers (100's of ms). (Risk for deep drilling)

Aerial Survey

- For some missions, aerial vehicles (balloons, blimps, airplanes) are enabling because either surface access is impossible or access is required to a much larger area than can be covered by ground vehicles. Control for aerial vehicles is much more complex than for ground vehicles, due to the dynamic effects of the (poorly understood) atmosphere and the need to navigate in three dimensions. (Some risk)

Deliverable Descriptions for Capability 10.5 Robotics for Solar System Exploration

Autonomous Instrument Deployment

- Current missions require multi-day, highly complex command cycles to approach and place instruments on targets of interest. Handling this autonomously is extremely enhancing, especially for remote, long-duration missions. This requires advanced sensor-guided dexterous manipulation for precision placement and advanced techniques for autonomously collecting and validating instrument data.

On-Board Autonomous Science

- This capability considers larger scientific goals, such as what in an area is of scientific interest, which experiments are most relevant to characterize that site, and how to carry out those autonomously experiments. Dealing with high levels of uncertainty in state estimation and task planning is critical, as is having highly flexible, contingent plans to deal with the unexpected.

Human-Robotic Field Science

- Field science includes site survey, site characterization, science data collection, and sample acquisition and processing. For complex, remote missions, automating many of these activities will be highly enhancing. To perform such tasks autonomously, robot systems will need a basic understanding of the methods and goals of scientific investigation, as well as the capabilities to perceive, plan, and execute such plans. Advanced manipulation capabilities for sample acquisition and processing will be critical. (Some risk)

Deliverable Descriptions for Capability 10.5 Robotics for Solar System Exploration

Proximate Telepresence

- In many missions, the humans will be near the robots but will be supervising them from a safe distance (e.g., in a habitat or on orbit). To facilitate the interaction, the robots should have capabilities similar to humans (especially in terms of manipulation) and the level of control between robots and humans should be highly flexible ("sliding autonomy"). Situational awareness of the supervisor needs to be high, which can be facilitated with both multi-modal feedback and high-level interpretation (by the robot) of sensor data. Safeguarding to prevent harm to the robots is critical.

Shoulder-to-Shoulder Interaction

- In some missions, humans and robots will be co-located on site, working together. At a basic level, the robots will need to understand and communicate with the astronauts using both speech and gesture. In addition, in many cases they will need to infer (without communication) the behaviors and intentions of the astronauts and alter their activities accordingly to support the astronauts' goals. Safeguarding to prevent harm to the humans is critical. (Some risk)

Capability 10.6
Robotics for Lunar and Planetary Habitation

Sub-Team Chair: Illah Nourbakhsh, NASA/ARC
Presenter: Paul Schenker, JPL

Capability 10.6
Robotics for Lunar and Planetary Habitation

- Robotic capabilities are instrumental to preparing for human habitation, maintaining surface habitats, providing support for human surface operations both in-habitat and in the field, and aiding in the collection of in-situ resources for human habitation.
- Robotic capabilities in lunar and planetary habitation make long-term habitation feasible by greatly reducing risk and cost.
- Specific sub-capabilities include:
  - Site development (survey, excavation, initial construction, resource deployments)
  - Site maintenance (inspection, repair, assembly, materials transport & warehousing)
  - In situ resource production (robotic support to extraction, transport, manufacturing)
  - Field logistics and operations support (materials & equipment transport & warehousing)
  - Human-robot interaction (H/R task allocation, teleoperation, remote supervisory control, etc.)

Benefits of Capability 10.6
Robotics for Lunar and Planetary Habitation

- Robotic ISRU, robotic precursor preparation and ongoing robotic mission support are *enabling* for length of stay targets and operational cost targets due to impact on sustainability and affordability.

- Human safety is *enhanced* through precursor robotic site preparation.

- Field operations productivity is *enhanced* through robotic "mule" support and robotic mobile communication networking.

- Astronaut productivity is *enhanced* by lowering maintenance and inspection overhead assigned to human crew.

- Ground-crew interaction productivity is *enhanced* by improved human-robot interfaces.

Summary State-of-the-Art for Capability 10.6 Robotics for Lunar and Planetary Habitation

- **Robotics has not been used for lunar or planetary habitation. Related state-of-art capabilities demonstrated in flight are:**
  - **MER Long-range navigation, 10M+ navigation**

- **State-of-art can be indirectly measured from sub-capabilities with terrestrial deployment, TRL6 and below:**
  - **Site development: Autonomous robotic excavation and site shaping has been demonstrate by joint CMU – Caterpillar front loader system.**
  - **Site development: Communication infrastructure deployment by various university research groups in the DARPA *Centibots* program has set up networks using robot teams in unexplored urban areas.**
  - **Site maintenance: Dexterous manipulation under teleoperation has been demonstrated in analog environments by both Ranger and Robonaut research teams with astronaut glove-level dexterity and 6x slowdown.**
  - **Field logistics and operations support: Long-distance autonomous navigation has been demonstrated on the order of 100km total distance traveled.**
  - **Field logistics and operations support: Architectures for perception, planning and control have demonstrated efficacy in Mars-analog tests at JPL and Ames.**
  - **Human-robot interaction: No identified sub-capability has demonstrated significant present-day success.**

Requirements /Assumptions for Capability 10.6 Robotics for Lunar and Planetary Habitation

Manned Missions

- Spiral 2: **2015-2020 CEV LLO and EVA lunar surface ops**
  - Robotic precursor surface operations
- Spiral 3: **2020 Lunar surface habitat**
  - Human/Robotic habitat preparation, maintenance and repair
  - Human/Robot field operations and ISRU experiments
- Spiral 5: **2030+ Martian surface habitat and exploration**
  - Human/Robotic habitat preparation, maintenance and repair
  - Human/Robot field operations and ISRU

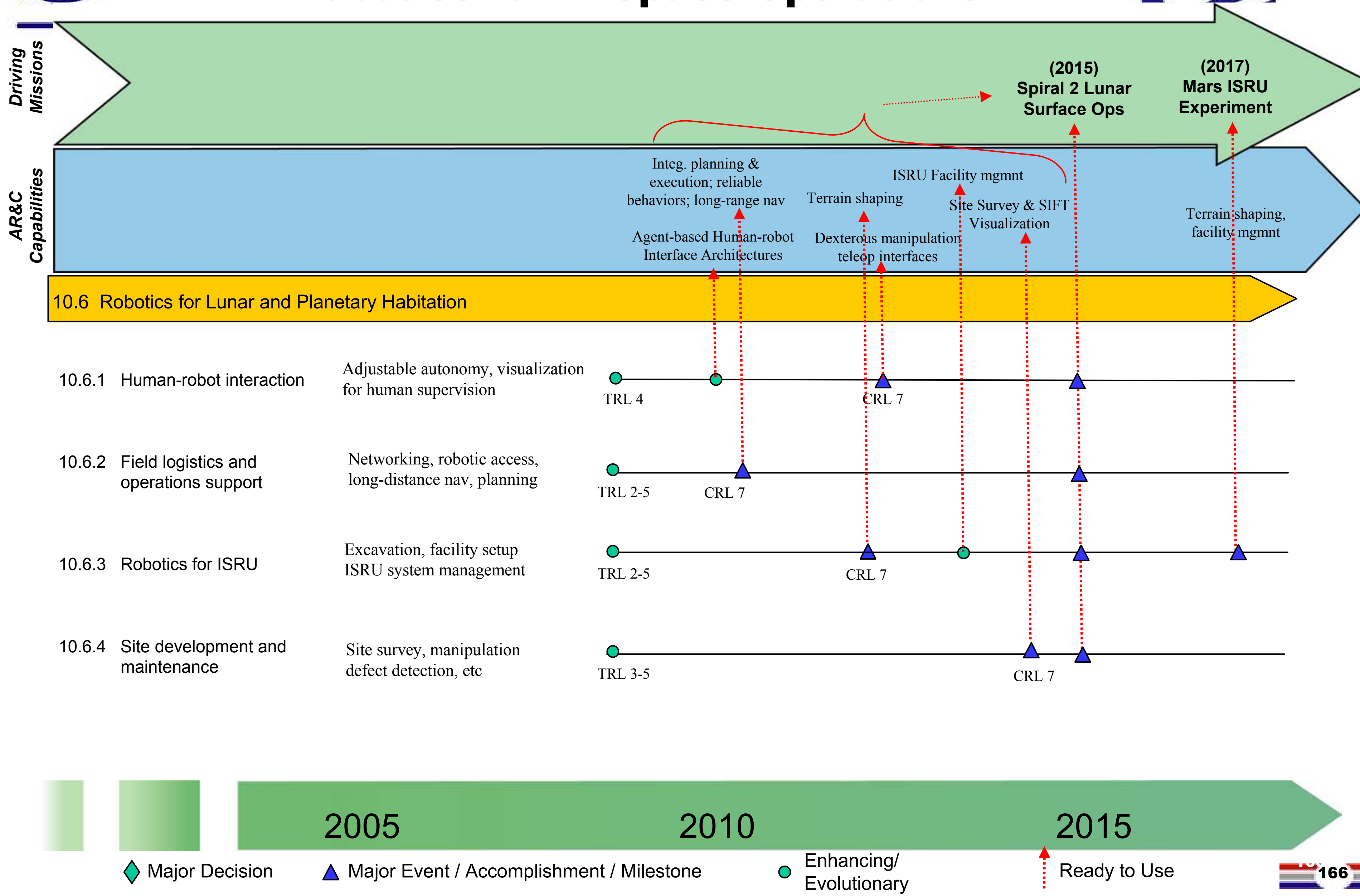
Un-manned Missions

- Lunar robotic missions 2016
- Mars ISRU experiment: 2017
- Mars precursor missions for habitat construction 2025+

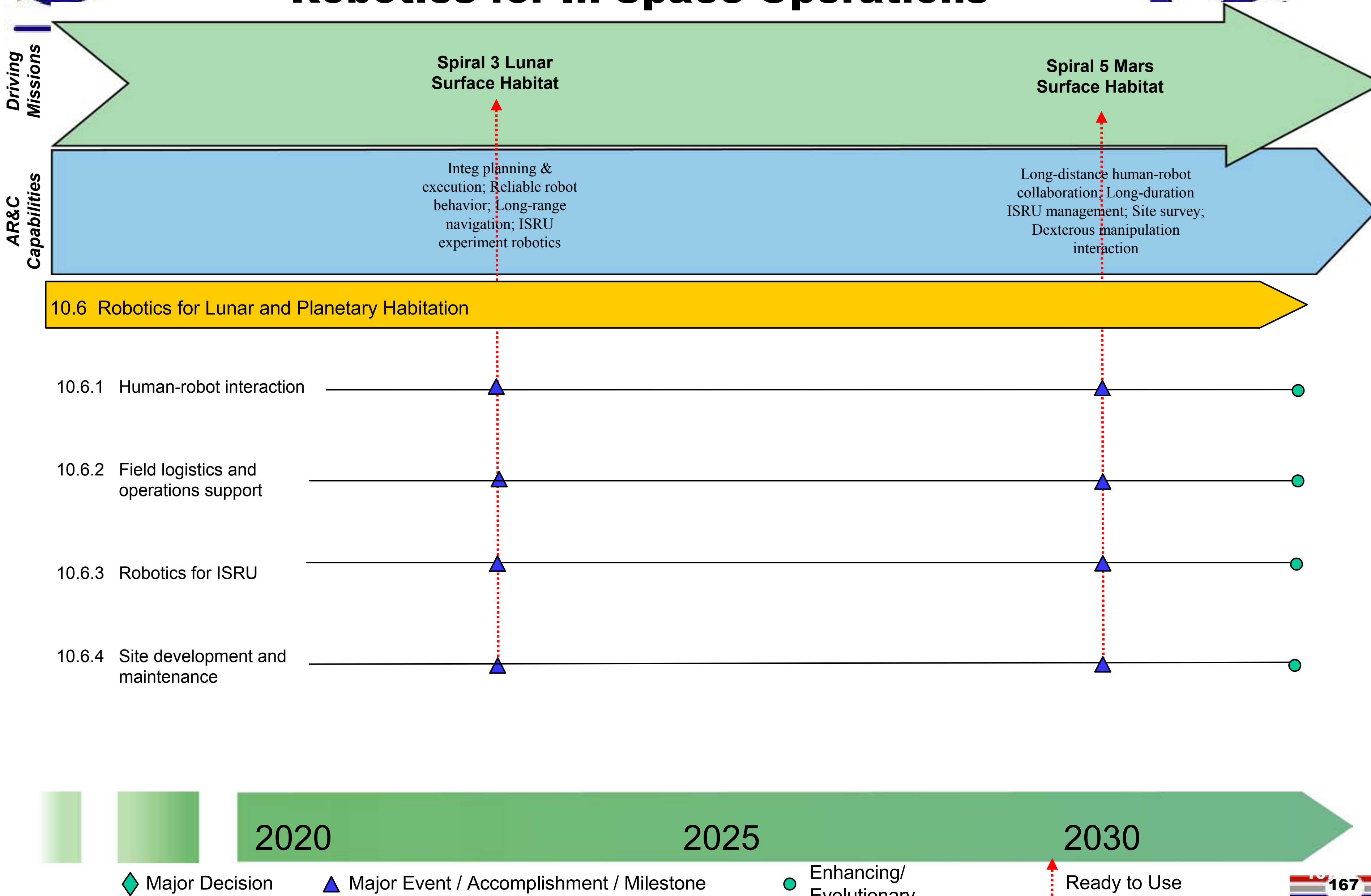
Assumptions

- Human habitation drives primary ISRU need due to requirement for sustainable presence
- Cost and safety arguments will necessitate human-robot teaming and thus human habitation suggests human-robot joint efforts
- Habitation is long-term, not for 6 hours only but days and weeks

Deliverables for Capability 10.6
Robotics for In-Space Operations



Deliverables for Capability 10.6
Robotics for In-Space Operations



Deliverables for Capability 10.6
Robotics for Lunar and Planetary Habitation

- Human-robot interaction, including adjustable autonomy and visualization for human supervision
  - Driver: Spiral 2 (Lunar Lander, Surface Ops), 2015
  - CRL 7 date: 2008
  - Interfaces: 6-RASP
- Field logistics and operations support, including networking, robotic access, long-distance navigation and planning, etc.
  - Driver: Spiral 2 (2015) and Spiral 3, Lunar surface habitat
  - CRL 7 date: 2010
  - Interfaces: 6-RASP and 5-Communication and Navigation
- Robotics for ISRU, including excavation, facility setup, and ISRU system management
  - Driver: Spiral 2 (Lunar Lander), 2015; Mars ISRU Experiment, 2017
  - CRL 7 date: 2012
  - Interfaces: 13-ISRU
- Site development & maintenance, including site survey, manipulation, defect detection, etc.
  - Driver: Spiral 2, Surface Ops and Spiral 3, Lunar/Mars surface habitat (2020)
  - CRL 7 date: 2015
  - Interfaces: 9-HES&M

Deliverable Definitions

– **Human-robot interaction, including adjustable autonomy and visualization for human supervision**
  - Humans must operate and supervise robotic and human-robot team systems, from direct robot teleoperation in close quarters and over long distance to remote supervisory strategic commanding and guidance, including human/robot task allocation, flexible multi-team member task allocation, adjustable autonomy, and supervision of work crews.

– **Field logistics and operations support, including networking, robotic access, long-distance navigation and planning, etc.**
  - In order to enable material transport, refueling, equipment transport, long-distance exploration, field science and other activities, technology must enable mobile networking, remote telepresence for mixed local-remote exploration and science teams; robotic access to otherwise inaccessible extreme terrain, autonomous planning, execution and control for long-distance and long-term operations and intelligent energy management for hybrid power systems. (Moderate risk)

– **Robotics for ISRU, including excavation, facility setup, and ISRU system management**
  - Robotics will play a critical role in supporting both precursor and ongoing activities for ISRU, including facility setup (piping setup, tracking assembly, site preparation); site terrain shaping and excavation for both teleoperated and autonomous robotic team large-scale excavation / terrain shaping; and system-level ISRU feedback, maintenance, inspection, adjustment and control. (High risk)

– **Site development & maintenance, including site survey, manipulation, defect detection, etc.**
  - From initial site survey, initial construction and resource deployments and collection to ongoing inspection, repair and regular maintenance operations, robotics will provide support for site development and long-term maintenance. Robotic technologies will include dexterous manipulation, perception, resource collection and warehousing control, site clean-up, site survey and visualization and visualization, parts collection and preparation for construction, communication and navigation infrastructure deployment. (High risk)

Breakthrough Capabilities for Robotics for Lunar and Planetary Habitation

Visual learning and recognition

- Although advances in vision are consistent and of great practical use, especially recent object recognition work in the vein of spatially invariant feature detection, breakthrough advances in the areas of visual recognition of human-made and natural objects across extreme environmental variation, coupled with *learning*, enabling fielded humans to explain and identify what characteristics to look for and how to categorize what is seen for interpreted perception, would significantly lower the cost and risk associated with robotic inspection and robotic manipulation of structures. This capability has the potentially to trigger one to rethink the costs of long-duration stays on the moon and on Mars.

Robotic tactile dexterity

- Best forecasts will project that robotic dexterity will approach that of a EVA-suited human in the near future. If revolutionary advances in robotic tactile, feedback-based manipulation enable human naked hand-level dexterity and specific energy with human-level tactile feedback, this would completely change the regime of tasks that will be performed by robots during surface habitation activities. This revolutionary progress, requiring both changes in muscle motor technology and surface sensing technology, would dramatically lower the cost of in-space and surface assembly and maintenance activities by more than an order of magnitude.

Maturity Level – Capability 10.6
Robotics for Lunar and Planetary Habitation

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Site development & maintenance	Site Survey & Visualization	3-5	6	Spiral 2	2015
	SIFT-based Visual detection	3-5	6	Spiral 2	2015
Site maintenance	SIFT-based Visual defect detection	3-5	6	Spiral 2	2015
Field logistics & operations support	Integrated planning & execution systems	2-4	6	Spiral 2,3	2010
	Reliable Atomic Robot Behaviors	2-5	6	Spiral 2,3	2010
	MER long-range rover navigation	[+]	6	Spiral 3	2025

Maturity Level – Capability 10.6
Robotics for Lunar and Planetary Habitation

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Human-robot interaction	Agent-based Human-Robot Interface Arch.'s	4	6	Spiral 2	2008
	Dexterous manipulation teleop interfaces	4-5	6	Spiral 2	2008/2012
Robotics for ISRU	Terrain Shaping	2-5	6	Spiral 2, Mars ISRU exp	2010/2010 +
	Facility setup, ISRU management	2-3	6	Spiral 2, Mars ISRU exp	2012

Maturity Level – Technologies for Capability 10.6 Robotics for Lunar and Planetary Habitation

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Integrated Planning & Execution Systems		Three-tiered planning, sequencing and executive systems	2-5	Flexibility, Scale	2010
Agent-based Human-Robot Interface Architecture	Architecture, Dialogue handling, Comm. Network	KQML message-passing semantic protocols for agent interoperation	4-5	Field trialing	2008
Reliable atomic robot behaviors	Sensor and actuator logic	Numerous in research	2-5	Robustness, Predictability	2010
Terrain shaping	Excavation, soil planning, handling	Scanner-based topology modeling and scanning plus force-controlled 2 DOF excavation	4-5	Robustness, field trialing	2010/ 2020
Site Survey and Visualization	Safe approach, tracking, planning	Single cycle instrument placement	5-6	Remote site broad survey	2015
Vision-based defect detection and Object recognition	Object modeling, training, tracking	Spatially invariant visual feature tracking	3-5	Robustness, illumination	2015
Dexterous manipulation teleoperation interfaces		Human-level high DOF teleoperation robots	4-6	Control lag, robustness, cost	2012
Long-range autonomous navigation		Visual odometry-based closed loop navigation	5-6	Workload	2020

Metrics for Capability 10.6
Robotics for Lunar and Planetary Habitation

Advanced Planning & Integration Office

Metric	Technology / Sub-Capability	SOA	Target Value Fig of Merit	Need Date
# human interventions per task	Site development & maintenance	> 10	< 3	2012
Structural connections per hour	Site development	< 10	> 30	2015
Average distance navigated per human intervention	Field logistics and operations support	<100m	1000m+	2020
Proportion of navigation goals achieved	Field logistics and operations support	96% (MER)	99%	2020
% reduction of human cognitive load	Human-robot interaction	<< 10%	25%	2008 (OASIS)
Maximum parallel human-robot supervisions	Human-robot interaction	~ 1	3+	2020 (Mars)
Cubic meters excavation per hour	Robotics for ISRU	?	?	2015

Capability 10.7
Robotics for In-Space Operations

Sub-Team Chair: Ron Diftler, NASA/JSC

Presenter: Paul Schenker, JPL

Capability 10.7
Robotics for In-Space Operations

- **This capability area defines the robotic systems needed for assembly, inspection and maintenance, and human-robot interaction in space. This includes:**
- **Assembly**
  - Mass Manipulation (large, medium, small, fragile)
  - Preparation (Unpack, Identify, Order, …)
  - Connecting (Align, mate, verify)
  - Self Assembly (deployment, docking, etc..)
- **Inspection**
  - Structural (Mechanical Damage, Air Leaks, Deterioration)
  - Access (Under Thermal Blankets, Delicate Surfaces, Confined Space locations)
  - Component/System Failure Detection (Fault Detection, Non- Destructive Eval)
- **Maintenance**
  - Mass Manipulation (Medium, Small)
  - Locomotion (moving to points along fragile structures)
  - Staging, (Protection Removal, Temporary Stowage, Connector removal, etc…)
  - Human Rated Interface Manipulation (Crew and Robots use same interface to manipulate objects)
  - Dexterous Manipulation
- **Human-robot interaction**
  - Multi-agent teams (Assistants, Surrogates)
  - Intent Communication (Feedback, Task Verification, …)
  - Time Delay Compensation

Benefits of Capability 10.7 Robotics for In-Space Operations

- **In-Space Robotics assembly** is *enabling* for building exploration systems too large for single launch – solar tugs, large telescopes, space stations, etc…
- **In-Space Robotic Inspection** is *enabling* for reducing crew workload, thereby reserving crew time for science and exploration and for providing more precise results.
- **In-Space Robotic Maintenance** is *enabling* for reducing crew workload, thereby reserving crew time for science and exploration.
- Additional benefits:
  - Reduced EVAs → Increased Safety, Reduced crew Health issues
  - Enhancing the option for nuclear operations
  - More options from an operations standpoint, i.e., Minuteman
  - Support unmanned CEV, Ground control operations

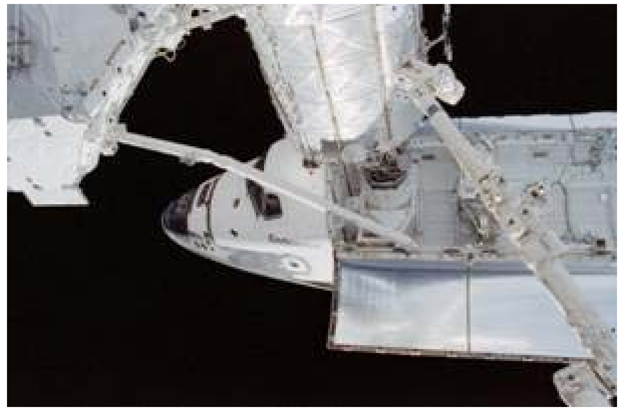
Current State-of-the-Art for Capability 10.7 Robotics for In-Space Operations

- **The state of the art for robotics for In-Space Operations includes the Shuttle Arm, Station Arm, Japanese ETS VII arm, ROTEX, MFD, Inspector, XSS-10, AERCam/Sprint, Charlotte.**
  - Simple end-effectors requiring dedicated robotic interface
  - Operational target based vision systems
  - Experimental force sensing.
- **The state of the art for In-Space Robotic Control Operations:**
  - SRMS release and capture of satellites – Bread and Butter
  - Teleoperation and ground control,
  - Stored sequences for control mode.
  - Single Arm manipulation
  - Limited time delay compensation for USA
  - ROTEX – autonomous capture of ball via ground control – IVA Experimental Flight
  - Supervised Autonomy work performed by Japanese: ETS-VII – Experimental flight
    - Worked with Significant time delay

Current State-of-the-Art for Capability 10.7 Robotics for In-Space Operations

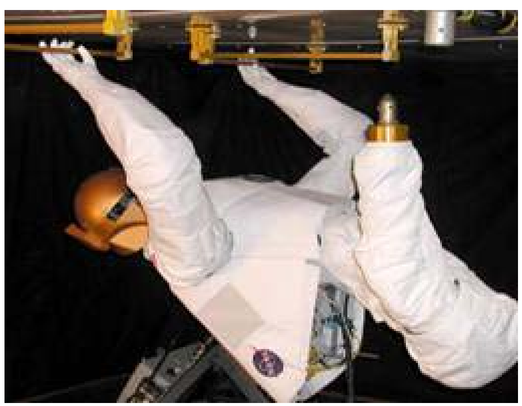
- The state of the art for In-Space Robotic Assembly:
  - SRMS and SSRMS work horses – Manual Control
  - Proven Large Mass Manipulation - ISS
- The state of the art for In-Space Robotic Inspection:
  - Surface Inspection Only
  - Human visual inspection through robotic cameras
  - Japanese MFD/Shuttle experiment - surface flaw detection
  - AERCam/Sprint Experiment – visual data
  - Ground Control starting for SSRMS
- The state of the art for In-Space Robotic Maintenance:
  - All experimental – task board – ETS VII
- The state of the art for Human/Robot Teams:
  - Crew Positioning using Shuttle, Station arms
  - Release and re-capture of free flyer AERCam/Sprint
  - Human finalizing mating after arms dock large payloads

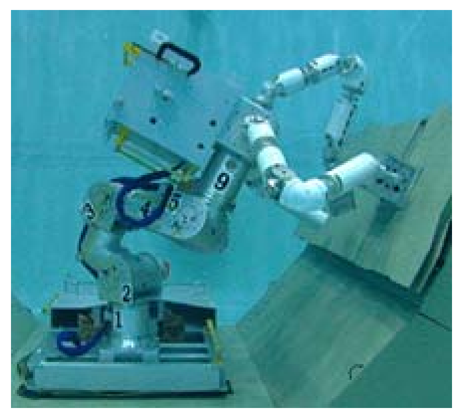
Current State-of-the-Art for Capability 10.7 Robotics for In-Space Operations



Above: flight

Below: R&D



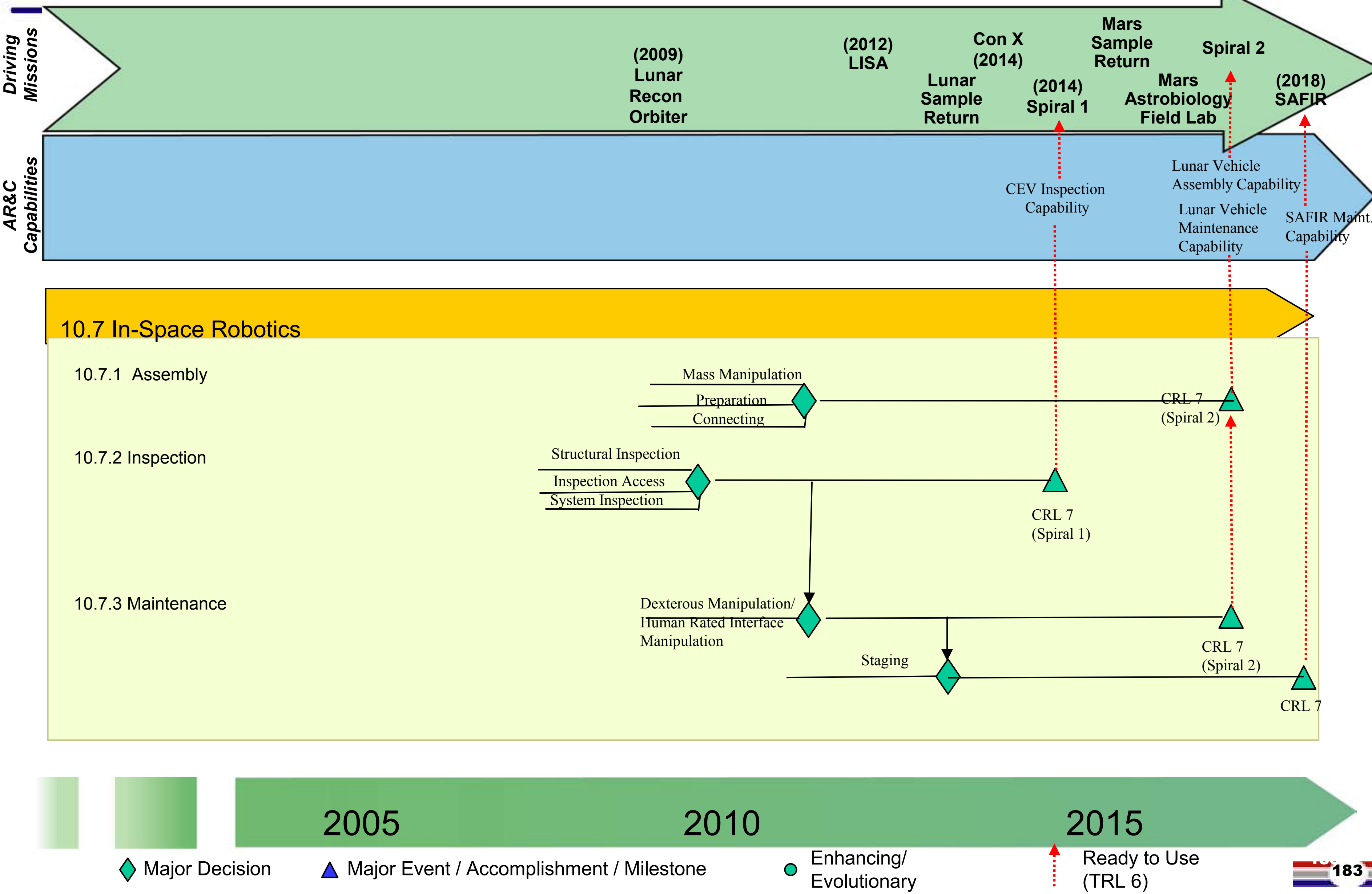


In-Space Robotics in Support of Manned Missions

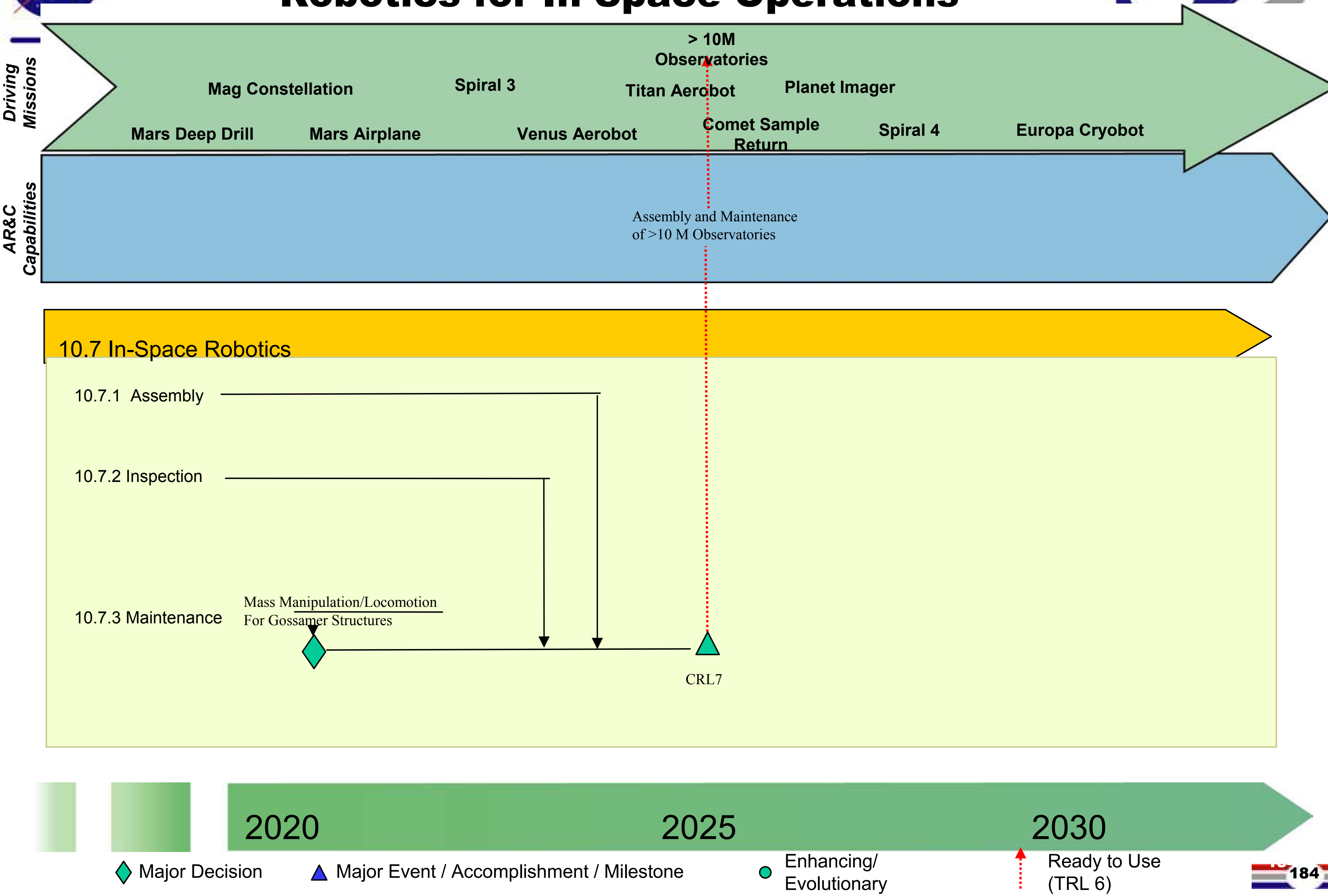
- **Spiral 1: 2014** CEV LEO
  - Robotic Inspection
  - Robotic Maintenance
- **Spiral 2: 2015-2020** CEV LLO and EVA lunar surface ops
  - Robotic Assembly of Lunar Vehicles
  - Robotic Inspection and Maintenance of Lunar vehicles
  - Multi-Agent Teams
- **Spiral 3: 2020** Lunar surface habitat
  - Robotic Maintenance of In-Orbit Systems
    - Space Solar Power Plant
- **Spiral 4: 2025** Mars transit and vicinity ops
  - Robotic Assembly of Mars Vehicles
  - Robotic Inspection and Maintenance of Mars vehicles
- **Spiral 5: 2030+** Martian surface habitat and exploration
  - Robotic Maintenance of In-Orbit Systems
    - Space Solar Power Plant

- In-Space Robotics in Support of Unmanned Missions
  - **Observatories**
    - Robotic Inspection and Maintenance for Telescopes
      - LEO -
      - GEO -
      - L1 -
      - L2 – SAFIR -2016, Observatories > 10 Meters - 2020

Deliverables for Capability 10.7
Robotics for In-Space Operations



Deliverables for Capability 10.7 Robotics for In-Space Operations



Deliverables for Capability 10.7 Robotics for In-Space Operations

- Inspection (internal, external, automated, sniffers)
  - Driver - CEV
  - Spiral 1 – TRL6 - 2009
  - IST, ATO
- Access for Inspection
  - Driver – CEV (Nozzles, panels, bays, radiators)
  - Spiral 1 – TRL6 - 2009
  - IST, ATO
- Connecting (Align, mate, verify, all power, fluid systems not just docking)
  - Driver – Assembly of Lunar Vehicles
  - Spiral 2 – TRL6 - 2010
  - IST, ATO

Deliverables for Capability 10.7 Robotics for In-Space Operations

- Dexterous Manipulation/Human Rated Interface Manipulation
  - Driver – Maintenance of Lunar Vehicles
  - Spiral 2 – TRL6 - 2010
  - IST, ATO, HESM
- Staging (Protection Removal, Temporary Stowage, Connector removal, etc…)
  - Driver – SAFIR Telescope Maintenance
  - Other– TRL6 - 2016
  - IST, ATO
- Mass Manipulation/Locomotion (Gossamer structures, multi-segmented reflectors)
  - Driver – Advanced Observatories > 10 Meters
  - other– TRL6 - 2020
  - IST, ATO

Deliverable Descriptions for Capability 10.7 Robotics for In-Space Operations

- Inspection (internal and external)
  - Visual and non-visual inspection through cameras, laser range images, hydrazine sniffers, leak detectors, etc.. on free flyers, manipulator end effectors, climbing robots. Looking for micrometeoroid damage, launch damage. Part of this done manually from the ground and on orbit. Need to increase precision and automation. (some risk)
- Access for Inspection
  - The ability to remove protective coverings to gain entry for inspection: panels, blankets. The ability to inspect in hard to reach areas: inside nozzles, along radiators. (moderate risk)
- Connecting (Align, mate, verify, all power, fluid systems not just docking)
  - Currently crew goes out and makes a significant portion of power, fluid, communication connections after arms dock modules. Future robots/vehicles should provide this capability for unmanned assembly prior to crew arrival. (some risk)

Deliverables Descriptions for Capability 10.7 Robotics for In-Space Operations

- Dexterous Manipulation/Human Interface Manipulation
  - Future vehicles for the moon will be complex modular, reconfigurable systems. A high level of dexterity in both manipulator arms and hands will be needed to efficiently work with these vehicles. (moderate risk)
  - All lunar vehicles that require maintenance will require human interfaces or special tooling to interface with robotic interfaces. Human rated interface manipulation would eliminate the need for both robot and human interfaces and special tooling to make robotic interfaces compatible with EVA gloves. (high risk)

- Staging (Protection Removal, Temporary Stowage, Connector removal, etc…)
  - Space Station planned robotic maintenance is limited to removal and replacement of boxes with robotic interfaces. A future capability will incorporate removal of numerous parts, ordering, temporary stowage, part preparation for removal and insertion, etc…. Robots need this capability to off-load crew. (high risk)

- Mass Manipulation/Locomotion (Gossamer structures, multi-segmented reflectors)
  - Observatories with large than 10 meter mirrors can not be launched in a single vehicle. A manipulation system that will apply minimal loads during assembly and maintenace is required for these unmanned systems. (high risk)

Breakthrough Capabilities for 10.7 Robotics for In-Space Operations

Advanced Planning & Integration Office

Mass Manipulation/Locomotion for Gossamer Structures Activities

- Future observatories will employ gossamer structures to achieve maximum aperture size for minimum weight. To achieve this goal a new class of robots is needed that can move across light and fragile structures while imparting minimal loads that may need to be significantly less than those an EVA astronaut would apply during climbing. This breakthrough class of robots will transport the materials for construction, and provide assembly and maintenance capabilities. Multi-legged systems that can distribute loads widely over a structure and minimize forces during motion are a prime candidate for achieving this capability. Efficient free fliers are a secondary candidate.

Space Suit Level Human Dexterity

- Removing the barrier between tasks performed by suited crew and robots will provide an immense cost savings by eliminating the need to provide a separate set of tooling for both robots and suited humans. In-Space operations will change dramatically as robots with human level dexterity “earn their stripes” by performing as assistants during EVA in-space operations. The percentage of robotic maintenance tasks currently limited to 50% on space station will grow substantially allowing crew to spend more time exploring and performing science. Human level dexterity will be achieved through a system level approach that combines multi-fingered hands integrated with a manipulator system constructed to provide the dexterous envelope than an astronaut can achieve through entire body motion. In addition, sensing used by both the robot’s automated control routines and tele-operators will provide the necessary feedback to maintain proper force levels during dexterous operations.

Maturity Level – Capabilities for 10.7 Robotics for In-Space Operations

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Structural Inspection (Needs More Automation)	Free Flyers Climbers/Crawlers Machine Vision Manipulators	3-7	6	Spiral 1 – CEV LEO	2009
Inspection Access	Dexterous Robotic Arms Dexterous End Effectors Specialized End Effectors Robotic Bore Scopes	3	6	Spiral 1 – CEV LEO	2009
System Failure Inspection/Detection (cross cutting but included for discussion)	Machine Vision/imagine analysis Fluid Detection: Oxygen Hydrazine, Ammonia Radiation Detection Plasma Detection	2-3	6	Spiral 1 – CEV LEO	2009
Robotic Connecting	Specialized End effectors Multi-fingered Hands Force Control	4-5	6	Spiral 2 – CEV LLO and EVA lunar surface	2010
Dexterous Manipulation	Small high DOF arms Multi-fingered Hands Force Control Proximity/Tactile Sensing	4-6	6	Spiral 2 – CEV LLO and EVA lunar surface	2010

Maturity Level – Capabilities for 10.7 Robotics for In-Space Operations

Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Staging – maintenance	Small High DOF arms RF ID-Tags Machine Vision End Effectors/Hands	4-6	6	SAFIR Telescope	2016
Human Rated Interface Manipulation	Small high DOF arms Multi-fingered Hands Force Control Proximity/Tactile Sensing	4-5	6	Spiral 2 – CEV LLO and EVA lunar surface	2010
Mass Manipulation (Large) (SSRMS Proven)	Large Robotic Arms Free Flyers for Moving Mass	2-7	6	Spiral 3/4 – LLO/ Mars Transit vehicles	2010
Mass Manipulation (Gossamer Structures)	Low Reaction Force Crawlers	2	6	Observatories > 10 meters	2020

Maturity Level – Technologies for 10.7 Robotics for In-Space Operations

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Free Flyers for Inspection	Propulsion System Miniaturized Sensors	Rechargeable Propulsion, Docking System MEMS gyros	4-6 5-6	Integrated Ground/Flight Test	2009
Machine Vision beyond targets	Camera Calibration Object Recognition Pose Estimation	Patterns Templates Templates	5 4 3	Environmental Speed/Memory Robustness	2009
Climbers/Crawlers	Low Backlash Actuators	Harmonic Drives	4-9	Packaging	2009
Small, Medium Sized Manipulators	High Power Density Motors Miniature Motor Drivers Miniature Sensors	Rare Earth Hybrids Optical	6-9 4-9	Packaging Packaging Packaging	2010
Force Control	Load Cells	6- Axis load cells	4-7	Temperature Compensation, Size	2010

Maturity Level – Technologies for 10.7 Robotics for In-Space Operations

Technology	Components	Candidates	Current TRL	Key Gaps	Need Date
Multi-Fingered Hands	Miniature High Output Actuators	Brushless DC	7-9	Size	2010
		Magnetic Shape Memory	2-3	Packaging	
	Miniature Sensors	Hall Effect	4-6	Reliability	
Proximity/Tactile Sensing	Proximity Sensors	LEDs	4	Environmental	2010
Large Robotic Arms	Low Backlash Gearbox	Large Harmonic Drives	4-6 (9- smaller ones)	scale	2015
Free Flyers for Moving Large Mass	Propulsion system	Stored Gas	0	efficiency	2015
Low Reaction Force Crawlers	Force Control	Damping Control	4-7	Computational Capability Sensor Environmental Issues	2020

Metrics for 10.7
Robotics for In-Space Operations

Metric	Technology / Sub-Capability	Target Value	Need Date
Time to Inspect CEV for external structural damage	Autonomous Free Flyer/ Structural Inspection	2 hours	2009
Time to Inspect CEV engine Nozzle	Tendril Robot/Inspection Access	1 hour	2009
Percentage of Robotic connector Mating for Lunar Vehicle	Specialized End Effector/ Assembly Connecting	80%	2010
Percentage of Robotic Maintenance on Lunar Vehicle	Multi-fingered Hands/Dexterous Manipulation	90%	2010
Percentage of tools used by Robot and EVA	Multi-fingered Hands/ Human-Robot Interface Commonality	95%	2010
Successful Robotic Telescope Repair	Dexterous Manipulators/ Maintenance Staging-Connecting	1	2016
Force Level while transversing a Gossamer structure	Crawler robots/ Mass manipulation on Gossamer Structure	< 2 N	2020

Overview

- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- **Computing Systems (Mike Lowry)**
- Conclusion

Autonomy and Robotics Capability 10.8 Computing Systems (Robust Software)

NASA Co-Chair: Michael Lowry, Ames
External Co-Chair: Michael Evangelist, CMU

March 30, 2005

Capability

Capability Summary

Robust computing software that provides high assurance for space-based system-level capabilities including command and control, science data handling, vehicle health management, and fault protection functions envisioned over the next 20 years. The purpose of the capability is to provide software mission assurance and cost-effective robust computing for the autonomy and robotic capabilities of the future.

Benefits

- **High assurance:** Enable reliability of software-based capabilities for NASA missions, particularly advanced autonomy and robotic capabilities. Residual design defects will be minimized, and computing systems will have the capability of recovering from hardware faults and software faults. Many error classes will be eliminated.
- **Cost-Effectiveness:** methods for development and validation of aerospace software that minimize human labor. Architectures that facilitate adoption of commercial components where compatible with mission-critical assurance.
- **Sustainability:** software systems that are maintainable over a mission lifecycle. Reuse of components across missions. Migration of software to new flight processors and avionics architectures as hardware technology improves.
- **Predictable Software Engineering*:*** Software development for NASA space systems will be matured into an engineering discipline with a well-understood trade-space and trusted products. As early as mission trade studies, the trade-space of different software solutions on system-level functions will be capable of being analyzed.

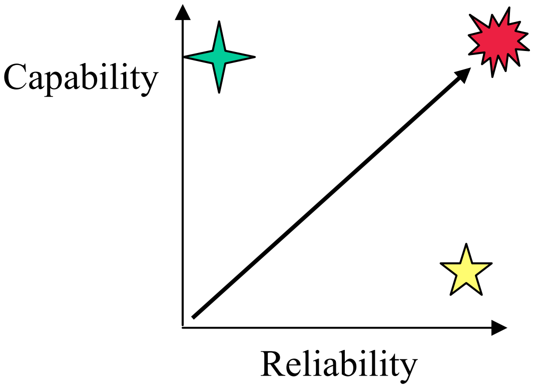
Capabilities

1. **Advanced testing and analytic tools** that provide assurance better than hardware-in-the-loop (HIL) high-fidelity testbeds alone.
   - Advanced testing enables covering an order of magnitude more scenarios without increasing cost and human labor.
   - Analytic tools provide guaranteed assurance of absence of many error classes.
2. **V&V for Autonomy and Adaptive Systems**
   - Methods that enable reliability for capability 10.
3. **Fault Tolerance** for computing faults.
   - Smart redundancy, micro-rebooting, software-enabled radiation tolerance, fault containment, software fault recovery.
4. **Model-based software development**.
   - Certifiable and automated software generation from engineering design models and requirement specifications.
   - Cost-effective maintenance, upgrade, and recertification.
5. **Predictive Models of software engineering** components, methods, and technologies.

State of Art

Advanced Planning & Integration Office

Commercial sector historically stresses time-to-market and capability over assurance. Many commercial software products are mature with only incremental feature upgrades. Large product distribution to amortize development costs. Assurance: statement coverage considered adequate for testing. Size: XP is about 40MSLOC

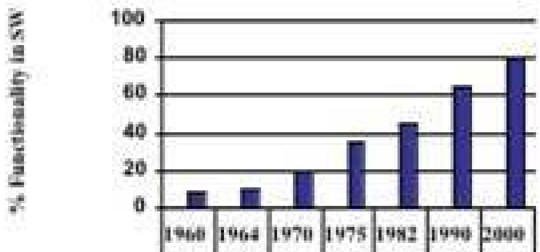


Traditionally aerospace has stressed assurance over cost. Many aerospace systems have limited distribution over which to amortize development costs. Productivity has held nearly constant - rising from 7 to 10 SLOC per person per day over last 20 years. Assurance: extensive branch/statement coverage, MC/DC required for commercial aerospace. Size: ISS is about 2MSLOC

NASA has pacing needs in aerospace computing due to mission length, light-time delays, radiation, lower tolerance for risk. Autonomy and robotics will exceed the limits of traditional aerospace capabilities, but reliability cannot be compromised - it will need to be enhanced. Many NASA systems are one-offs. Size and other risk factors for the software implementing these capabilities is not known, part of the general problem of calibrating software and determining trade-space of solutions.

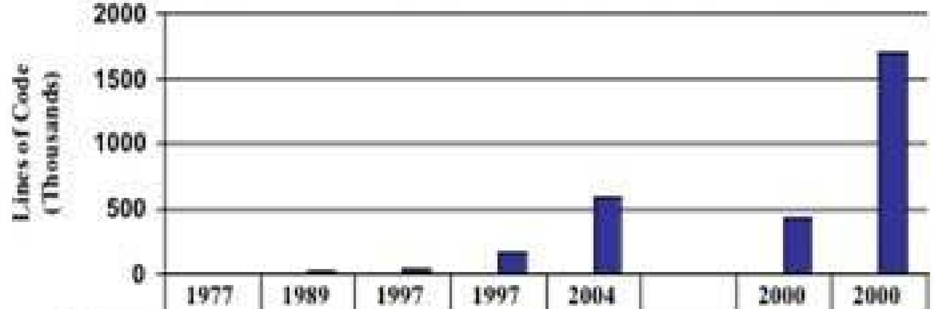
Benefits

Computing systems are the most cost-effective means of implementing a broad spectrum of mission capabilities. Hence over time, an increasing percentage and number of aerospace mission functions reside in computing systems. New capabilities for autonomy and robotics will accelerate this trend. *(Data from military aerospace)*



	1960	1964	1970	1975	1982	1990	2000
System	F4	A7	F11	F15	F16	B2	F22
%SW Funct	8	10	20	35	45	65	80

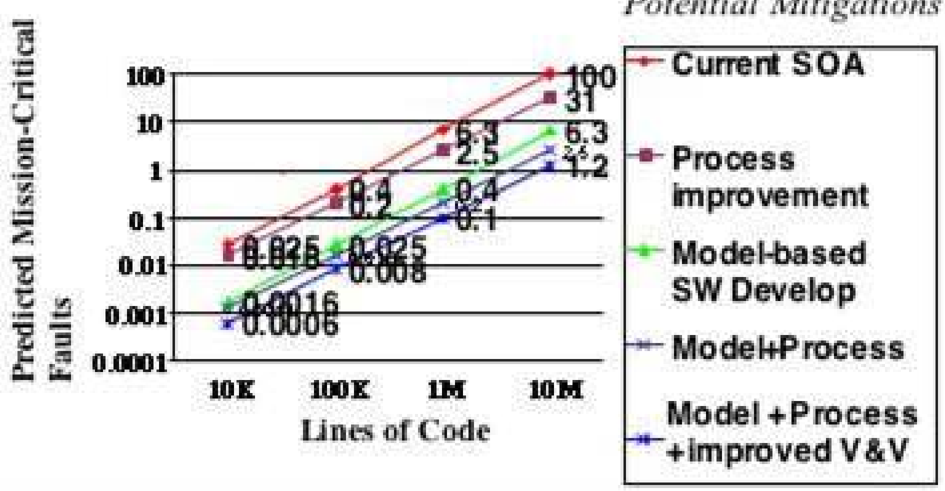
The result is analogous to Moore's law: an exponentially increasing size of flight software systems as the capabilities embedded in aerospace computing systems are increased. *(Data is from NASA robotic and manned mission flight software, by mission date. Progression is by start date of mission development.)*



	1977	1989	1997	1997	2004		2000	2000
Mission	Voyager	Galileo	Cassini	MPF	MER	Manned	Shuttle	ISS
KSLOC	3	8	32	160	580	Missions	430	1700

However, without advances in software engineering for flight systems, these increasing capabilities come at a significant reliability risk, as well as increasing cost and schedule. Residual software defects increase faster than proportional to exponentially increasing size of code (due to supra-linear growth of module-module interactions.) Mission assurance is risked unless better mitigations are developed. New capabilities for autonomy and robotics especially require advances in high-assurance computing. *(Data is extrapolated from COCOMO-based model calibrated to Mars missions SLOC and mission failures.)*
Cost and schedule for flight computing system development follow similar curves and are bottlenecks in mission projects.

Potential Mitigations



Pre-decisional Draft

State of the Art

• Verification and validation of mission software is labor-intensive and expensive, typically accounting for 60% to 80% of overall development costs in mission-critical aerospace software. Validation bottleneck is scarcity of high-fidelity HIL test-stands.

• Computing faults are pervasive in unmanned missions and space station. These are often of little consequence during non-critical mission phases, and typically fixed through reboot. However, there is no known method of finding only those types of errors that are mission-critical. Bleed-through of faults from non-mission critical components to critical components have caused mission failures.

• Aerospace software development is expensive and labor-intensive to meet process-based assurance.

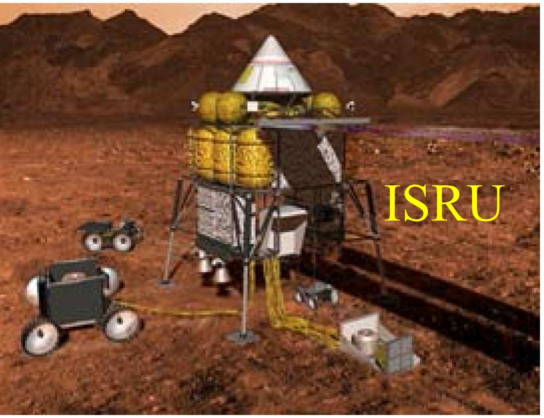
• The superficial malleability of computing systems for implementing changing system requirements leads to addressing computing solutions late in the mission lifecycle - leading to assurance, cost, and schedule problems.

• The tradespace for computing systems solutions - from radiation tolerance through software validation methods through architectures for real-time control - is not well understood.

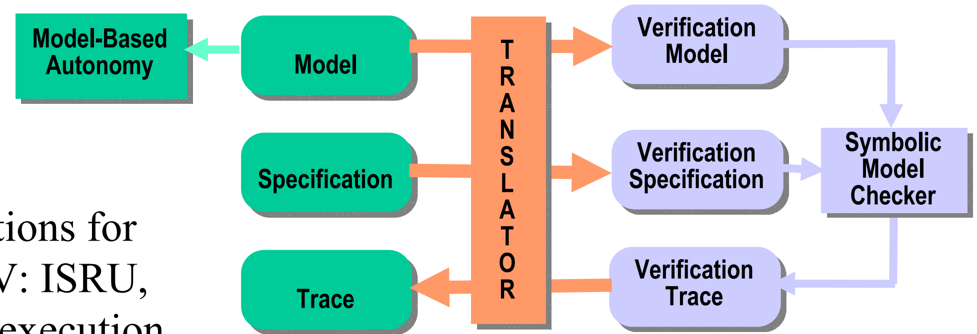
10.8.1: Advanced testing & Analytic Assurance

- **Advanced testing and analytic V&V** methods that provide assurance better than hardware-in-the-loop (HIL) high-fidelity testbeds alone.
  - Calibrated hierarchy of testbeds with accelerated, model-based testing. Massive simulations of critical mission phases such as precision EDL on accelerated software testbeds.
  - Measurement and characterization of false negatives/false positives between HIL and software simulators& analysis tools to optimize use of HIL testbeds.
  - Analytic tools that provide guaranteed assurance for specific error classes (memory out-of-bounds, race conditions, runtime errors, non-compliance with flight rules, etc.)
  - Early lifecycle detection of errors through tool-based analysis at requirements and design level.

10.8.2: V&V for Autonomy and Adaptive Systems

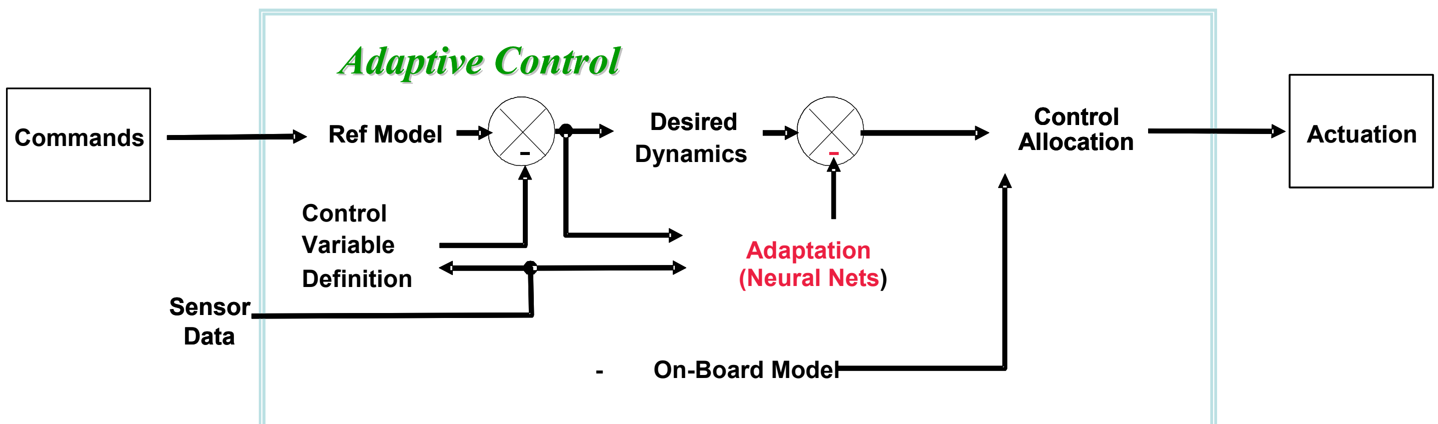


Pacing applications for autonomy V&V: ISRU, ISHM, robust execution, planning and scheduling, etc.



Lyuponov stability analsysis, white-box monitoring of neural net during adaptation scenario simulation, monitoring of adaptation stability during run-time.

Pacing applications for adaptive systems V&V:Mars airplane, aerobots, process control.



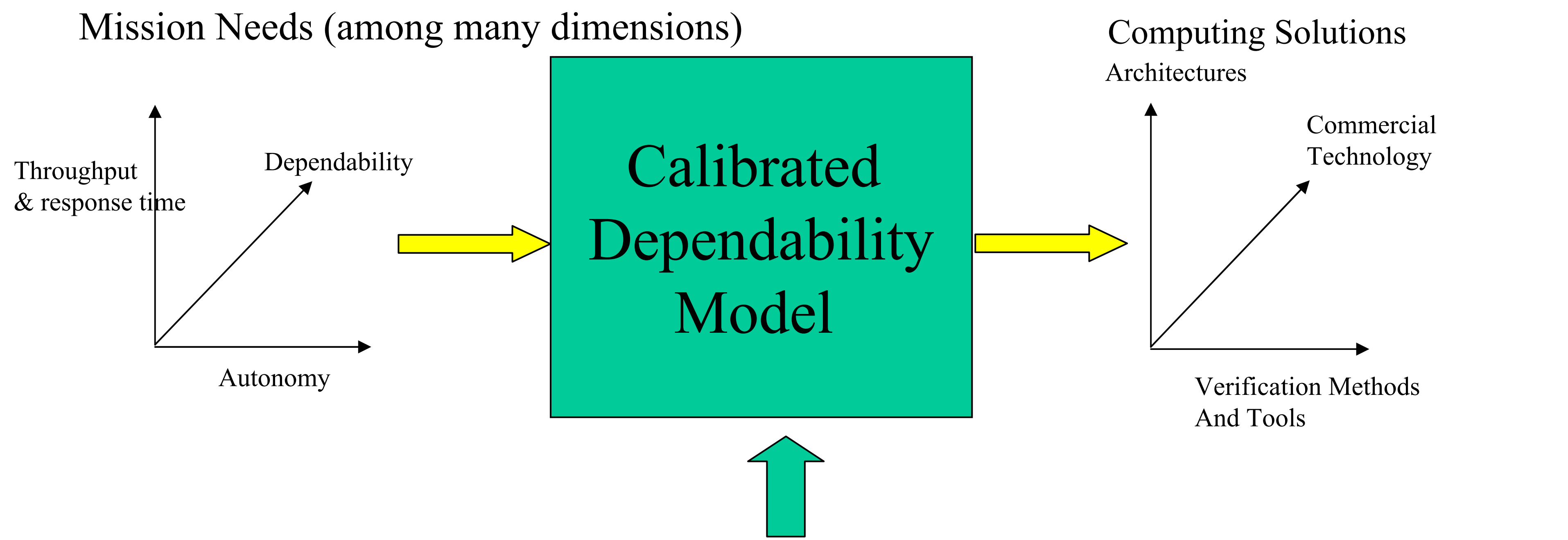
10.8.3 Fault Tolerance

- New approaches to fault handling for both hardware (e.g., radiation) and software faults
  - Smart redundancy (pool of reconfigurable redundant computing resources) for effectiveness and weight/power.
  - Smart software failure detection
  - Software architectures for robust radiation tolerance.
  - In-situ diagnosis of computing faults
  - Firewalls between software at different levels of criticality
  - Recovery through micro-rebooting, automated work-arounds, automated synthesis of component replacements

10.8.4 : Model-Based Software Development

- NASA flight systems will be crossing the threshold where unaided labor-intensive development processes are not effective to achieve the capability and reliability required within constrained cost and schedule.
  - Capture of machine-analyzable and testable requirements.
  - Design models close to engineering models used by sub-system, system, and SOS engineers.
  - Largely automated code generation from design models and requirements with precise traceability to both.
  - Increasing automation of verification, validation, and certification.
  - Support for iterative development, with human effort no greater than scope of changes to requirements and design models. Automation of back-end of ‘V’.

10.8.5: Predictive Models of Software Eng.



RT OS
Architectures
V&V methods
Etc.

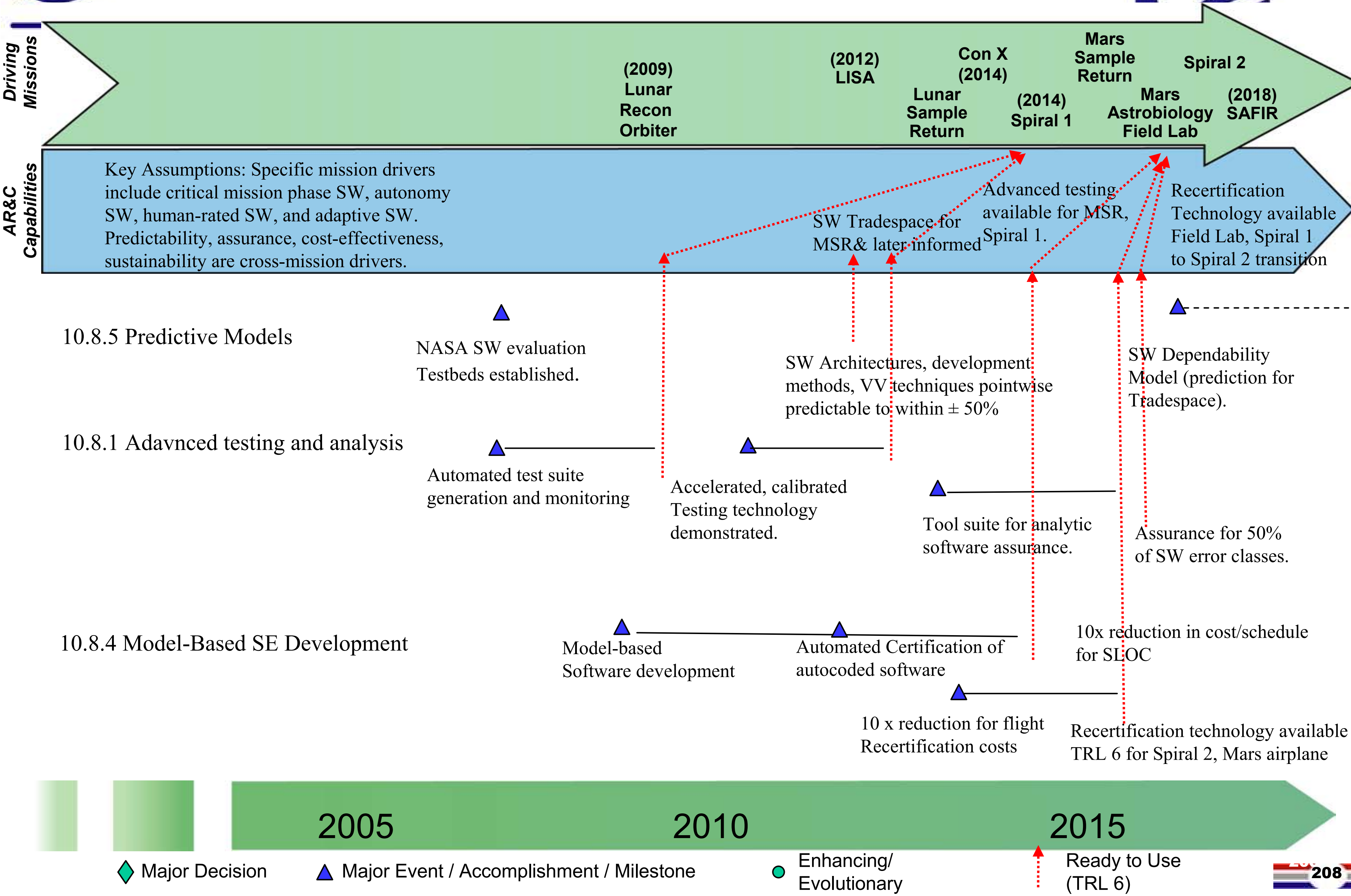
Computing Technology Evaluation Testbeds

Calibration and Validation against NASA needs

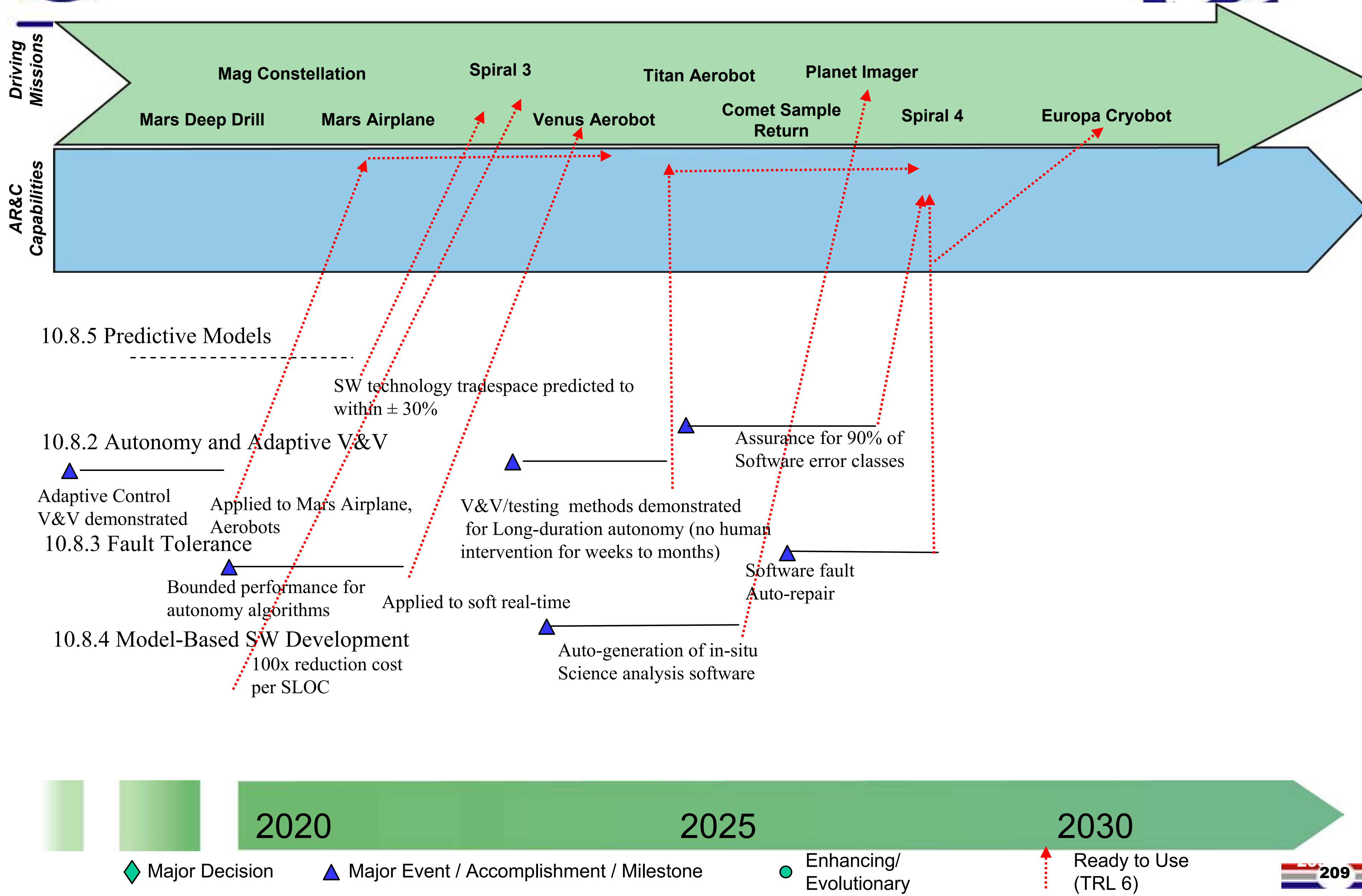
Requirements/Assumptions

- Computing system capability benefits cut across NASA space missions, but technology advances are unlikely to be funded for specific missions.
- The primary driver is safety and mission assurance.
- Secondary drivers are development cost required to support previous and new mission functions, and computing throughput/storage.
- Capability development needs to be designed from the beginning to be used across many different missions to increase safety and decrease cost.
- Barriers to adoption of capabilities need to be addressed:
  - Capabilities need to be validated and evaluated against trade-space for mission design to reduce barrier to mission adoption.
  - Capabilities should be packaged as separably adoptable parts.

Capability 10.8 Computing Systems (Software) Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Deliverables

- **10.8.1 Advanced Testing and Analytical Tools**
  - 10x number of scenarios that can be tested to same level of assurance as high-fidelity testbed at same cost. Example: 10,000 scenarios tested for Mars Sample Return Martian launch at cost of 1,000 scenarios on high-fidelity testbed. (Moderate risk)
  - Residual errors less than .1 per thousands source lines of code (KSLOC) (Moderate risk)
    - Driver: Mars Sample Return
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA
- **10.8.2 V&V for Autonomy and Adaptive Systems**
  - V&V methods for robust execution (slight risk).
    - Driver: Lunar robotic sample return, 2011; all other complex science and exploration missions
    - CRL 7 date: 2009
    - Interfaces: 10.2 AR&C/ISHM, 10.3 AR&C/AVC, 10.4 AR&C/APC&EA
  - V&V methods for model-based diagnosis. (Moderate risk)
    - Driver:ESMD Spiral 1
    - CRL 7 date: 2009+
    - Interfaces: 10.2 AR&C/ISHM, 10.3 AR&C/AVC, 10.4 AR&C/APC&EA, System Engineering
  - V&V methods for adaptive control, with on-board monitoring. (Moderate risk)
    - Driver: Mars Airplane, Aerobots, Process Control
    - CRL 7 date: 2015+
    - Interfaces: 10.3 AR&C/AVC, 10.4 AR&C/APC&EA

Deliverables

- **10.8.3 Fault Tolerance**
  - Software Fault Containment, Robustness for Computer Hardware Faults (Slight risk)
    - Driver: Spiral2&3, MSR
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA, System Engineering, 10.x
  - Software Fault Recovery (Extensive risk)
    - Driver: Spiral 3&4, Europa Cryobot
    - CRL 7 date: 2015
    - Interfaces: 10.2 AR&C/ISHM
- **10.8.4 Model-Based SW Development**
  - Recertification costs reduced to $1000 per thousand source lines of code (KSLOC) (Moderate risk)
    - Driver: Spiral2&3
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA
- **10.8.5 Predictive Models of SW Engineering**
  - Software costs and schedules predictable to within 20% error in 90% of missions (Moderate risk)
    - Driver: Spirals 2&3
    - CRL 7 date: 2010
    - Interfaces: 15-SEC/RA

Maturity Level

Sub-Capability	Technology	Current CRL	Required CRL	Driver	Need Date
Automated/accelerated/ calibrated testing technology	Test suite generation/monitoring	4	6	MSR, Spiral 2	2010
Analytic assurance	Calibration to HIL	3		Spiral 1/2	
Software Engineering Technology Evaluation Testbeds	JIT testbed, instrumentation	4-5	6	Spiral 2	2009
Fault Tolerant hardware and software	Comp. Architect,	3-5	6	MSR, Spiral 2	2012
Certified automated SW generation	Integrated generation and V&V	4-5	6	Spiral 2	2009
Maintainability& reusability	Iterated develop. Environments/tools	3	5	Spiral 2	2009
Precision recertification	Dependency analysis, targeted Testing	3	6	Spiral 2	2012

Capability Need/Gap Assessment

Advanced Planning & Integration Office

Sub Capability			
Predictive Models of Software Engineering	Variance between predicted metrics and actual metrics (parameterized by mission phase from trade studies through deployment).	Software engineering architectures/methods/technologies are not considered until late in mission lifecycle. Familiarity of design team with past mission software engineering practices.	Evaluation testbeds for software engineering technologies, to enable transition of new SW technologies to missions.
Advanced Testing and Analysis tools **Fault Tolerance** **V&V Autonomy and Adaptive Systems**	Residual defects Measurable assurance Computing fault tolerance Assurance for advanced autonomy, robotics, adaptive control	Expensive and exhaustive testing on high-fidelity testbeds Human review with limited tool support (e.g., code scanners). Expensive low-level hardware redundancy. Coarse methods of fault tolerance. Demonstrations of model compliance for model-based autonomy, model-checking for robust execution, black-box monitoring of adaptive systems.	Calibrated hierarchy of testbeds with accelerated, model-based testing. Analytic, tool-based approaches. Assurance based on solid engineering principles, validated by space-flight. Smart redundancy . New approaches to fault handling for both hardware (e.g., radiation) and software faults. Model-validation, automated checking of robust execution systems, envelope and white box monitoring of adaptive systems

Capability Need/Gap Assessment

Sub Capability			
Model-Based SW Development	Development cost per LOC/function Develop time (i.e., time elapsed from design to code)	Custom programming. 7loc/developer/day	Product families Certified software generation from engineering models
Model-Based SW Development	Maintainability Reusability Recertification	V&V are bottlenecks in maintenance Š even bug fixes are seen as risky. Estimated 25% reuse of MPF on MER. Full-up revalidation testing.	Tools and methods for iterated development that address V&V Lightweight architectures Targeted recertification testing through dependency analysis

Metrics

Metric	Benefit / Sub-Capability	SOA	Target Value	Need Date
Predictable performance of Software Engineering Technologies and Methods	High Assurance/ Cost-effectiveness	Anecdotal/ Qualitative	± 30%	2014
Residual defects per KSLOC for flight software	High Assurance	0.5 to 2	< 0.01	2012
Measurable Assurance - % Error classes excluded	High Assurance	< 15%	> 90%	2016
SLOC /person/day	Cost-effectiveness/ High Assurance	7	>100	2012
Recertification cost per KSLOC of system	Sustainability	$10K (ISS)	< $1K	2012
Maintenance cost - KSLOC maintained per person	Sustainability	<1.2 (Shuttle)	> 100	2014

Capability 10.9
Flight Avionics

Sub-Team Chair: Leon Alkalai, JPL
Presenter: Leon Alkalai?, JPL

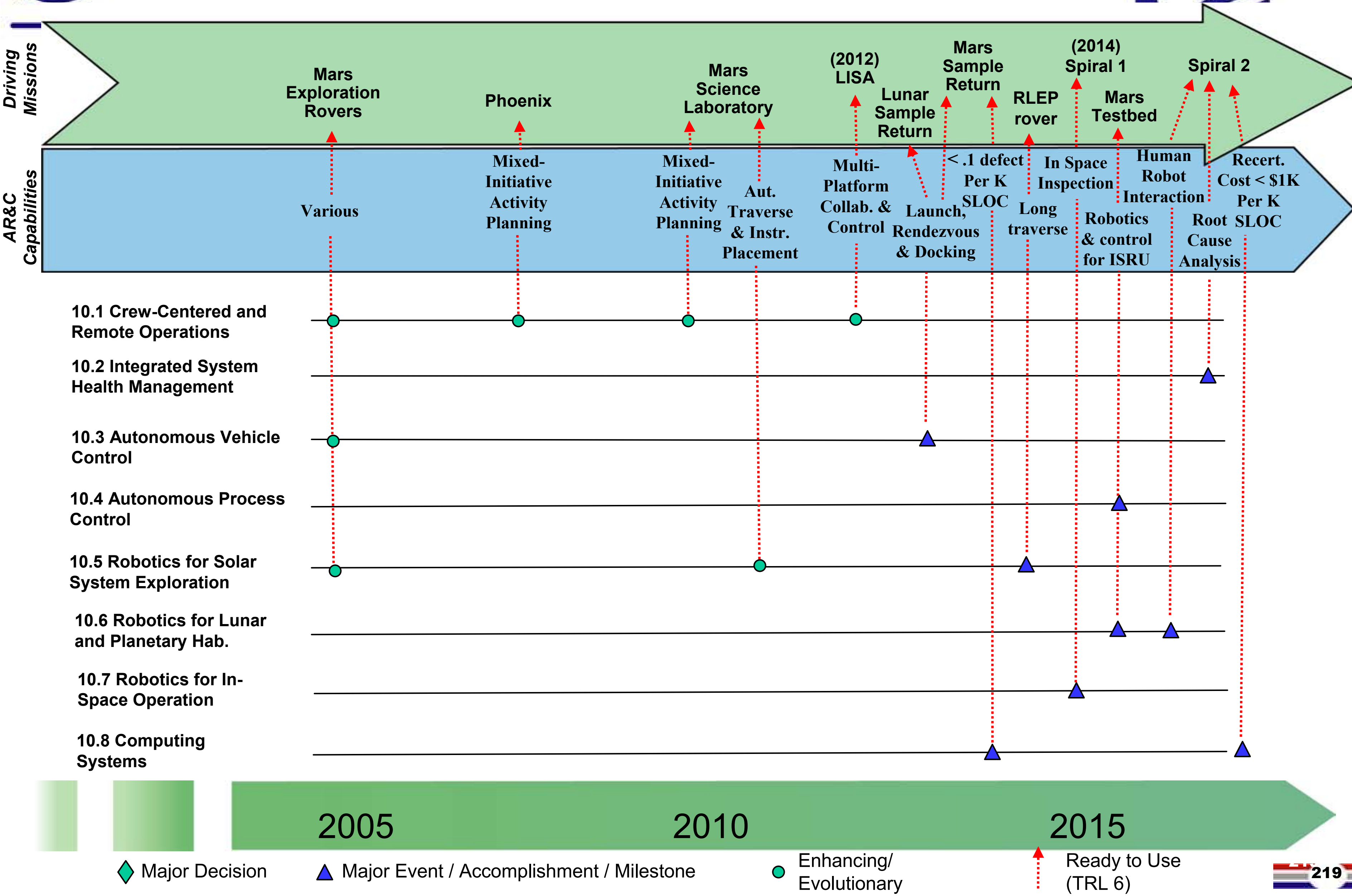
Capability 10.9
Flight Avionics

- **This capability** is to provide NASA missions with a standard set of hardware components that can be adapted and customized to fit mission-specific needs.
  - Flight Computers
  - Data Storage
    - Volatile
    - Nonvolatile
  - Interface/Buses (I/O)
  - Engineering Sensors
  - GN&C Sensors
  - Power management and distribution
- **Which of these sub-capabilities should be considered within AR&C?**

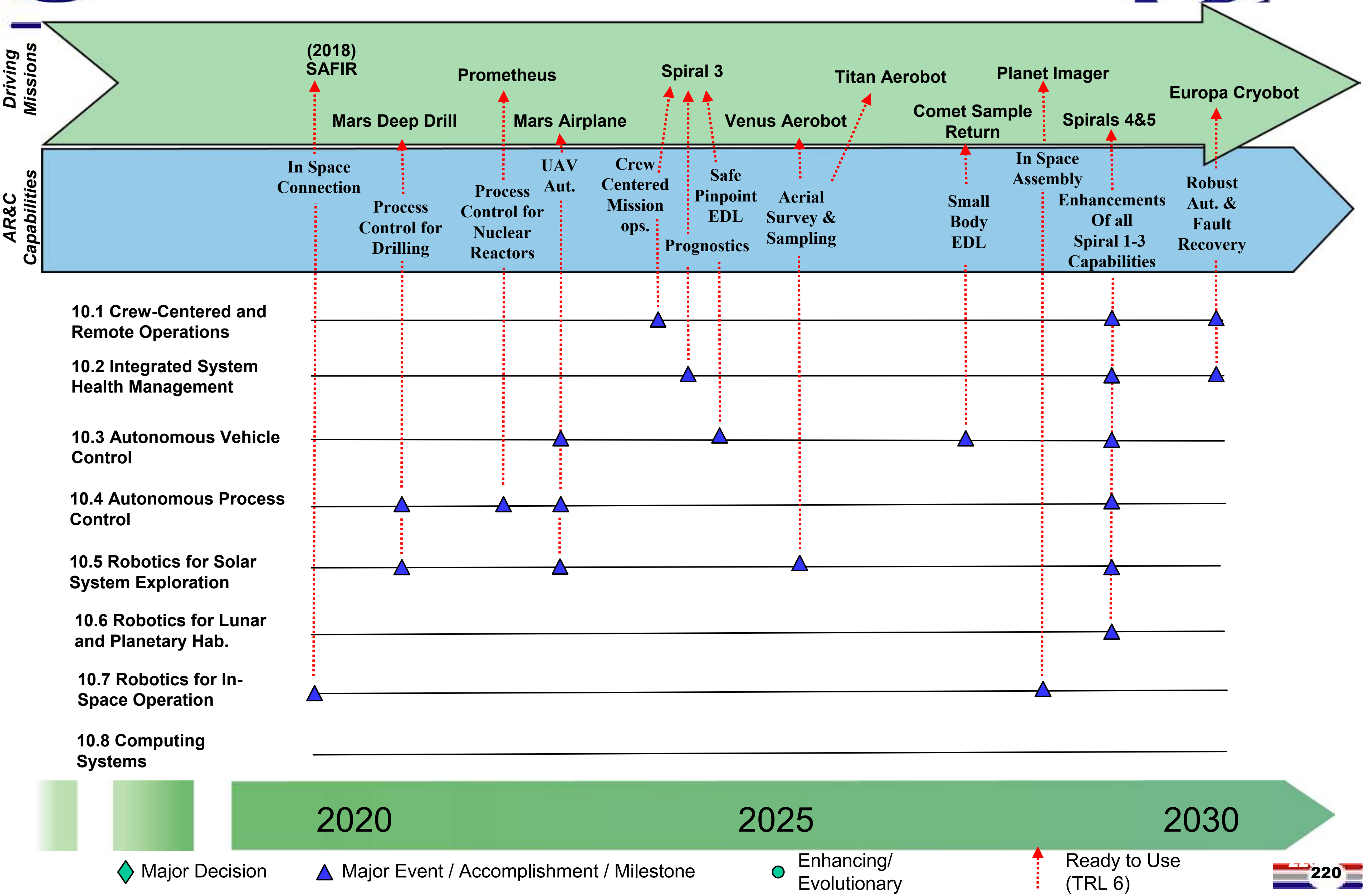
Overview

- Introduction (Steve Zornetzer)
- Process, Mission Drivers, Deliverables, and Interfaces (James Crawford)
- Autonomy (James Crawford)
  - Crew-Centered and Remote Operations
  - Integrated Systems Health Management
  - Autonomous Vehicle Control
  - Autonomous Process Control
- Robotics (Paul Schenker)
  - Robotics for Solar System Exploration
  - Robotics for Lunar and Planetary Habitation
  - Robotics for In-Space Operations
- Computing Systems (Mike Lowry)
- **Conclusion**

Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Autonomous Systems, Robotics, and Computing Systems: Capability Roadmap



Breakthrough Capability Rollup

Capability	Enables
Autonomy and control for deep drilling (10.4, 10.3, 10.5, and 10.2)	Sub-surface search for evidence of life on Mars and Europa
Dependable, and affordable robotic in-orbit maintenance (10.7 and 10.3)	Instrument change-out and long term operation of observatories
Dependable and affordable robotic in-orbit assembly (10.7 and 10.3)	Large aperture telescopes, affordable human exploration beyond earth-moon neighborhood.
Dependable autonomy for aerobots and sub-surface (10.4, 10.1, and 10.5)	Aerial Mars survey. Surface access on Titan. Search for evidence of life on Europa.
Surface mobility to cliffs and other current inaccessible sites (10.5).	Search for evidence of life on Mars in areas showing possible recent fluid flow
Largely automated CEV and habitat operations (10.1 and 10.2)	Human exploration of Mars.
Autonomous robotic surface construction and ISRU (10.6 and 10.4). Safe, dependable, pinpoint landing (10.3).	Affordable human habitation on Moon and Mars. Robotic site preparation in advance of manned surface missions

Summary of Key Deliverables

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	Mars	Solar Sys.	Lunar	Obs.	Earth Sci.	Sun-Earth	Spiral 1	Spiral 2	Spiral 3
10.1 Autonomous mission ops	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enabling, First driver	Enhancing	Enhancing	Enabling, First driver
10.1 Multi-platform collaboration				Enabling, First driver	Enabling	Enabling, First driver		Enhancing	Enhancing
10.2 Root-cause analysis	Enhancing	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling, First driver
10.2 Prognostics	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling, First driver
10.3 Rendezvous and Docking	Enabling, First driver		Enhancing	Enhancing				Enhancing	Enabling
10.3 Entry, descent, & landing	Enabling, First driver	Enhancing	Enhancing					Enhancing	Enabling
10.4 Nuclear reactor control		Enabling, First driver	Enhancing						Enabling, First driver
10.4 Sub-surface drilling	Enabling, First driver	Enabling	Enabling, First driver		Enhancing			Enhancing	Enhancing
10.5 Long traverse	Enabling, First driver	Enhancing	Enabling, First driver		Enhancing			Enhancing	Enhancing
10.5 Aerial survey and sampling	Enhancing	Enabling, First driver			Enabling				Enhancing
10.6 Human-robot interaction					Enhancing			Enhancing	Enabling, First driver
10.6 ISRU	Enabling, First driver		Enabling, First driver					Enhancing	Enabling
10.7 In-space inspection				Enhancing	Enhancing		Enhancing	Enhancing	Enabling, First driver
10.7 In-space connecting				Enabling, First driver				Enhancing	Enabling, First driver
10.8 <.1 defect per K SLOC	Enabling, First driver	Enabling	Enabling	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling
10.8 Recert. < $1K per K SLOC	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enhancing	Enabling, First driver	Enabling

SMD (Mars, Solar Sys., Lunar, Obs., Earth Sci., Sun-Earth) — ESMD (Spiral 1, Spiral 2, Spiral 3)

Legend: ✸ First driver; Red = Enabling; Yellow = Enhancing

Conclusions

- AR&C is heavily cross-cutting. Most capabilities are relevant to multiple missions and mission classes. In several cases, AR&C results will change theme roadmaps.

- In many cases AR&C is providing common control and execution software for hardware developed by other capability roadmaps. Close programmatic and technical collaboration is essential.

- Strategic needs differ from other areas:
  - Infrastructure needs for AR&C are modest.
  - Creating a talented and motivated workforce focused on NASA's unique challenges is essential (and difficult when NASA's R&D funding is unstable).
  - Additional focus on validation and verification of Autonomous and Robotic systems is also essential in order to enable mission infusion.

- Other government agencies (and private enterprise) have similar but distinct requirements.
  - Industry advances can be leveraged opportunistically but not assumed.
  - DoD advances should be leveraged in areas of overlap (e.g. machine vision and tele-robotics).

- NASA pacing challenges trace to three sources:
  - Extremely high dependability requirements for one-of-a kind systems
  - Communication latencies
  - Surface exploration of unknown and dynamic environments
  - Challenging manipulative tasks (in the presence of communications latencies)

BACKUP

Capability Roadmap Teams

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

National Research Council Dialogue to Assess Progress on

NASA's Transformational Spaceport & Range Technologies Capability Roadmap Development

General Background and Introduction

Darin M. Skelly
APIO Coordinator
March 31, 2005

Agenda

- General Background and Introduction of Capability Roadmaps "Title"
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

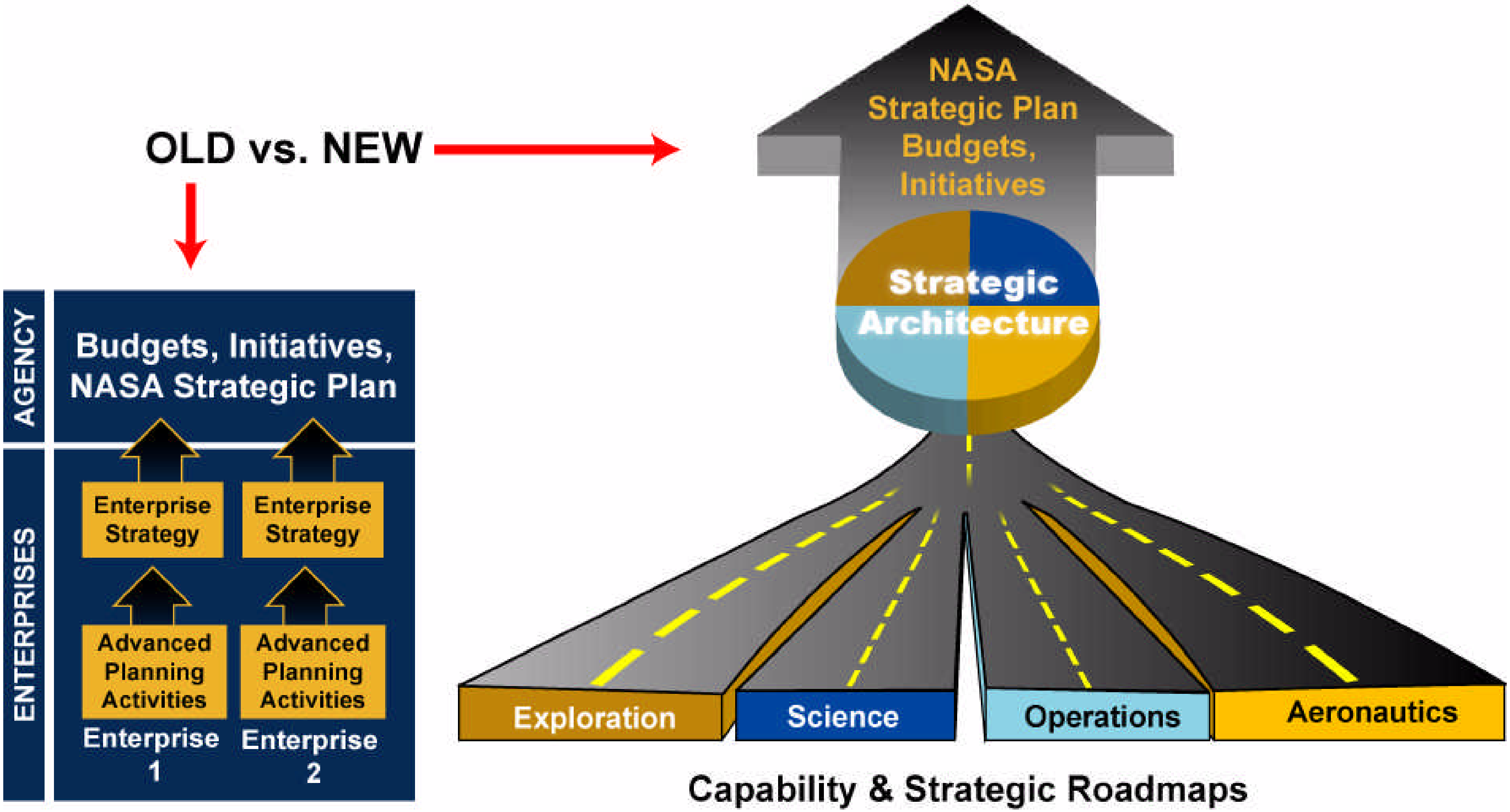
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

Agency Goals and Objectives

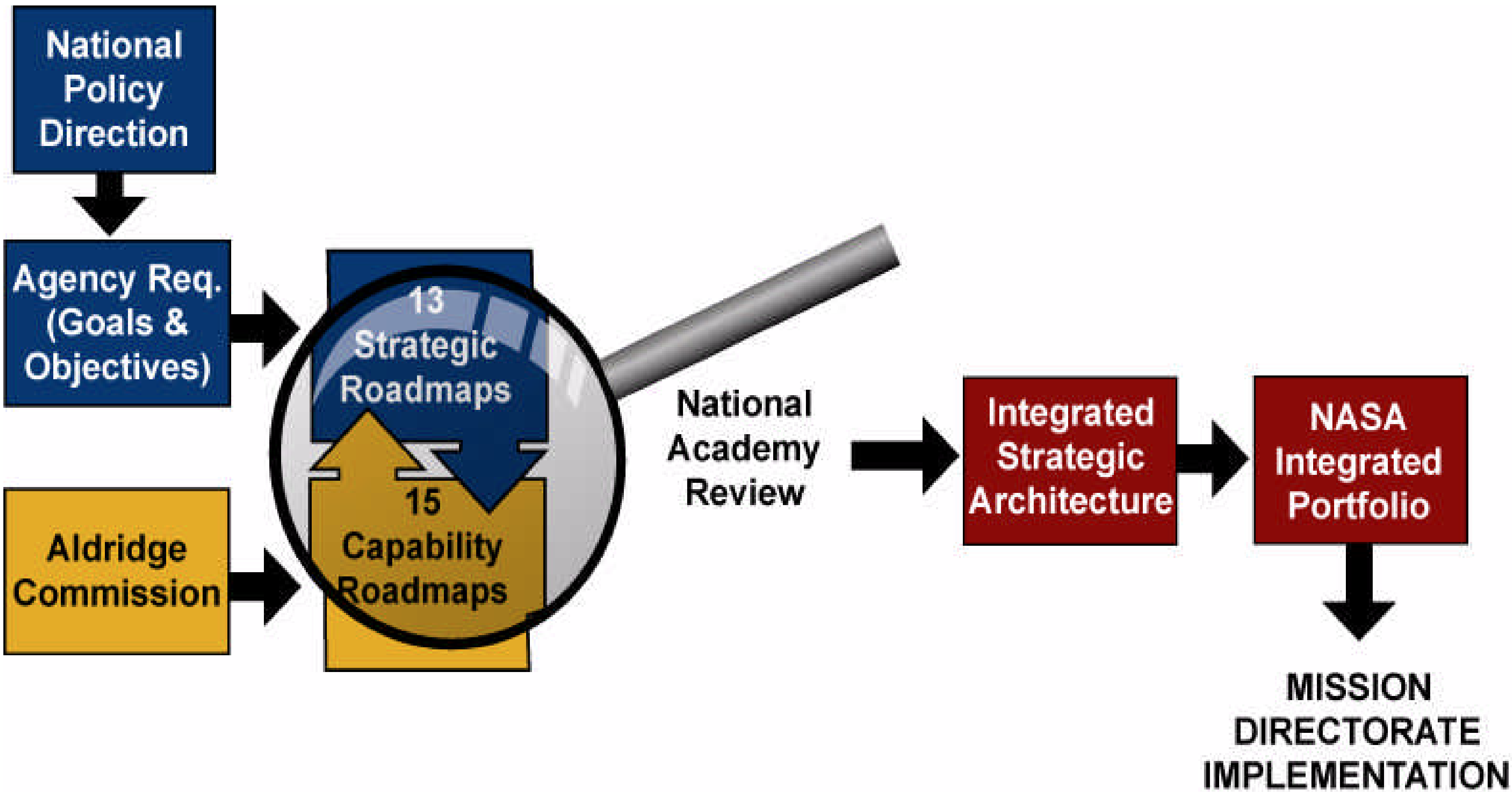
Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	Develop innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.	Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	Conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems. (SRM 9)
	Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)	Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)
	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)	

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Charles Elachi)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

Advanced Planning & Integration Office

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

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- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

  - Broad human and robotic science and exploration goals, priorities, anticipated discoveries
  - High-level milestones, options, and decision points
  - Implementation approaches, suggested missions

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

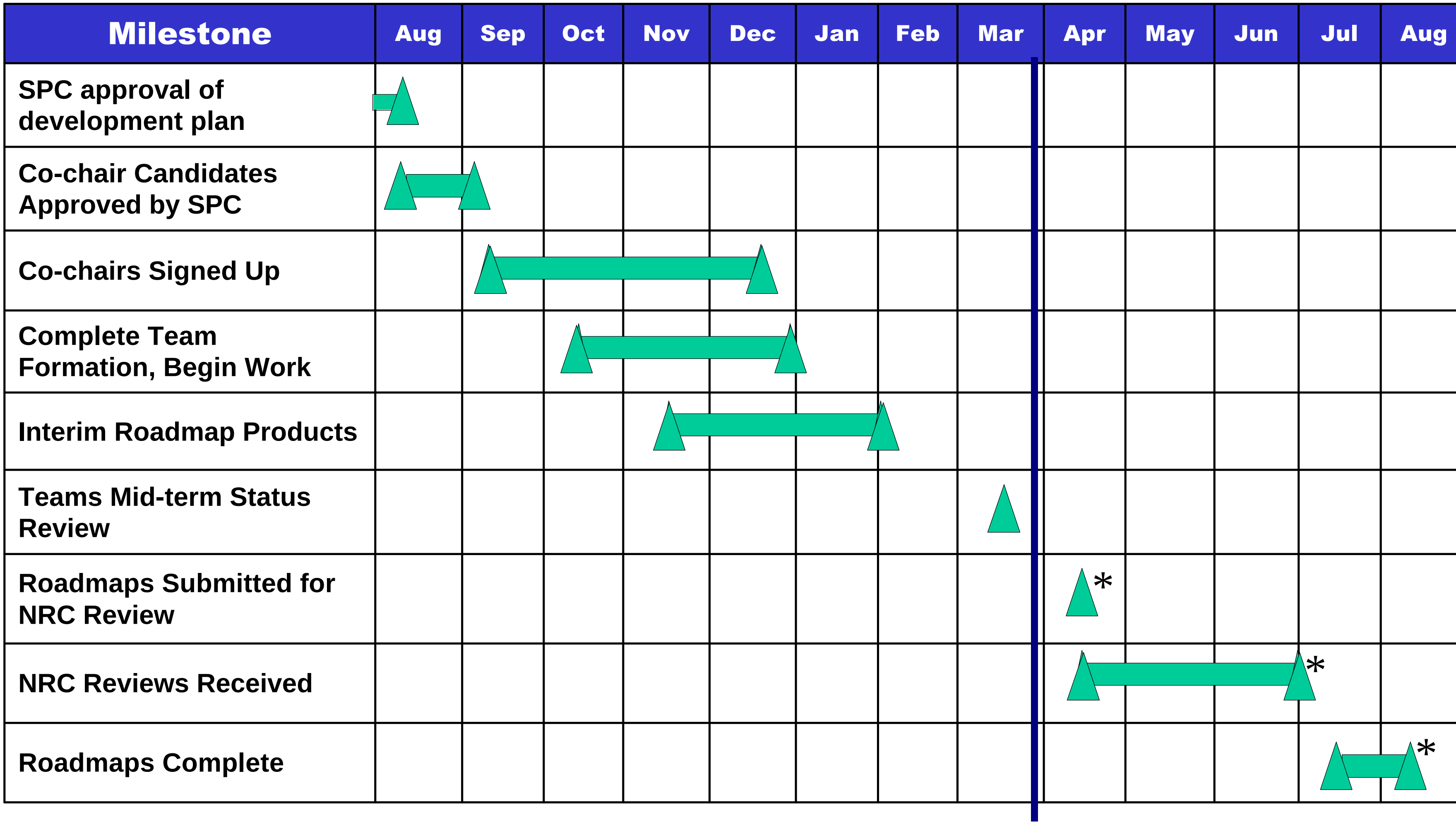
Directorate and APIO Coordinators Also with Each Team

– DoD Participation

Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule



Capability Roadmaps

Advanced Planning & Integration Office

- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

Advanced Planning & Integration Office

- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - **Phase 1 will be the development of capability roadmaps and associated technical products.**
    - **During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.**
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Process for Team Selection

- **Guidelines for Team Member Selection**
  - Small teams of 12 -15 members with participation from:
    - 1/3 Industry
    - 1/3 NASA & other Government Agencies
    - 1/3 Academia
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Advanced Planning & Integration Office

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
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Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

(Marked rows: High-Energy Power and Propulsion; In-Space Transportation; Advanced Telescopes and Observatories; Communication and Navigation; Human Exploration Systems and Mobility)

Capability Roadmaps - continued

Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
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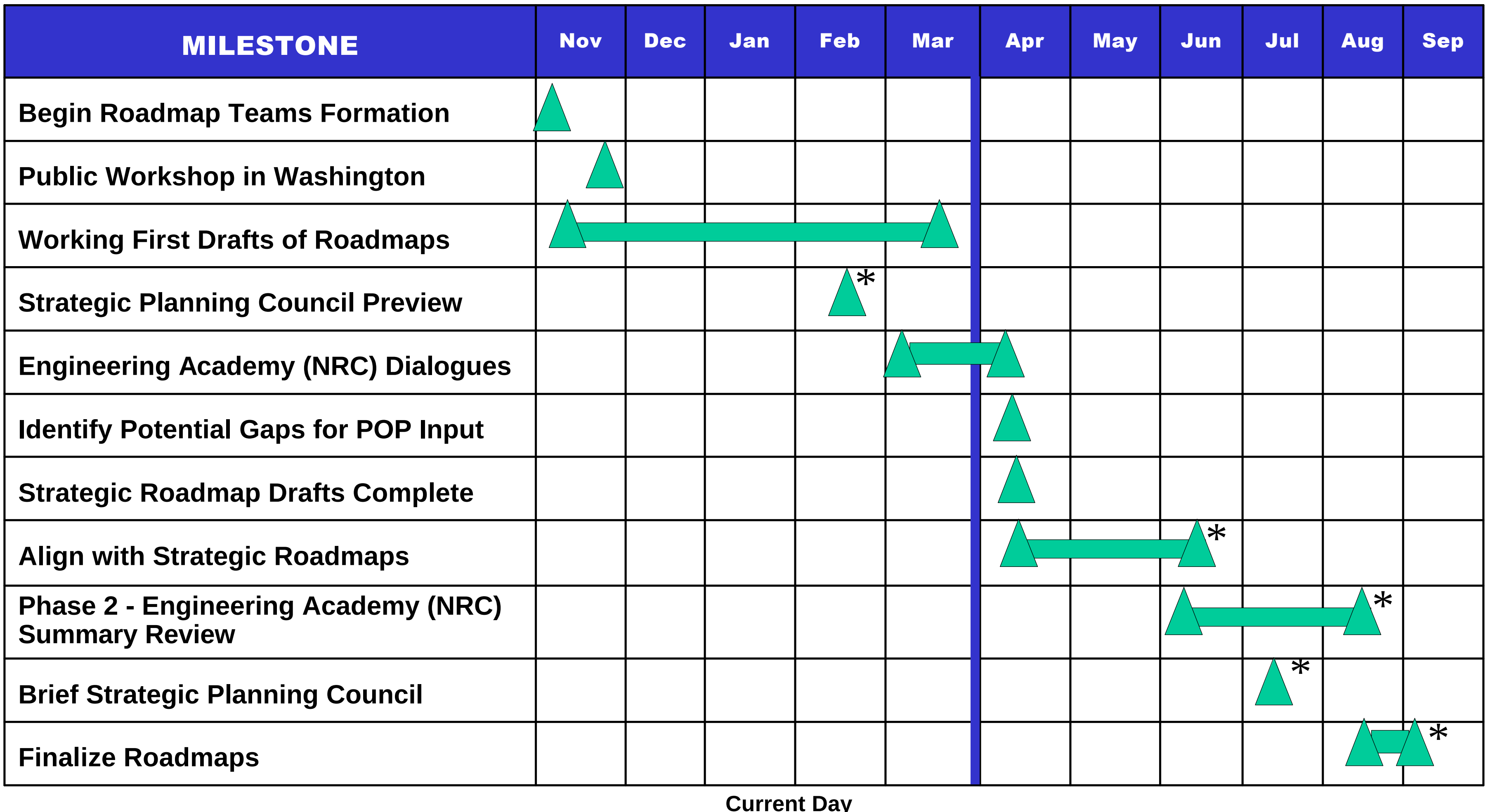
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

Advanced Planning & Integration Office



*Schedule under review.

Purpose of NRC Review

Advanced Planning & Integration Office

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

Technology Readiness Levels

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- **9** Actual System Proven in Operation
- **8** Actual System Qualified by Demonstration
- **7** System Prototype Demonstration in an Operational Environment
- **6** System/Subsystem Model or Prototype Demonstration in a Relevant Environment
- **5** Component and/or Breadboard Validation in a Relevant Environment
- **4** Component and/or Breadboard Validation in a Laboratory Environment
- **3** Analytical and Experimental Critical Functions Characteristic Proof-of-Concept
- **2** Technology Concept and/or Application Formulated
- **1** Basic Principles Observed and Reported

Capability Readiness Levels

Advanced Planning & Integration Office

Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

Crosswalk Matrix – Trans Spaceport & Range

Advanced Planning & Integration Office

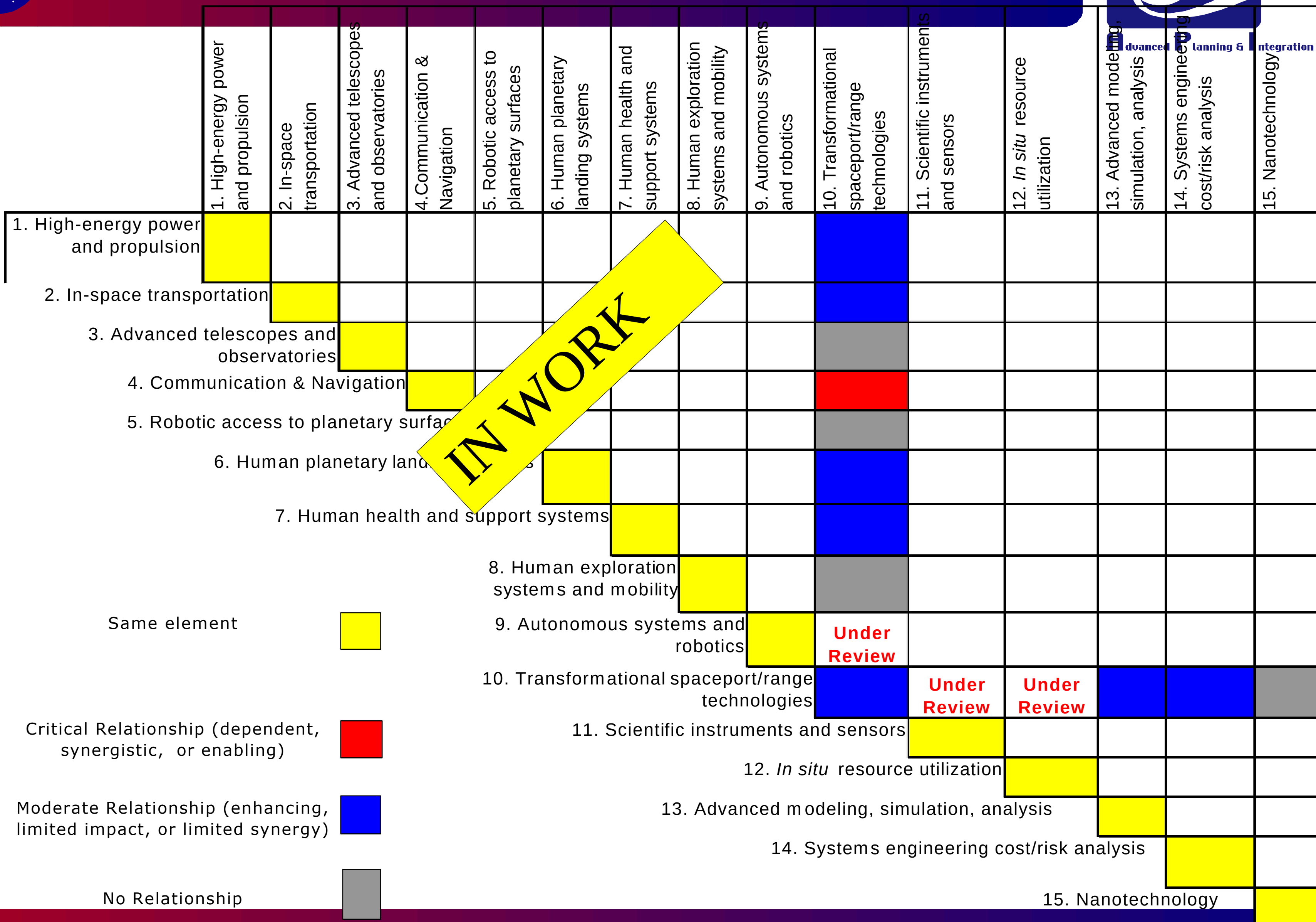
IN WORK

	1. High-energy power and propulsion	2. In-space transportation	3. Advanced telescopes and observatories	4. Communication & Navigation	5. Robotic access to planetary surfaces	6. Human planetary landing systems	7. Human health and support systems	8. Human exploration systems and mobility	9. Autonomous systems and robotics	10. Transformational spaceport/range technologies	11. Scientific instruments and sensors	12. *In situ* resource utilization	13. Advanced modeling, simulation, analysis	14. Systems engineering cost/risk analysis	15. Nanotechnology
1. High-energy power and	Same element	Moderate	Moderate	Moderate	Critical	Difference of Opinion	Critical	Critical	No Relationship	Moderate	No Relationship	Critical	Difference of Opinion	Moderate	Difference of Opinion
2. In-space transportation		Same element	Critical	Critical	Unknown	Critical	Critical	Critical	Critical	Unknown	Difference of Opinion	Difference of Opinion	Unknown	Critical	Moderate
3. Advanced telescopes and observatories			Same element	Critical	Moderate	Difference of Opinion	Moderate	Critical	Critical	Critical	Critical	Difference of Opinion	Critical	Moderate	Difference of Opinion
4. Communication & Navigation				Same element	Critical	Critical	Critical	Critical	Critical	Critical	Difference of Opinion	Moderate	Moderate	Moderate	Moderate
5. Robotic access to planetary surfaces					Same element	Critical	Critical	Unknown	Unknown	Unknown	Critical	Critical	Critical	Moderate	Moderate
6. Human planetary landing systems						Same element	Critical	Moderate	Critical	Moderate	Difference of Opinion	Critical	Difference of Opinion	Difference of Opinion	Moderate
7. Human health and support systems							Same element	Critical	Unknown	Unknown	Moderate	Moderate	Moderate	Critical	Critical
8. Human exploration systems and mobility								Same element	Critical	No Relationship	Moderate	Critical	Unknown	Critical	Moderate
9. Autonomous systems and robotics										Unknown	Moderate	Critical	Critical	Critical	Critical
10. Transformational spaceport/range technologies										Same element	No Relationship	No Relationship	No Relationship	Moderate	Moderate
11. Scientific instruments and sensors											Same element	Difference of Opinion	Difference of Opinion	Moderate	Critical
12. *In situ* resource utilization												Same element	Difference of Opinion	Difference of Opinion	Moderate
13. Advanced modeling, simulation, analysis													Same element	Critical	Moderate
14. Systems engineering cost/risk analysis														Same element	Difference of Opinion
15. Nanotechnology															Same element

Same element
Critical Relationship (dependent, enabling)
Moderate Relationship (enhancing, synergistic)
No Relationship
Difference of Opinion
Unknown

Crosswalk Matrix – Trans Spaceport & Range

Advanced Planning & Integration Office



Example linkage to other roadmaps

Interdependencies with Comm/Nav roadmap
(critical)
- Space-based communication network (e.g. TDRS)
- Ground Communications backbone
- **Space-based assets for telemetry/tracking**

Transformational Spaceport & Range

Comm/Nav roadmap
(critical)
- Critical dependence on assured TT&C, voice, and mission data transport links to Earth or Earth orbiter
- Critical dependence on highly reliable, highly available navigation
- Tradeoff of range radar or space-based range (SBR increases dependence on comm/nav and GPS)
- Range radar can provide autonomous tracking w/out dependence on vehicle TT&C
- Comm security needed
- Navigation provided by combination of autonomous and linked methods
- Requires time phasing of capability with missions

BACK-UP

Capability Readiness Levels Defined

Advanced Planning & Integration Office

- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  – The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  – A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modelling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  – A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  – An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  – The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).
  -full scale flight articles
  -demonstration in appropriate operational ‘envelope’
- **CRL 7: Capability Operational Readiness**
  – The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under “mission” conditions.

Crosswalk Matrix Ratings
Work In-progress

Advanced Planning & Integration Office

- **Critical Relationships (Red):**
  - Communications and Navigation Roadmap
    - Space-based assets for telemetry/tracking
- **Moderate Relationships (Blue):**
  - High Energy Power & Propulsion Roadmap
    - Potential unique launch site facilities/infrastructure needs for processing nuclear power sources/propulsion
  - In-space Transportation Roadmap:
    - Vehicle processing – pre-launch and launch
    - Telemetry/Tracking
  - Human Planetary Landing Systems Roadmap
    - Vehicle processing – pre-launch and launch
    - Telemetry/Tracking
  - Human Health and Support Systems Roadmap
    - Spaceport Infrastructure for crew pre-launch processing
    - Crew support equipment at launch site
    - Pad infrastructure (e.g., life support, comm, video, safety, etc.) for crewed vehicle
  - Advanced Modeling, Simulation, Analysis Roadmap
    - Modeling/Analysis for Range Safety (e.g., flight control ops, debris field analysis, expected casualty analysis, etc)
  - Systems Engineering Cost/Risk Analysis
    - Requirements Development, Design, Development of new Spaceport/Range Technologies

Capability 9.4
Servicing

Presenter:

Rud Moe

Servicing Description

- **Inspection and detection of faults, maintenance, repair, resupply, and upgrade of accommodating in-space and extraterrestrial systems.**
  - Maintenance: refurbishment of wear-out items, resupply of consumables, adjustment and realignment, cleaning or recoating of surfaces, exchange of degraded fluids, lubricants, filters, materials
  - Repair: replacement of or substitution for worn, damaged, or failed items at several levels of hierarchical modularity, reconstruction of structures or surfaces with fresh material
  - Upgrade: replacement or supplement of obsolete items with version having higher-performance or increased functionality
- **All servicing operations include reverification of system integrity and functionality**

Benefits of Servicing

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- **Extended mission life and systems reusability for increased sustainability**
  - Versatile ability for life extension allows efficient use of high-capitalizations systems
  - Extended reuse of heritage systems for new purposes or objectives
- **Increased performance through upgrade improves affordability**
  - Decoupling of systems to accommodate differential rates of technology advancement and obsolescence
  - New capability establishment
  - Exploitation through extended reuse of high-capitalization systems to support unique performance items
- **Mission rescue**
  - Reduction of consequences of failures or unexpected events and situations results in preservation of capital value and continuation of operations
  - Intervention using available items, tools, and materials for temporary (possibly degraded) operation
  - Revisit with design-to-case permanent replacement or supplementary components

Drivers & Assumptions for Servicing

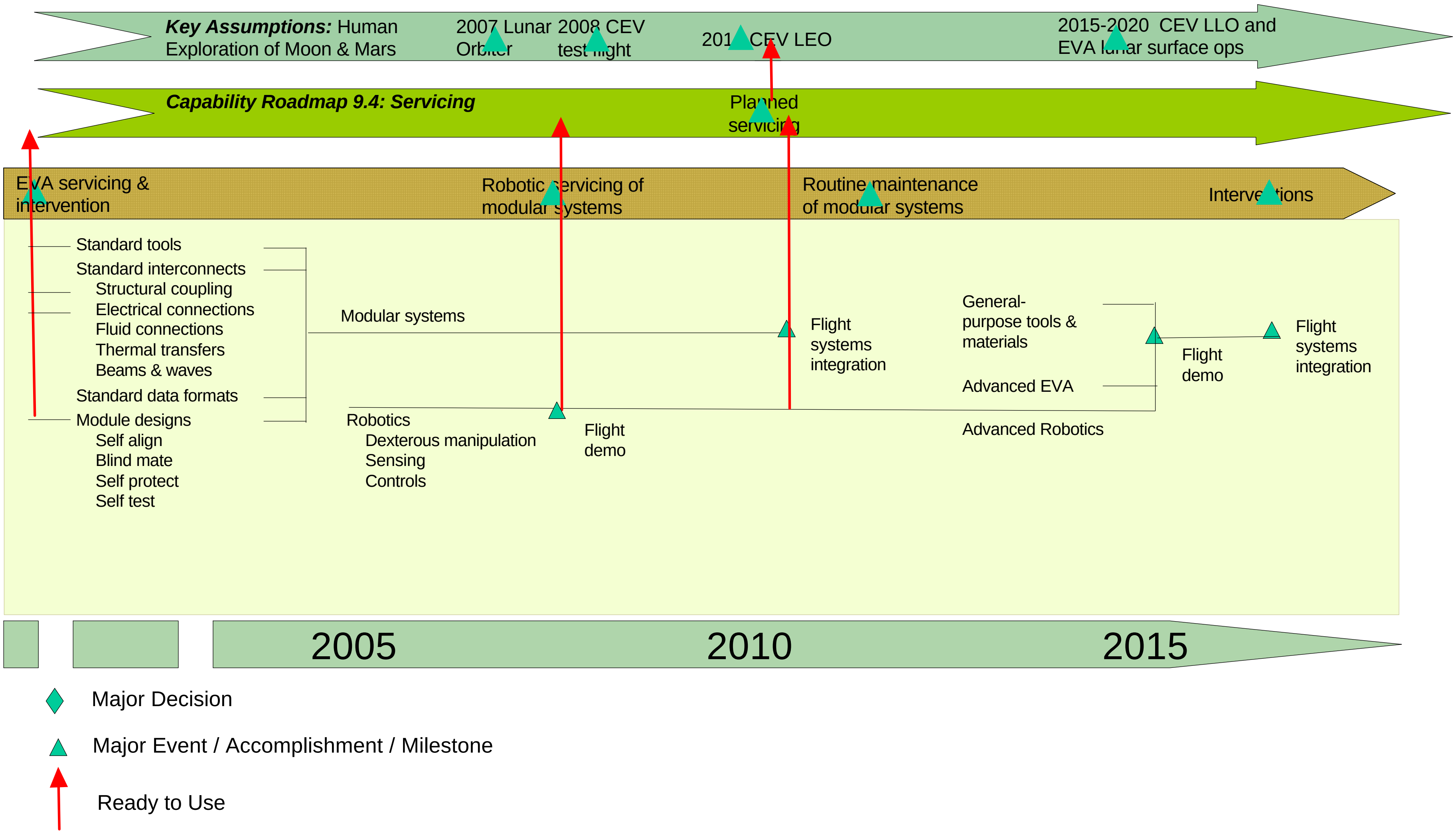
- **Logistics for provisioning of spares and upgrades**
  - Manufacture, inventory, launch, in-space and extra-terrestrial transport and storage of components, modules, spares, materials, tools, test equipment
- **Accommodation of systems to servicing agent abilities**
  - Modularity and separable interfaces, local force/torque reaction, self-alignment, self-protection, available power and data ports, built-in test, configuration databases
- **Accessibility of systems to servicing agents**
  - Affordable access Earth-to-space, in-space or extra-terrestrial transport from operations venue to servicing venue, proximity operations and capture/handling, gross positioning systems
- **Supporting systems for servicing operations**
  - Handling and temporary stowage, inventory controls, environmental protection, clean workspace, information and communication systems, general-purpose tools and test equipment, in-situ fabrication and feedstock
- **Servicing agent availability**
  - Robotics and/or human presence in-space and extra-terrestrial sites with supporting logistics and utilities, medicine and life support, transport, information and communication systems
- **Servicing agent abilities**
  - Mobility, sensing, handling and dexterous manipulation, positioning, aligning, connecting, disconnecting, advanced controls, on-board databases, autonomy, team coordination

Capability Breakdown Structure
9.4 Servicing

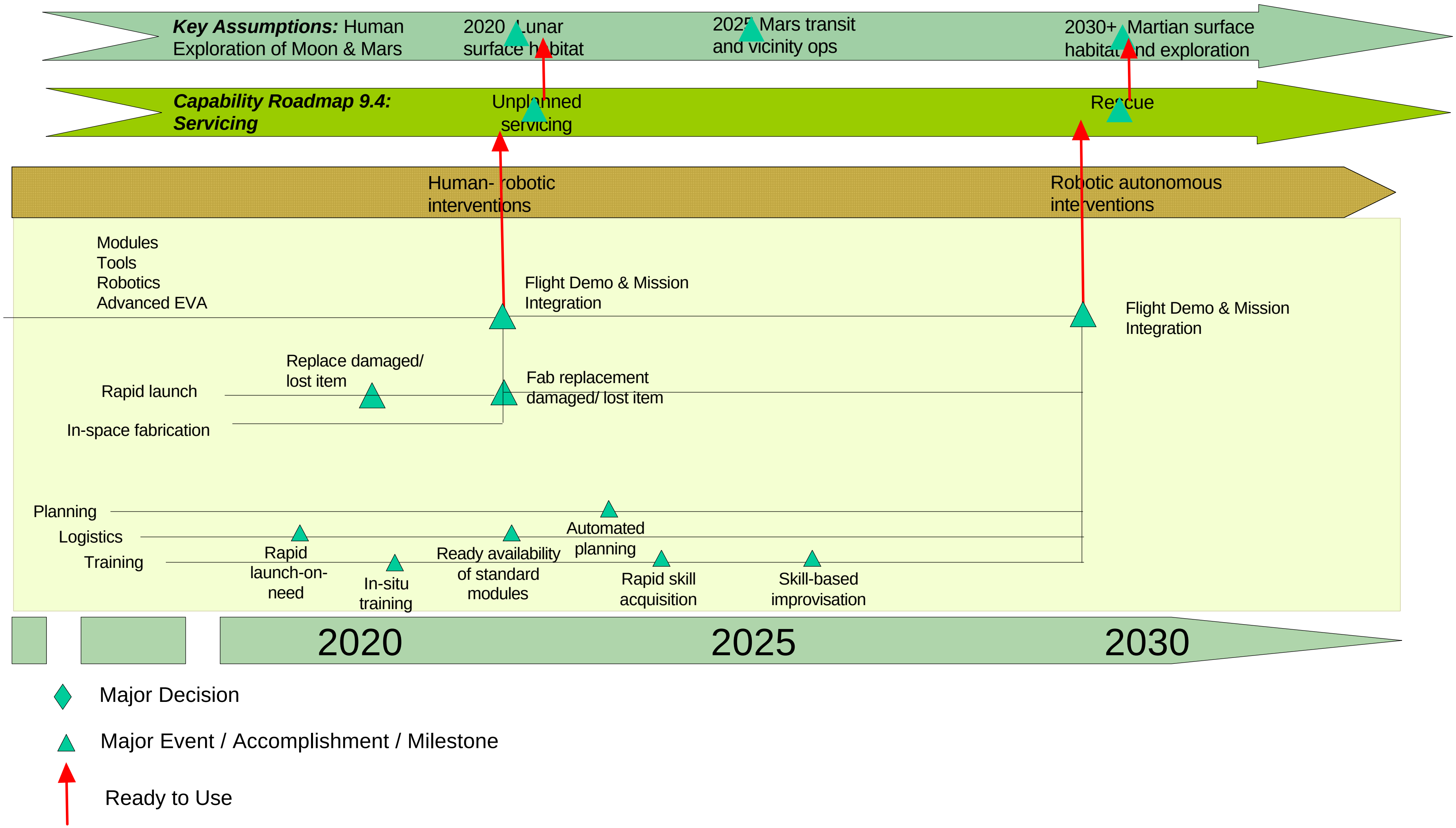
Advanced Planning & Integration Office

9.4.1	**Inspect & survey (monitoring)**
9.4.2	**Detect & isolate faults (diagnostics)**
9.4.3	**Perform planned maintenance**
9.4.3.1	Replace modular component
9.4.3.2	Replenish supplies
9.4.4	**Perform unplanned repair**
9.4.4.1	Assess repair options and available materials
9.4.4.2	Repair/replace component
9.4.5	**Install upgrades**
9.4.6	**Planning, logistics, training, etc.**

Roadmap for Servicing



Roadmap for Servicing



9.4 Servicing Critical Gaps

- TBD

Appendix with SOA details by WBS

Capability 9.4.1 Inspection

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- **Description:**
  – Tools and operations for inspecting systems, components, structures, etc. to determine status, operating condition, physical characteristics
  – Passive inspection techniques, active sensing approaches, combination
  – High degree of autonomy needed
- **Benefits**
  – Allow determination of system configuration or status with human intervention providing interpretation of non-autonomous cases.
  – Effective inspection systems can lower risk of repairs
- **Figures of Merit**
  – Amount of human supervision required, coverage of system, resolution and bandwidth, availability of inspection capability, complexity of inspections system, versatility of inspection system
- **General Assessment**
  – Current SOA is human intensive, reliant in-situ crew. External inspection tools are limited and lack autonomy. Many inspection approaches available, not well integrated with servicing systems.
- **Development Needed: Medium**

State-of-the-Art /Maturity Level /Capabilities for 9.4.1 Inspection

Capabilities	State-of-the-Art	TRL	Needs	Need TRL 6	Capability Date	CRL
9.4.1 Inspection					2015	5
9.4.1.1 Passive sensors: cameras (resolution, positioning, lighting, focus, iris, É), nonvisual sensors (proximity, haptic, acoustic conduction)	Shuttle, ISS, HST Robotic Servicing (HRSDM), AerCam	9	Multispectral sensing Hi Def resolution Coverage & positioning	2012		
9.4.1.2 Active sensors & scanners	LIDAR	6	Interferometry	2012		
9.4.1.3 Built-in	Telemetry	9				

Capability 9.4.2 Diagnostics

- **Description:**
  - Interpretation of inspection surveys and instrumentation data analysis and projection into the mission performance context
- **Benefits:**
  - Provides systems assessments of extant and impending degradations; provides specifics for servicing mission planning content and timing, design-to-case repair components and operations development
- **Figures of Merit:**
  - Percent coverage of possible failures/degradations
  - Percent of manual vs. automated assessment and planning
  - Time to failure/degradation identification
  - Impact to operations of reconfiguration for test
  - Amount of system resources required (MIPS, bytes, etc.)
- **General Assessment:**
  - Built-in instrumentation trend analysis is best current capability; in-situ assessment of overall configuration is reliant upon human interpretation; no autonomous capability to characterize and project system performance
- **Development Needed: High**

State-of-the-Art /Maturity Level /Capabilities for 9.4.2 Diagnostics

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Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Built-in test equipment	Boeing aircraft	9	Broader		2010	7
Integrated computational diagnostics and prognostics	Livingstone (L2)	4	Continued development; testing/demo under operational conditions	2008	2010	5
Diagnostic test planning and execution during operations	Livingstone (L2)	4	Continued development; testing/demo under operational conditions	2008	2010	5
Maintenance/repair planning and execution monitoring	Livingstone (L2)	4	Continued development; testing/demo under operational conditions	2008	2010	5

Capability 9.4.3 Perform Planned Maintenance

- **Description:**
  - Installs replacement modular components or consumable materials having standardized interfaces and procedure accommodations
- **Benefits:**
  - Versatile ability for life extension and efficient use of high-capitalizations systems
  - Extended life and reuse of heritage systems for new purposes or objectives
  - Reduced impact on mission times, costs, and risks relative to unplanned servicing
- **Figures of Merit:**
  - Compliance of modular systems with standard or generic interface connectors and formats
  - Number of disassembly steps needed for access
  - Robustness of modules designs for self-protection in space environment
  - Completeness of modules self-test functions
  - Type and complexity of agents required;
  - Type and complexity of infrastructure required
- **General Assessment:**
  - Depends strongly on modular systems design, human and robotic capabilities, logistics, and supporting systems; limited in size and mass of modular systems and sub-systems that have been replaced
- **Development Needed: Medium**

State-of-the-Art /Maturity Level /Capabilities for 9.4.3 Perform Planned Maintenance

Advanced Planning & Integration Office

Capabilities	State-of-the-Art	TRL	Needs	Need TRL 6	Capability Date	CRL
4.3 Perform planned maintenance					2010	5
4.3.1 Replace modular component						
EVA supported	ISS, HST	9				
Robotic	HRSDM	5	Robotic	2008		
		5	Task Autonomy			
4.3.2 Replenish supplies	Flight demo hardware	7	Mission integration	2010		

Capability 9.4.4 Perform Unplanned Repair

Advanced Planning & Integration Office

- **Description:**
  - Address mission unplanned events and situations during operations using available components, materials, tools, procedures, skills, and creativity; preserve valuable assets for continued operation
- **Benefits: Mission rescue**
  - Reduce consequences of failures or unexpected events and situations for preservation of capital value and continuation of operations
  - Intervention using available items, tools, and materials for temporary (possibly degraded) operation
  - Revisit with design-to-case replacement or supplementary components
- **Figures of Merit:**
  - Number of types of intervention possible
- **General Assessment:**
  - Highly advanced capabilities needed for robotic implementation; general-purpose tools and materials provide limited intervention capability even for human agents in-situ; rapid launch capability and in-space fabrication capability have potential for greatly reducing loss-of-mission risk
- **Development Needed: High**

State-of-the-Art /Maturity Level /Capabilities for 9.4.4 Perform Unplanned Repair

Capabilities	State-of-the-Art	TRL	Needs	Need TRL 6	Capability Date	CRL
Perform unplanned repair					2015	2
Intervention kit, EVA supported	Shuttle, ISS, HST	9	Robust capability			
Intervention kit, robotic supported	HRSDM	4	Robust capability	2015		
Improvisation skills, human supported	ISS, HST	6	Rescue capability	2020		
Improvisation skills, robotic autonomy	none	0	Auto-rescue capability	2030		

Capability 9.4.5 Install Upgrade

Advanced Planning & Integration Office

- **Description**
  - Many components and subsystems have technology advancement rates significantly shorter than the systems they are incorporated into and as a result become obsolete long before the system's intended duration of useful life is over.
  - As technology improves, replace or augment original hardware and software with higher performance, increased functionality, or new capbility.
  - Examples: HST servicing, nuclear reactor robotics, spacecraft software uploads
  - Upgrade potential is dependent on degree of interface standardization.
- **Benefits**
  - Enable adaptation to new circumstances and evolve faster than the systems-of-systems rate
  - Increase Functional Capability/Performance
  - Increase Reliability (MTBF) and Safety
  - Increase Maintainability/Supportability
  - Allow space systems to be entered into service more quickly (initial capability) and upgrade capability at a later time

Capability 9.4.5 Install Upgrade

- **Figures of Merit**
  - Time to Upgrade
  - Supporting Infrastructure Required
  - Cost of Use of Human and/or Robotic Agents
- **General Assessment**
  - SOA is advanced for upgrade by humans in space environment, but unproven for robotics in space environment. Need to significantly increase robotic capability.
- **Development Needed: Medium**

HST Servicing Mission

Nuclear Power Plant Telerobot

Robonaut Space Telerobot

State-of-the-Art /Maturity Level /Capabilities for 9.4.5 Install Upgrade

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
EVA upgrade of science instruments and components	HST servicing missions; ISS	9	Beyond LEO; control of harsh environmental	2012	2015	5
IVA upgrade of components	ISS	9	Cleanliness	2012	2015	5
Upgrade of spacecraft software	Upload to various spacecraft	9	Increased reliability	2008	2010	5
Autonomous upgrade of components	DARPA Orbital Express Advanced Technology Demo	5	Continued development. Launch of demo scheduled for 2006.	2015	2020	2
Teleoperated upgrade of components	HST robotic servicing mission; operational nuclear reactors; Robonaut	4-5	Continued development; testing/demo under operational conditions	2015	2020	2

Capability 9.4.6 Planning, Logistics, Training

Advanced Planning & Integration Office

- **Description:**
  - These are broad capabilities that span the entire sequence. Planning is defined as the ordering of steps required to complete a task or maneuver. Logistics is all of the support and movement planning of assemblies, parts, tools, equipment, and supplies necessary to meet the objectives of the servicing task. Training is the teaching and practicing of a skill or maneuver to be able to perform as expected.
- **Benefits:**
  - Planning, logistics, and training are integral to each other, and necessary to complete all servicing operations. Pre-planning and contingencies will increase the probability of success of the servicing operations. Logistics determines the whereabouts and timing of all the tools, consumables, and parts required. Training is necessary to insure that the task of servicing will occur as planned by man or robot.
- **Figures of Merit:**
  - Number of steps in the plan, Completeness of plan, including acceptable contingencies, Timeline for logistics, Transport Manifest, Skills Training Plan and competency test, Number of skills in training, Realistic Simulation based on update rate, fractal & polygon count, field-of-view
- **General Assessment:**
  - Planning, Logistics, and Training are commonplace today in NASA type missions, typically in a manual mode with some automated tools. Fully automated planning tools exist, but with less maturity at the mission level. Logistic tools are mature and verifiable through comprehensive checklists. Training exist, but could benefit from better tools and technologies to insure a higher level of preparedness.
- **Development Need: Low,** with room for technological improvements as available except for human-robot training

State-of-the-Art /Maturity Level /Capabilities for 9.4.6 Planning, Logistics, & Training

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
1. Planning						
Mission Planning	Apollo, Soyuz, Shuttle	6	Auto	-	2010	
Strategic Planning	Shuttle	7	Auto	-	2010	
Vehicle Planning	Shuttle	8	Integ.	-	2010	6
Trajectory Planning	Shuttle, Soyuz	9	Auto	-	2010	
Collision Avoidance	Manual Visualization	3	Dev.	2006	2008	
Dynamic Replanning	XSS-11	4	Real-Time	2006	2008	
2. Scheduling						
Automated	Shuttle	6	Real-Time	2010	2012	7
3. Logistics						
Logistics Planning	Shuttle PIC	9	Auto	-	2010	
Resource Allocation	New Millennium	6	Auto	2008	2010	6
Automated Tracking	Shuttle GSE	8	Common	-	2010	
Inventory Control	NASA Pre-Flight	8	Implement	-	2010	
4. Training						
Competency Program	Astronaut Program	9	Update	2008	2012	
Skill-based	Astronaut Program	9	w/ robot	2008	2012	
Knowledge-Based	Astronaut Program	4	experts	2006	2008	6
Simulation	Shuttle Training	6	hi-res	2006	2008	
Immersion	Laboratory	4	mature	2008	2012	
Testing & Checkout	Conventional	9	Auto	-	2012	

State-of-the-Art /Maturity Level /Capabilities for 9.4.6 Planning, Logistics, & Training

Sub-Capabilities	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
1. Planning						6
Auto Mission Planning	Apollo, Soyuz, Shuttle	5	Auto	2008	2008	
Auto Strategic Planning	Shuttle	7	-	-	2008	
Auto Vehicle Planning	Shuttle	8	-.	-	2008	
Smooth Trajectory Planning	Shuttle, Soyuz	9	-	-	2008	
Auto Collision Avoidance	Manual	3	Dev.	2006	2008	
Auto Dynamic Replanning	Visualization XSS-11	4	Real-Time	2006	2008	
2. Scheduling						7
Ground	Shuttle	8	-	-	2008	
On-board	Shuttle	6	Real-Time	2008	2010	
3. Logistics						6
Real-time Log. Planning	Shuttle PIC	5	Auto	2008	2010	
Off board Log. Plan	Shuttle	9	-	-	2008	
Resource Allocation	New Millennium	6	Auto	2008	2010	
Real-time Tracking	Shuttle GSE	8	Common	-	2008	
Auto Inventory Mgt	NASA Pre-Flight	8	Implement	-	2008	
Real-Time Traffic Model	Shuttle	8	Auto	-	2008	
Spares Planning	ISS	9	-	-	2008	

State-of-the-Art /Maturity Level /Capabilities for 9.4.6 Planning, Logistics, & Training

Advanced Planning & Integration Office

Sub-Capabilities	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
4. Training						
General Comprehension	Astronaut Program	9	Update	-	2008	
Situation-based	Military	6	infusion	-	2010	
Skill-based	Astronaut Program	9	w/ robot	-	2012	
Knowledge-Based	Astronaut Program	4	experts	2008	2010	6
Computer Sim.	Shuttle Training	6	hi-res	2008	2010	
Hardware-In-Loop Sim	Ground	4	custom	2008	2010	
Immersion Room	Laboratory	4	facility	2010	2012	
Immersion Desk	Laboratory	4	models	2010	2012	
Testing & Checkout	Conventional	9	Auto	-	2008	

State-of-the-Art /Maturity Level /Capabilities for 9.4.6 Planning, Logistics, & Training

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Technologies	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
1. Planning						6
Auto Mission Software	COTS-Grease	6	Auto	2010	2012	
Auto Strategic Software	4D-RCS, Mapgen	7	Auto	2010	2012	
Auto Vehicle Software	Remote Agent	8	Integ.	2008	2010	
Trajectory Algorithm	A*, D*	9	Auto	-	2008	
Col. Avoid Sensor	Manual Visualization	3	Dev.	2006	2008	
Col. Avoid Behavior	Potential Field, Occupancy-Grid	4	Mature	2006	2008	
Auto Replanning	State Machine Re-Planning	4	Real-Time	2006	2008	
2. Scheduling						7
Ground	COTS	9	-	-	2005	
On-board	Remote Agent	6	Optimization	2008	2010	
3. Logistics						6
Real-time Log. Planning	Shuttle PIC	9	Auto	-	2010	
Off board Log. Plan	COTS	9	-	-	2005	
Resource Allocation	New Millennium	6	Auto	2008	2010	
Real-time Tracking	Shuttle GSE	8	Common	-	2010	
Auto Inventory Mgt	NASA Pre-Flight	8	Implement	-	2010	
Real-Time Traffic Model	COTS	9	Contingency	-	2005	
Spares Planning	NASA Std	9	Contingency	-	2005	

Advanced Planning & Integration Office

Science Instruments and Sensors Capability Roadmap NRC Dialogue

NASA Co-Chair: Rich Barney, NASA

External Co-Chair: Maria Zuber, MIT

March 16, 2005

Agenda

Time	Topic	Presenter
7:30	Continental Breakfast	
8:00	Welcome and Review Process, Panel Chair & NRC Staff	
8:15	NASA Capability Roadmap Activity	Perry Bankston, NASA
8:30	12.0 Science Instruments & Sensors Overview	Rich Barney, NASA
	-Sub-Team Presentations-	
9:15	12.1 Microwave Instruments & Sensors	Chris Ruf, UMich
9:45	12.2 Multi-Spectral Imaging/Spectroscopy (vis-IR-FarIR)	Craig McCreight, NASA
	– Break –	
10:45	12.3 Multi-Spectral Sensing (UV-Gamma)	Brian Ramsey, NASA
11:15	12.4 Lasers/LIDAR Remote Sensing	Maria Zuber, MIT
	– Lunch –	
12:45	12.5 Direct Sensing of Particles, Fields & Waves	Dick McEntire, APL
1:15	12.6 In-Situ Instrumentation	Tim Krabach, NASA
1:45	Co-Chair Summary	Maria Zuber, MIT
	-Break-	
2:30	Open Discussion	NRC Panel

-Adjourn-

Capability Roadmap Team

Co-Chairs
NASA: Richard Barney, NASA/Goddard Space Flight Center
NASA Deputy: Juan Rivera , NASA/Goddard Space Flight Center
External: Dr. Maria Zuber , Massachusetts Institute of Technology

NASA
Brian Ramsey, MSFC
Bruce Spiering, Stennis
Tim Krabach, JPL
Soren Madsen, JPL
Paul Mahaffy, GSFC
Azita Valinia, GSFC
Craig McCreight, ARC

Industry
David Chenette, Lockheed Martin
Ron Polidan, Northrop Grumman
Rich Dissly, Ball Aerospace

Academia
Chris Ruf, Univ. Michigan
Steve Ackerman, Univ. Wisconsin
Suzanne Staggs, Princeton

Other/Independent
Richard McEntire, JHU/APL
David Glackin, Aerospace
Shyam Bajpai, NOAA

Coordinators
Directorate: Harley Thronson, SMD
APIO: Perry Bankston, JPL

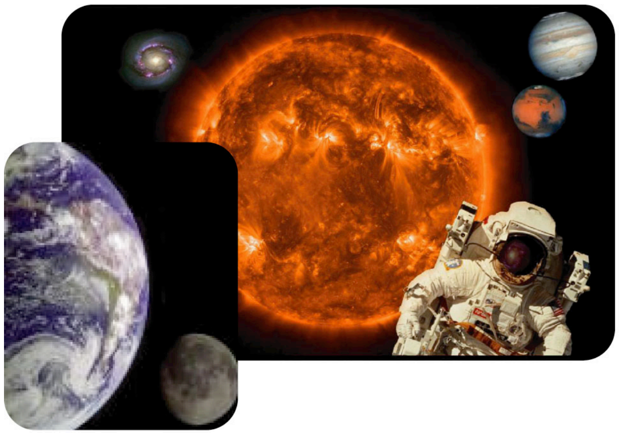
Ex-Officio
Carl Stahle (GSFC-Nano CRM)
Louis Barbier (NASA-SEU Technologist)
Thomas Black (National Reconnaissance Office)
Amy Walton (Earth Science and Technology Office)

Capability Roadmap Description

- The Science Instruments and Sensors roadmaps include capabilities associated with the collection, detection, conversion, and processing of scientific data required to answer compelling science questions driven by the Vision for Space Exploration and The New Age of Exploration (NASA's Direction for 2005 & Beyond).
  - Driving design reference missions
  - Science measurement
  - Capability/technology gaps
  - A description of the developments (including alternate paths and options) required to advance a priority capability to spaceflight
- Specific science instrument and sensor groups include the following:
  - Microwave Instruments and Sensors
  - Multi-Spectral Imaging / Spectroscopy (Vis-IR-FIR)
  - Multi-Spectral Sensing (UV-Gamma)
  - Laser / LIDAR Remote Sensing
  - Direct Sensing of Particles, Fields, and Waves
  - In Situ Instrumentation
- The Science Instruments and Sensors roadmaps will not include:
  - Instruments and sensors performing "engineering" functions
  - Instrument accommodations on a variety of platforms (orbiting, landers, rovers, probes, aerial vehicles)
  - Astronaut tools required to use instruments and sensors
  - Large sets of systems and associated technologies necessary to collect, concentrate and combine electromagnetic bands ranging from gamma-rays to radio waves, and including gravity-waves

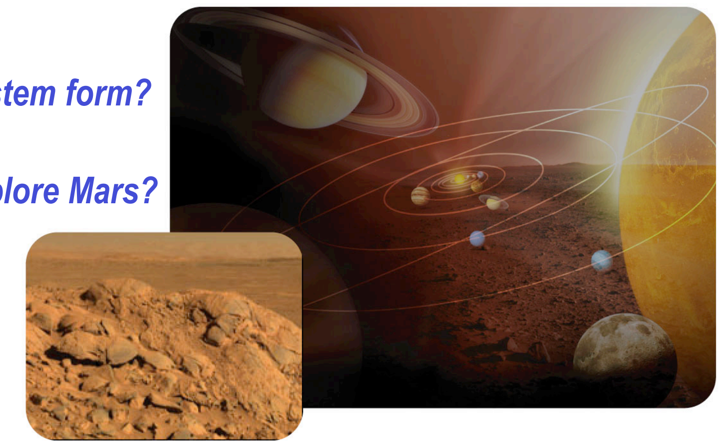
Compelling Science Questions

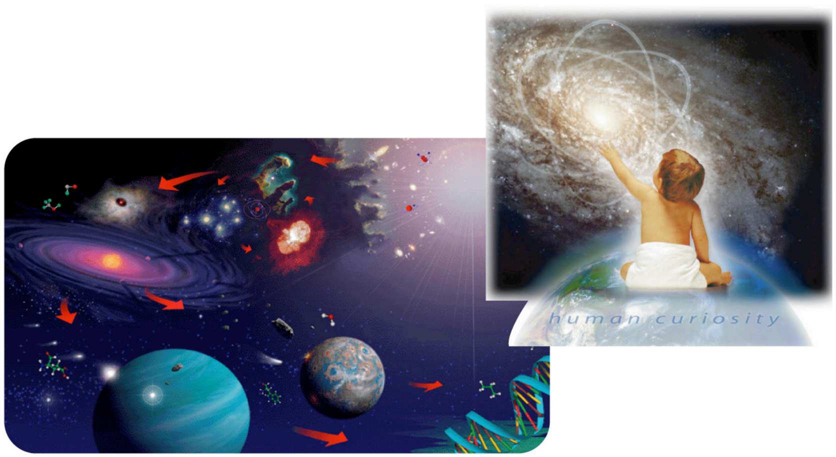
Answers to questions as old as human curiosity have always seemed beyond the reach of science..
UNTIL NOW!



- *Understand the fundamental physical processes of the space environment – from the Sun to Earth, to other planets, and beyond to the interstellar medium.*
- *Observe, understand, and model the Earth system to discover how it is changing and to understand the consequences for life on Earth*
- *Define the origins and societal impacts of variability in the Sun-Earth connection.*

•How did the solar system form?
•How does life begin?
•How can Humans explore Mars?





•How did the Universe begin?
•Does time have a beginning and an end?
•Where did we come from?
•Are we alone?

Top Level Assumptions

- Design reference missions and strategic science measurement needs must be driven by the Vision for Space Exploration and the New Age of Exploration (NASA's Direction for 2005 and Beyond).
  - Supplemental information was obtained (and documented) from science working group interactions, presentations to the Strategic Roadmap Teams, and science/engineering technical presentations.
- Development of realistic Science Instrument and Sensor roadmaps is dependent upon *many* CRM team development activities. Dual membership occurs within the following CRM teams:
  - Advanced Telescopes and Observatories
  - In Situ Resource Utilization
  - Nanotechnology
- Roadmap Format:
  - Capability needs are shown in the timeline to be met 3-5 years before mission launch.
  - Missions timelines were provided by APIO/SMD via design reference missions or the strategic mission framework.
  - Missions listed with an * are not traceable to a currently defined design reference mission, however, the science measurement is dependent upon significant instrument and sensor capability development.

12. Capability Breakdown Structure

Advanced Planning & Integration Office

Science Instruments and Sensors 12.0

Co-Chair: Richard Barney, NASA/GSFC
Co-Chair: Maria Zuber, MIT
Deputy: Juan Rivera, NASA/GSFC

CAPABILITIES / SUB-CAPABILITIES

12.1 Microwave Instruments and Sensors

Chair: Soren Madsen, JPL
Co-Chair: Chris Ruf, UM

- 12.1.1 Radar Altimetry
- 12.1.2 Real Aperture Radar
- 12.1.3 Synthetic Aperture Radar
- 12.1.4 Interferometric SAR
- 12.1.5 Radar Subsurface Sounding
- 12.1.6 Passive Microwave Real Aperture Imager
- 12.1.7 Passive Microwave Synthetic Aperture Imagers
- 12.1.8 Passive Microwave Sounder
- 12.1.9 GPS - Radio time-of-Flight triangulation
- 12.1.10 Other Technology

12.2 Multi-Spectral Imaging/Spectroscopy (vis-IR-FIR)

Chair: Craig McCreight, ARC
Co-Chair: Ron Polidan, NGST

- 12.2.1 Visible Imagers, Photometers, Radiometers, Sounders
- 12.2.2 Visible Imagers, Photometers, Radiometers, Sounders
- 12.2.3 Visible Spectral (& hyperspectral) Imagers
- 12.2.4 IR/FIR Imagers, Photometers, Radiometers, Sounders
- 12.2.5 IR/FIR Spectrometers/ Interferometers
- 12.2.6 IR/FIR Spectral (& hyperspectral) Imagers

12.3 Multi-Spectral Sensing (UV-Gamma)

Chair: Brian Ramsey, MSFC
Co-Chair: David Chenette, LM

- 12.3.1 UV Imaging and Spectrometry
- 12.3.2 UV Interferometry
- 12.3.3 X-Ray Imaging and Spectrometry
- 12.3.4 X-Ray Timing and Polarimetry
- 12.3.5 X-Ray Interferometry
- 12.3.6 Gamma Ray Imaging and Spectrometry

12.4 Laser/LIDAR Remote Sensing

Chair: Maria Zuber, MIT
Co-Chair: Richard Barney, GSFC

- 12.4.1 Altimeters
- 12.4.2 Transponders
- 12.3.3 Atmospheric LIDARS
- 12.4.4 Spectrometers
- 12.4.5 Interferometers

12.5 Direct Sensing of Particles, Fields and Waves

Chair: Dick McEntire, APL
Co-Chair: Carl Stahle, GSFC

- 12.5.1 Energetic Particle and Plasma Imagers and Spectrometers
- 12.5.2 High Energy Particle Detector Systems
- 12.5.3 Magnetometers
- 12.5.4 Electric Fields and Wave Instruments
- 12.5.5 Gravitational Waves and Fields Instruments

12.6 In Situ Instrumentation

Chair: Tim Krabach, JPL
Co-Chair: Rich Dissly, BATC

- 12.6.1 Imaging/Microscopy
- 12.6.2 Mineralogical/Elemental Analysis
- 12.6.3 Chemical Detection and Identification
- 12.6.4 Isotope Analysis/ Age Dating
- 12.6.5 Biological Detection and Identification
- 12.6.6 Geophysical Measurements
- 12.6.7 Sample Handling and Preparation
- 12.6.8 In Situ Instrument Engineering

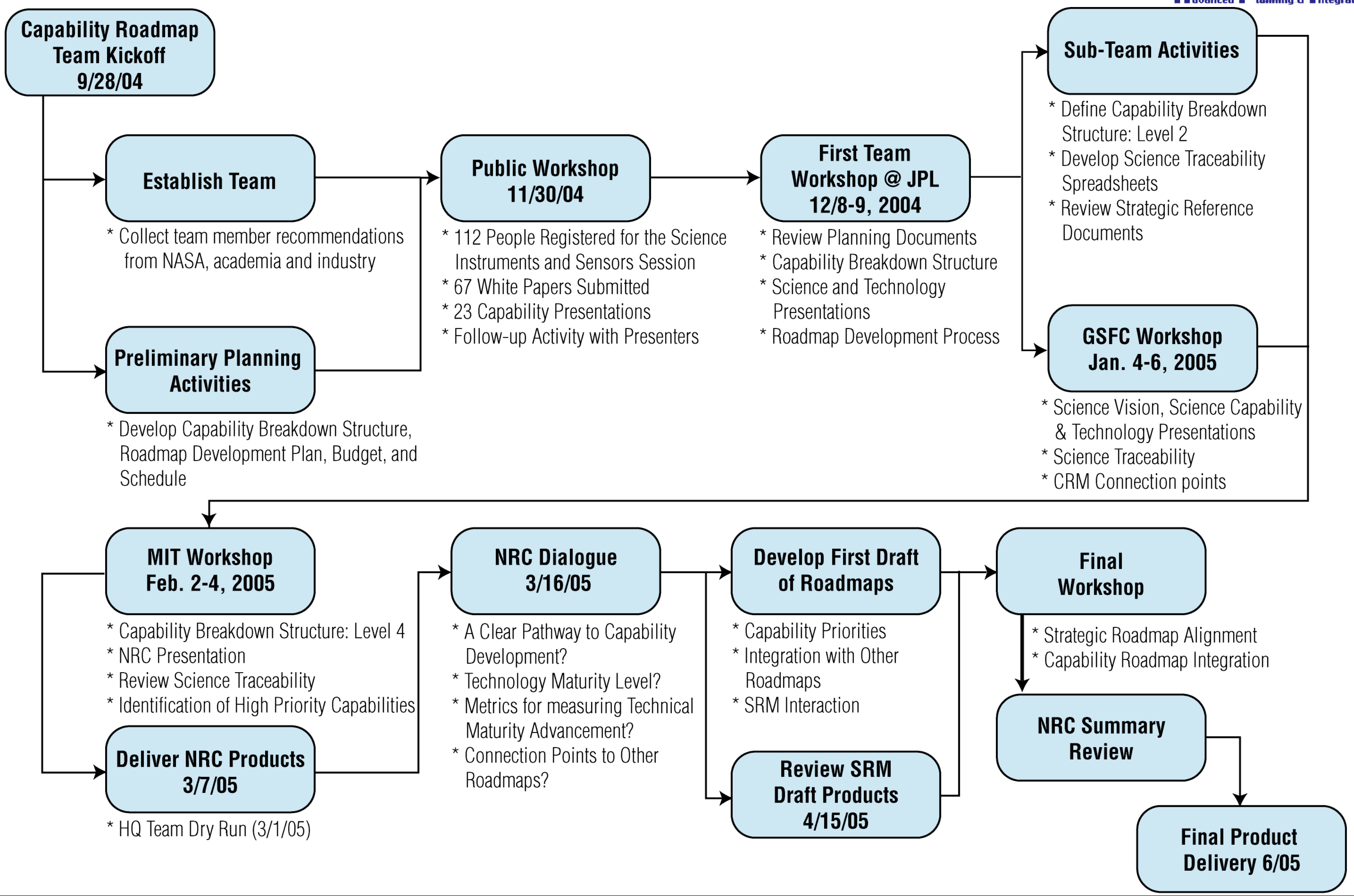
Roadmap Development Approach

Advanced Planning & Integration Office

- Science Instruments and Sensors is a broad and diverse roadmapping topic with significant science measurement application challenges.
  - Previous instrument and sensor roadmapping efforts were limited to specific science measurement priorities (Earth Science, Universe, Solar System, etc.).
  - Emphasis was placed on identifying instrument and sensor capabilities that would enable multiple design reference missions.
- Extensive participation from past, present, and future Principal Investigators was encouraged at public meetings and workshops.
  - Development of science instruments and sensors is a competed, peer reviewed process where lessons learned can influence future missions.
  - Specific technology implementation strategies are the outcome of the proposal process and not the science instruments and sensors roadmap strategic planning activity.
- Sub-Capability elements were prioritized by the degree of cross-cutting applicability to multiple design reference missions.
  - Do they enable or enhance scientific discovery?
  - Do they have broad application across instrument and sensor capabilities?
  - Do they meet the needs of multiple design reference missions?

Roadmapping Process

Advanced Planning & Integration Office



Strategic Traceability

- Science Instrument and Sensor capability needs can be traced directly back to the following top-level strategic documentation (detailed list is shown in backup charts):
  - The Vision for Space Exploration
  - The New Age of Exploration: NASA Strategic Objectives for 2005 and Beyond
  - A Journey to Inspire, Innovate, and Discover: President's Commission Report
  - Our Changing Planet: The US Climate Change Science Program for Fiscal Years 2004 and 2005
  - Design Reference Missions
  - NASA Enterprise Strategies
  - National Research Council Reports

- A Science Traceability Database was developed to establish, track, and communicate linkages between compelling science questions, design reference missions, science instrument measurement needs, and critical instrument and sensor capabilities/technologies gaps.
  - NASA design reference missions, existing enterprise roadmaps, science measurement priorities, and science and engineering community input was collected, reviewed and documented.
  - Interim Earth, Planetary Science, Sun-Solar System and Astrophysics spreadsheets were presented to several Strategic Roadmap Teams for review.

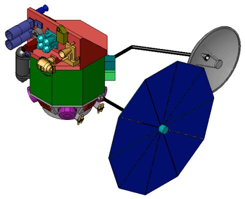
Science Traceability Matrix
(Example)

Advanced Planning & Integration Office

Strategic Roadmap	NASA Science Doc*	Science Question	Relevant Missions (DRM exceptions noted in red)	Launch Date	Measurement Parameter	Measurement Scenario	Target Body	Tech Gap Exists ?	Scenario Doc. Ref*	CBS Ref	Technology Component Development	Orbit
8	16	Is there observational evidence supporting the hypothesis that the early universe underwent a period of rapid inflation?	Einstein Inflation Probe	2012-2020	Polarization structure of the cosmic microwave background	Map the polarization structure of the cosmic microwave background	Cosmic Microwave Background	Yes	15,16	12.1	Very large microwave arrays, 100 mK cryo-cooler, wide-band receiver	
10	11	What are Dynamics of Sun's Magnetic Transition Region between Photosphere and Upper Chromosphere?	Magnetic Transition Region Probe (MTRAP)	2020	Velocity and Vector Magnetic Fields in Chromosphere/ Corona	Doppler Imager/ Magnetograph	Sun	Yes	11	12.2	Large, lightweight UV reflective optics; Up to 16K x 16K CCDs with high QE at 150 nm and low power	S/C at GEO
10	11	How similar and different are fundamental auroral acceleration processes at Jupiter and the Earth?	Jupiter Polar Orbiter (JPO)	2009	Auroral imagery	Vis/UV auroral imager	Jupiter	Yes	11	12.3	TDI image synthesis & relative motion compensation; synchronized shutter for imager radiation shielding	Polar orbit around Jupiter
9	2, 3	How can weather forecast duration and reliability be improved?	Global Tropospheric Winds	2013	Atmospheric wind profile	Coherent Doppler wind lidar	Earth's atmosphere	Yes	5	12.4	2 J/pulse laser with 12 Hz PRF and 3 year life; 0.75 m lightweight diffraction-limited optics; high precision optical alignment;	
10	11	How Does the Magnetotail Control Energy Flow in the Magnetosphere, and What Processes Control Magnetotail Structure and Dynamics?	Magnetospheric Constellation (MC)	2021	Fields & Particles	In Situ Instruments	Earth's Magnetosphere	Yes	11	12.5	Nanosatellites and miniaturized rad-tolerant low mass/power instruments	50-100 Nanosats in Nested Orbits
2	7, 8	Characterize the geology and geophysics of the shallow Martian crust at one site, particularly as it relates to interpreting present habitability.	Mars Deep Drill	2018	Investigate the thermal characteristics of the Martian subsurface	Drill (10 m to 50 m)	Mars	Yes	7, 8	12.6		

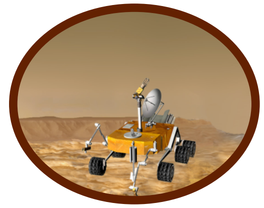
Mission Drivers

Lunar Recon. Orbiter

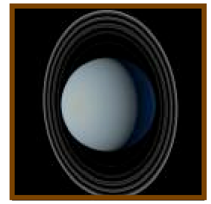


Constellation-X

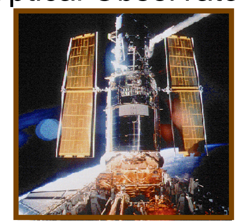
Astrobiology Field Lab



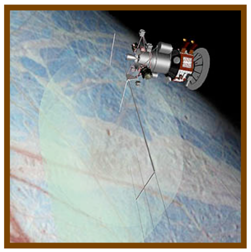
Uranus Orbiter with Probes



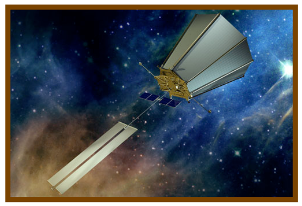
Large-Aperture UV/ Optical Observatory



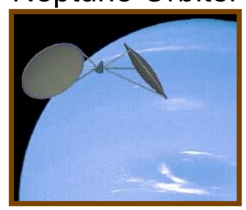
Europa Geophysical Orbiter



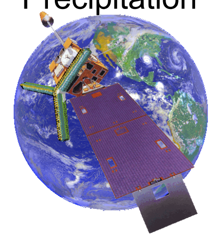
TPF-C



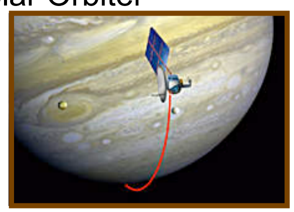
Neptune Orbiter



GEO Global Precipitation

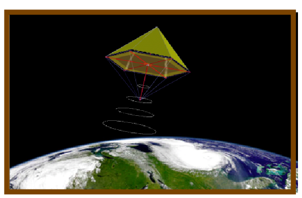


Jupiter Polar Orbiter w/ Probes

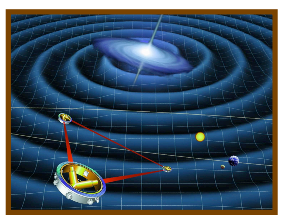


Mars Sample Return

GEO/MEO InSAR

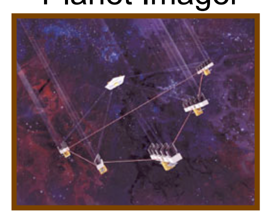


LISA



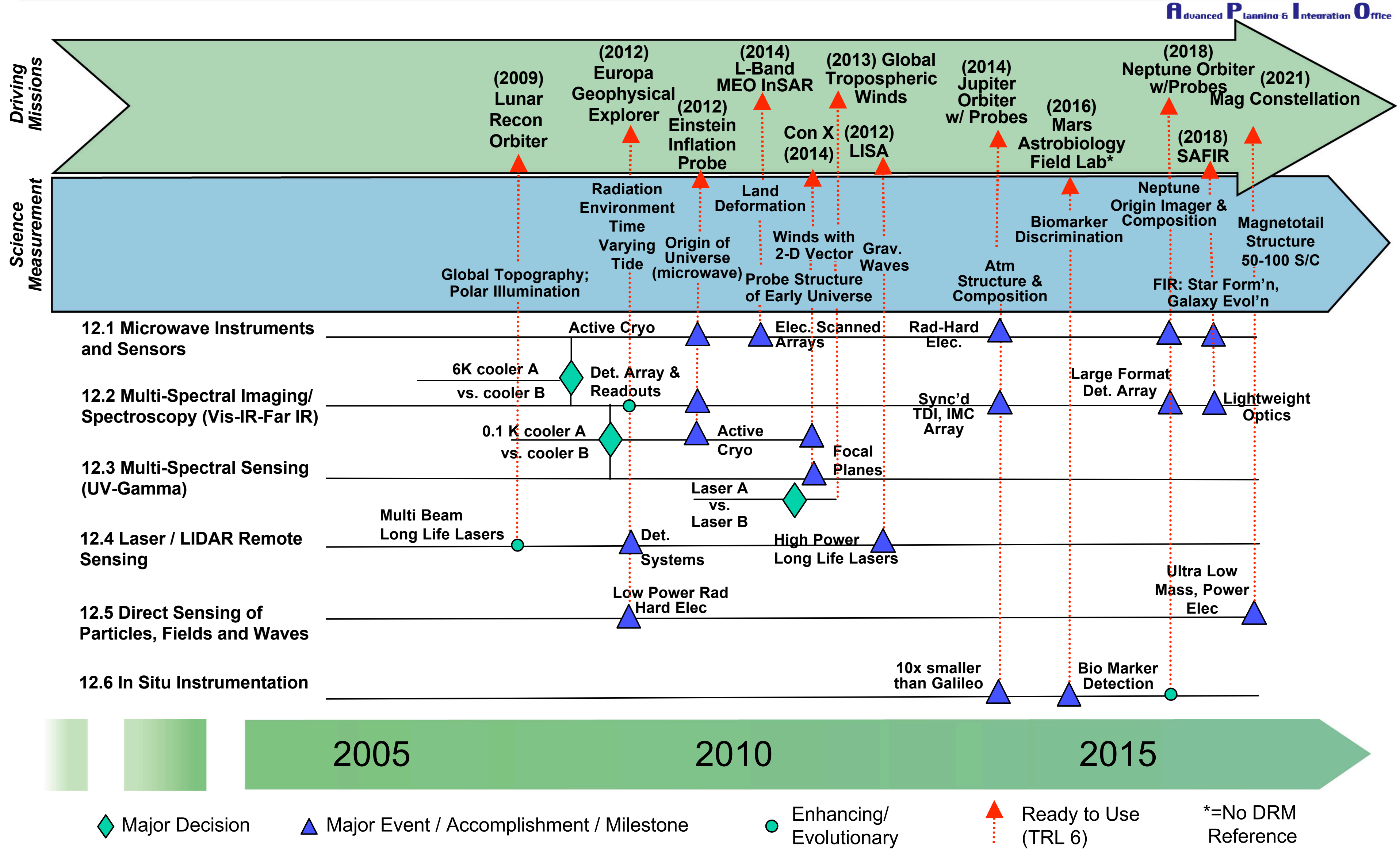
SAFIR

Planet Imager



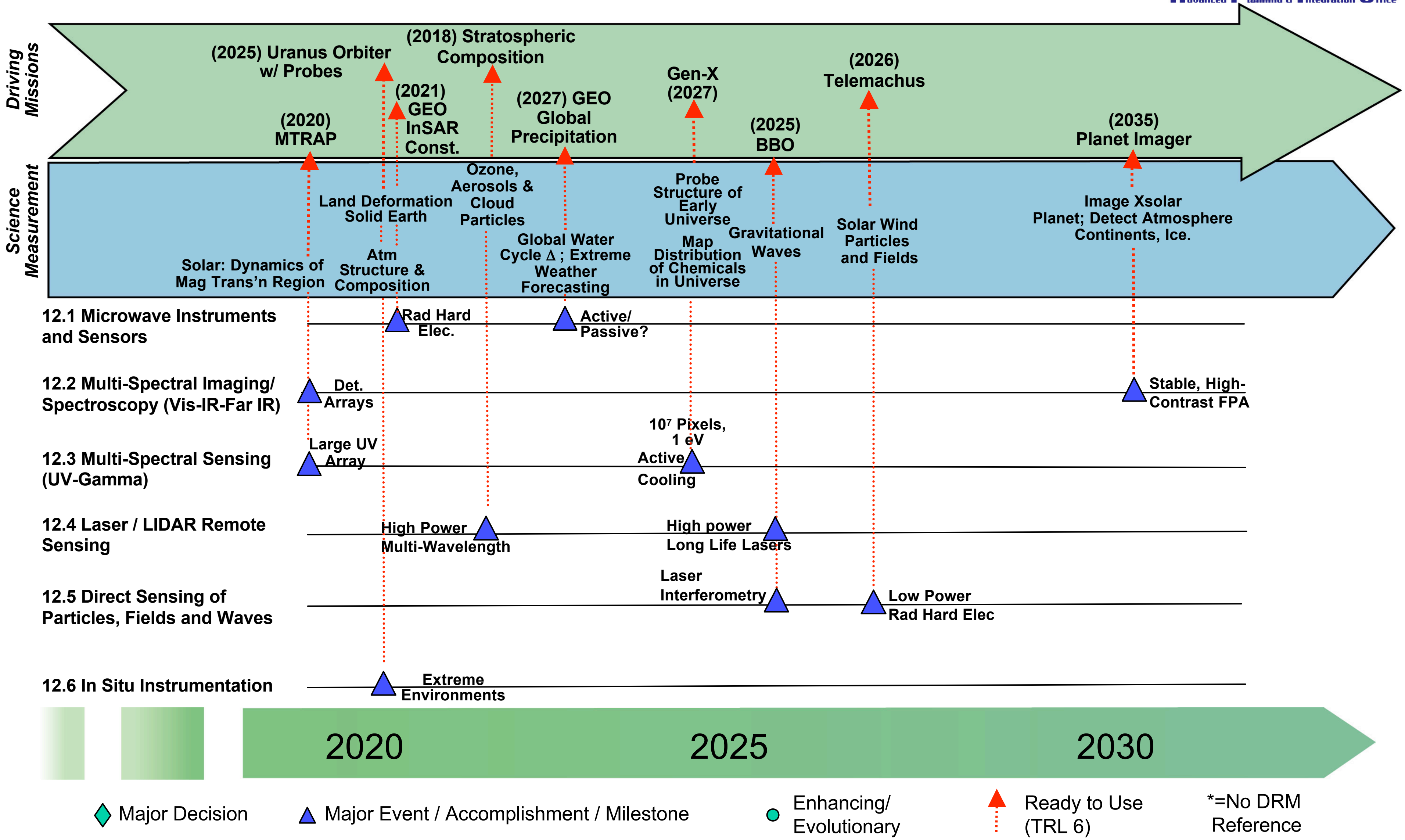
2010 2020 2030

Science Instruments and Sensors Near Term Capability Roadmap



Science Instruments and Sensors
Far Term Capability Roadmap

Advanced Planning & Integration Office



Connection Points: Capability Roadmaps

Advanced Planning & Integration Office

	Capability Roadmap	Flow	Connection Points
	1. High-energy power and propulsion		
	2. In-space transportation		
S	3. Advanced telescopes and observatories	↔	Dr. Ron Polidan is a member of both CRM teams. Optics, Interferometry, Structures, and Active Cryogenic Systems.
EH	4.Communication & Navigation	→	Future optical and RF communication systems and sensor web navigation
D	5. Robotic access to planetary surfaces	→	Robotic access for remote sensing orbital reconnaissance, surface analysis, and sample return.
	6. Human planetary landing systems		
EH	7. Human health and support systems	←	Radiation detection and environmental monitoring technologies
LS	8. Human exploration systems and mobility	↔	Access to exploration targets, InSitu analysis, sample return, mobile sensor platforms, environmental sensing
LS	9. Autonomous systems and robotics	↔	Robotic Systems for surface exploration
	10. Transformational spaceport/range technologies		
S	12. *In situ* resource utilization	↔	Dr. Rich Dissly is an ex officio member of the ISRU team. Resource assessment and processing relationship
LS	13. Advanced modeling, simulation, analysis	↔	Systems architecture studies, applications for science discovery and analysis, and instrument design tradespaces.
EH	14. Systems engineering cost/risk analysis	→	Requirements development, technical solution, process management, risk management
D	15. Nanotechnology	→	Dr. Carl Stahle is an ex officio member of the Nanotechnology team. Sensing and devices, mechanisms, electronics, modeling

No Relationship
Critical Relationship (dependent (D), synergistic (S))
Moderate Relationship (enhancing (EH), Limited Synergy (LS))

Connection Points: Strategic Roadmaps

Advanced Planning & Integration Office

	Strategic Roadmap	Connection Points
Critical	1. Lunar: Robotic and Human Exploration	Minimal Design Reference Missions
Critical	2. Mars: Robotic and Human Exploration	Presented at Meeting #1 and MEPAG follow up. MEPAG reference missions provide strategic guidance.
Critical	3. Solar System Exploration	Design Reference Missions are defined and strategic guidance documentation has been reviewed.
Critical	4. Search for Earth-Like Planets	Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed. (POC: Eric Smith)
No	6. International Space Station	
No	7. Space Shuttle	
Critical	8. Universe Exploration	Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed. . (POC: Kathy Flanagan)
Critical	9. Earth Science and Applications from Space	Design Reference Missions are defined and strategic guidance documentation has been reviewed. (POC: Azita Valinia)
Critical	10. Sun-Solar System Connection	Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed.
No	11. Aeronautical Technologies	
No	12. Education	
No	13. Nuclear Systems	

- Green: No Relationship
- Red: Critical Relationship
- Yellow: Moderate Relationship

Science Instruments and Sensors Capability Roadmap Team

12.1 Microwave Instruments and Sensors

Name	Organization	Primary Expertise
Soren Madsen	NASA JPL (Co-Lead)	Radar
Chris Ruf	Univ. Michigan (Co-Lead)	Atmosphere & Ocean Radiometry
Dave Glackin	Aerospace	Earth Remote Sensing Satellites
Suzanne Staggs	Princeton	Cosmic Microwave Background
Azita Valinia	NASA Goddard	Earth Science Technology
Juan Rivera	NASA Goddard	Instruments Design/Engineering
Shyam Bajpai	NOAA SIS	Operational Weather Satellites

12.1 Microwave Instruments and Sensors

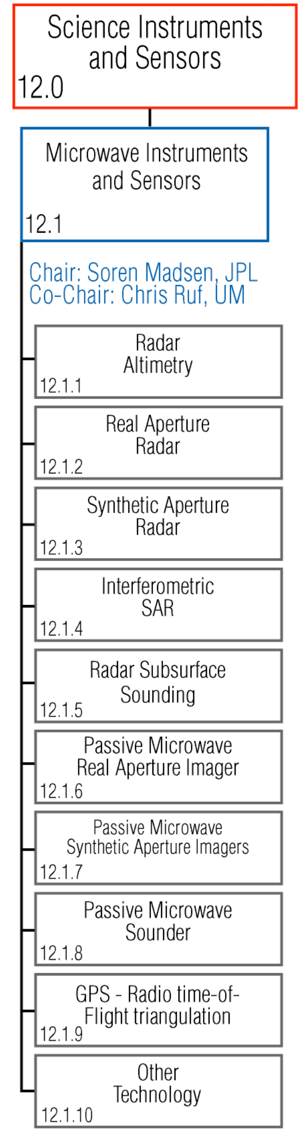
Advanced Planning & Integration Office

Capability Description

- Active (Radar & GPS) and Passive (Radiometer) microwave remote sensing instruments operating in the electromagnetic spectrum at wavelengths from 10 km to 100 µm(at frequencies from 30 kHz to 3 THz, respectively)

Reference Documentation

- **Astronomy & Astrophysics**
  - Astronomy and Astrophysics in the New Millennium, 2001, NRC Report, Astronomy and Astrophysics Survey Committee
  - Connecting Quarks with the Cosmos, 11 Science Questions for the New Century, NRC Report
  - Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team
- **Earth Science**
  - Strategic Plan for US Climate Change Science Program, 2003
  - Earth Science Enterprise Strategy, 1 Oct 2003
  - Earth Science Research Plan: 6 Jan 2005 Draft
  - NASA ESTO "Earth-Sun System: Potential Roadmap and Mission Development Activities" 23 Dec 04 Draft Briefing
- **Planetary Science**
  - New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)
- **Sun-Solar System**
  - Sun-Earth Connection Roadmap: 2003 - 2028
  - The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
  - Earth-Sun System: Potential Roadmap and Mission Development Activities (Draft) 12/03



12.1 Microwave Instruments and Sensors

Capability Benefits

Astronomy and Astrophysics:
- What powered the big bang?
- How and when did galaxies first form?
- What are the properties of the earliest stars?

Planetary Science:
- How long did it take Jupiter to form, and how was the formation of the Uranus and Neptune different from that of Jupiter and Saturn?
- Confirm the presence of interior oceans on Europa, measure ice thickness, elucidate formation of surface features

Earth System Science:
- How does the cryosphere respond to and affect global environmental change?
- How do atmospheric trace constituents respond to and affect global environmental change?
- How are global precipitation, evaporation, and the cycling of water changing?
- How can weather forecast duration & reliability be improved?

Earth System Science, (continued)
- How are variations in local weather, precipitation and water resources related to global climate variation?
- How is the Earth's surface being transformed by naturally-occurring tectonic and climatic processes?
- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- What are the effect of clouds and surface hydrologic processes on Earth's climate?

Assumptions

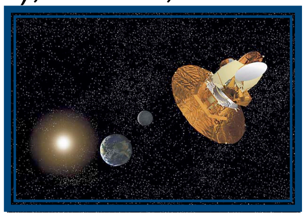
Roadmapping Philosophy
– Highlight capabilities that enable the maximum number of science applications
– Capability roadmaps are developed at Level 3 (subsystems) to highlight cross-cutting between Level 2 (instrument type) areas

What isn't covered
– Non-microwave electromagnetic science instruments
– Non science microwave (*e.g.* Entry, Descent & Landing navigation)
– *In situ* microwave science instruments & sensors

12.1 Microwave Instruments and Sensors

History/Current Missions

Astronomy & Astrophysics: WMAP, Herschel (*aka* FIRST), Planck, SOFIA (airborne)



Wilkinson Microwave Anisotropy Probe

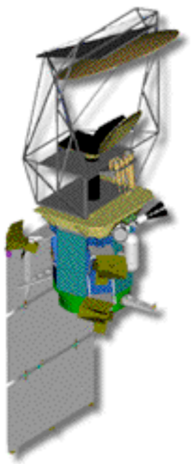
Planetary Science: Pioneer, Apollo–17, Magellan, Cassini, MARSIS

Cassini

Earth System Science: MSU, AMSU, MLS, MLS-2; SeaSat, DMSP, WindSat; SIR-A,B,C; SRTM; NScat, QuikScat; GeoSat, TOPEX, Jason; ESMR, TRMM

SeaSat

DMSP



WindSat

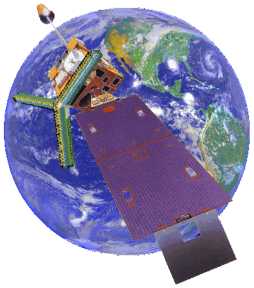
Mission/Strategic Drivers

Astronomy & Astrophysics: Einstein Inflation Probe, SAFIR

Planetary Science: Jupiter Polar Orbiter/Probes, Neptune Orbiter/Probes, Prometheus (JIMO a.o.)

Jupiter Polar Orbiter

Earth System Science: Ice Thickness, Global Tropospheric Aerosols, Global Soil Moisture, Ocean Surface Winds, GEO Global Precip, mmWave GEO Radar, Land deformation InSAR, Ocean Circulation and Eddies, Cloud System Structure, Land deformation repeat pass InSAR

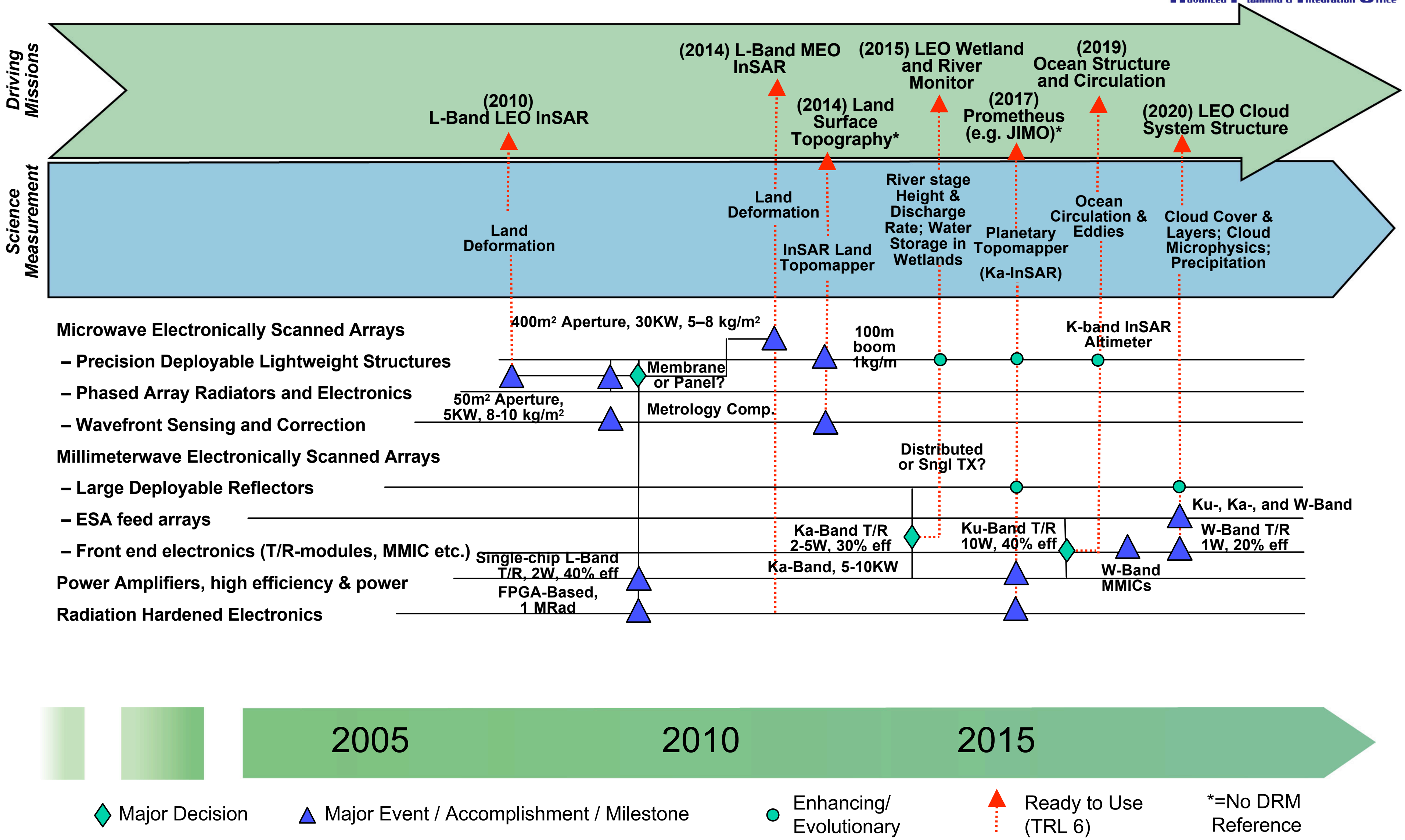


GEO Global Precip

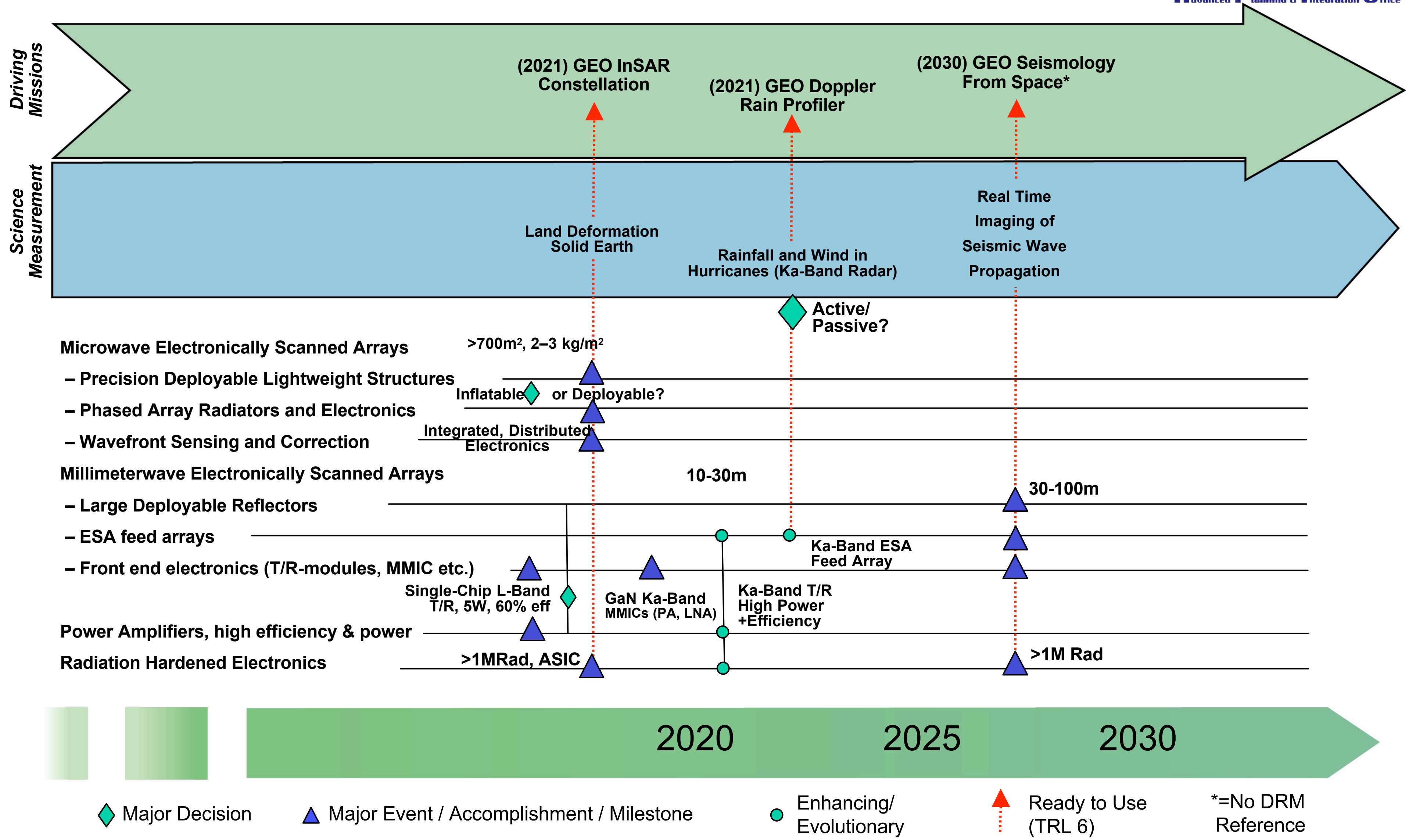
12.1 Capability Need/Gap Assessment

Sub Capability	Figures of Merit	Current Technology	Needed Technology
Interferometric SAR	Temporal and Spatial Resolution, swath width	Moderate High efficiency L-band T/R modules, Moderate ~30m^2 antennas	Large (400–700m^2), deployable antennas, High efficiency rad-hard T/R modules, Digital Beam Formation (DFB) Rad-hard processor
Millimeter Wave RAR, SAR, and Interferometry	Electronic Beam Steering, Phase stability, Transmitted power, Receiver noise figure.	Non-deployable antenna; mechanical beam steering, Discrete power amplifier (EIK)	Large deployable antenna, Electronic Beam Formation, High freq. T/R modules
Millimeter wave Polarimeter Arrays, Spectrometers & Sounders	Noise limit, frequency resolution, bandwidth, number of pixels, degree of system integration; DC power requirement	non-Quantum limit cryo receiver; moderate power consumption; 10s of pixels;individual ass'y; moderate bandwidth digital autocorrelator	Quantum limit cryo receiver, 1000s pixels; highly integrated; wideband digital autocorrelator, Rad-hard processor, high efficiency Cryocooler
Passive Synthetic Aperture Microwave Imagers	Spatial resolution, swath width, number of frequency/polarization channels, DC power, noise limit	TRL 6 synthetic aperture aircraft demos; TRL 4 MMIC correlating receivers, TRL 4 ASIC correlators	Low power MMIC receiver, massively parallel digital correlator, Rad-hard processor

12.1 Microwave Instruments and Sensors (Active)
Near Term Capability Roadmap

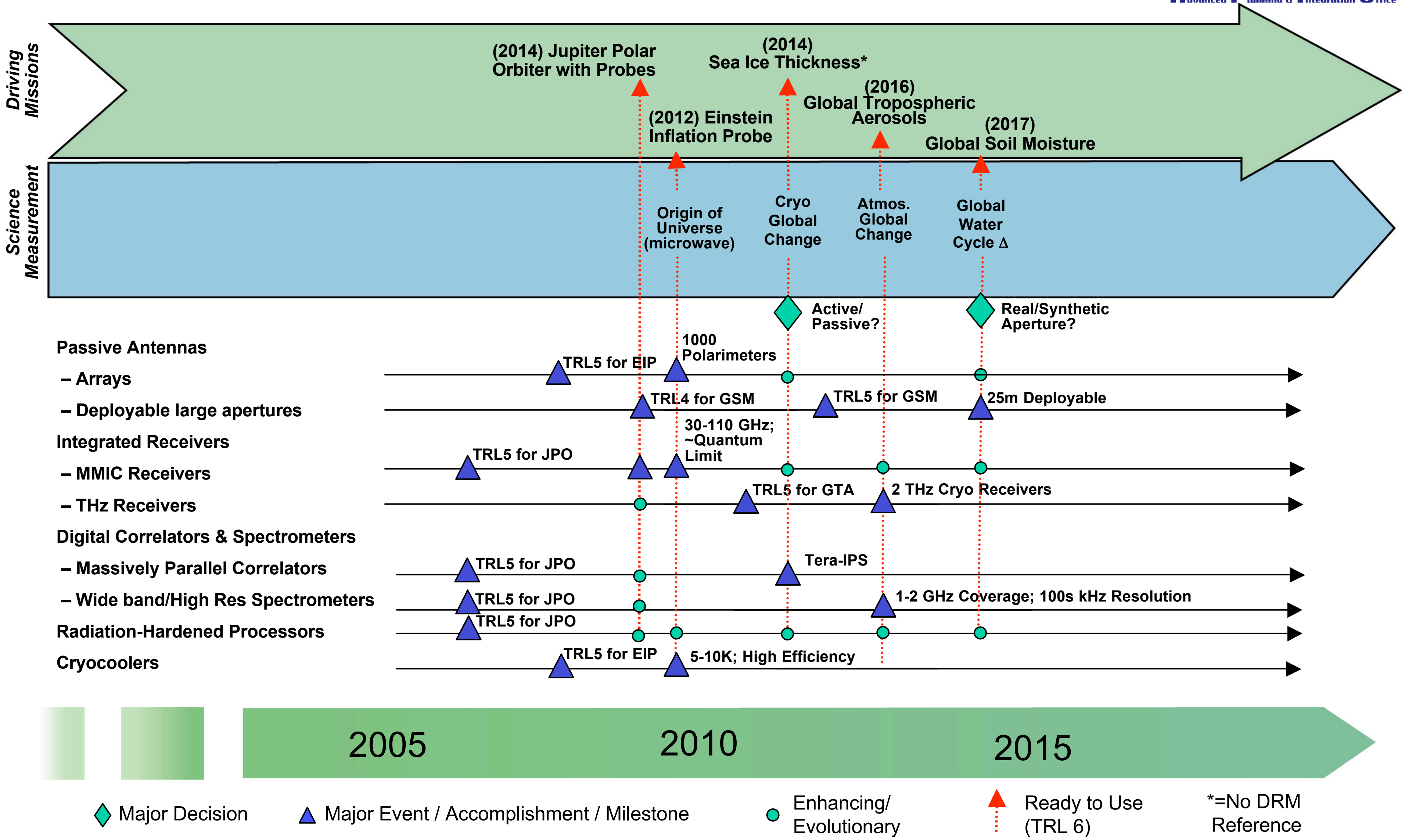


12.1 Microwave Instruments and Sensors (Active)
Far Term Capability Roadmap

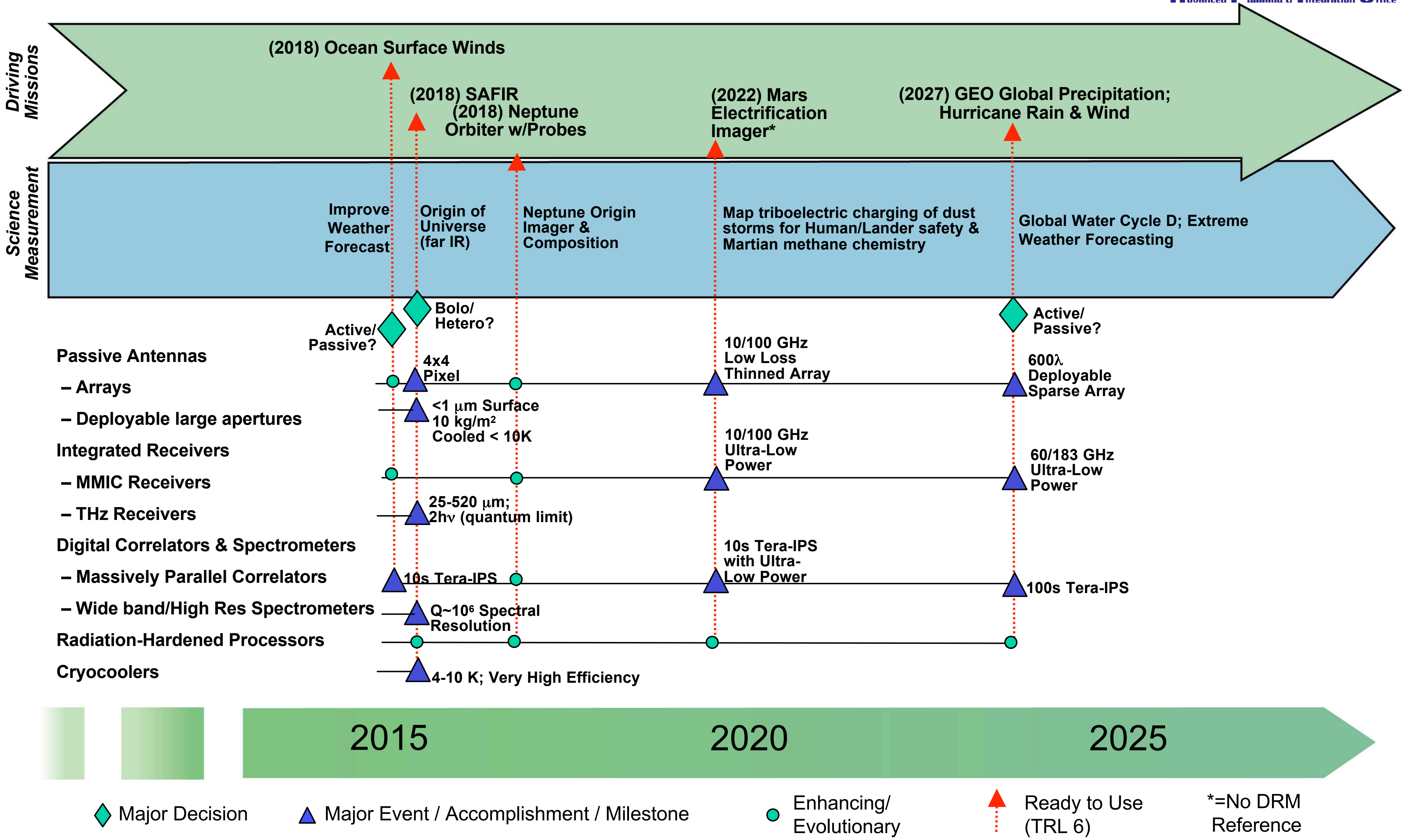


12.1 Microwave Instruments and Sensors (Passive)
Near Term Capability Roadmap

Advanced Planning & Integration Office



12.1 Microwave Instruments and Sensors (Passive)
Far Term Capability Roadmap



12.1 Capability Maturity Assessment

Advanced Planning & Integration Office

Sub Capability	Integrated Technologies	State-of-the-Art	Req Perf @TRL 6	Mission Driver	Need Date
Microwave Interferometric SAR	Lightweight L-band ESA	Rigid panels, 10-15 kg/m^2 Plus deployment structure	Lightweight manifold, Interconnects, signal distribution, integrated T/R modules. 2-3kg/m^2	InSAR LEO/ MEO/ GEOSync	2007/ 2010/ 2017
			Adaptive wavefront sensing and control. Thermal mgmt.	InSAR (see above)	2010/ 2017
	Low cost, efficient L-band T/R modules	10-30W, 40% eff, 4-5 chip MCM, $1K/module, Tx/Rx only	Single chip T/R (GaAs, SiGe, or CMOS), Rad Hard, Aperture Integrated, 60% eff, $100/mod	InSAR (See above)	2007–17
			Integration of Waveform Generator and Dig receivers For DBF.	InSAR MEO/GEO	2010–17
Millimeter Wave Radar	Efficient MMIC T/R Modules	Exist up to X-band 10W, 30% efficiency	10W @ Ku-band, 40% eff, Phase stable	Ocean Structure Cloud Structure	2015
			5W @ Ka-band, 30% eff, Phase stable	LEO Wetland… Cloud; Topo	2010/11/15
			1W @ W-band, 20% eff, 4dB NF	Cloud System Structure	2015
			Higher power, efficiency GaN Ka-band electronics	GEO Doppler Rain Profiler	2016
	MMW Electronically Scanned Array (ESA)	Exist up to X-band, 5-10KW ESA, 10-15kg/m^2	Ku-band ESA, 5KW	Cloud Structure	2015
			Ka-band ESA, 1KW	LEO Wetland	2011
			W-band ESA, 500W	Cloud Structure	2015

12.1 Capability Maturity Assessment

Advanced Planning & Integration Office

Sub Capability	Integrated Technologies	State-of-the-Art	Req Perf @TRL 6	Mission Driver	Need Date
Millimeter wave Polarimeter Arrays, Spectrometers & Sounders	THz Receivers	currently ~100 element array @ 110 GHz; 2 THz but not cryo	~1000 element @ 110 GHz	Einstein Inflation Probe	2009
			Individual elements @ 2 THz (cryo but not quantum limit)	Global Tropo Aerosols	2013
			3 THz, cryo, quantum limit	SAFIR	2015
	Wide band / High res spectrometers	Input bandwidth currently ~1 00 MHz for autocorrelator & polyphase digital spectrometers	Current BW @ TRL 6	E. I. P.	2009
			4-8 GHz BW	G. T. A.	2013
			Same performance in Hi Rad Environment	SAFIR	2015
Passive Synthetic Aperture Microwave Imagers	MMIC Receivers	500 mW @ < 60 GHz	500 mW @ < 37 GHz	Sea Ice Thickness	2011
			250 mW @ < 37 GHz	Ocean Sfc Winds	2015
			100 mW @ < 90 GHz	Neptune Orbiter	2015
			250 mW @ < 200 GHz	GEO Global Precip	2018
	Massively Parallel correlators	1 Tera instruction per second (TIPS)	1 TIPS @ TRL 6	S. I. T.	2011
			10 TIPS	O. S. W.	2015
			10 TIPS Hi Rad Environment	N. O.	2015
			100 TIPS	G. G. P.	2018

12.1 Microwave Instruments and Sensors

Other Key Technologies

Technology elements were prioritized by the degree of cross-cutting applicability to multiple DRMs. Following are elements critical (i.e. enabling) to certain DRMs but not sufficiently cross-cutting to be assigned a high priority.

- Global Soil Moisture Mission
  - Precision deployable/inflatable structures (other than reflectors)
  - Control of Spinning apertures (balancing)
- Solar Radio Bursts & Termination Shock
  - Large Data Storage
- Next Generation Geodetic Networks/Observatory
  - Next Generation GPS/GNSS receivers

Capability Dependencies

- Cross-cutting between Microwave and other groups' DRMs
  - Rad-hard processors
  - Cryo-coolers
- Cross-cutting between Microwave DRMs
  - MMIC RF Technology
  - Large scale ASIC digital signal processing
  - Rad-hard processors
- Cross-cutting between major science themes
  - Earth Science missions serve as capability test beds for other missions
    - Nimbus NEMS&SCAMS => TIROS MSU => DMSP SSM/T
    - SeaSat SAR => Magellan SAR
    - Jason MMICs => JUNO Water/Ammonia Radiometer
    - MLS receivers & spectrometers => Jupiter & Neptune Orbiters

- ***Microwave Science instruments have historically led to breakthrough science, enabled operational measurement capabilities and provided technology for critical exploration initiatives.***

Science Instruments and Sensors Capability Roadmap Team

12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

Name	Organization	Primary Expertise
Craig McCreight	NASA Ames (co-lead)	IR detectors for astronomy
Ron Polidan	Northrop Grumman (co-lead)	UV-visual-IR sensors, instrum systems
Bruce Spiering	NASA Stennis	Vis-IR remote sensing instrum'n / oceans
Steve Ackerman	U. Wisconsin	Meterology, cloud science, aerosols
Rich Dissly	Ball Aerospace	*In situ*, & atmospheric applications
Tim Krabach	NASA-JPL	LWIR to FIR detectors

12.2 Multispectral Imaging/Spectroscopy (vis-IR-FIR)

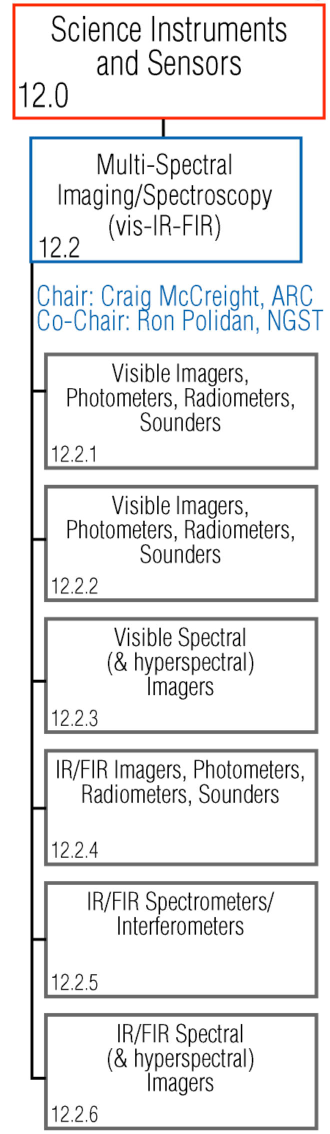
Advanced Planning & Integration Office

Capability Description

- Instrument-level, & component, needs for advanced imaging & spectroscopy in the visible and infrared regions, extending from 0.4 - 1000+ μm. Consideration includes key support technologies, *e.g.,* cryogenics for IR.

Reference Documentation *(partial)*

- **Astronomy & Astrophysics**
  - Astronomy and Astrophysics in the New Millennium, 2004, NRC Astronomy and Astrophysics Survey Committee (Note that this is a National Academy study rather than a specific NASA roadmap)
  - Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team
  - Origins Roadmap *(2003)*
- **Earth Science**
  - Strategic Plan for US Climate Change Science Program, 2003
  - Earth Science Enterprise Strategy, 1 Oct 2003
  - Earth Science Research Plan: 6 Jan 2005 Draft
  - NASA ESTO "Earth-Sun System: Potential Roadmap and Mission Development Activities" 23 Dec 04 Draft Briefing
- **Planetary Science**
  - New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)
- **Sun-Solar System**
  - Sun-Earth Connection Roadmap: 2003 - 2028
  - The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
  - Earth-Sun System: Potential Roadmap and Mission Development Activities (Draft) Dec 2003



12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

Capability Benefits

Earth Science:

- How do trace atmospheric constituents affect global climate change?
- How is climate change affected by trends in solar irradiation?
- How can weather forecasting be improved and made more reliable?

Planetary Science:

- What processes marked the initial stages of planet & satellite formation?
- Which processes produce & maintain habitable zones within the solar system?
- How long did it take for Jupiter to form, & how did its formation differ from that of the other gas giant planets?

Sun-Solar Studies:

- What are the dynamics of the sun's transition region?
- What are the similarities between auroral acceleration processes of different planets?

(Universe & Earth-like planet search):

- Is there evidence of life in other planetary systems?
- How are planetary systems formed, & what are their properties?
- Did the early universe undergo a process of rapid expansion?

Sub-Team Assumptions

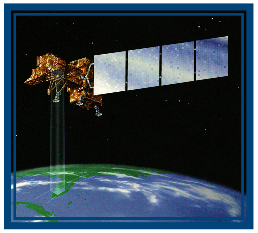
- Vis-IR near-field sensing, or measurements within planetary atmospheres, covered by *in situ*
- Important overlaps with telescope technology team (long-baseline systems) in developing advanced interferometers
- Agency will support necessary infrastructure (fabrication, testing, expertise)

12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

Advanced Planning & Integration Office

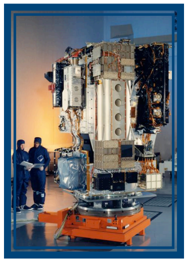
History/Current Missions

Earth Science: LandSat, Ikonos, Quickbird 2, MODIS (Terra, Aqua), AIRS (Aqua)



Planetary: THEMIS, VIMS (Cassini), HiRISE & CRISM (Mars Recon Orbiter), TES (Mars Global Surveyor)

Sun-Solar: LASCO, MDI-SDI (SOHO), SOT (Solar-B), SECCHI/STEREO



Astronomy: IRAC, IRS, MIPS (Spitzer), ACS (HST), NIRCam, NIRSpec, MIRI (JWST)

Mission/Strategic Drivers

Earth Science: Black Carbon, Total Column Ozone, GEO Coastal Carbon, L2 Earth Atmosphere Solar Interferometer, LEO Cloud Particle Structure, GEO Lightning Imager

Planetary Science: Jupiter Polar Orbiter/Probes, Europa Geophysical Explorer, Neptune Orbiter/Probes

Sun-Solar: MTRAP, Jupiter Polar Orbiter/Probes

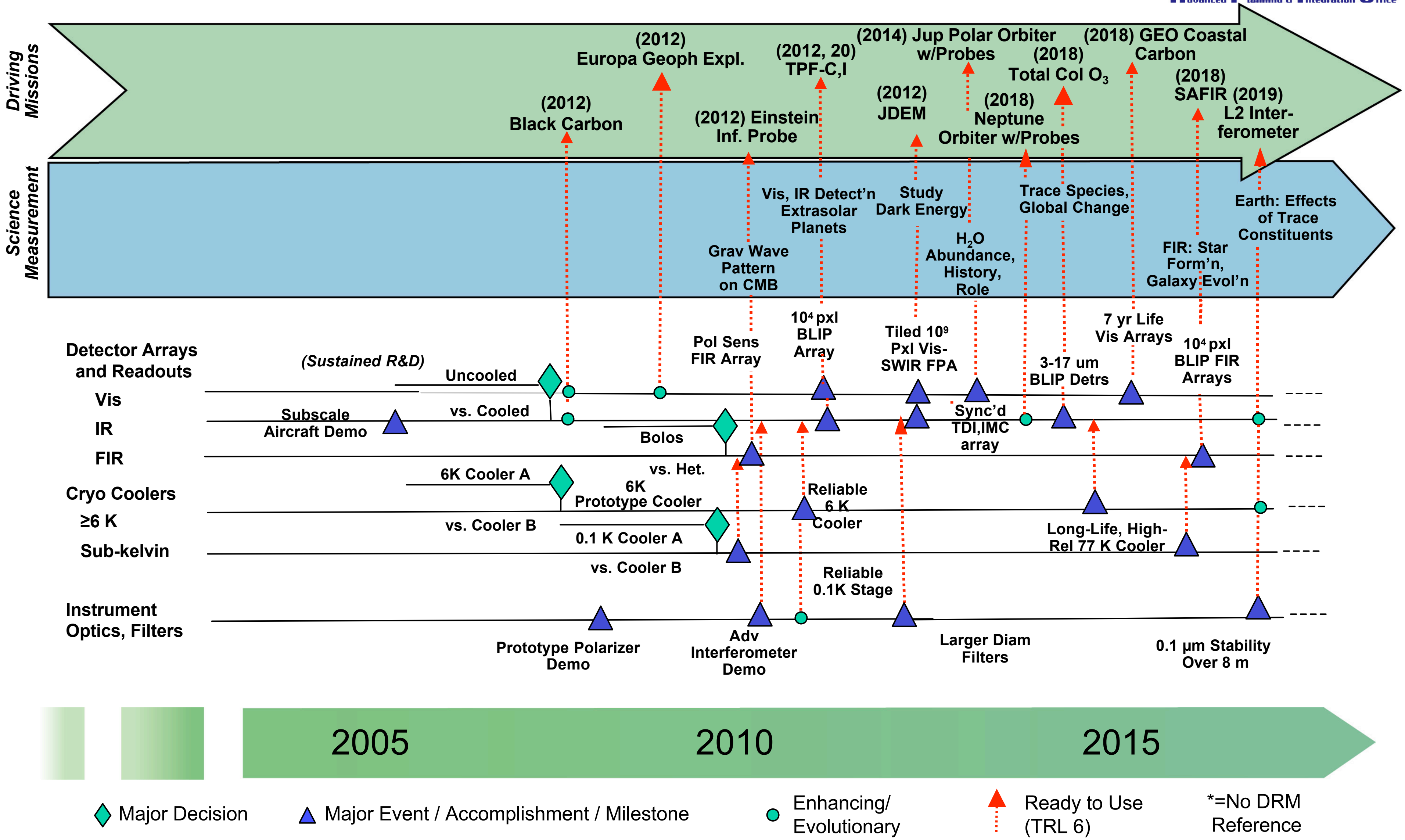
Universe+Earth-like Planets: TPF-C, TPF-I, Einstein Inflation Probe, JDEM, Lg Ap. UVO Observ, SAFIR, Life Finder, Planet Imager/Mapper

12.2 Capability Need/Gap Assessment

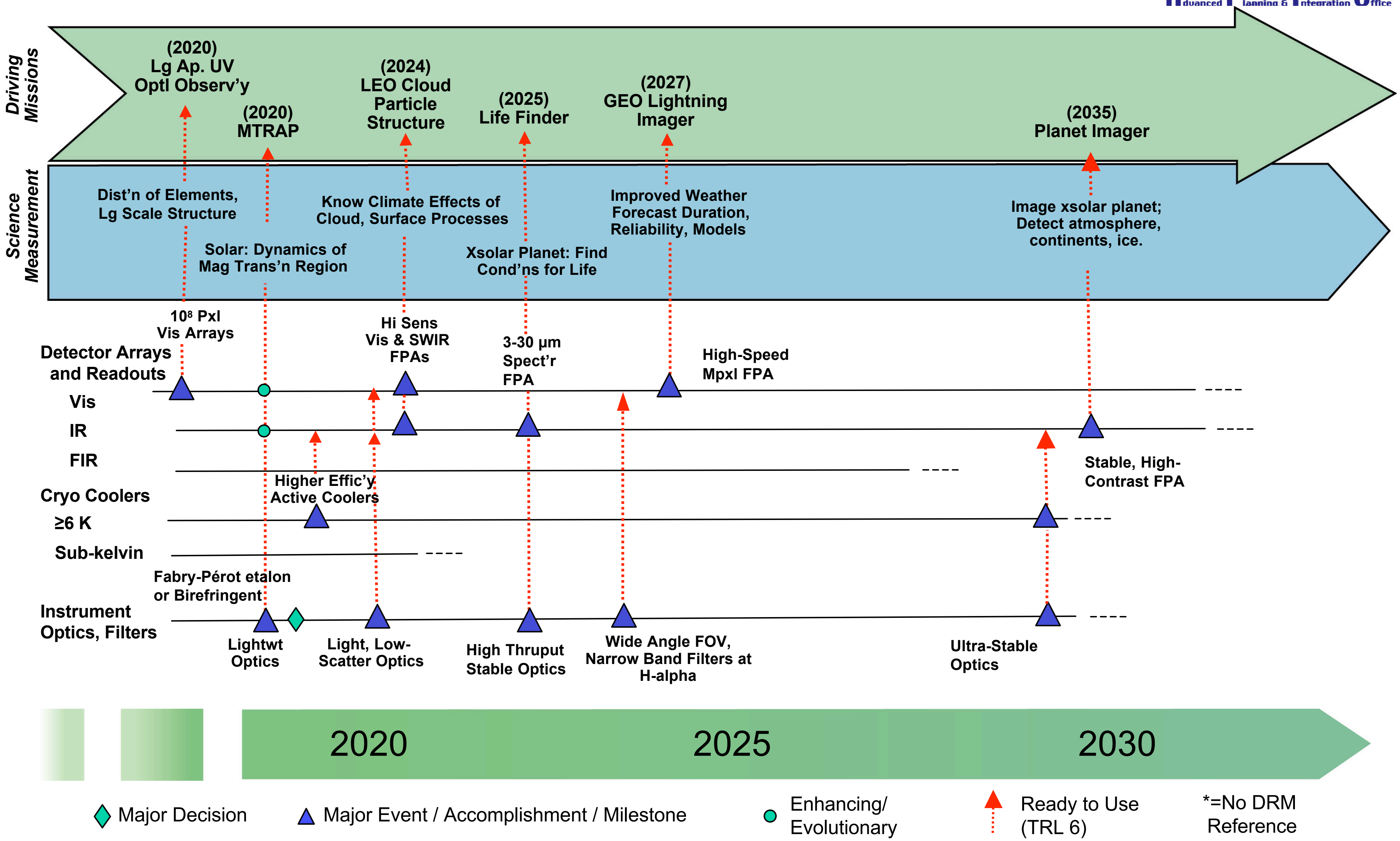
Sub Capability	Figures of Merit	Current Technology	Needed Technology
Visible Detector Arrays	Pixel Count, Uniformity Quantum Efficiency Noise Crosstalk	≤1 k x 2 k format Radiation degradation Transition (CCD <-> CMOS) Few, changeable foundaries	>2 k x 2 k format; mosaics Radiation tolerance Stable fabrication infrastructure
IR Detector Arrays	Pixel Count Noise Power Dissipation Temperature Frame Time, and ability to sync to scene	~1E4 pxls for some applications ~1E6 pxls for astrophysics, limited mosaics Low-T's required Irregular effects	Large formats for all applications; mosaics Higher T arrays proven Wider spectral response Linear, fast response High-throughput fab & testing
Far-IR Detector Arrays	Pixel Count, Uniformity Quantum Efficiency Noise Crosstalk	Parallel investigations of best detection approaches Early development of readout / mux approaches Limited system demonstrations	Mature 1E4 pxl background -limited arrays Demonstration of polarization, & 0.1-0.3 K cryogenics High-T FIR broadband detectors Stable fab & testing
≥6 K Cryocoolers for Space	Cooling Power Ultimate temperature Thermodynamic Efficiency Lifetime Vibration	Limited flight experience Sig. reluctance to adopt in projects Life tests in lab-preliminary but encouraging	Flight experience No reluctance to adopt in projects Long-life proven in lab (unattended)
Sub-kelvin coolers	Cooling Power Ultimate temperature Thermodynamic Efficiency Lifetime	Few systems developed & qual'd for flight Alternate systems under investigation	Mature, high-efficiency systems for zero-g Proven when staged to adv. 6 K coolers
Instrument Optics	Transmissivity Spectral resolution Element diameter and uniformity Survives thermal cycling	Moderate size filters Moderate capability dispersive instruments Emerging active masks	Large, high-τ filters Large, powerful dispersive instruments Proven masks, & other techniques

12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR) Near Term Capability Road

Advanced Planning & Integration Office



12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR) Far Term Capability Road



12.2 Capability Maturity Assessment

Advanced Planning & Integration Office

Sub Capability	Integrated Technologies	State-of-the-Art	Required Performance (@TRL 6)	Mission Driver	Need Date (@TRL 6)
Visible Photometer / Camera	Visible focal plane, readout electronics, imaging optics	2 k x 4 k pixel CCD. Two-chip FPA. Conventional drive electronics. ~5 e^- noise	~5E8 BLIP CCD pxls at 140 K. ASIC. 4 e^- noise	JDEM	2008
			High contrast FPA w/ coronograph	TPF-C	2008
			~1E8 pxl vis array mosaic, photon counting	Lg UVO Obs	2016
IR Photometer / Sounder / Camera	IR focal plane, adv readout, adv optics, cryocooler	2 k x 2 k pixel near-IR array. Lab cryocooler.	~2E8 BLIP NIR pxls at 140 K (4 e^- noise) +ASIC	JDEM	2008
			~1E6 room temp array, 0.02 K NEΔT	Neptune Pol Orbiter	2014
		320 x 240 μbolo array (THEMIS). 0.04 K NEΔT	3-17 μm BLIP arrays	Total Col O_3	2014
Far IR Imaging Instrument	FIR bolometer array with readout, 6 K cooler, sub-K cooler	~400 element arrays; ~1E-18 W/√Hz. Unproven muxing. Lab cryocoolers	1E3 pxl BLIP array with polarization sensitivity	Einstein Infl Probe	2008
			1E4 pxl BLIP array; NEP 1E-18 W/√Hz	SAFIR	2014
Adv Vis and IR Spectrometers	Focal planes, readouts, dispersive optics & mech'sms	Small-scale instruments f space, <Mpxl arrays. Ground-based interferometers.	IR Imaging FTS configuration. ~1E6 pxls	Neptune Pol Orbiter	2014
			8 m boom, 0.1 μm path stab'y	L2 Interf'r	2015
			1E3 pxl BLIP array; NEP 1E-20 W/√Hz	SAFIR	2014
			Hi-thruput filter at 10 μm; high contrast FPA High-stability demo	TPF-I	2016

12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

Other Key Technologies

- Intra-instrument calibration sources
- Imaging optics
- Data processing & compression systems (real-time feature extraction, *etc.*)
- Mechanisms

Connection Points to Other Roadmaps

- *In situ*
- UV-gamma sensing
- Microwave (sub-mm astrophysics)
- Telescopes
- Nanotechnology
- Infrastructure (fabrication, test, expertise)

- ***Sustained development of larger-format, higher-sensitivity focal plane arrays is key to meeting future instrument needs, across the spectrum.***
- ***Important component (e.g., optics) and support (e.g., cryogenics) technologies are also critical, & they need to be proven at the instrument-system level.***

Science Instruments and Sensors Capability Roadmap Team

12.3 Multi-spectral Sensing, UV – Gamma

Name	Organization	Primary Expertise
Co-Lead Brian Ramsey	NASA MSFC	X-Gamma Instrumentation
Co-Lead David Chenette	Lockheed Martin	Space Radiation Measurements
Ron Polidan	Northrop Grumman	UV Instrument Systems
Juan Rivera	NASA GSFC	Instruments Design/Engineering
Azita Valinia	NASA GSFC	Earth Science Technology

12.3 Multi-spectral Sensing, UV – Gamma

Capability Description

- This contains all the capability requirements to enable remote sensing and scientific investigations (Imaging, Spectrometry, Polarimetry, Timing, and Interferometry) for the UV to gamma ray wavelength range (_ < 0.4 _m)

Reference Documentation

- **Astronomy & Astrophysics**
  - Astronomy and Astrophysics in the New Millennium, 2004, NRC Astronomy and Astrophysics Survey Committee (Note that this is a National Academy study rather than a specific NASA roadmap)
  - Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team
- **Earth Science**
  - Strategic Plan for US Climate Change Science Program, 2003
  - Earth Science Enterprise Strategy, 1 Oct 2003
  - Earth Science Research Plan: 6 Jan 2005 Draft
  - NASA ESTO "Earth-Sun System: Potential Roadmap and Mission Development Activities" 23 Dec 04 Draft Briefing
- **Planetary Science**
  - New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)
- **Sun-Solar System**
  - Sun-Earth Connection Roadmap: 2003 - 2028
  - The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
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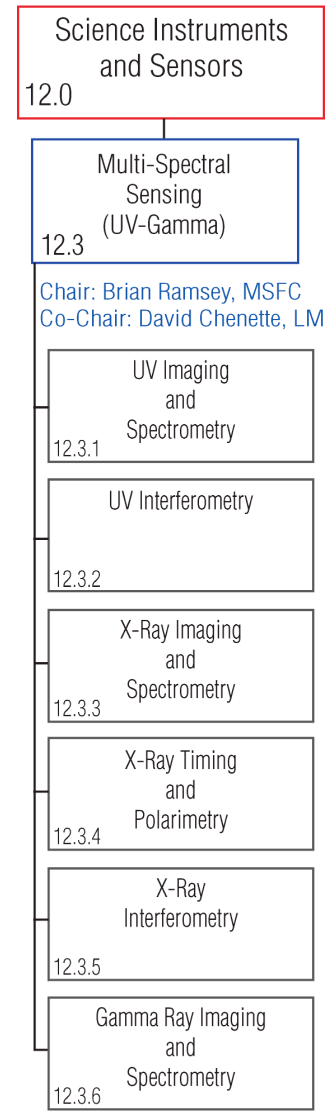


12.3 Multi-spectral Sensing, UV – Gamma

Capability Benefits

Universe & Earth-like planet search:

- Determine origin of stars, planets, life
- Determine origin of elements
- Probe early universe
- Map distribution of dark matter
- Perform black hole census
- Probe formation and evolution of black holes
- Probe space and time around black hole

Sun-Solar Studies:

- Measure and understand the magnetic transition region
- Determine the dynamics of the sun's transition region
- Determine solar reconnection mechanisms
- Probe structure of region between heliosphere and local galactic environment

Sub-Team Assumptions

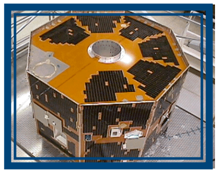
- Light-weight, high-resolution, grazing & normal incidence and diffractive optics, plus coatings, are covered by Advanced Telescopes and Observatories(CRM #4)
- Formation flying capabilities and necessary metrology are covered by CRM #4
- Cooling of large structures (including large-area detectors) and general thermal control covered elsewhere
- Adequate provisions made at the appropriate time for calibration and testing
- Advanced data handling capabilities are available when needed (high-speed telemetry, data compression, etc)

12.3 Multi-spectral Sensing, UV – Gamma

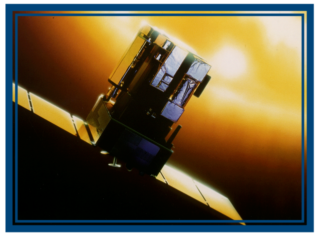
History/Current Missions

– ***Sun-Solar:***

SOHO (1995)
IMAGE (2000)
RHESSI (2002)
Solar-B (2006)
STEREO (2006)

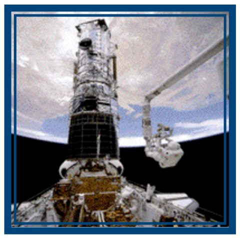


IMAGE


SOHO

– ***Universe & Origins:***

EUVE (1992)
HST (1990)
FUSE (1999)
Uhuru (1970)
Einstein (1978)
Chandra (1999)
Compton GRO (1991)
GLAST (2007/8)


HST

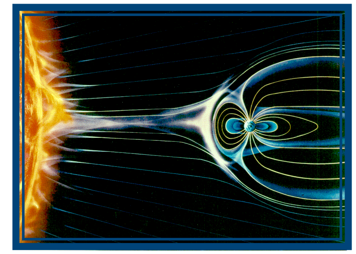

FUSE


Chandra

Mission/Strategic Drivers

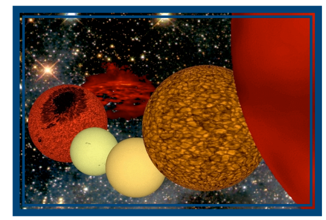
– ***Sun-Solar:***

MTRAP (2020)
RAM (2032)
SCOPE (2033)



– ***Universe+Earth-like Planets:***

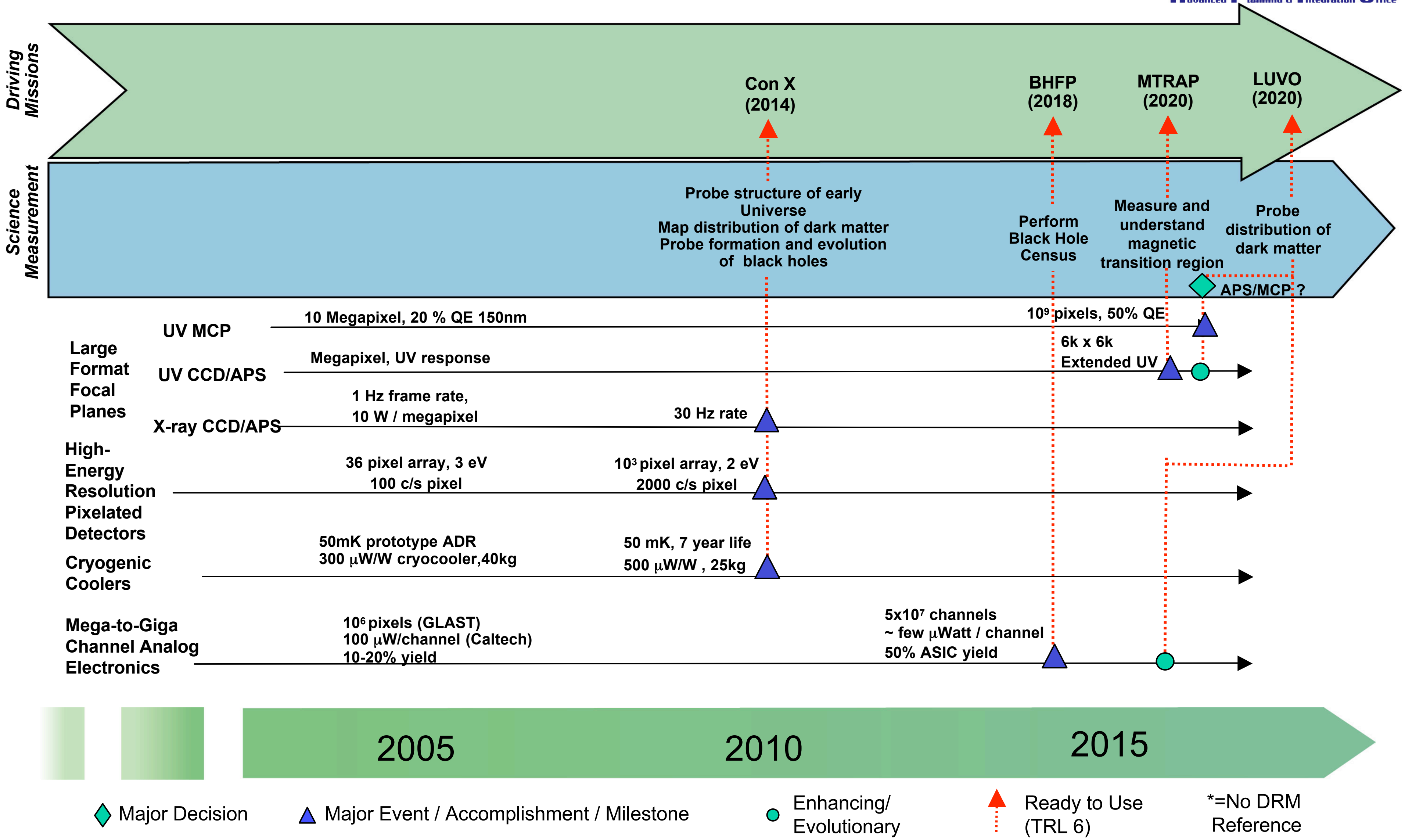
Constellation-X (2014)
Black Hole Finder Probe (2018)
Large UV Observatory (2020)
Black Hole Imager (2025)
Advanced Compton Telescope (2026)
Gen-X (2027)
Stellar Imager (2034)



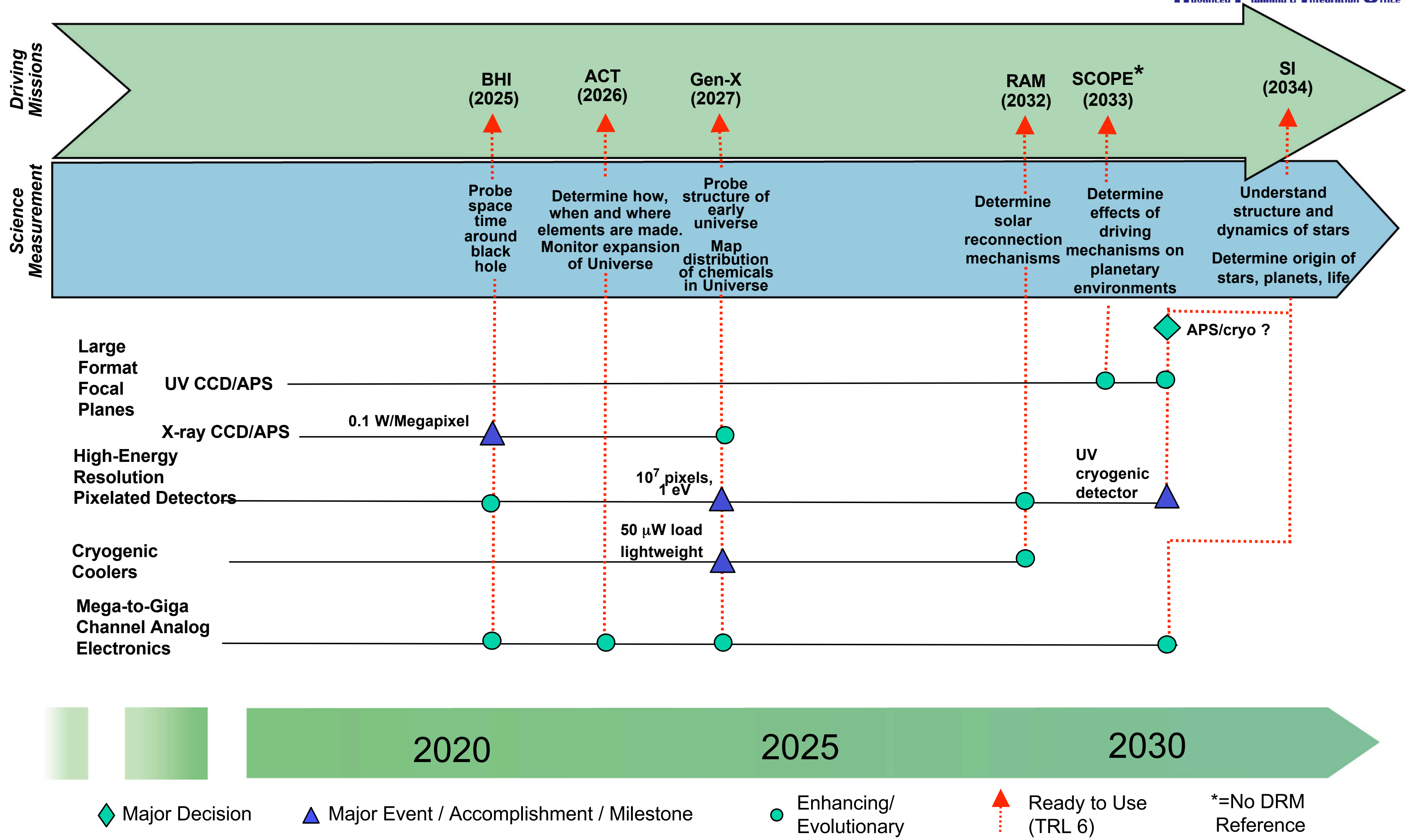
12.3 Capability Need/Gap Assessment

Sub Capability	Figures of Merit	Current Technology	Needed Technology
UV Imaging and Spectrometry	Large-format focal plane detectors: Microchannel plate performance	Limited by quantum efficiency and overall number of pixels	Factor of 10 increase in pixel number and factor of 2-5 increase in quantum efficiency
UV & X-ray Imaging and Spectrometry	Large-format focal plane detectors: CCD and active pixel sensor performance	Megapixel CCDs with moderate power requirements, moderate readout speeds, and limited UV and X-ray response	Larger CCDs with two orders of magnitude less power (possible change of technology to active pixel sensors), faster readout rate, and extended UV (< 200 nm) and x-ray (> 6 keV) response
X-Ray Imaging and Spectrometry	High-energy-resolution pixelated detector performance	Limited energy resolution, pixel array sizes and count rate capability	Factor of 2 and 4 (near and far term) improvement in energy resolution, 30 and 3.10^{5} (near and far term) increase in pixel number and factor of ten increase in rate capability
	Cryogenic cooler performance	Limited lifetime (laboratory prototype) continuous (50mk) coolers Cryocoolers requiring too much power and weight.	Long-lifetime (7 year) systems Reduced mass and power (factors of two) and increased robustness
Gamma Ray Imaging and Spectrometry	Readout electronics power, noise, yield and architecture	Systems cannot handle future channel counts and noise requirements Low custom-chip yields (10-20%) Typical current architecture leads to long interconnects.	Systems to handle 100 x more channels with low-noise interconnects Factor of 2-5 increase in custom chip yield (due to large number needed) Novel ways to interconnect to reduce noise and provide near seamless arrays

12.3 Multi-Spectral Sensing (UV-Gamma)
Near Term Capability Road



12.3 Multi-Spectral Sensing (UV-Gamma) Far Term Capability Road



12.3 Capability Maturity Assessment

Sub Capability	Integrated Technology	Figures of Merit	State of the Art	Required Performance (@ TRL 6)	Mission Driver	Need Date (@TRL 6)
UV Imaging and Spectrometry	Large Format Focal Plane Detectors : Microchannel Plates	Overall size	10^7 pixels	10^9	LUVO	2016
		Quantum efficiency	10-15%	50%	LUVO	2016
UV & X-Ray Imaging and Spectrometry.	Large Format Focal Plane Detectors : CCDs and Active Pixel Sensors	Total pixels	Megapixel	> 10^8 (UV)	MTRAP	2016
		Pixels / chip	Megapixel	6k x 6k, buttable (UV)	MTRAP	2016
				4k x 4k, 4-side buttable (X-ray)	BHI	2021
		Power	10 W / Megapixel	0.1 W / Megapixel	BHI	2021
		Resolution	120 eV @ 6 keV	< 120 eV	BHI	2021
		Readout speed	1 Hz	30 Hz	Con-X	2010
		Response	> 150 nm, below ~ 6 keV	Extended UV response	MTRAP	2016
				X-ray response above 6 kev	Gen X	2023
X-Ray Imaging and Spectrometry	High-Energy-Resolution Pixelated Detectors	Energy resolution	6 eV , 6 keV ASTRO-E	2 eV (Con-X),	Con-X	2010
			2.7 eV in lab	1eV (Gen-X)	Gen-X	2023
		Number of pixels	36 pixels array (ASTRO-E)	10^3 pixel	Con-X	2010
				10^7 pixel	Gen-X	2023
		Count rate capability	100 c/s per pixel	> 10^3 c/s-pixel	Con-X	2010
	Cryogenic Coolers	Temperature	50 mK	50 mK	Con-X	2010
		Load	5 μW	5 μW	Con-X	2010
				~ 50 μW	Gen-X	2023
		Operation	Continuous ADR	Continuous or duty cycle > 95%	Con-X	2010
		Lifetime	lab prototype	7 year	Con-X	2010
		Efficiency	300 μW/W (cryocooler)	500 μW/W	Con-X	2010
Gamma-Ray Imaging and Spectrometry	Mega-to-Giga Channel Analog Electronics	Number of channels	10^6 (GLAST)	5.10^6-10^8	BHFP	2014
		Power/channel	100μW / channel (Caltech)	100μW-2μW /channel	BHFP	2014
		Noise/channel	200 e rms (no interconnects)	< 300 e rms with interconnects/coupling	BHFP	2014
		Yield	10-20%	50% for 10^4 ASICs	BHFP	2014

12.3 Multi-spectral Sensing, UV – Gamma

Other Key Technologies

- High-resolution, light-weight optics
- Formation flying
- Precision metrology
- On-board data processing, storage, and high-bandwidth telemetry
- Cooling of large area detectors and thermal control in general
- On ground (and in flight) calibration of high-resolution detector systems and associated optics

Connection Points to Other Roadmaps

- Telescopes and large structures
- Telecommunications
- Advanced modeling
- Infrastructure (fabrication, test, expertise)

- ***The key development for the UV through X-ray range is higher-performance focal plane detectors and their associated systems.***

- ***For gamma-ray missions, the driving technology requirement is low-power electronics and architectures supporting Mega-to-Giga channel instruments.***

Advanced Planning & Integration Office

Science Instruments and Sensors Capability Roadmap Team

12.4 Laser/LIDAR Remote Sensing

Name	Organization	Primary Expertise
Maria Zuber	MIT (co-lead)	Laser ranging and altimetry
Richard Barney	NASA/GSFC (co-lead)	Laser instrument design
Richard Dissly	Ball Aerospace	In Situ and atmospheric instrumentation

12.4 Laser/LIDAR Remote Sensing

Advanced Planning & Integration Office

Capability Description

- Laser/LIDAR remote sensing includes active laser and LIDAR instrumentation used on situ, roving, aerial and orbital platforms and operating from the ultraviolet to near-infrared wavelengths.

Reference Documentation

- **Astronomy & Astrophysics**
  - Astronomy and Astrophysics in the New Millennium, 2004, NRC Beyond Einstein: From the Big Bang to Black Holes, 2003
  - Connecting Quarks with the Cosmos (2003)
- **Earth Science**
  - Strategic Plan for US Climate Change Science Program, 2003
  - Earth Science Enterprise Strategy, 1 Oct 2003
  - Earth Science Research Plan: 6 Jan 2005 Draft
  - NASA ESTO "Earth-Sun System: Potential Roadmap and Mission Development Activities" 23 Dec 04 Draft Briefing
- **Planetary Science**
  - New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)
  - Solar System: Executive Summary from Solar System Exploration Program (2003)
  - Solar System Exploration Roadmap (2003)
- **Sun-Solar System**
  - Sun-Earth Connection Roadmap: 2003 - 2028
  - The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
  - Earth-Sun System: Potential Roadmap and Mission Development Activities (Draft) Dec 2003
  - Solar and Space Physics and Its Role in Space Exploration

Science Instruments and Sensors
12.0

Laser/LIDAR Remote Sensing
12.4

Chair: Maria Zuber, MIT
Co-Chair: Richard Barney, GSFC

Altimeters
12.4.1

Transponders
12.4.2

Atmospheric LIDARS
12.3.3

Spectrometers
12.4.4

Interferometers
12.4.5

12.4 Laser/LIDAR Remote Sensing

Illustrative Capability Benefits

- **Earth Science:**
- What do the distributions of ozone, aerosols and climate change imply about present-day climate?
- How do tropospheric winds affect weather?
- What do the distributions of trace gases imply for global warming?
- What is the three-dimensional structure of the world's vegetation?
- What are the implications of photosynthetic efficiency for biological productivity?

Planetary Science:

- What is the surface evolution of the solid planets and how does surface geology relate to planetary thermal evolution?
- What is the history of volatile compounds, especially water, across the solar system?
- What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Astrophysics & Search for Earthlike Planets:

- What happens at the edge of black holes?
- What is the nature of the pre-inflation universe?

Assumptions

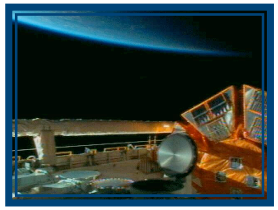
- Receiver optics and infrastructure also addressed by Advanced Telescopes and Observatories Capability Roadmap.
- Agency will support risk reduction activities, including aircraft and ground-based prototype testing.
- Sensors must reach technical maturity 3-5 years before launch.
- Some Earth science sensors have direct planetary applications and vice versa.
- Astrophysical applications using metrology included.
- Tradeoffs:
    - Detection probability: power vs. aperture vs. detector sensitivity
    - Spatial coverage: # beams vs. scanning vs. pixelated detectors
- Not covered here: optical communication, landing range finders, *in situ* systems.
- Other things that matter: platform stability, alignment, precise & stable oscillators, precision optics, rad-hard, low-noise electronics

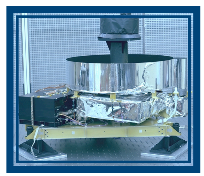
12.4 Laser/LIDAR Remote Sensing

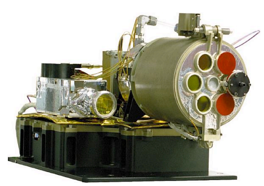
Advanced Planning & Integration Office

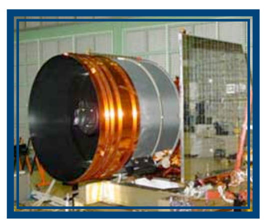
Past/Current Missions

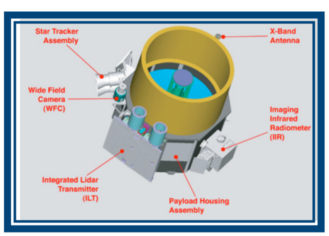
–Clementine LIDAR -- 1994
– LITE -- 1994
– NEAR NLR -- 1997
– MGS MOLA -- 1999
– SLA 1 & 2
– Icesat/GLAS -- 2003
– MESSENGER MLA -- launched 2004
– CALIPSO/CALIOP -- 2005 launch
– ALADIN/AEOLIS ADM -- 2007 launch
– LRO LOLA -- 2008 launch











Future Driving Missions

–- **Earth Science:**
- –CALIPSO/CALIOP
- –Tropical Winds
- – High Resolution CO_2
- –Advanced Land Cover Change
- – Stratospheric Composition
- – Photosynthetic Efficiency

- **Planetary Science:**
- - Lunar Reconnaissance Orbiter
- - Europa Geophysical Orbiter
- - Mars High-resolution Spatial Mapper

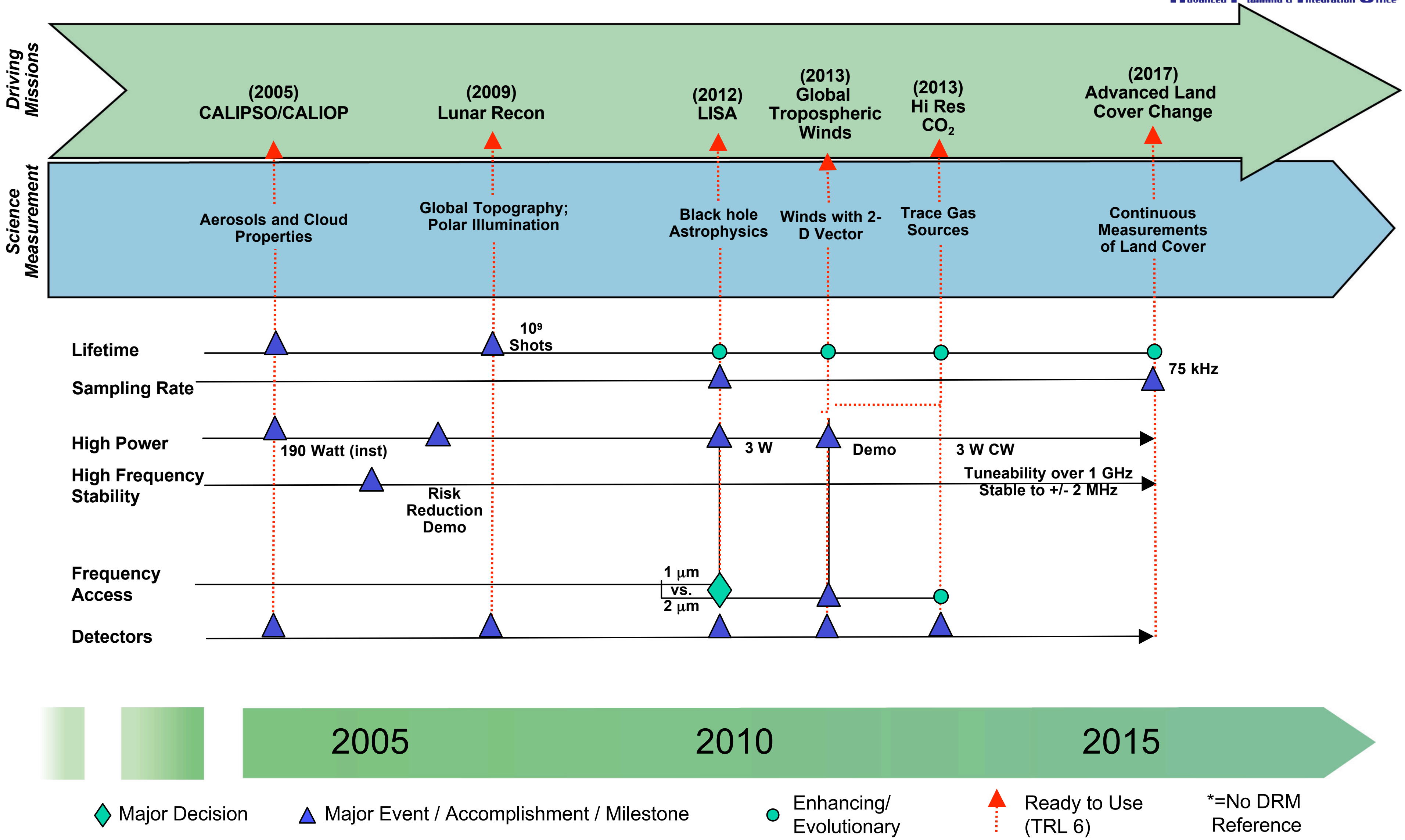
- **Universe+Earth-like Planets:**
- - LISA
- - Big Bang Observer

12.4 Capability Need/Gap Assessment

Advanced Planning & Integration Office

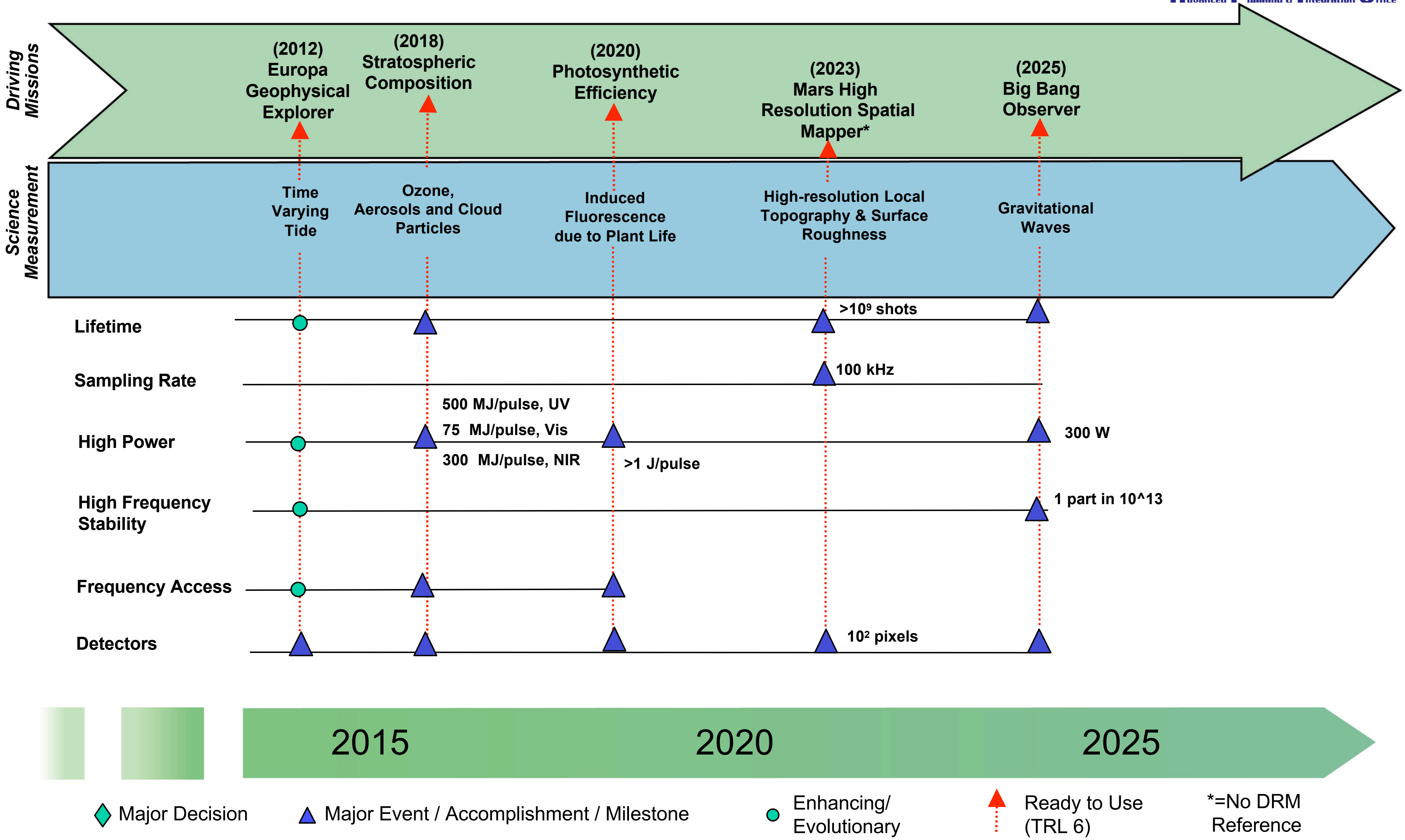
Sub Capability	Figures of Merit	Current Technology	Needed Technology
Ranging Altimeters/ Backscatter LIDARS	Time of flight Signal intensity Detector sensitivity	Single laser profiling systems	Multiple beams, scanning or pixelated detectors with long lifetime.
Doppler Wind Profilers	Doppler shift of narrow linewidth beam	Demonstrated from ground & aircraft; Orbital sensors underdevelopment	Longer lifetime, increased resolution for Earth and planetary applications
Surface/Atmosphere Reflectance Spectrometers	Detect presence of chemical component and concentration through absorption, fluoresence at targeted wavelengths	Demonstrated from aircraft	Requires high-power systems with tunability and fine range gating
Interferometers	Precise measurement of distance	Demonstrated in lab	Advanced systems capable of operation in orbit and free space.

12.4 Laser/LIDAR Remote Sensing Near Term Capability Road



12.4 Laser/LIDAR Remote Sensing Far Term Capability Road

Advanced Planning & Integration Office



12.4 Capability Maturity Assessment

Sub Capability	Integrated Technologies	State-of-the-Art	Required Performance @ TRL 6	Mission Driver	Need Date (@TRL 6)
Ranging Altimeters/ Backscatter LIDARS	Surface coverage Range resolution Sampling rate	5 beams along track 10 cm 40 Hz	Near-total surfical sampling 1 cm 10^2 kHz	Europa Geophysics Orbiter Advanced Land Cover Change Mars High resolution Mapper	2009 2014 2020
Doppler Wind Profilers	Laser lifetime Laser energy Laser tunability Frequency lock settiling time	None space qualified	3-5 years 2 J/pulse +/- 5 GHz 10 msec	Global Tropospheric Winds	2010
Surface/Atmosphere Reflectance Spectrometers	Laser power Laser frequency access Laser frequency stability	None space qualified	3 W various; particularly IR +/- 2 MHz, continuously tunable over 1 GHz	High Resolution CO2 Stratospheric Composition Photosynthetic Efficiency	2011 2014 2016
Interferometers	Laser power Laser lifetime Laser frequency stability Laser tunability Laser noise Laser phase measurement	30 mWatt <1 year 1 part in 10^13 (lab) Engineering Model 10^-11 m (in lab) 10^-4 over +/- 50 kHz	300 Watt >5 years 1 part in 10^13 (space) +/-5 GHz 10^8 improvement 10^-12 over 1 λ	LISA Big Bang Observer	2009 2022

12.4 Laser/LIDAR Remote Sensing

Advanced Planning & Integration Office

Other Key Technologies

- Radiation-hard electronics
- Imaging optics
- Mechanisms

Connection Points to Other Roadmaps

- *In situ*
- Telescopes & structures
- Data processing & storage
- Advanced communications
- Infrastructure (fabrication, test)
- Nanotechnology
- Formation Flying

- ***Key challenge is to develop reliable, efficient, space-qualified laser sources at wavelengths required by science.***
- ***Identified tradeoffs dictate that competition must be used to choose optimal designs.***
- ***Funding transition from low TRL (~1) to mid TRL (~4) is essential to risk and cost management.***

Science Instruments and Sensors Capability Roadmap Team

12.5 Direct Sensing of Particles, Fields and Waves

Name	Organization	Primary Expertise
Richard McEntire	JHU/APL	Particle Instrumentation
Carl Stahle	NASA GSFC	Detector Systems
Tim Krabach	NASA JPL	LWIR to FIR Detectors
Paul Mahaffy	NASA GSFC	Analytical Systems
Dave Chenette	Lockheed Martin	Space Radiation Measurement

12.5 Direct Sensing of Particles, Fields and Waves

Advanced Planning & Integration Office

Capability Description

- Direct sensing of Particles, Fields and Waves includes both in-situ and remote sensing of particles (ions, electrons, neutral atoms, from plasma energies to over 100 MeV), electric, magnetic, and gravity fields; and gravitational, electric, magnetic and plasma waves. The measurements cover the entire range of space environments from earth, solar, planetary, interplanetary, to galactic and beyond.

Reference Documentation

- **Astronomy & Astrophysics**
  - Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team
- **Earth Science**
  - Earth Science Enterprise Strategy, 1 Oct 2003
  - Earth Science Research Plan: 6 Jan 2005 Draft
- **Sun-Solar System**
  - Sun-Earth Connection Roadmap: 2003 – 2028
  - The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
  - Earth-Sun System: Potential Roadmap and Mission Dev. Activities (Draft) 12/03
- **Planetary Science**
  - New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)

Science Instruments and Sensors
12.0

Direct Sensing of Particles, Fields and Waves
12.5

Chair: Dick McEntire, APL
Co-Chair: Carl Stahle, GSFC

Energetic Particle and Plasma Imagers and Spectrometers
12.5.1

High Energy Particle Detector Systems
12.5.2

Magnetometers
12.5.3

Electric Fields and Wave Instruments
12.5.4

Gravitational Waves and Fields Instruments
12.5.5

12.5 Direct Sensing of Particles, Fields and Waves

Capability Benefits

Gravitational Waves and Fields

- What is the geometry of the Universe and the nature of dark energy?
- Is there observational evidence supporting the hypothesis that the early universe underwent a period of rapid inflation?
- How do super massive black holes at the centers of galaxies form or evolve and what happens when they merge?
- What are the motions of the Earth's interior, and how do they directly impact our environment?
- How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas-giant sibling, Saturn?

Assumptions

Laser transmit/receive telescopes, and laser telescope pointing actuator will be covered by the Advanced Telescopes and Observatories CRM.

Laser development will be covered by Laser/LIDAR sub-team.

Development of technology for astrophysics needs to measure gravitational waves will be sufficient for measurements of the gravity field for planetary and earth science applications

12.5 Direct Sensing of Particles, Fields and Waves

Capability Benefits

Energetic Particles, Fields and Waves

- What is the origin and societal impact of variability in the Sun-Earth system?
- How is the supersonic solar wind produced, and how does it evolve from the Sun's transition region to the boundary of the heliosphere?
- How and where are solar energetic particles accelerated, what is their composition, how do they propagate through the heliosphere? What is their impact on the safety of extended manned exploration of the moon, Mars and beyond?
- What is the detailed structure of the heliosphere, how does it change with time and modulate the intensity of galactic cosmic rays?
- What is the nature of the interstellar medium, and how does the heliosphere interact with it?
- How does the space environment and ionosphere and upper atmosphere of the Earth respond to varying external and internal influences? What are the coupling mechanisms? How do interactions at other planets compare? What can magnetic field measurements tell us about the internal structure of these planets?
- What are the fundamental processes that operate in space plasmas; how is energy transferred from stressed magnetic fields to heat plasmas and accelerate particles?

Assumptions

Most future direct measurement missions will be multi-spacecraft and/or very limited in payload mass, power and cost. While many individual Particles and Fields measurement needs can be met with present technology, deliberate evolutionary miniaturization of instruments and electronics is extremely important to enhance or enable these future missions.

Miniaturization and reduction in mass and power needs are shared with the in-situ and remote-sensing teams, and for spacecraft avionics.

12.5 Direct Sensing of Particles, Fields and Waves

Past / Current Missions

Terrestrial

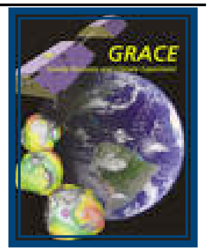
GRACE

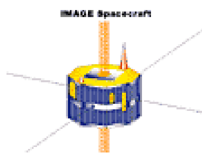
Polar

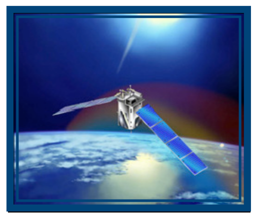
IMAGE

TIMED

Cluster





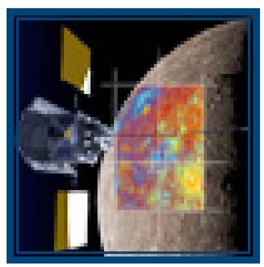


Planetary

Galileo

Cassini

Messenger

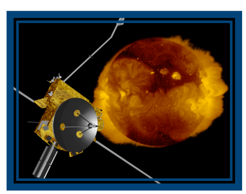


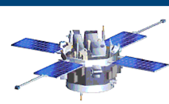
Heliospheric

Voyager

Ulysses

ACE





Future Driving Missions

Terrestrial: Ionosphere/Thermosphere Storm Probes (ITSP), Radiation Belt Storm Probes (RBSP), Geospace Electrodynamics Connection (GEC), Magnetospheric Constellation

Planetary: Jupiter Polar Orbiter/Probes (JPO), Europa Orbiter

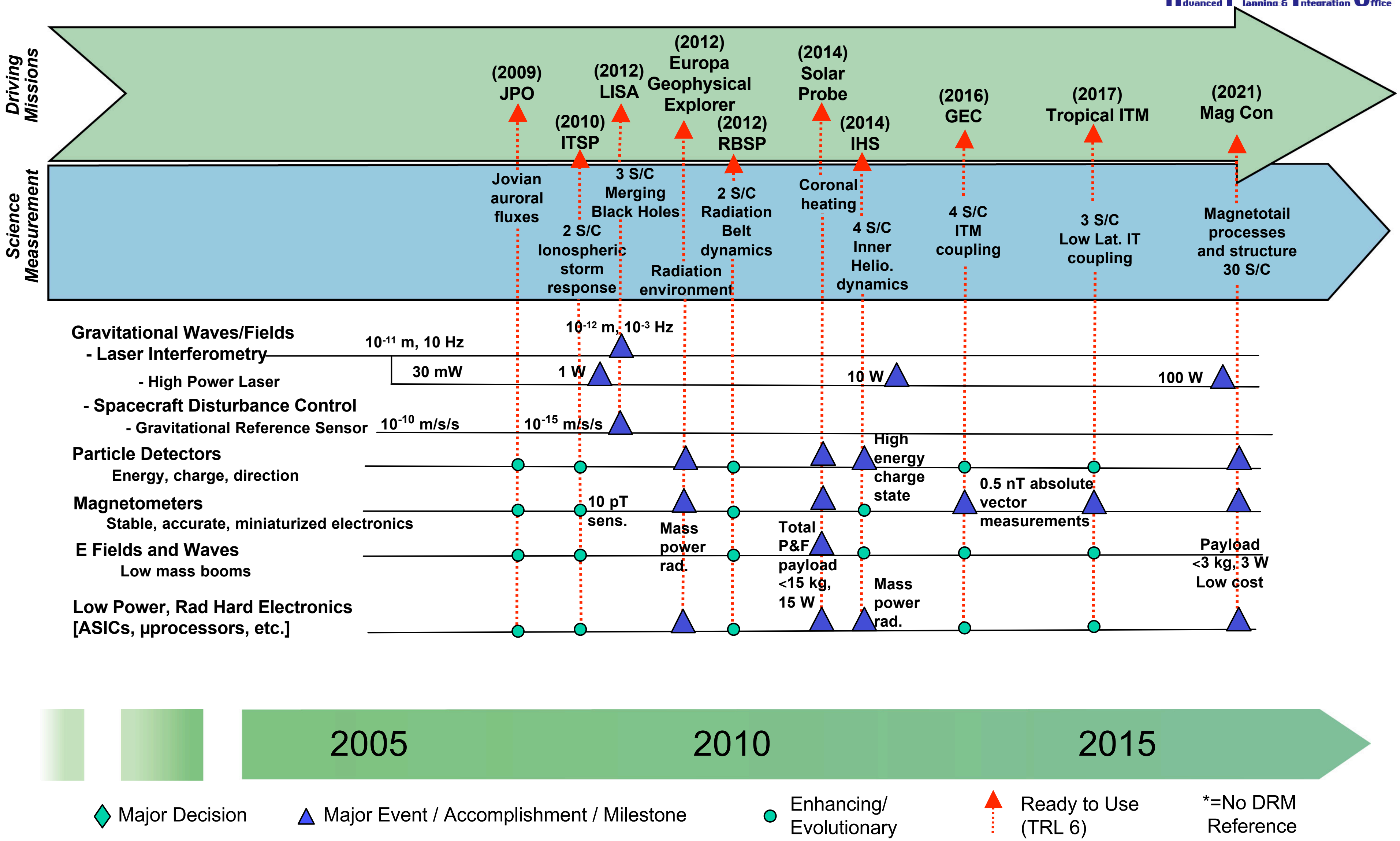
Heliospheric: Solar Probe (SP), Inner Heliosphere Sentinels (IHS), Telemachus, Interstellar Probe (ISP), Heliospheric Imager and Galactic Observer (HIGO)

Astrophysics: Laser Interferometer Space Antenna (LISA), Big Bang Observer (BBO)

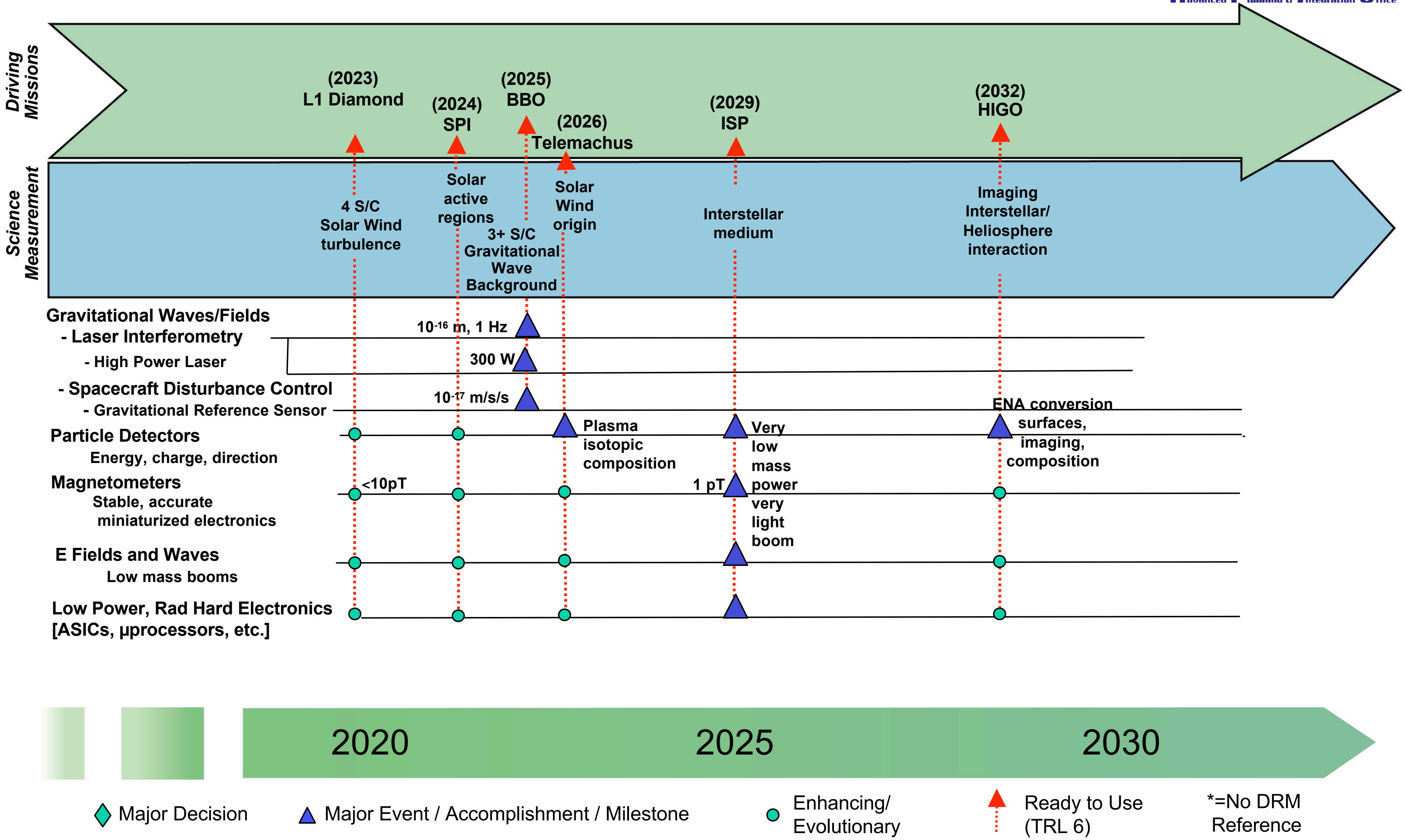
12.5 Capability Need/Gap Assessment

Sub Capability	Figures of Merit	Current Technology	Needed Technology
Gravitational Waves and Fields	High sensitivity to low frequency (10^{-3} – 1 Hz) relative displacement of proof masses	Laser Interferometry	High power, stable, long-life lasers; Interferometer system; Disturbance compensation system (DISCOS);Telescope accuracy and pointing
Particle Detectors (plasmas, energetic electrons, ions, neutrals)	Energy/species/charge coverage and resolution, Solid angle coverage and resolution, Dynamic range	Electrostatic analyzers; Time-of-Flight (TOF) and Solid State Detector (SSD) telescopes	Compact sensors with better energy/angle coverage; Low threshold array detectors; UV blind gratings; Conversion surfaces; Highly integrated signal processing
Vector magnetometers Scalar magnetometers	Sensitivity, Absolute accuracy, Radiation tolerance, Orientation knowledge, Spacecraft magnetic field contamination	Vector: Fluxgate Scalar: He Precession 3 - 10 m boom	New fluxgate cores or alternate Miniature scalar sensors Mrad tolerant electronics Multi-sensor systems: 0.5 to 1 m booms
Measurement of EM waves DC Electric Fields	Frequency coverage (DC-40 MHz), Sensitivity 3 axis Sensitivity	Mix of analog & digital electronics in pass bands, each with a different receiver 50 m spin plane boom, 2.25 kg 10 m spin axis boom, 5 kg	Highly flexible, digital coverage of entire bandwidth; Lower power, mass, cost Lightweight electric field booms, reliable deployment for both spinning & non-spinning spacecraft
Lower power, radiation hard electronics	Low power, Radiation hard (>1 Mrad), High speed, High resolution, Reliable	Relatively high power processors; Low efficiency DC converters; High power A/D; HVPS limited reliability; Large.	More standard components that are radiation hard, low power, and miniature.

12.5 Direct Sensing of Particles, Fields and Waves



12.5 Direct Sensing of Particles, Fields and Waves



12.5 Capability Maturity Assessment

Sub Capability	Integrated Technologies	State-of-the-Art	Required Performance (@TRL 6)	Mission Driver	Need Date (@TRL 6)
Gravitational Waves and Fields	High power, stable, reliable lasers; S/C DISCOS; Gravitational Reference Sensor (GRS)	30 mW laser, life < 1 yr Interferometry 10^{-11} m, 10Hz GRS: 10^{-10} m/s/s	1 W laser, life ≥ 5 yr Interferometry 10^{-12} m, 10^{-3} Hz GRS: 10^{-15} m/s/s 300 W laser, life ≥ 5 yr Interferometry 10^{-16} m, 1 Hz GRS: 10^{-17} m/s/s	Laser Interferometer Space Antenna (LISA) Big Bang Observer (BBO)	2008 2021
Particle Detectors (plasmas, energetic electrons, ions, neutrals)	Ion implanted SSD detectors and arrays; MCP TOF systems; Signal processing; HVPS	SSD energy thresholds ≥ 10 keV; Limited arrays and higher power; Soft integrated electronics.	Ion implanted SSDs 15 µm to 5 mm thick; Large arrays; Low power, low noise, rad hard electronics; UV suppression grids;Stable charge conversion coatings	RBSP Solar Probe, IHS ISP HIGO	2008 2010 2025 2028
Vector Magnetometers Scalar Magnetometers	Vector field: fluxgate Absolute scalar: He Electronics: > 16 bit A/Ds, stable oscillator	Fluxgate: 10 pT, 0.1 nT/week; Scalar (He): 1 pT, 1 ppm 30 krad electronics Boom (3 - 10 m)	Low noise core material Multi-sensor system Rad hard electronics (~ Mrad) 1 pT vector sensitivity < 1 W Low resource: <0.2 W, <0.1kg	All Solar Probe, ISP Europa, RBSP ISP Mag Con	2010 2010 2008 2025 2017
Measurement of EM waves DC Electric Fields	A/D converter DSP (Digital Signal Processor chip) Antenna	8 bits, ≤ 20 Msps @ 500 mW Non-rad hard, > 1 W 50 m spin at 3 kg 10 m axial at 5 kg	18 bits @ 80 Msps @ < 100 mW Rad hard, 250 mW, 10^3 pt. FFT at 3 MHz 50 m spin, ≤ 1 kg (inc. sensor) Axial ~ 20 m, rigid, ≤ 2 kg	RBSP Solar Probe ISP	2008 2010 2025
Lower power, radiation hard electronics	Microprocessor DC/DC converters A/D converters HVPS	~ 10 Mps/W Efficiencies ~ 20 - 50% 14 bits, 10MHz, 250mW 150 - 400 gm	100 Mps/W, on par with cellphone technology Efficiencies ~ 85% ≥ 14 bits, 80 MHz, 50 mW Standard design, < 100 gm	Europa Geo Explorer Solar Probe All multi-spacecraft missions	2008 2010 2008 on

12.5 Direct Sensing of Particles, Fields and Waves

Other Key Technologies

- MEMS
- High quality mirrors
- Miniaturization of S/C avionics
- Manufacturing cost reductions for multiple S/C

Connection Points to Other Roadmaps

- Laser Remote Sensing
- Formation Flying
- Advanced telescopes and observatories
- Visible-UV sensing
- In-Situ instruments
- Nanotechnology
- Infrastructure (fabrication, test, calibration)

- ***Gravitational Wave measurements address fundamental cosmological physics, and can be made from space over key frequencies (10^{-3} - 1 Hz) with a sensitivity impossible to achieve on the Earth. The technology advances needed will be synergistic with other missions.***

- ***Particles and Fields measurements are planned at many locations in planetary magnetospheres and throughout and beyond the heliosphere. Deliberate evolutionary advances in instrumentation and electronics are needed to enhance mission science and reduce mission cost – and are synergistic with In-Situ and many other mission areas.***

Science Instruments and Sensors Capability Roadmap Team

12.6 In-Situ Instrumentation

Name	Organization	Primary Expertise
Tim Krabach	NASA-JPL (co-lead)	Astrobiological systems
Rich Dissly	Ball Aerospace (co-lead)	Analytical systems
Paul Mahaffy	NASA-Goddard	Analytical systems
Richard McEntire	JHU-APL	Particles and fields
Dave Chenette	Lockheed Martin	High-energy detectors

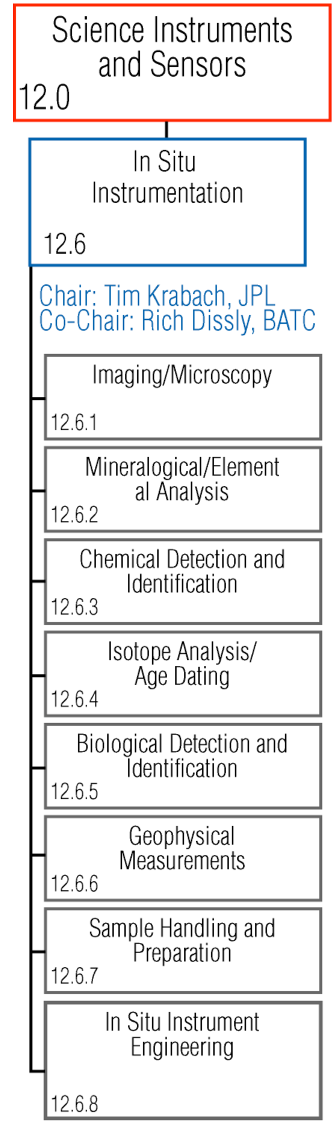
12.6 In-Situ Instrumentation

Capability Description

- In-situ covers a wide range of measurement techniques and capabilities, with the defining characteristics that the instruments must be in close proximity with the investigation target.
- **Includes** technologies essential to NASA science missions involving:
  - Landed planetary exploration (e.g. Mars Science Laboratory)
  - Sample return (e.g. Genesis)
  - Atmospheric probes (e.g. Huygens)
- Also **includes** key technologies for NASA exploration missions:
  - Prospecting for in-situ resources on the moon and Mars

Reference Documentation

- **Planetary Science**
  - New Frontiers in the Solar System: An Integrated Exploration Strategy (Space Studies Board, NRC, 2003)
  - NASA Solar System Exploration Roadmap (2003)
  - Mars Exploration Program Analysis Group Mission Science Steering Group Reports (2004)
    - Astrobiology Field Laboratory SSG
    - Groundbreaking Mars Sample Return SSG
    - Mars Deep Drill Missions SSG
  - Lunar – Under development



12.6 In-Situ Instrumentation

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Capability Benefits

Planetary Science:

- What processes marked the initial stages of planet & satellite formation?
- Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?
- How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas-giant sibling, Saturn?
- How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?
- What is the history of volatile compounds, especially water, across the solar system?
- What is the nature of the organic material in the solar system? Its history?
- What global mechanisms affect the evolution of volatiles on planetary bodies?
- Does (or did) life exist beyond Earth?
- Why did the terrestrial planets differ so dramatically in their evolution?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?
- What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

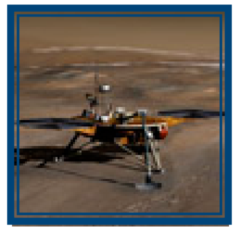
Sub-Team Assumptions

- Vis-IR far-field sensing, or measurements outside of planetary atmospheres, covered by **Multi-spectral Imaging subteam**
- In-situ measurements of interplanetary plasmas covered in **Particles, Fields and Waves subteam**
- In-Situ sensors for astronaut health and safety are **not** covered by this group
- General curatorial facilities for sample return will be covered by NASA, including quarantine facilities, independent of this assessment
- Analytical instrumentation and mission-specific environmental maintenance for returned samples are not necessarily provided; **this team has not covered capability needs in this area yet**
- Complete in situ instrument development must include appropriate environmental testbeds for evaluation of components, subsystems, and instruments;

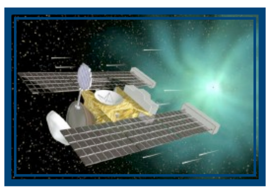
12.6 In-Situ Instrumentation

Past / Current Missions

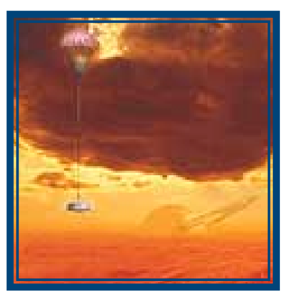
- **Mars**
  - Viking
  - Pathfinder
  - MER
  - Phoenix
  - MSL



- **Sample Return**
  - Apollo
  - Genesis
  - Stardust



- **Other Planetary**
  - Pioneer Venus Probes
  - Galileo Probe
  - Huygens Lander



Future Driving Missions

Mars: Astrobiology Field Lab, Groundbreaking Mars Sample Return, Deep Drill, Long-Lived Lander Network

Sample Return: Lunar South Pole-Aitken Basin SR, Comet Surface SR, Comet Cryogenic SR, Asteroid SR, Venus Surface SR, Mercury SR

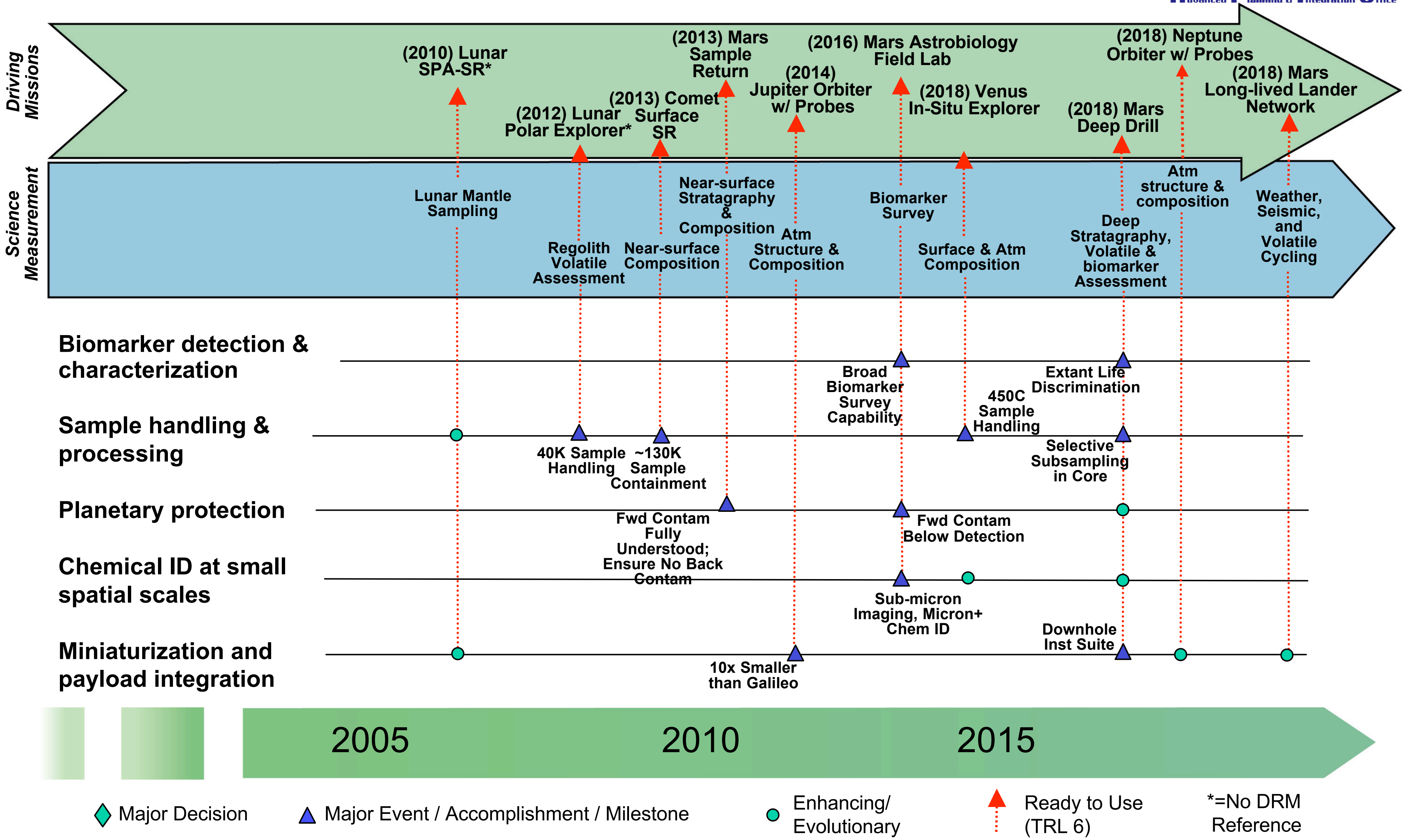
Other Planetary: Lunar Seismic Network, Venus In-Situ Explorer, Jupiter Polar Orbiter/Probes, Neptune Orbiter/Probes, Europa Pathfinder Lander, Titan Explorer, Europa Astrobiology Lander, Uranus Orbiter/Probes, Neptune Orbiter w/ Triton Lander

12.6 Capability Need/Gap Assessment

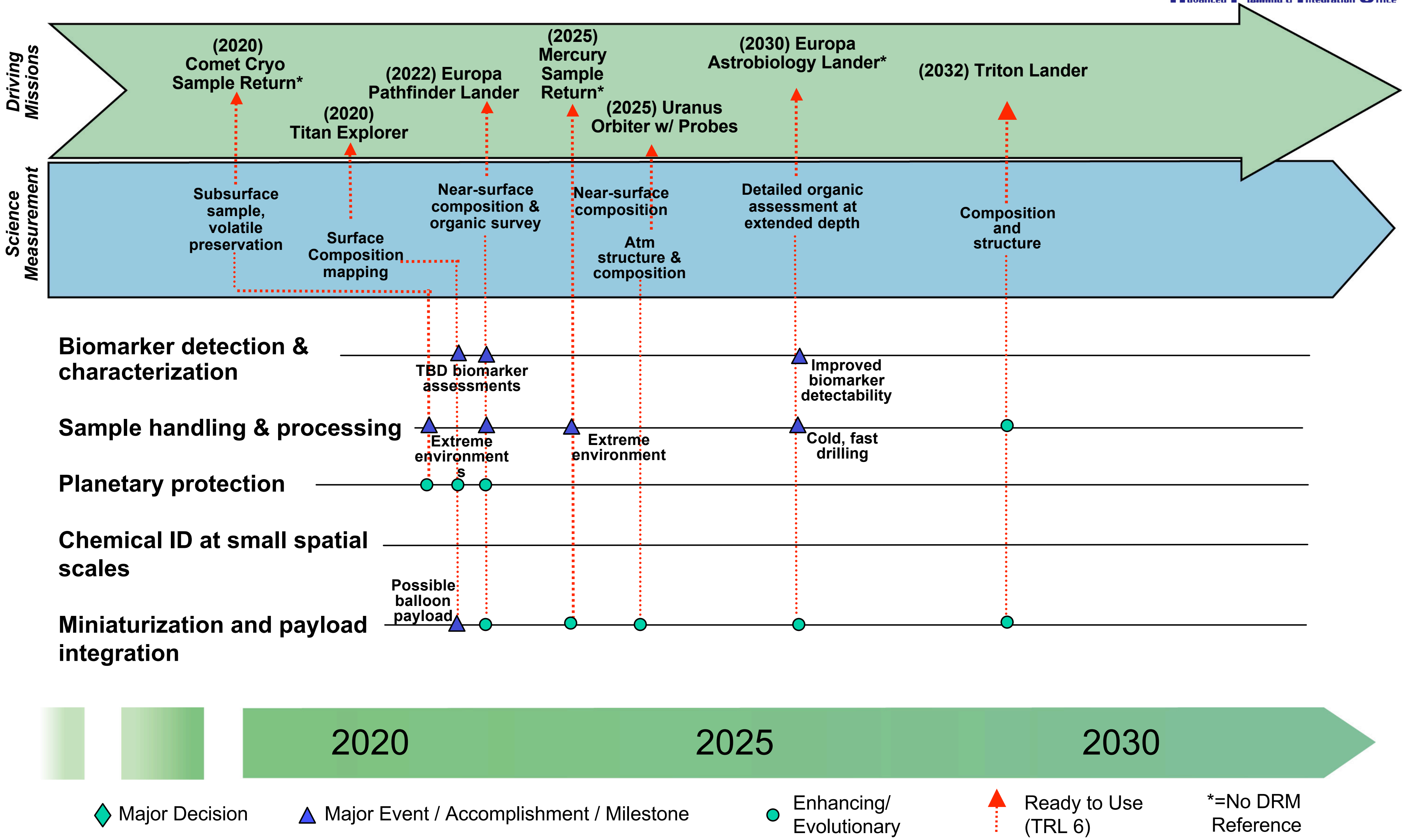
Sub Capability	Figures of Merit	Current Technology	Needed Technology
Biomarker Detection and Characterization	• Sensitivity • Selectivity • Contamination ID and quantification	• Characterization of viable organisms that can be cultured • Terrestrial contamination exceeds detection limits	• Quantitative assessment of all organic material • Technology to ensure isolation from terrestrial contamination
Sample Handling & Preparation	• Operability in relevant environment • Degree of sample alteration • Subsampling accuracy	• Bias from particle size and density • Qualitative ability to preserve volatile fractions • Operability over limited temperature ranges	• No bias or fractionation in end-to-end sample handling chain, even in multi-phase samples • Ability to selectively subsample in primary sample acquisition • Operability from 40K to 750K
Planetary Protection	• Sensitivity to detection of viable organisms • Breadth of detection of viable organisms • Degree of sterilization	• Characterization of viable organisms that can be cultured • Detection levels well below sterilization levels	• Characterization of any viable organisms • Sterilization levels on par with detection levels
Chemical Identification at Small Spatial Scales	• Spatial resolution • Sensitivity • Selectivity or mass resolution	• Micron-level chemical and isotopic assessment in terrestrial labs • AFM for crude surface analysis	• Micron-level chemical and isotopic assessment in flight package
Miniaturization, Ruggedization, and Payload Integration	• Mass • Power • Volume • Shock/Vibe tolerance • Survivability in extreme environments	• Payload elements developed separately, little common mass and power elements	• Payload elements developed together minimize mass and power resources

Capability 12.6 In-Situ Instrumentation Near Term Roadmap

Advanced Planning & Integration Office



Capability 12.6 In-Situ Instrumentation Far Term Roadmap



12.6 Capability Maturity Assessment

Advanced Planning & Integration Office

Sub Capability	Integrated Technologies	State-of-the-Art	Req Perf @TRL 6	Mission Driver	Need Date (@ TRL 6)
Biomarker assessment	Multiple assay techniques	Lab-based commercial systems	ppb sensitivity and miniaturization to flight scales	Mars AFL	2012
Sample Handling	Cryo mechanisms	MER	40K demo	Lunar Polar Explorer	2009
	Subsampling	MER RAT	mm-scale sampling of sedimentary layers	AFL	2012
	Sample phase preservation	MER	No heating of samples above -20C	AFL	2012
Planetary Protection	Sensitive assays	Subset of viable spores cultivated	Full range of viable life characterized	Mars SR	2009
	Contamination control in sample handling	Organic contamination in lunar sample of tens of ppb	Sub-ppb organic contamination in returned samples	Mars SR	2009
Chem ID at small spatial scales	Minaturized imaging systems Miniaturized composition probes	Submicron imaging, Phoenix AFM Lab-based systems	Submicron imaging combined with chemical / isotopic analysis	Mars AFL	2012

12.6 In-Situ Instrumentation

Advanced Planning & Integration Office

Other Key Technologies

- Environmentally relevant testbeds
- Payload system integration
- Mechanisms in extreme environments
- Electronics in extreme environments
- Distributed processing

Connection Points to Other Roadmaps

- Atmospheric entry systems
- Landing systems
- Planetary surface and subsurface access
- Cryogenic sample handling
- Remote sensing and sounding of surface/subsurface composition
- Nanotechnology

- ***Robust 'mid-TRL programs needed to close gap between needed and available capabilities for lunar and non-Mars destinations (for example, a MIDP-like program for New Frontiers)***
- **In situ performance should be validated in relevant testbeds prior to competitive selection (for example, instrument breadboard sensitivity and precision proven in realistic Mars testbed)**
- ***In situ instrument development will be key enabling technology for exploration missions to the Moon, Mars, and beyond; specific driving missions may change, but driving science likely will not.***

Science Instruments and Sensors Capability Roadmap
Co-Chair Summary

NASA Co-Chair: Rich Barney, NASA

External Co-Chair: Maria Zuber, MIT

March 16, 2005

Science Instruments and Sensors
Key Sub-Capabilities

- **12.1 Microwave Instruments and Sensors**
  - Large deployable antennas
  - Integrated high efficiency T/R modules
  - Radiation hard electronics
  - Quantum limited cryogenic receivers
  - High frequency, low power MMIC receivers
  - Large scale digital spectrometers and correlators (rad-hard FPGAs and ASICs)
  - Low power, long life cryocoolers

- **12.2 Multi-Spectral Imaging / Spectroscopy (vis-IR-FIR)**
  - Low power, long life Coolers
  - Detectors & Readout Electronics (large format, better sensitivity)
  - Optics (dispersive/imaging; instrument level including filters, coolers,polarimeters)

- **12.3 Multi-Spectral Sensing (UV-Gamma)**
  - Large format CCDs / active pixel sensors
  - High-energy-resolution single-photon detectors
  - Low power, long life cryogenic coolers to achieve less than 0.1K
  - Mega-to-Giga channel analog electronics
  - Optics (Normal / grazing incidence, higher-energy optics, gratings)

- **12.4 Lasers / LIDAR**
  - High energy lasers (for atmospheric sensing, formation flying, etc.)
  - Quality control of laser systems (all components)
  - Frequency stability & selection
  - Spatial coverage: multibeam, scanning, pixelated detectors
  - High-sensitivity detectors

- **12.5 Direct Sensing of Fields Particles, and Waves**
  - High power lasers
  - Spacecraft disturbance compensation systems
  - Detectors and detector arrays,
    light weight rigid booms
  - Compact, rad hard, high integration electronics and sensors

- **12.6 In Situ Instrumentation**
  - Sample Handling in Multiple Relevant Environment as a function of Mission specific target
  - Sample Acquisition on the surface of Mars
  - Miniaturization for instruments and integrated payloads (Nano) electronics; better integrated across the board.

Key Technical Challenges (to date)

- **Major challenges in development required technologies/capabilities:**
  - **Science Payloads may operate in severe environments:**
    - Jovian radiation belts
    - Venus surface environment (460C, 90 bars)
    - Outer planet surfaces and atmospheres (sub 100K)
  - Flight demonstration to retire risks that require an orbital flight will continue to be a pacing item for the introduction of new technologies required to reduce capability gaps.
  - Infrastructure investments are required to develop performance testing capabilities for long term technology development.
- **Science Payloads are (usually) extremely resource constrained.**
  - Limited mass, volume, power and data rate
  - Impacts applicability of cryogenically cooled sensors
  - High fidelity instrument systems models are required to perform early risk assessments and technical resource trade studies.
- **Linkage of orbital and ground-based observations (sensor webs) represents a significant future opportunity for Earth and solar system studies.**

Technology Program Challenges

- Prioritization of capabilities/technologies needed to achieve the Vision for Space Exploration must be traceable to science measurement needs.
- A sustained, low TRL, science instrument component technology development program is needed to close identified capability gaps.
- An organized, prioritized technology plan that is well coordinated with and supported by the science community served is key to acquiring technology funding.
- Proposal teams to share their experiences and "wish lists" of technologies that would have made their science more achievable and competitive.
- Commercial/Academia partnerships with NASA are essential to implementing technology solutions required to narrow or close critical capability gaps.

Summary

- **The Science Instruments and Sensors Capability Roadmap team has investigated current NASA exploration and science measurement strategies, design reference missions, and science instrument/sensor technology roadmaps to identify critical science measurement capability gaps and assess future technology development needs…..a work in progress.**
  - Excellent interaction with the public Science and Engineering communities at open meetings and workshops
  - Limited discussions with Strategic Roadmap Teams has been very productive

- **Several key sub-capabilties have been identified that cut across instrument and sensors capabilities. NASA technology investment in these sub-capabilities will enable several exploration missions.**

- **Need for maturation plan / program for enabling advanced instrument insertion into flight.**

- **Integration with the Strategic Roadmap Teams is key to developing science instrument and sensor roadmaps that are responsive to strategic mission needs.**

- **<u>Competed, peer-reviewed development programs are best approach for NASA.</u>**

Forward Work

- **Make changes to roadmaps based on verbal feedback from NRC review.**
- **Receive the draft Strategic Roadmaps by April 15th.**
  - Continue productive interchange with SRM teams.
- **Make changes to CRM Title roadmaps to ensure consistency with Strategic Roadmaps requirements.**
- **Develop rough order of magnitude cost estimates for the CRM Title Capability Roadmap (awaits input on current investment from NASA).**
- **Prepare for 2nd NRC Review which will address 4 additional questions:**
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?
- **Complete Capability Roadmaps by June, 2005.**

Advanced Planning & Integration Office

Backup

Reference Documentation (Docushare Library)

- The Vision for Space Exploration
- The New Age of Exploration (NASA's Direction for 2005 & Beyond).
- A Journey to Inspire, Innovate, and Discover: President's Commission Report
- Our Changing Planet: The US Climate Change Science Program for Fiscal Years 2004 and 2005
- Design Reference Missions
  - APIO DRMs
    - Solar System Exploration - 2000 to 2035 (Draft 3): DRM_SSE
    - Earth-Sun System: Potential Roadmap and Mission Development Activities *(12/23/04)*
    - Universe Design Reference Missions *(12/13/04)*
    - Architecture Study #2, Human Exploration of Mars, Artificial-Gravity Nuclear Electric Propulsion Option *(7/15/03)*
    - Reference Mission Version 3.0 Addendum to the Human Exploration of Mars *(6/01/98)*
    - Mars 98 Reference Mission: Reference Mission of the NASA Mars Exploration Study Team *(7/7/97)*
    - Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities *(07/01/03)*
    - The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities *(12/01)*
  - Other DRMs
    - Advanced Mission Studies: Mars Exploration Program Analysis Group
      - Astrobiology Field Laboratory-2013 (Biosignature Detection)
      - Ground Breaking Mars Sample Return
      - Mars Deep Drill: Explore Active Hydrothermal Habitats
      - Mars Deep Drill: Search for Evidence of Past Life

Reference Documentation
(Docushare Library)

- Enterprise Strategies
  - Earth Science Application Plan
  - Earth Science Research Plan *(Draft)*
  - Sun-Earth Connection Roadmap (2003-2028)
  - Physics of the Universe: A Strategic Plan for Federal Research
  - Solar System Exploration Roadmap
  - Origins Roadmap *(2003)*
  - Structure and Evolution of the Universe Roadmap

- National Research Council Reports
  - Astronomy and Astrophysics in the New Millennium Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board
  - Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan Committee to Review the U.S. Climate Change Science Program Strategic Plan
  - New Frontiers in the Solar System: An Integrated Exploration Strategy Solar System Exploration Strategy, NRC
  - Solar and Space Physics and Its Role in Space Exploration Committee on Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative, NRC
  - The Sun to the Earth -- and Beyond: A Decadal Research Strategy in Solar and Space Physics Solar and Space Physics Survey Committee
  - The Sun to the Earth -- and Beyond: Panel Reports Solar and Space Physics Survey Committee, Committee on Solar and Space Physics
  - Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, Committee on the Physics of the Universe, NRC

Exploration/Science Traceability

Advanced Planning & Integration Office

	* References:
Earth	1: Strategic Plan for US Climate Change Science Program, 2003
	2: Earth Science Enterprise Strategy, 1 Oct 2003
	3: Earth Science Research Plan: 6 Jan 2005 Draft
	4: Earth Science Applications Plan, 2004
	5: NASA ESTO "Earth-Sun System: Potential Roadmap and Mission Development Activities" 23 Dec 04 Draft Briefing
Planetary Science	6: New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)
	7: Mars Deep Drill Search for Evidence of Past Life, Sylvia Miller, John Essmiller, David Beaty, JPL, January 16, 2004
	8: Mars Deep Drill Explore Active Hydrothermal Habitats, Sylvia Miller, John Essmiller, David Beaty, JPL, January 16, 2004
	9: Astrobiology Field Laboratory - 2013 Biosignature Detection, Roger Dhiel, JPL, March 10, 2004
	10: Groundbreaking Mars Sample Return, Richard Mattingly, JPL, March 8, 2004
Sun-Solar	11: Sun-Earth Connection Roadmap: 2003 - 2028
	12.: The Sun to the Earth - And Beyond: A Decadal Research Strategy in Solar and Space Physics
	13: Earth-Sun System: Potential Roadmap and Mission Development Activities (Draft) Dec 2003
Astrophysics	14. Astronomy and Astrophysics in the New Millenium, 2004, NRC Astronomy and Astrophysics Survey Committee
	15. Design Reference Missions -- Universe, NASA Document
	16. Beyond Einstein: From the Big Bang to Black Holes, 2003, Structure and Evolution of the Universe Roadmap Team
	17. Origins, Roadmap of the OSS Origins Theme, 2003,
	18. Benford, D. "SAFIR: Single Aperture Far Infrared Observatory"
	19. Young, E. et al "Detector Needs for Long Wavelength Astrophysics",

Missions Referenced in Roadmaps

(sorted by mission name)

Design Reference Mission	CBS	Launch
Advanced Compton Telescope	12.3	2026
Advanced Land Cover Change	12.4	2017
*Astrobiology Field Laboratory**	*12.6*	*2016*
Big Bang Observer	12.4	2025
	12.5	2025
Black Carbon	12.2	2012
Black Hole Finder Probe-Einstein	12.3	2018
Black Hole Imager	12.3	2025
CALIPSO/CALIOP	12.4	2005
*Comet Cryo Sample Return**	*12.6*	*2020*
Comet Surface Sample Return	12.6	2013
Constellation-X	12.3	2014
Einstein Inflation Probe	12.1	2012
	12.2	2012
*Europa Astrobiology Lander**	*12.6*	*2030*
Europa Geophysical Explorer	12.2	2012
	12.4	2012
	12.5	2012
Europa Pathfinder Lander	12.6	2022
Generation-X	12.3	2027
GEO Coastal Carbon	12.2	2018
GEO Doppler Rain Profiler	12.1	2021
GEO Global Precip	12.1	2027
GEO In SAR Constellation	12.1	2021
GEO Lightning Imager	12.2	2027
Geospace Electrodynamics Connection (GEC)	12.5	2016
*GEO Seismology from Space**	*12.1*	*2030*

Legend:
*Missions**= Capability driven missions not currently listed in the APIO/SMD reference documentation.

Launch Date=Earliest Opportunity

CBS=Capability Breakdown Structure

Missions Referenced in Roadmaps

(sorted by mission name)

Advanced Planning & Integration Office

Design Reference Mission	***CBS***	***Launch***
Global Soil Moisture	12.1	2017
Global Troposheric Winds	12.4	2013
Global Tropospheric Aerosols	12.1	2016
Heliospheric Imager and Galactic Observer (HIGO)	12.5	2032
Hi Res CO2	12.4	2013
Inner Heliosphere Sentinels (HIS)	12.5	2014
Intersteller Prob	12.5	2029
Ionosphere Thermosphere Storm Probes	12.5	2010
Joint Dark Energy Mission	12.2	2012
Jupiter Polar Orbiter	12.5	2009
Jupiter Polar Orbiter with Probes	12.6	2009
	12.1	2014
	12.2	2014
L1 Diamond	12.5	2023
L2 - Earth Atmosphere Solar Interferometer	12.2	2019
*Land Surface Topography**	*12.1*	*2014*
Large Aperture UV Optical Observatory	12.2	2015-2020
	12.3	2020
Laser Interferometer Space Antenna	12.4	2012
Laser Interferometer Space Antenna	12.5	2012
L-band LEO InSAR	12.1	2010
L-band MEO InSAR	12.1	2014
LEO Cloud Particle Structure	12.2	2024
LEO Cloud System Structure	12.1	2020
Leo Wetland & River Monitor	12.1	2015

Legend:
*Missions**= Capability driven missions not currently listed in the APIO/SMD reference documentation.

Launch Date=Earliest Opportunity

CBS=Capability Breakdown Structure

Missions Referenced in Roadmaps

(sorted by mission name)

Design Reference Mission	CBS	Launch
Life Finder	12.2	2025
*Lunar Polar Explorer**	*12.6*	*2012*
Lunar Recon Orbiter	12.4	2009
*Lunar SPA-SR**	*12.6*	*2010*
Magnetic Constellation	12.5	2021
Magnetic Transition Region Probe (MTRAP)	12.2	2020
	12.3	2020
Mars Deep Drill	12.6	2018
*Mars Electrification Imager**	*12.1*	*2022*
*Mars High Resolution Spatial Mapper**	*12.4*	*2023*
Mars Long Lived Lander Network	12.6	2018
Mars Sample Return	12.6	2014
*Mercury Sample Return**	*12.6*	*2025*
Neptune Orbiter w/Probes	12.1	2018
	12.2	2018
	12.6	2018
Ocean Structure and Circulation	12.1	2019
Ocean Surface Winds	12.1	2018
Photosynthetic Efficiency	12.4	2020
Planet Imager	12.2	2035
Planet Mapper	12.2	2045
Prometheus (JIMO)	12.1	2017

Legend:
*Missions**= Capability driven missions not currently listed in the APIO/SMD reference documentation.

Launch Date=Earliest Opportunity

CBS=Capability Breakdown Structure

Missions Referenced in Roadmaps

(sorted by mission name)

Design Reference Mission	***CBS***	***Launch***
Radiation Belt Storm Probes	12.5	2012
Reconnection and Microscale	12.3	2032
*Sea Ice Thickness**	*12.1*	*2014*
Single Aperture Far-Infrared Observatory (SAFIR)	12.1	2018
	12.2	2018
*Solar Connections Observatory for Planetary Environments (SCOPE)**	*12.3*	*2033*
Solar Polar Imager	12.5	2024
Solar Probe	12.5	2014
Stellar Imager	12.3	2034
Stratospheric Composition	12.4	2018
Telemachus	12.5	2026
Titan Explorer	12.6	2020
Total Column Ozone	12.2	2018
TPF, C-I	12.2	2012, 2020
Triton Lander	12.6	2032
Tropical ITM Couplet	12.5	2017
Uranus Orbiter w/Probes	12.6	2025
Venus In-Situ-Experiment (Explorer)	12.6	2018

Legend:
*Missions**= Capability driven missions not currently listed in the APIO/SMD reference documentation.

Launch Date=Earliest Opportunity

CBS=Capability Breakdown Structure

Acronyms

Advanced Planning & Integration Office

- ACE- Advanced Composition Explorer
- ACS- Advanced Camera for Surveys
- ACT- Advanced Compton Telescope
- ADR-Adiabatic Demagnetization Refrigerator
- AFL- Astrobiology Field Laboratory
- AIRS- Atmospheric Infrared Sounder
- Aladdin/AEOLUS ADM- ESA Aladdin (Satellite) AEOLUS Atmospheric Dynamics Mission (Doppler Wind Lidar)
- AMSU-Advanced Microwave Sounding Unit
- APL- John Hopkins University Applied Physics Laboratory
- ARC- Ames Research Center
- ASIC-application-specific integrated circuit
- ASTEP- Astrobiology Science and Technology for Exploring Planets
- ASTID- Astrobiology Science and Technology Instrument Development
- ATO- Advanced Telescopes and Observatories
- BATC- Ball Aerospace and Technologies Corporation
- BBO- Big Bang Observer
- BHFP- Black Hole Finder Probe
- BHI- Black Hole Imager
- BLIP- background limited infrared photo-detector
- Bolos- Bolometer Arrays
- BW- bandwidth
- Calipso/CALIOP Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations/
- Cloud Aerosol Lidar with Orthogonal Polarization.
- CCDs- Charge Coupled Devices
- Cluster- it is a Mission to study small-scale structures of the magnetosphere and its environment in three dimensions. Cluster is constituted of four identical spacecraft that will flight in a tetrahedral configuration.
- CMB- Cosmic Microwave Background
- CMOS complementary metal-oxide semi-conductor
- Con-X- Constellation-X
- CRISM- Compact Reconnaissance Spectrometer for Mars

Acronyms

- CRM- Capability Roadmap
- CSSR- Comet Surface Sample Return
- DBF- Digital Beam Formation
- DC- direct current
- DMSP- Defense Meteorological Satellite Program
- DRMs- Design Reference Missions
- DSP- Digital Signal Processor chip
- EG- Europa Geophysics
- EIP- Einstein Inflation Probe
- ESA- electronically scanned arrays
- ESMR-Nimbus-5 Electrically Scanning Microwave Radiometer
- ESTO- Earth Science Technology Office
- Far IR- Far Infrared
- FIR- Far Infrared
- FOV- Field- of-View
- FPGA- Field-Programmable Gate Array
- GaAs- Gallium Arsenide
- GEC- Geospace Electrodynamics Connection
- Gen X-Generation X
- GEO- Geosynchronous Orbit
- GEO Coastal C- GEO Coastal Carbon
- GEOSAT- Geodetic Satellite Mission
  GGP- GEO Global Precipitation
- GLAST- Gamma Ray Large Area Space Telescope
- GPS- Global Positioning System
- GPS/GNSS- Global Positioning System/Global Navigation Satellite System
- GRACE- Gravity Recovery and Climate Experiment
- GSFC- Goddard Space Flight Center
- GSM- Global Soil Moisture
- GTA- Global Tropospheric Aerosols
- HCIPE- High Capability Instruments

Acronyms

- HIGO- Heliospheric Imager and Galactic Observer
- HIRISE- High Resolution Imaging Science Experiment
- HRes CO2- High Resolution CO2
- HST- Hubble Space Telescope
- HVPS- High Voltage Power Supply
- ICESAT/GLAS- Ice, Cloud and land Elevation Satellite/Geoscience Laser Altimeter System
- IHS- Inner Heliosphere Sentinels
- IMAGE- Imager for Magnetopause to Auroral Global Exploration
- InSAR (MEO)- Interferometric Synthetic Aperture Radar
- IPS- integrated power systems
- IR- Infrared
- IRAC- Infrared Array Camera (Spitzer)
- IRS- Infrared Spectrograph (Spitzer)
- ISP- Interstellar Probe
- ITSP-Ionosphere/Thermosphere Storm Probes
- JIMO- Prometheus Jupiter Icy Moons Orbiter
- JPL- Jet Propulsion Laboratory
- JPO- Jupiter Polar Orbiter
- JPOP- Jupiter Polar Orbiter Probes
- JWST- James Webb Space Telescope
- LASCO- Large Angle and Spectrometric Coronagraph Experiment
- LEO- Low Earth Orbit
- Leo LFSM- LEO Low Frequency Soil Moisture
- LF- Life Finder
- LFF InSAR- L-band Formation Flying InSAR
- LHP- Loop Heat Pipe
- LIDAR- Light Detection and Ranging
- LISA- Laser Interferometer Space Antenna
- LITE- Lidar in Space Technology Experiment
- LM- Lockheed Martin
- LOLA- Lunar Reconnaissance Laser Altimeter

Acronyms

Advanced Planning & Integration Office

- LRO- Lunar Reconnaissance Orbiter
- Lunar SPA-SR- Lunar South Pole-Aitken Basin Sample Return
- LUVO- Large Aperture Ultraviolet Optical Observatory
- LWIR- Long Wave Infrared
- L2 Interfr- L2 Interferometer
- MARSIS- Mars Advanced Radar for Subsurface and Ionosphere Sounding
- MC- Magnetospheric Constellation
- MCM- multi-chip module
- MCP- Micro-channel Plate
- MDI/SOI- Michelson Doppler Imager/Solar Oscillations Investigation
- MEMS- Micro-Electro-Mechanical Systems
- MEO- Mid Earth Orbit
- MER- Mars Exploration Rover
- MER RAT- Mars Exploration Rover Rock Abrasion Tool
- MHRSM- Mars High Resolution Spatial Mapper
- MIPS- Multiband Imaging Photometer for SIRTF
- MIRI- Mid Infrared Instrument
- MIT- Massachusetts Institute of Technology
- MLA- Mercury Laser Altimeter
- MLS- Microwave Limb Sounder
- MMIC- Monolithic Microwave Integrated Circuit
- MMS- Magnetospheric Multiscale
- mmWave- millimeter wave
- MMW- millimeter wave
- MODIS- Moderate Resolution Imaging Spectro-radiometer
- MGS MOLA – Mars Global Surveyor Mars Orbiter Laser Altimeter
- MIDP- Mars Instrument Development Program
- MRO- Mars Reconnaissance Orbiter
- MSFC- Marshall Space Flight Center
- MSL- Mars Surface Laboratory
- MSU- Microwave Sounding Unit

Acronyms

- MTRAP- Magnetic Transition Region Probe
- Nano- Nanotechnology
- NEAR NLR- Near Laser Rangefinder
- NGST- Northrop Grumman Space Technology
- NIRCam- Near Infrared Camera
- NIRSpec- Near Infrared Spectrometer
- NO- Neptune Orbiter
- NOAA- National Oceanic and Atmospheric Administration
- NRC- National Research Council
- NRO- National Reconnaissance Office
- NSCAT-NASA Scatterometer
- OSS- Office of Space Science
- OSW- Ocean Surface Winds
- Phoenix AFM- Phoenix Atomic Force Microscope
- PI- Planet Imager
- PIDDIP- Planetary Instrument Development and Definition Program
- PM- Planet Mapper
- QE- Quantum Efficiency
- QGG- Quantum Gravity Gradiometer
- QuickScat- NASA Quick Scatterometer
- RAM- Reconnection and Microscale
- RBSP- Radiation Belt Storm Probes
- SAFIR- Single Aperture Far Infrared Observatory
- SAR- Synthetic Aperture Radar
- SC- Stratospheric Composition
- S/C- Spacecraft
- SCOPE- Solar Connections Observatory for Planetary Environments
- SeaSat-JPL-designed Earth-orbital mission, launched in 1978, to flight-test five instruments
- SECCHI/STEREO- Sun Earth Connection Coronal and Heliospheric Investigation/Solar Terrestrial Relations Observatory
- SEU- Structure and Evolution of the Universe

Acronyms

Advanced Planning & Integration Office

- SI- Stellar Imager
- SiGe- Silicon Germanium
- SIR-A,B, C- Spaceborne Imaging Radars- A, B, C
- SIT- Sea Ice Thickness
- SLA 1 and 2- Shuttle Laser Altimeters 1 and 2
- SMD- Science Mission Directorate
- SOFIA- Stratospheric Observatory for Infrared Astronomy
- SOHO- Solar and Heliosphere Observatory
- SOT- Solar-B Solar Optical Telescope
- SP- Solar Probe
- SPI- Solar Probe Imager
- SRTM- Shuttle Radar Topography Mission
- SSD- Solid State Detector
- SSED- Solar System Exploration Division
- SSES- Solar System Exploration Subcommittee
- SWIR FPA- Short Wave Infrared Focal Plane Assembly
- TDI- Time Delay and Integration
- TES- Thermal Emission Spectrometer (Mars Global Surveyor)
- THEMIS- The History of Events and Macroscale Interactions During Substorms
- TIMED- Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics
- TIPS- tera instruction per second
- TOF- Time-of-Flight
- TOPEX- TOPEX/Poseidon- Joint US-French orbital mission
- TPF-C- Terrestrial Planet Finder-Coronagraph
- TPF-I- Terrestrial Planet Finder- Interferometer
- T/R- transmitter/receiver
- TRL- Technology Readiness Level
- TRMM-Tropical Rainfall Measuring Mission
- UM- University of Michigan
- UV- Ultraviolet

Acronyms

- UW- University of Wisconsin
- VIMS- Visual and Infrared Mapping Spectrometer (Cassini)
- Vis- Visible
- VISE- Venus In Situ Explorer
- WindSat- Ocean Surface Wind Measurements from Space
- WMAP- Wilkinson Microwave Anisotropy Probe

In-Situ Resource Utilization (ISRU) Capability Roadmap Progress Review

Gerald B. Sanders - NASA Chair
Dr. Michael Duke - External Chair
April 12, 2005

Presentation Agenda

8:00 – 8:30	Introduction by APIO	R. Mueller
8:30 – 9:15	13.0 Level 1 Overview for ISRU	G. Sanders
9:15 – 9:45	- ISRU Architecture for ESMD	G. Sanders
9:45 – 10:30	13.1 Resource Extraction	L. Gertch
10:30 – 11:15	13.2 Resource Handling & Transportation	K. Sacksteder
11:15 – 12:00	13.3 Resource Processing	W. Larson
12:00 – 1:00	Lunch	
1:00 – 1:45	13.4 Surface Manufacturing w/ In-Situ Resources	P. Currieri
1:45 – 2:30	13.5 Surface Construction	K. Romig
2:30 – 3:15	13.6 Surface Product/Consumable Storage & Distribution	R. Johnson
3:15 – 3:45	13.7 Unique ISRU Dev. & Cert. Capabilities	D. Linne
3:45 – 4:10	ISRU Commercialization	B. Blair
4:10 – 4:30	ISRU Presentation Summary	G. Sanders
4:30 – 5:30	Wrap up by NRC panel: synthesis of comments and recommendations	
5:30	Adjourn	

Presentation Material

- In-Situ Resource Utilization (ISRU) Capability Roadmap: Level 1
  - Capability Roadmap Team
  - Benefits of the ISRU
  - Capability Description and Capability Breakdown Structure
  - Interdependency with other Capability Teams & Internal Links
  - Roadmap Process and Approach
  - Top-Level Metrics & Assumptions
  - Roadmap
  - Development Strategy

- ISRU 'Emphasized' Architecture Overview
  - ISRU-Enhanced Architectures Aimed At NASA Human Exploration Initiative
  - ISRU-Commercial Architecture Aimed At All Government & Commercial Applications

- ISRU Capability Elements: Level 2 and below
  - Capability Description, CBS, Attributes, & Benefits
  - Capability Requirements and Assumptions
  - Interdependency with other Capability Teams & Internal Links
  - Roadmap for Capability
  - Capability Current State-of-the-Art
  - Maturity Level - Capabilities
  - Maturity Level – Technologies
  - Gaps, Risks, & Strategy
  - Metrics
  - Level 3 charts as backup

- ISRU Capability Roadmap Wrap-up
  - ISRU Capability Challenges
  - ISRU Capability State of the Art
  - Gaps, & Risks Roll-up
  - ISRU Capability Roadmap Team Recommendations
  - Summary and Forward Work

Capability Roadmap Team – Level 1

Co-Chairs

NASA: Gerald B Sanders, NASA/JSC
External: Dr. Michael Duke , Colorado School of Mines

Government: NASA

- Diane Linne, GRC
- Kurt Sacksteder, GRC
- Stu Nozette, HQ
- Don Rapp, JPL
- Mike Downey, JSC
- David McKay, JSC
- Kris Romig, JSC
- Robert Johnson, KSC
- William Larson, KSC
- Peter Curreri, MSFC

Industry

- Ed McCullough, Boeing
- Eric Rice, Orbitec
- Larry Clark, Lockheed Martin
- Robert Zubrin, Pioneer Astronautics

Academia

- Brad Blair, Colorado School of Mines
- Leslie Gertsch, Univ. of Missouri/Rolla

Other/Critical Volunteers

- Dale Boucher, NORCAT
- Trygve "Spike" Magelssen, Futron
- Alex Ignatiev, Univ. of Houston
- Darryl Calkins/Army Cold Regions Research & Eng. Lab
- Klaus P. Heiss, High Frontier
- Tom Simon, JSC
- Ron Schlagheck, Laurent Sibille, Ray French, Julie Ray, & Mark Nall, MSFC

Coordinators

Directorate: John Mankins, ESMD
APIO/JPL: Rob Mueller, Affiliation

- **Further list of volunteers for each ISRU Element team**
- **Broad ISRU industry & academic community** (Space Resources Roundtable & STAIF Conferences)

What are Space Resources?

- Traditional 'Resources':
  – **Water, atmospheric constituents, volatiles, solar wind volatiles, minerals, metals**, etc.

- Energy
  – Permanent/Near-Permanent Sunlight
    • Stable thermal control & power/energy generation and storage
  – Permanent/Near-Permanent Darkness
    • Cold sink for cryo fluid storage & scientific instruments

- Environment
  – Vacuum/Dryness
  – Micro/Reduced Gravity
  – High Thermal Gradients

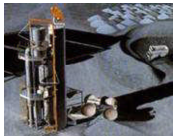
- Location
  – Stable Locations/'Real Estate':
    • Earth viewing, sun viewing, space viewing, staging locations
  – Isolation from Earth
    • Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

The purpose of In-Situ Resource Utilization (ISRU) is to harness & utilize these resources to create products & services which enable and significantly reduce the mass, cost, & risk of near and long-term space exploration

Uses of Space Resources for Robotic & Human Exploration

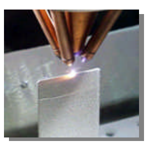
Team 13: In-Situ Resource Utilization

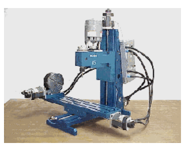





Mission Consumable Production

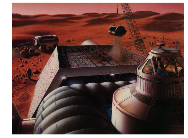
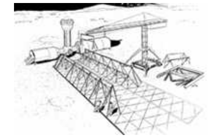
- ➢ **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- ➢ **Fuel cell reagents for mobile** (rovers, EVA) & stationary backup power
- ➢ **Life support consumables** (oxygen, water, buffer gases)
- ▪ Gases for science equipment and drilling
- ▪ Bio-support products (soil, fertilizers, etc.)
- ▪ Feedstock for in-situ manufacturing & surface construction

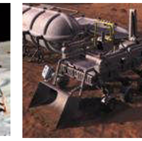





Manufacturing w/ Space Resources

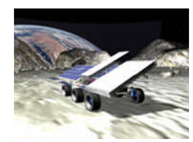
- ➢ **Spare parts manufacturing**
- ▪ Locally integrated systems & components (especially for increasing resource processing capabilities)
- ▪ High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)

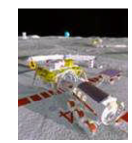





Surface Construction

- ➢ **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, plates, water, hydrocarbons, etc.)
- ➢ **Landing pad clearance**, site preparation, roads, etc.
- ▪ Shielding from micro-meteoroid and landing/ascent plume debris
- ▪ Habitat and equipment protection

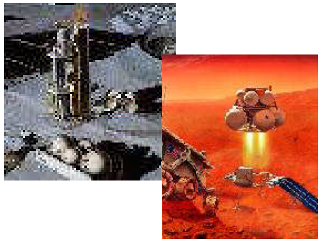
Space Utilities & Power

- ➢ **Storage & distribution of mission consumables**
- ▪ Thermal energy storage & use
- ➢ **Solar energy** (PV, concentrators, rectennas)
- ➢ **Chemical energy** (fuel cells, combustion, catalytic reactors, etc.)

Benefits of ISRU: Critical for Affordable, Flexible, & Sustainable Exploration

Space Resource Utilization

Mass Reduction



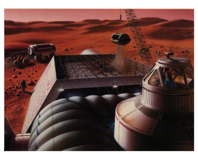
Propellant Production

- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit

Cost Reduction

- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes DDT&E cost

Risk Reduction & Flexibility



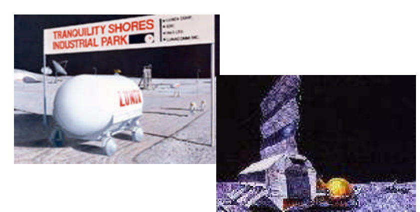
- Number of launches & mission operations reduced
- Reduces dependence on Earth
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy
- Radiation & Plume Shielding

Expands Human Presence

- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.
- Substitutes sustainable infrastructure cargo for propellant & consumable mass

Enables Space Commercialization

- Develops material handling and processing technologies
- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities



NASA Vision & Exploration Challenges

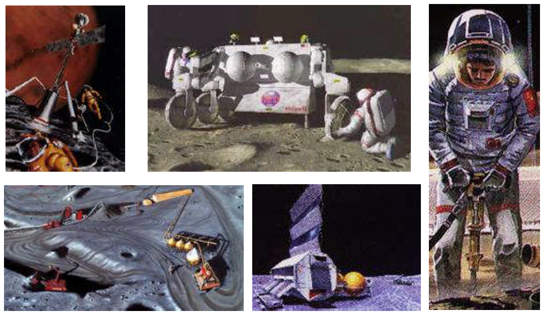
To Meet NASA's Mission and to meet the challenge "to explore the universe and search for life" robotic and human exploration must be **Sustainable, *Affordable*, Flexible, *Beneficial***, and ***Safe***

Strategic Challenges	How ISRU Meets Challenge
Margins & Redundancy	**Use of common technologies/hardware and mission consumables enables** swapping/cross use
	See ASARA
Reusability	**Production of mission consumables (propellants, fuel cell reagents, science gases, etc.) enables** reuse **of typical single use assets**
Modularity	**ISRU utilizes common technologies/hardware with life support, fuel cell power, and propulsion systems**
As Safe As Reasonably Achievable (ASARA)	**Use of** functional/dissimilar redundancy **for mission critical systems (such as life support) increases mission safety**
	ISRU can eliminate aborts **which may occur without capabilities: life support, power, spare parts, etc.**
	ISRU can reduce number of launches and mission operations increasing mission success probability
	Use of in-situ materials for radiation shield enable lower levels of radiation exposure **compared to Earth provided shielding**
Robotic Networks	**ISRU incorporates robotic networks to enable ISRU capabilities before human occupation**
Affordable Logistics Pre-Positioning	**ISRU enables** large mass leveraging **of pre-positioned hardware into usable mission products and consumables (space parts, propellants, life support gases, etc.)**
Energy Rich Systems & Missions	**Regeneration of fuel cell reagents and common mission consumables and hardware enables** power-rich surface elements**, such as EVA suits, robotic assistants, and rovers, without the cost/overhead associated with multiple nuclear assets (RTGs)**
Access to Surface Targets	**Production and regeneration of propellants and fuel cell reagents enables transport rovers and robotic and human surface hoppers at a** fraction of the cost **compared to dedicated missions launched from Earth**
Space Resource Utilization	**All of above**

In-Situ Resource Utilization Elements

Team 13: In-Situ Resource Utilization

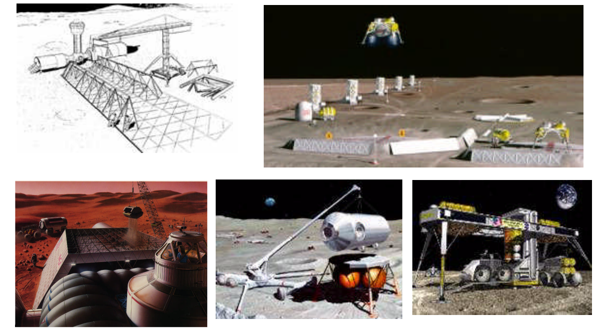
In-Situ Resource Extraction & Transport



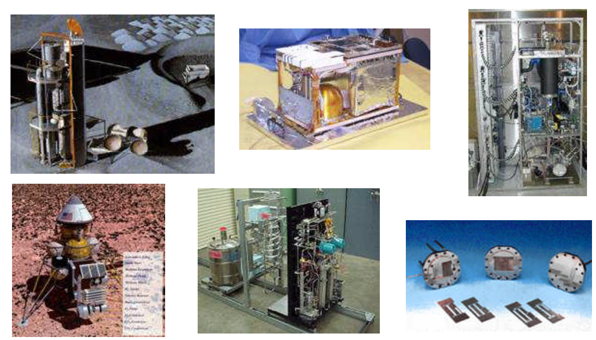
Involves assessment of resources, and extraction, excavation, and delivery of resources in low and micro-g environments, including the simple extraction and separation of resources from bulk resources

Surface Construction

Involves processes and operations for constructing elements & infrastructure on planetary surfaces using materials produced from planetary resources

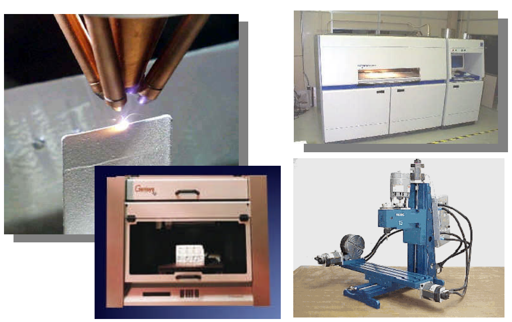


Resource Processing



Involves multi-step thermal, chemical, and electrical processing of extracted resources into products with immediate use or as feedstock

Surface Manufacturing w/ Space Resources



Involves production of replacement parts, complex products, machines, and integrated systems from one or more processed resources

Surface ISRU Product and Consumable Storage & Distribution

Involves the ability to efficiently store and transfer the resource processing reagents and products, including resource recovery and system health approaches.

In-Situ Resource Utilization (ISRU)
Capability Breakdown Structure

Team 13: In-Situ Resource Utilization

In-Situ Resource Utilization — 13.0

Chair: Jerry Sanders/JSC
Co-Chair: Mike Duke (CSM)

Resource Extraction — 13.1

Chair: L. Gertch/UMR & Don Rapp/JPL

- Resource Assessment — 13.1.1
- Resource Acquisition — 13.1.2
- Resource Beneficiation — 13.1.3
- Site Management — 13.1.4

Material Handling & Transportation — 13.2

Chairs: Kurt Sacksteder/GRC & Dale Boucher/NORCAT

- Fixed Site Transportation — 13.2.1
- Mobile Material Transportation — 13.2.2
- Payload Material Handling — 13.2.3
- Cross Platform Capabilities, Reliability and Logistics — 13.2.4

Resource Processing — 13.3

Chairs: Bill Larson/KSC & Larry Clark/LMCO

- Mission Consumable Production (Life Support & Propellant — 13.3.1
- Feedstock Production for In-Situ Manufacturing — 13.3.2
- Feedstock Production for Surface Construction — 13.3.3
- Common Critical Components — 13.3.4

Surface Manufacturing with In-Situ Resources — 13.4

Chair: Peter Curreri/MSFC & Ed McCullough/Boeing

- Additive Manufacturing Techniques — 13.4.1
- Subtractive Manufacturing Technologies — 13.4.2
- Formative Manufacturing Technologies — 13.4.3
- Locally Integrated Energy Systems — 13.4.4
- Locally Integrated Systems & Components — 13.4.5
- Manufacturing Support Systems — 13.4.6

Surface Construction — 13.5

Chair: Kris Romig/JSC & Eric Rice/Orbitec

- Site Planning — 1.5.1
- Surface & Subsurface Preparation — 1.5.2
- Structure/Habitat Fabrication — 1.5.3
- Radiation & Micro Meteoroid Debris Shielding — 1.5.4
- Structure & Site Maintenance — 1.5.5
- Landing & Launch Site — 1.5.6

Surface ISRU Product & Consumable Storage and Distribution — 13.6

Chair: Robert Johnson/KSC & Robert Zubrin/Pioneer Ast.

- Surface Cryogenic Fluid & Propellant Storage & Distribution — 13.6.1
- Chemical Reagent Storage & Distribution — 13.6.2
- Gas Storage & Distribution — 13.6.3
- Water & Earth Storable Fluid Storage & Distribution — 13.6.4
- Utility Connections & Interfaces — 13.6.5
- Hazard Detection & Suppression — 13.6.6

ISRU Unique Development & Certification Capabilities — 13.7

Chair: Diane Linne/GRC & Mike Downey/JSC

- Modeling & Standards — 13.7.1
- Simulants — 13.7.2
- Unique Test Environments (1-g) — 13.7.3
- Reduced Gravity Test Environments — 13.7.4

Roadmap Charter Assumptions With Other Capabilities

- Initial surface power needs will be provided by *High Energy Power & Propulsion*
  - Stationary Nuclear and/or solar power; mobile fuel cells/batteries for surface mobility
  - *ISRU* will provide fuel cell consumable storage & distribution & may provide infrastructure power growth (generation and power management & distribution)
- *ISRU* will provide surface propellant storage and distribution for ascent & hopper propulsion, to *In-Space Transportation*
- *ISRU* will provide backup life support consumable production, storage, and distribution for *Human Health & Support Systems*
- Space propellant depots will be provided by *In-Space Transportation*
  - *ISRU* may provide propellants for delivery to depots
- Surface Mobility assets for ISRU excavation and transport will be provided by the *Human Exploration Systems & Mobility* capability
  - *ISRU* will provide unique excavation and material handling & transportation units
- *Scientific Instruments & Sensors* should be provide instruments to locate and quantify potential resources
  - *ISRU* <u>may</u> be responsible for sensors for in-situ evaluation of resource characteristics and performance
  - 6
- *Autonomous Systems & Robotics* will provide autonomous control & failure detection, isolation, & recovery hardware and software
  - *ISRU* will provide unique excavation, transport, & processing software
- *ISRU* will provide any construction requiring use or manipulation of local materials
  - Habitat construction through assembly of pre-built units delivered from Earth would be provided by *Human Health & Support Systems*
- ISRU will provide manufacturing processes that use local materials or in-situ products

Interdependency Chart Format Overview

Team 13: In-Situ Resource Utilization

Example ISRU to Other Capabilities

ISRU Products To Other Capabilities

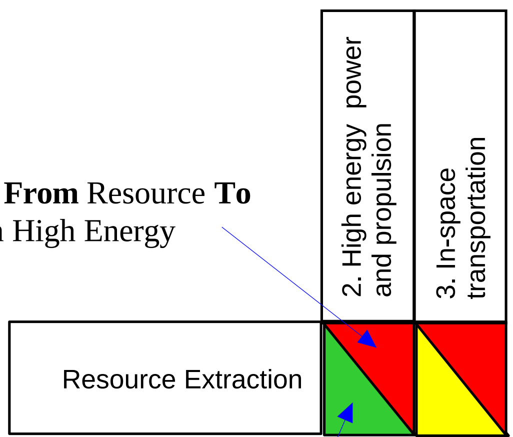
- H_2 & ^3He for NTR & fusion; Ar for electric
- Solar array and collector manufacturing & assembly
- Rectenna fabrication for orbital power beaming
- Thermal storage material production & fabrication
- Radiation shields for nuclear reactors

Capability Products To ISRU

- Solar & nuclear power to support power-intensive ISRU activities

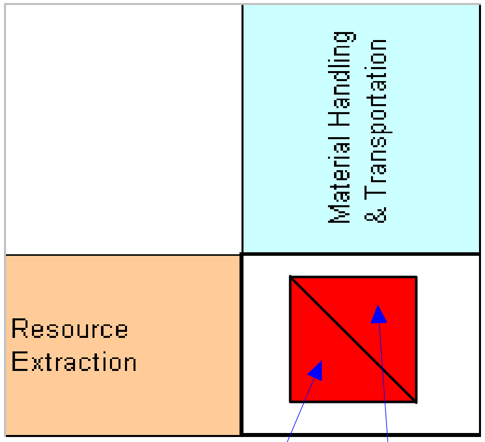
ISRU Element to Other Capabilities

Criticality **From** Resource **To** Extraction High Energy



Criticality **From** High Energy **To** Resource Extraction

ISRU Element to Other Element

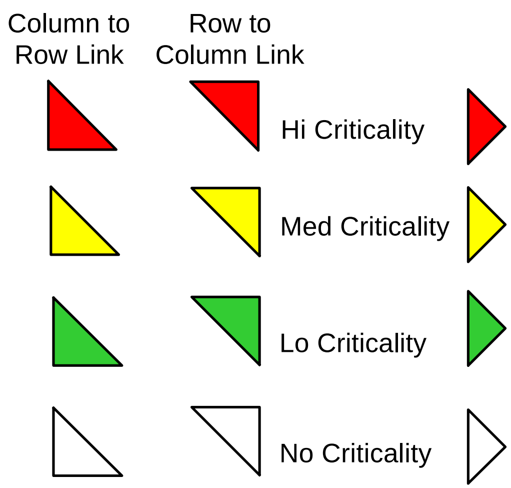


Criticality **From** Material Handling & Transportation **To** Resource Extraction

Criticality **From** Resource Extraction **To** Material Handling & Transportation

Symbol Key

- Color Denotes Criticality
- Arrow Point Denotes Direction



ISRU Product Interdependency With Other Capabilities

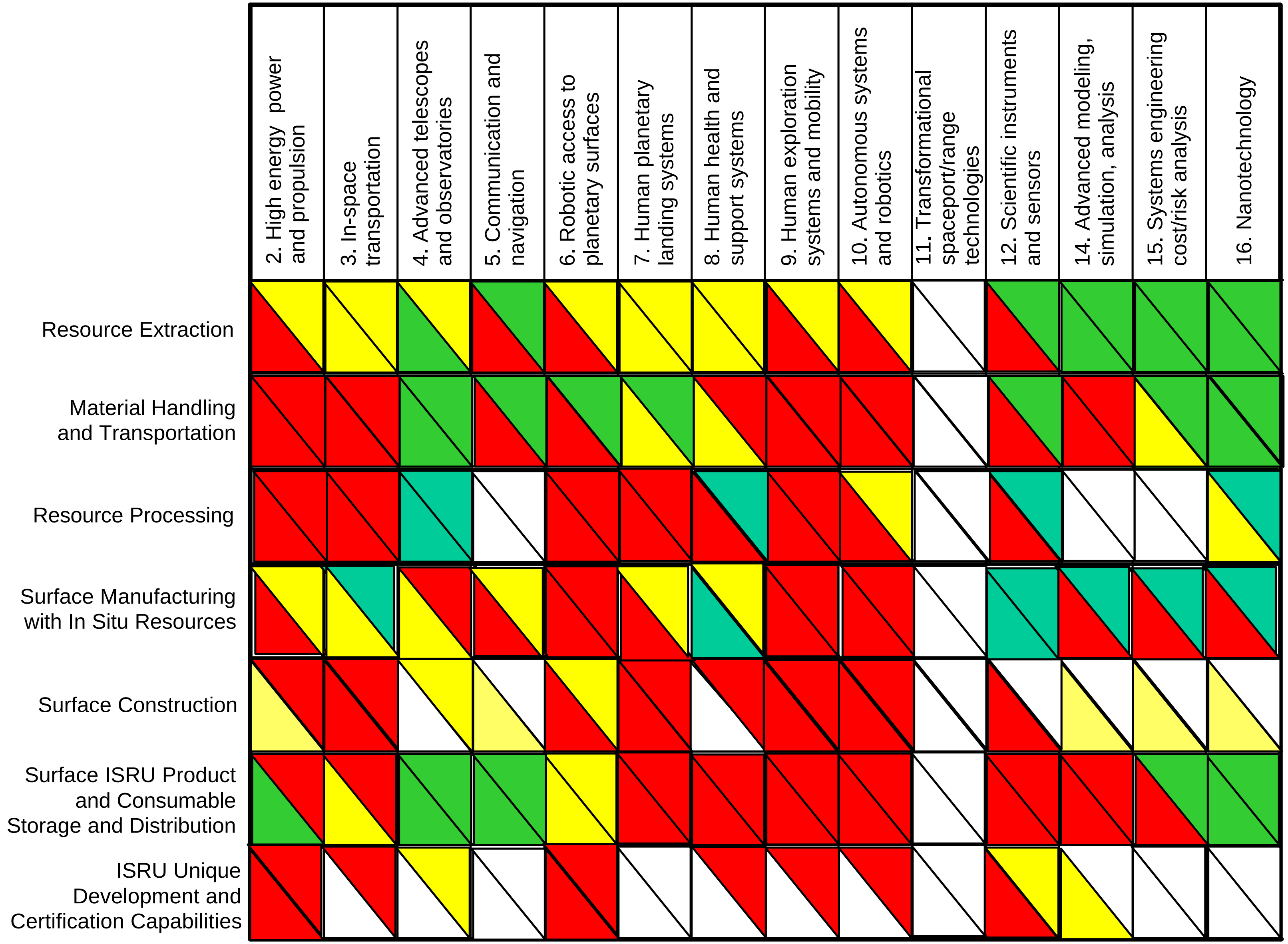
ISRU Products To Other Capabilities	Capability	Capability Products To ISRU
• H_2 & ^3He for NTR & fusion; Ar for electric • Solar array and collector manufacturing & assembly • Rectenna fabrication for orbital power beaming • Thermal storage material production & fabrication • Radiation shields for nuclear reactors • Power cable deployment; in-situ provided power management & distribution	High-Energy Power & Propulsion (2)	• Initial solar & nuclear power to support power-intensive ISRU activities • Mobile/high-density power sources.
• Propellant production and pressurant/purge gases for lander reuse and in-space depots • Aeroshells from Regolith	In-Space Transportation (3)	• ISRU-compatible propulsion • Delivery of ISRU products to sites of exploration and in-space depots
• Shaping crater for collector • In-situ construction and fabrication; foundation design & peparation • Gases for inflatable structures • Raw materials for space based observatory manufacture	Advanced Telescopes & Observatories (4)	
• Raw materials for infrastructure	Telecommunications and Navigation (5)	• Mobile equipment navigation. • Fast communication among systems components.
• Production of fuel cell reagents for rovers (vs solar arrays or RTGs for certain missions) • Propellant production for surface hoppers or large sample return missions	Robotic Access to Planetary Surfaces (6)	• Resource location & characterization information • Surface mobility system design & experience • Pre-positioning & activation of ISRU assets
• Landing pads/plume debris shielding • Propellant production/storage/transfer for lander reuse	Human Planetary Landing Systems (7)	• Precision landing • Delivery of ISRU capabilities to sites of exploration

ISRU Product Interdependency With Other Capabilities (Cont.)

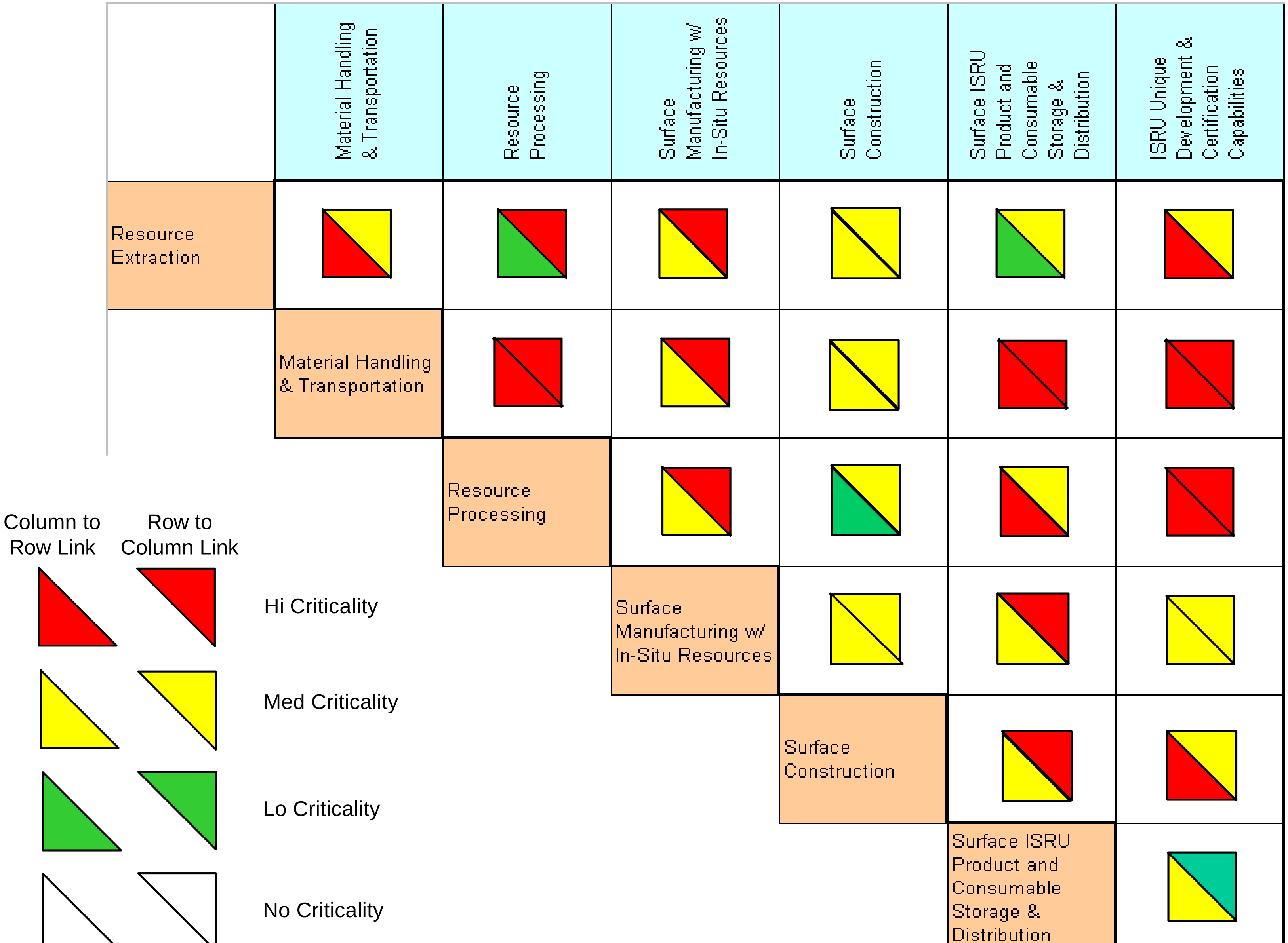
Team 13: In-Situ Resource Utilization

ISRU Products To Other Capabilities	Capability	Capability Products To ISRU
• Habitat/shelter fabrication • Gases for inflation & buffer gases • Life support consumable production for backup • Radiation & micro-meteoriod debris shields from in-situ material • Soil & bio-feedstock for plant growth • Materials for in-situ manufacturing	Human Health and Support Systems (8)	• Carbon-based waste products as resource for ISRU • Common hardware for possible modularity with ISRU systems
• Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots • O_2 production for EVA • Soil stabilization/dust control • Roadway infrastructure • Engineering properties of regolith	Human Exploration Systems & Mobility (9)	• Crew/robotics/rovers to perform ISRU surface activities
• Fuel cell reactants for surface vehicles and aero-bots • New & replacement parts for robotic systems	Autonomous Systems & Robotics (10)	• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation
• Gases and explosives for science equipment • Increased sample and measurement density for science studies.	Scientific Instruments & Sensors (12)	• Resource location & characterization information • Self Calibrating or Extended Calibration Life Sensors
	Advanced Modeling, Simulation, & Analysis (14)	• Resource formation models. • Mining and reclamation method evaluation. • Resource delivery and distribution models. • Granular material performance models.
	Nano-Technology (16)	• Nanotube catalysts for Microchemical Reactors

ISRU Element Interdependency With Other Capabilities



ISRU Element Interdependency Summary



ISRU Roadmap Process and Approach

- Establish work structure that will be utilized in Phase I and II
  - Form separate teams for each main ISRU CBS Element (6) with co-leads from different NASA centers and industry/academia
    - Volunteers from NASA, industry, & academia supported each Element team
  - Form separate team to examine Design Reference Architectures & Missions (DRAs/DRMs) and work with ISRU CBS teams to determine applicability and uses, and propose/work mission studies to define benefits/impacts
  - Establish ties to leads in other linked-dependant Capability Roadmaps:

    High Energy Power & Propulsion, In-Space Transportation,Robotic Access to Planetary Surfaces, Human Planetary Landing Systems, Human Health & Support Systems, Human Exploration Systems & Mobility, Autonomous Systems & Robotics, Instruments & Sensors)
- CBS Element Co-Leads will identify/lead external volunteers to develop roadmap products for their Element
- Chairs & Element Leads will integrate roadmap elements
- Method of performing work:
  - Weekly telecoms of Chairs with CBS element leads (Steering Committee)
  - Weekly telecoms of CBS element activities
  - Outreach Workshops (Space Resources Roundtable 11/04, APIO Workshop 11/04, & STAIF 2/05)
  - Face-to-face team meetings (3)

Top Level ISRU Metrics

- **Concept Evaluation Criteria**
  - Complexity/Risk
    - ISRU process/service
    - Compared to "bring from Earth" approach
  - Ability to Enable Mission Goals/Objectives
    - Sustained human presence & long-term self-sufficiency
    - Ability of hardware/technology to be used in multiple applications & destinations
  - Growth potential

- **Process Evaluation Criteria**
  - 'Launch mass saved' or 'Launch mass avoided' (immediate & long-term)
    - Ability to provide immediate/early impact on mission
    - Rate of return on investment by Gov or Commercial Enterprise
  - Reliability/Mean Time Between Repairs (MTBR)
  - Equipment/system working life
  - Mass of product/service vs Mass of ISRU "system"
  - Production rate or mass of product vs Unit power consumed
  - Mass throughput (volumetric or mass flowrate)
  - Percent of Earth consumable required (immediate & long-term)
  - Degree of system/process autonomy

Design Framework/Reference Mission Requirements & Assumptions or ISRU CRM

- Information & metrics from mission studies that did include ISRU (Mars '98) were utilized to the maximum extent possible
  - Mission and transportation asset information from other studies were also used to the maximum extend possible
- Because almost all missions studies to date have not include ISRU from the start, notional ISRU architectures were created to determine impacts & relative benefits
  - **ISRU-Emphasized Architectures** Aimed at NASA Human Exploration Initiative
    - ISRU-Enhanced Architecture
    - Derivation 1: Direct Return – ISRU Architecture
    - Derivation 2: E-M L1 propellant for Moon/Mars
  - **ISRU Commercial Architecture** Aimed at All Government (NASA Human & Science, DOD, NOAA) & Space Commercial Applications
- ISRU Incorporation & Evolution Philosophy
  - Characterize resources and validate ISRU concepts in Spiral 1

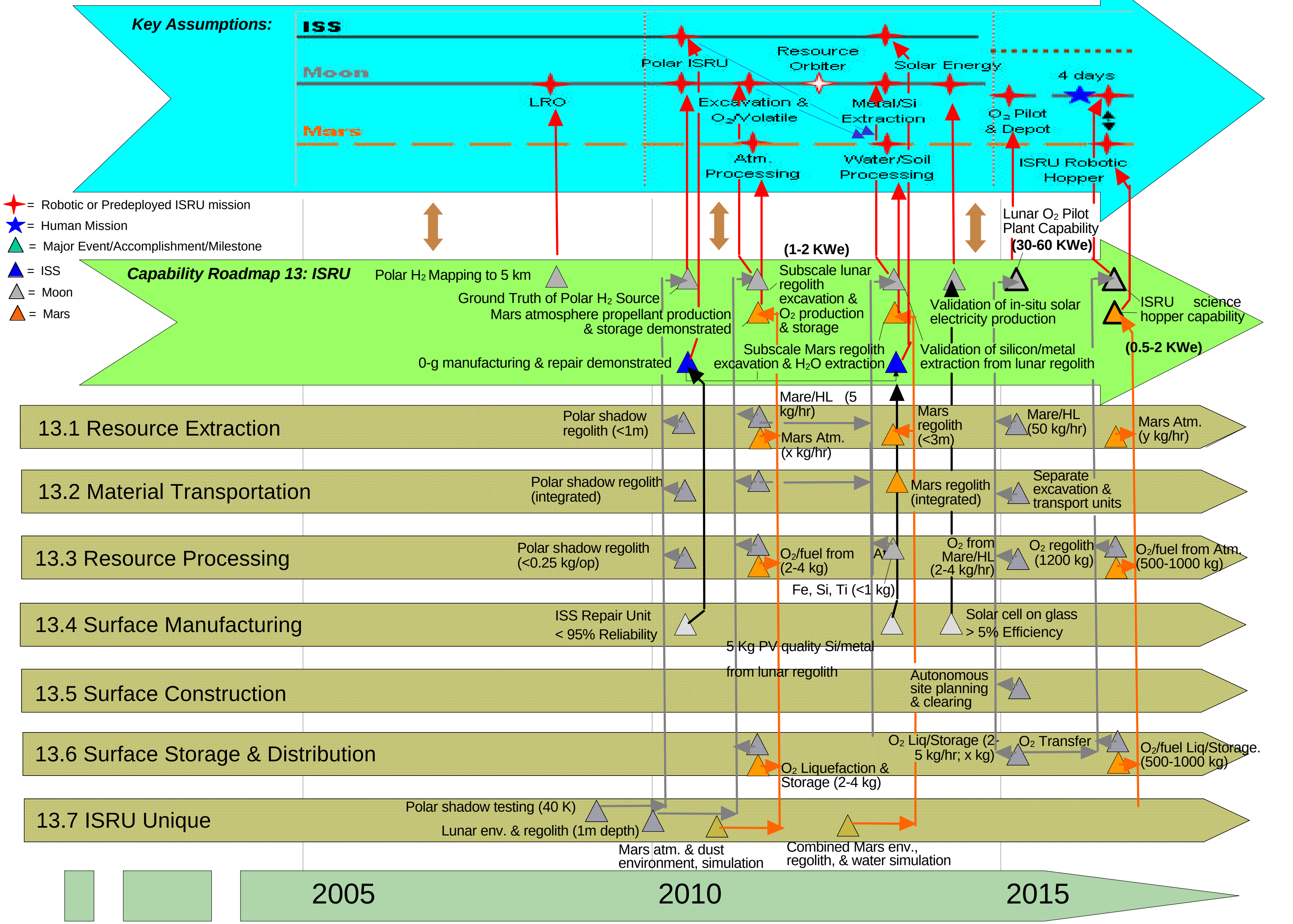
    Perform ISRU pilot operations in Spiral 2 to enhance missions and support full use at start of Spiral 3
  - Develop lunar ISRU as a precursor to Mars missions as well as enable sustained human lunar operations

Note: The cost for implementing demonstrations & missions in the defined ISRU Architectures has not yet been performed. It should also be noted that a Driving Principle of ISRU incorporation is to reduce costs both in the near and far-term. Therefore, reprioritization and rescheduling may need to be necessary

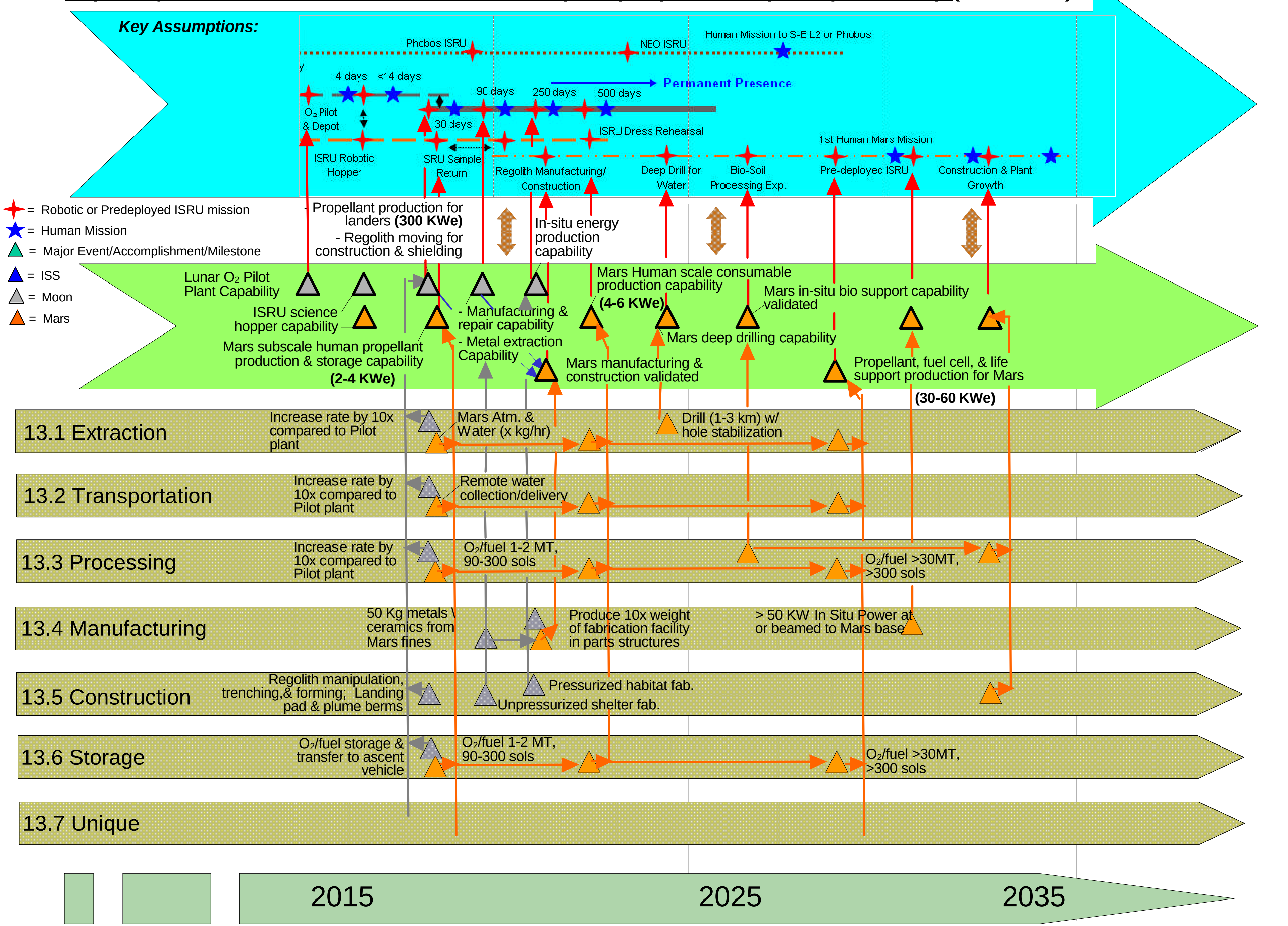
ISRU Usage & Incorporation Assumptions

- Spiral 2 & beyond
  - Surface mobility systems will utilize In-situ produced fuel cells reagents
  - ISRU systems sill generally be pre-deployed by robotic missions and will operate autonomously for extended periods of time
  - Power systems will be available (either Earth emplaced or ISRU enhanced) to supply the needs of ISRU systems even in the permanently shadowed craters of the moon.
- Spiral 3 & beyond:
  - Reusable landers will land “empty” and be refueled on the surface
  - Long-term missions will require the production of manufacturing feedstocks
  - Permanent presence on other planetary bodies will require the in-situ production of construction materials
- Architecture assumptions
  - For conservatism, Lunar ISRU assumed oxygen production thru hydrogen reduction of regolth
  - Production of propellants for surface to orbit ascent as minimum
    - Human Lunar ascent vehicles require 20-30 MT of propellant
    - Human Mars ascents vehicles require 30-50 MT of propellant
  - Significant power (nuclear) required at start of vehicle propellant production capabilities:
    - +300 KWe for Moon in +2018
    - +30 KWe for Mars in +2028

Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2005 to 16)



Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2015 to 35)



Top-Level ISRU Development & Integration Strategy

- **Not Everything Can Be Funded Immediately**
- Need *Early, Achievable, & Visible* milestones & successes
  - Must ensure constant delivery of products; with incremental growth in both number of products & quantity of products
  - Early missions must require minimum infrastructure and provide the biggest mass/cost leverage
  - Surface construction and manufacturing will start with simple/high leverage products and expand to greater self-sufficiency capability
- Need to take Evolutionary approach In development & missions
  - Early hardware needs to be achievable, not optimized
  - Early hardware needs to be scalable to future missions
  - Each design/demonstration activity needs to build on lessons learned from previous work and show clear benefit metrics
  - Research activities and technology development must be continuously performed and focused to enable sustained momentum and growth
  - Capabilities need to be able to grow with growth in:
    - Resource & process understanding
    - Human surface activities
- No single process or technology is best
  - Develop two or more approaches if possible to ensure success

In-Situ Resource Utilization (ISRU)

Emphasized Architecture Overview

ISRU Capability Roadmap Team

NASA Chair: Jerry B. Sanders, NASA/JSC, gerald.b.sanders@nasa.gov
External Chair: Dr. Michael Duke, Colorado School of Mines, mduke@mines.edu

Architecture Concepts

- ***Current Lunar Mission Architecture Options***
  - Option A: Lunar Evolution
  - Option B: Early Outpost
  - Option C: Early Lunar Resources
  - Option D: Expedited Moon-to-Mars

- ***ISRU-Emphasized Architectures* Aimed At NASA Human Exploration Initiative**
  - ISRU-Enhanced Architecture
  - Derivation 1: Direct Return – ISRU Architecture
  - Derivation 2: E-M L1 propellant for Moon/Mars

- ***ISRU-Commercial Architecture* Aimed At All Government (NASA Human & Science, DOD, NOAA) & Commercial Applications**

Current Lunar Mission Architecture Options

- Option A: Lunar Evolution
  - Robotic missions start prior to 2010 and continue throughout lunar program
  - Human ‘sortie’ missions begin in 2015 to 2020 timeframe
  - Expanded lunar science and Mars short-stay mission demonstrated in 2020 to 2025 timeframe
  - Decision in 2025-2030: 1) continue as ‘outpost’, 2) develop ‘base’ for long-term stay tests, 3) develop expanded ‘McMurdo’ type base, 4) decrease lunar activities, & 5) abandon human lunar activities

- Option B: Early Outpost
  - Minimize ‘sortie’ missions and focus on early Mars short-stay and expanded lunar science in 2015 to 2020
  - Same Decision as Option A: Lunar Evolution but now in 2020 to 2025 timeframe

Option C: Early Lunar Resources (leverage ISRU to maximum extent possible)
  - Same start as Option B: Early Outpost which continues into 2020-2025 period
  - Also Decision made in 2020-2025 timeframe

- Option D: Expedited Moon-to-Mars
  - Human ‘sortie’ missions begin in 2015-2020 timeframe geared towards Mars operation development & testing
  - This option does not conduct missions for purpose of demonstrating technologies
  - Human Lunar activities end in 2020 to 2025 time period

ISRU-Enhanced Architectures Aimed At NASA Human Exploration

Space Resource Utilization Dependencies

Architecture dependant:

- Long stay vs short stay *(mission consumable mass increases with stay time)*
- Pre-deploy vs all in one mission *(pre-deploy allows longer production times but requires precision landing)*
- Multiple mission to same destination vs single missions *(multiple missions enables gradual infrastructure and production rate build up)*
- High orbit vs low orbit rendezvous *(increase in Delta-V increases benefit of in-situ produced propellant)*
- Reuse vs single mission *(reuse allows for single stage vs two stage landers and lower cost propellant depots at E-M L1)*

Customer dependant:

- ISRU use must be designed into subsystems that utilize the products *(propellants, radiation shielding, energy storage, surface equipment, spare parts, etc.)* from the start to maximize benefits

Objectives of Lunar ISRU Development & Use

- Identify and characterize resources on Moon, especially polar region
- Demonstrate ISRU concepts, technologies, & hardware that reduce the mass, cost, & risk of human Mars missions as early as possible to utilize at start of Spiral 3
  - Excavation and material handling & transport
  - Oxygen production and volatile/hydrogen/water extraction
  - Thermal/chemical processing subsystems
  - Cryogenic fluid storage & transfer
- Use Moon for operational experience and mission validation for Mars
  - Pre-deployment & activation of ISRU assets
  - Making and transferring mission consumables *(propellants, life support, power, etc.)*
  - Landing crew with pre-positioned return vehicle or ‘empty’ tanks
  - ‘Short’ (<90 days) and ‘Long’ (300 to 500 days) Mars surface stay dress rehearsals
- Develop and evolve lunar ISRU capabilities that *enable* exploration capabilities
  - ex. Long-range surface mobility, global science access, power-rich distributed systems, enhanced radiation shielding, etc.
- Develop and evolve lunar ISRU capabilities to support sustained, economical human space transportation and presence on Moon
  - Lower Earth-to-Orbit launch needs
  - Enables reuse of transportation assets and single stage lander/ascent vehicles

  Lower cost to government thru *government-commercial* space commercialization initiatives

Objectives of Mars ISRU Development & Use

- Utilize Earth-based, ISS, and Lunar ISRU development, testing, and experience to maximum extent possible

- Identify and characterize resources on Mars, especially water
  - Utilize information from past, current, and planned Science missions to provide critical environment, resource, and design data when possible

- Develop and evolve Mars ISRU capabilities that reduces cost, mass, and risk of human exploration and *enable* exploration capabilities as early as possible
  - ex. Surface mobility & hoppers, power-rich distributed systems, enhanced radiation shielding, manufacturing/construction, plant growth/food production, etc.

- Perform ISRU demonstrations in step-wise approach to increase confidence in environment/resource understanding and reduce mission application uncertainties

  Experiment development time, 26 month gaps in missions, trip times, and extended surface operations mean lessons learned from one mission can only influence missions 2 or 3 opportunities (4 or 6 years) later
  - Parallel investigations of atmospheric and regolith/water-based processing with convergence before human mission

- Enable human missions beyond Mars (gateway to asteroid belt?)
  - ISRU on Phobos/Deimos; Mars-Sun L1 depot; ….
  - Space exploration is “a journey, not a race”

ISRU-Emphasized Architecture Attributes

- No Earth launch vehicle assumption made
- Crew of 4 or 6 assumed up to permanent presence; TBD (12) at permanent presence
- Characterize resource, environment, & engineering unknowns as early as possible
  - Lunar polar and global resources;   Mars water form and availability
  - Higher resolution of minerals/resources & surface topography
  - Critical material & engineering properties
- Utilize ISS for ISRU-related research
  - Manufacturing & repair
  - Gravity influences on fluid behavior, material handling, and processing
- Develop single robust primary lunar exploration site:
  - Initial checkout flights could be to at different locations until final site selected
  - Use primary site before access other locations (e.g. McMurdo Station approach)
  - Evolve to ‘Short’ (<90 days) and ‘Long’ (500 days) Mars surface mission dress rehearsals
- Demonstrate ISRU in Spiral 2 and Utilize ISRU to support missions at start of Spiral 3
  - Robotically pre-deploy and operate assets/capabilities: enable large mass/capability leverage
  - Use modular approach to incrementally develop and expand/grow capabilities
  - Develop life support backup, power, & manufacturing/repair capabilities
  - Begin use of lunar derived propellants & reusing transportation elements
    - Lunar oxygen; fuel trades still required
    - Initially propellant for lunar ascent (to LLO, E-M L1, or direct Earth return)
    - Increase capability to deliver propellant to E-M L1 and potentially LEO
- Develop lunar infrastructure and operations to *enable* sustainable lunar operations in parallel with a Mars exploration program

ISRU-Emphasized Architecture Benefits

Spiral 1 Benefits

- Lunar resource characterization and mapping for future human missions
- Validation of critical ISRU processes in actual environment (i.e. Lunar oxygen production, hydrogen/water extraction, excavation, etc.)

Spiral 2 Benefits:

- Demonstrate critical ISRU systems as additional capability in Spiral 2 and enable use at start of Spiral 3
  - Extra oxygen for EVA & life support use (possibly extend mission duration)
  - Extra power for operations & science

Spiral 3 Benefits:

- Lower mission costs:
  - 300 MT/yr reduced life support logistics for crew (LUNOX study)
  - Reduced transportation costs
    - Reuse of assets ($10's to $100's M)
    - Reduction in payload to LEO; 1/3rd compared to Non-ISRU architecture
- Increased mission capabilities
  - Increased landed payload capability with lunar propellant (x MT)
  - Smaller reusable lander; reduced penalty for increased redundancy/engine-out
  - Higher level of radiation protection for crew (ASARA)
  - Power rich exploration
  - Global surface access for increased science at significantly reduced cost compared to dedicated mission launched from Earth
  - Lunar ISRU-derived infrastructure (habitats, life support, power, etc.)

ISRU-Emphasized Architecture Benefits

Spiral 3 Benefits (Cont.):

- Reduced mission risk (Spare manufacturing & repair, lower radiation, reduced number of mission events, etc.)
- ISRU operation and mission impact experience for Mars missions (Spiral 5)

  Early Spiral 3/Shortened Spiral 2 timeline for reduced architecture costs

  Increased science with extended surface mobility and global access

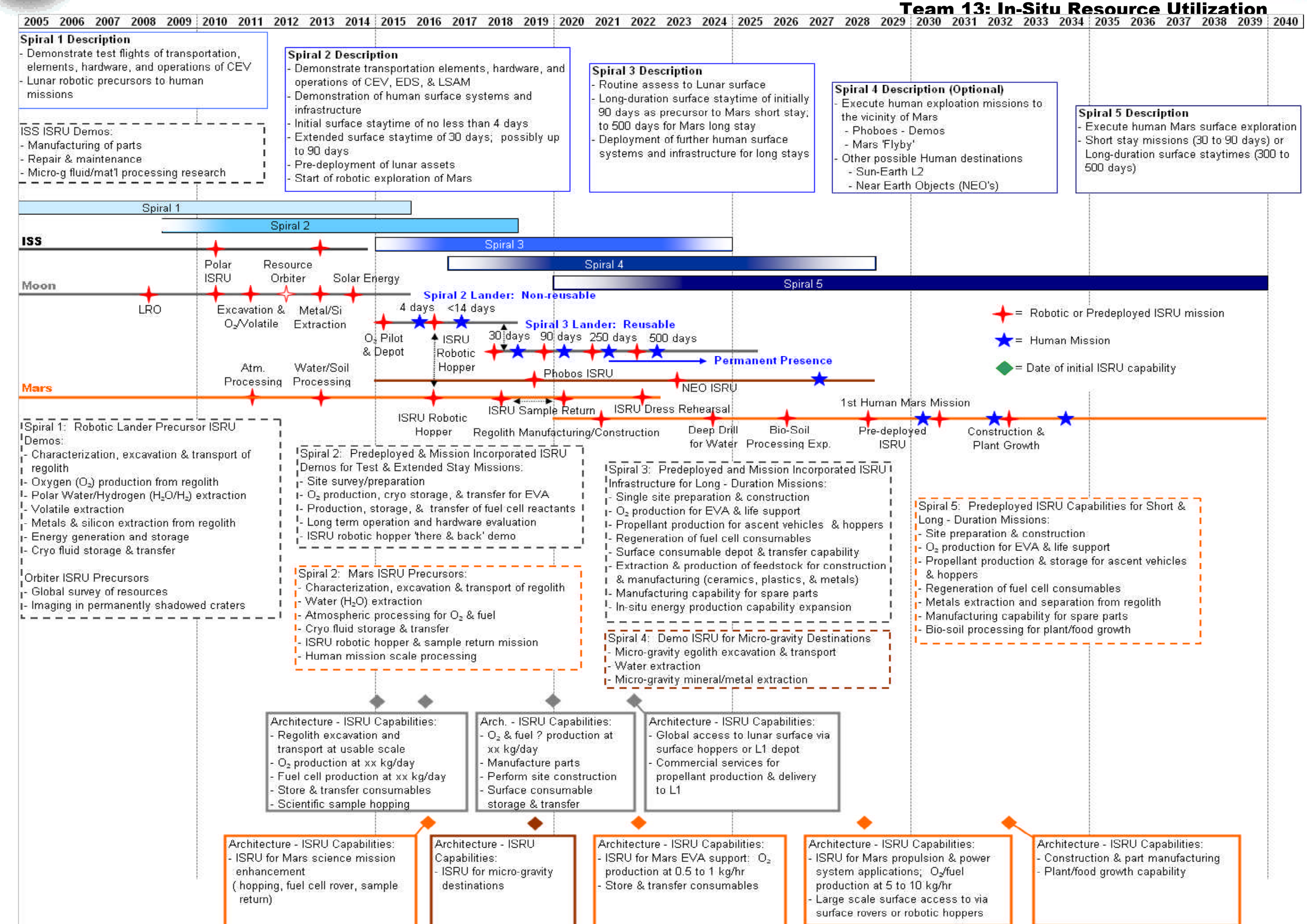
Spiral 4 Benefits:

- Examination of resource processing and use in micro-gravity
- Possible ISRU-Consumable depot on Phobos for Mars and beyond transportation

Spiral 5 Benefits:

- Lower mission mass (>20% reduction)
- Smaller landers/ascent vehicles; reduced penalty for increased redundancy/engine-out
- Global robotic sample acquisition access with ISRU hoppers
- Long duration surface stay consumables
- Reduced mission risk (more insitu capabilities, lower radiation, reduced number of mission events, etc.)

Notional ISRU-Supported Mission Timeline



ISRU Architecture Applications & Capabilities

High Criticality-to-Mission Success/Cost Areas Strongly Affected by ISRU

- *Transportation* (In-space and surface)
- *Energy/Power* (Electric, thermal, and chemical)
- *Life Support* (Radiation protection, consumables, habitable volume, etc.)
- *Sustainability* (repair, manufacturing, construction, etc.)

ISRU Demonstrations & Capabilities

- Spiral 1 Resource Characterization and ISRU Validation Demonstrations
  - Characterization, excavation & transport of regolith
  - Oxygen (O_2) production from regolith (possibly propellant for Lunar sample return)
  - Polar Water/Hydrogen (H_2O/H_2) extraction
  - Volatile extraction (H_2, He/^{3}He, N_2, etc.)
  - Metals extraction and separation from regolith
  - Energy generation and storage (solar & thermal)
  - Cryo fluid storage & transfer
  - Orbital ISRU Precursors: Global survey of resources& imaging in permanently shadowed craters
- Spiral 1 ISRU-Related Activities on the International Space Station (ISS)
  - Available hardware possible: Rapid Prototyping, Combustion Synthesis, Microgravity Glovebox)
  - Manufacturing of parts: Demos and CEV & ISS parts fabrication (Polymer fabrication, direct metal/ceramic fabrication, mechanical properties comparison & analysis, etc.)
  - Repair & maintenance (Shuttle repair, lunar soil fusion, joining dissimilar materials, etc.)
  - Micro-g fluid/mat'l processing research (separators, reactors, fluidized beds, etc.)
  - Ultra-high vacuum for solar cell growth

ISRU Arch. Applications & Capabilities (Cont.)

- Spiral 2 Lunar ISRU Demonstrations & Mission Enhancements
  - Scalable excavation & transport of regolith
  - Site survey/preparation
  - Production, storage, & transfer of oxygen (O_2) and fuel cell reactants for EVA and surface mobility (use cryo tanks from lander or advanced cryo technology demonstration)
  - Long term operation and hardware evaluation
  - ISRU robotic hopper demonstration with 'there & back' capability; increased science, landing hazard avoidance, & human-related propulsion capabilities and synergism to Mars exploration

- Spiral 2 Mars ISRU Demonstrations & Mission enhancements
  - Site survey/preparation
  - Characterization, excavation & transport of regolith
  - Water (H_2O) extraction
  - Atmospheric processing for O_2 & fuel
  - Cryo fluid storage & transfer
  - ISRU robotic hopper & sample return mission
  - Human mission scale processing

ISRU Arch. Applications & Capabilities (Cont.)

- Spiral 3 Lunar ISRU Mission Applications
  - Single site preparation & construction (berms, radiation shielding, habitat deployment, etc.)
  - O_2 production for EVA & life support backup and growth
  - Propellant production & storage for ascent vehicles & hoppers
  - Regeneration of fuel cell consumables
  - Surface consumable storage depot & transfer capability
  - Extraction & production of feedstock for construction & manufacturing
  - Manufacturing capability for spare parts
  - In-situ energy production capability expansion (solar & thermal)

- Spiral 4 Small Body Demonstrations & Applications (Phobos, NEOs, etc.)
  - Micro-gravity regolith excavation & transport
  - Micro-gravity water extraction, separation, and processing
  - Micro-gravity mineral/metal extraction

- Spiral 5 Mars Demonstrations & Applications
  - Site preparation & construction
  - O_2 production for EVA & life support
  - Propellant production & storage for ascent vehicles & hoppers
  - Regeneration of fuel cell consumables
  - Metals extraction and separation from regolith
  - Manufacturing capability for spare parts
  - Bio-soil processing for plant/food growth

Direct Return - ISRU Architecture

Architecture Attributes

- HLLV: 120 MT to LEO; 40 MT to LLO; 25 MT to lunar surface
- 25 MT payload can be Habitat, Cargo, or wet Earth Return Vehicle (ERV)
- ERV returns crew directly to Earth (no rendezvous)
- Large scale lunar oxygen (O_2) production
  - Water production if available
- Other attributes similar to Nominal ISRU Architecture

Benefits

- Number of Moon/Mars hardware elements developed is minimized
  - Common HLLV, Eliminates LSAM Development
- Number of mission-critical operations is minimized
  - Lower launches and no orbital rendezvous
- Cost & risk per person-day on Moon greatly reduced
  - Direct Return mission launch mass is lower than LOR once in situ-LOx is available.
  - Heavy cargo lander allows early delivery of substantial hab/lab to surface. Eliminates non-cost effective short-stay mission phase.
  - Safe haven on surface enhances crew safety.
  - Return launch window is always open.
- Accelerates transition to more productive Spiral 3

Additional Spiral 3 Benefits:

- Maximum ISRU leverage:
  - Global surface access with hoppers at significantly reduced cost (8 to 14 Lunar sites explored for delivery of one launch of fuel) [Zubrin study]
  - Reduction in Lunar launch requirements plus hardware commonality allows Mars program to proceed in parallel
- Accelerates transition to Mars, without abandoning Moon.

Propellant to Earth-Moon L1 for Moon/Mars

Architecture Attributes

- Assumes reusable/maintainable space transportation assets (3 or more missions)
  - Landers, trans-stages, crewed vehicles, surface & space depots, Earth aeroshells)
- Staging at Low Earth Orbit (LEO) and Earth-Moon (E-M) Lagrange Point (L1)
- Lunar propellant transferred to E-M L1 and possibly to LEO
- Propellant used for
  - Lunar ascent/descent to/from E-M L1
  - Return to Earth from E-M L1
  - Earth LEO to E-M L1 (long range)
- Propellant delivery to E-M L1
  - If only Lunar Oxygen (LunOx) then transfer via chemical propulsion; long-term – tether or elevator
  - If lunar water is available, transfer as water/ice via chemical propulsion or electro-magnetic launcher (best case)
- Depot at E-M L1 can provide low Delta-V to other destinations.
  - E-M L1 to Earth-Sun L1 = 850 m/s
  - E-M L1 to Mars = 1470 m/s

  Note: Earth to LEO = 9200 m/s

Benefits

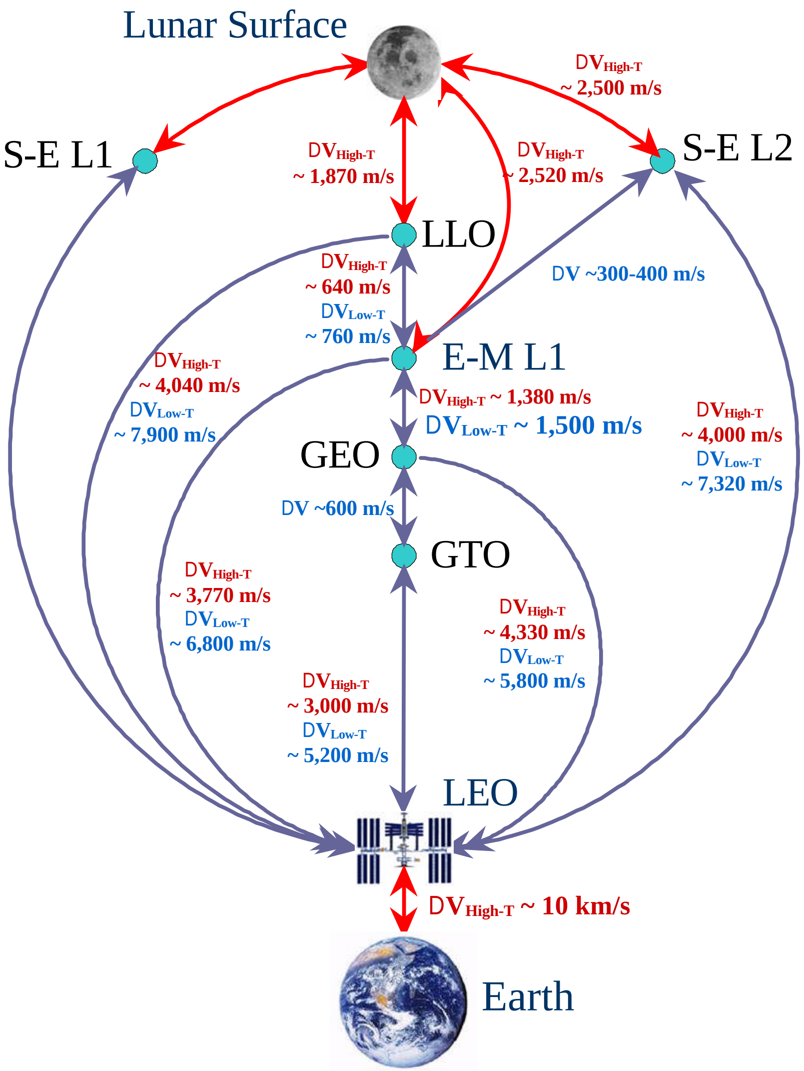
Additional Spiral 3 Benefits:

- Maximum ISRU leverage:
- Cost & risk per person-day on Moon further reduced
- Significantly reduced Earth launch rates and costs
  - Initial Mass in LEO is about 1/3 to 1/4 of that compared to non-ISRU mission [CSM study]
  - Reuse of space assets can further reduces initial mass to 1/8 of non-ISRU mission [CSM study]

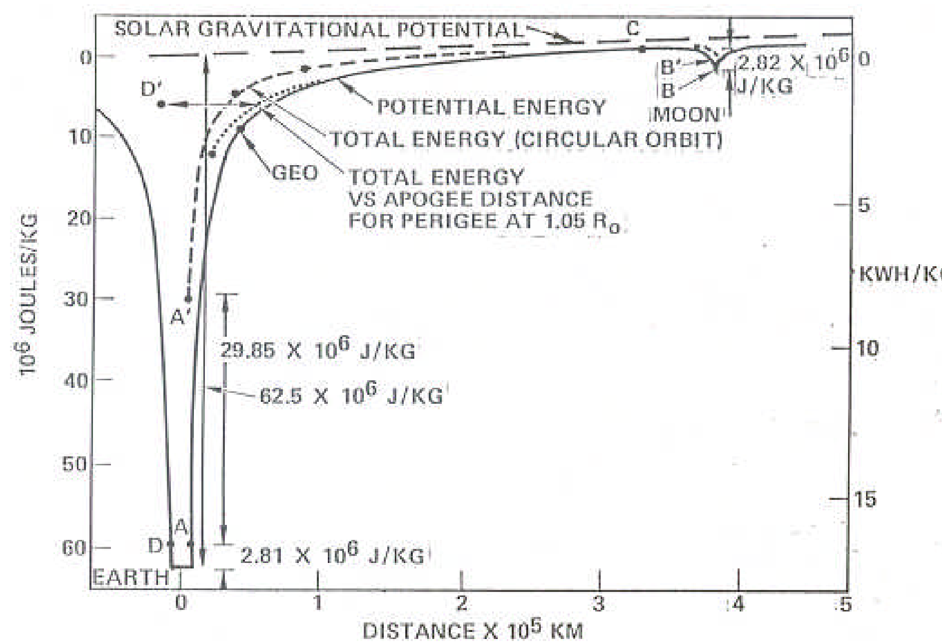
Additional Spiral 5 Benefits

- Significantly reduced Earth launch rates and costs

Transfer Impulses in Near-Earth Space



LEO	Low Earth Orbit
GTO	GEO Transfer Orbit
GEO	Geostationary Orbit
EM L1	Earth-Moon Libration Point L1
SE L1	Sun-Earth Libration Point L1
SE L2	Sun-Earth Libration Point L2
LLO	Low Lunar Orbit



ISRU Sub-Element 13.1
Resource Extraction

Dr. Leslie Gertsch - External Chair
Don Rapp - NASA Chair
April 12, 2005

Resource Extraction Capability Roadmap Team

Co-Chairs

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- Jim Richard, Electric Vehicle Controllers Ltd.
- Jack Wilson & James Powderly, Honeybee Robotics
- Kevin Payne, Lockheed-Martin
- Dale Boucher, Northern Center for Advanced Technology
- Eric Rice, Orbitec

Academia

- Richard Gertsch, Michigan Technological University
- Brad Blair, Colorado School of Mines

Other/Critical Volunteers

- Most of the above are volunteer contributors
- Broad ISRU industry & academic community (Space Resources Roundtable & STAIF Conferences)

Capability 13.1 Resource Extraction

Resource Extraction provides raw materials -- gas, liquid, and solid -- from the local environment by removing them, concentrating them, and preparing them for further processing, manufacturing, or direct use. It is the first step in "living off the land" in a sustainable manner.

It consists of four parts:

Resource Assessment determines what is available, where it is, what form it is in, and how it can best be extracted.

Resource Acquisition separates and removes the target raw material -- gas, liquid, and/or solid -- from its original location to Resource Beneficiation.

Resource Beneficiation converts the raw material into a form suitable for direct use, manufacturing, or further processing.

Site Management comprises supplemental capabilities needed for safe, effective operation.

Resource Extraction

Team 13: In-Situ Resource Utilization

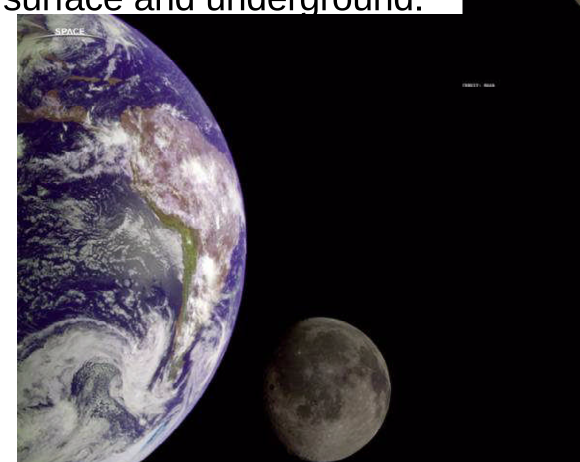
- In-Situ Resource Utilization 13.0
  - Resource Extraction 13.1
    - Resource Assessment 13.1.1
      - Prospecting 13.1.1.1
      - Delineation 13.1.1.2
      - Development 13.1.1.3
    - Resource Acquisition 13.1.2
      - Atmospheric Gases 13.1.2.1
      - Underground Liquids and Gases 13.1.2.2
      - Regolith 13.1.2.3
      - Rock 13.1.2.4
      - Mixed Materials 13.1.2.5
      - Excavated Openings as Product 13.1.2.6
      - Waste Materials 13.1.2.7
    - Resource Beneficiation 13.1.3
      - Change of Phase 13.1.3.1
      - Particle Size Change 13.1.3.2
      - Separation 13.1.3.3
      - Internal Materials Handling 13.1.3.4
    - Site Management 13.1.4
      - Site Planning 13.1.4.1
      - Dust Control 13.1.4.2
      - Anchoring 13.1.4.3
      - Ground Stability Control 13.1.4.4
      - Transportation and Storage 13.1.4.5
      - Monitoring 13.1.4.6
      - Auxiliary Operations 13.1.4.7
      - Waste Management 13.1.4.8
      - Site Reclamation 13.1.4.9

Blue outline = major capability needed for 2005-2035

Dashed outline = commonality with other capability(ies)

Attributes and Benefits of Resource Extraction

- Provides feedstock for local manufacture of:
  - **Propellants**.
  - Commodities (**life support gases**, buffer gases, liquids, etc.).
  - Structural members for construction of telescopes, research facilities, etc.
  - Repair items (tools, parts, etc.)
- Provides additional raw materials for:
  - **Bulk radiation shielding**.
  - Construction materials.
- Excavates regolith and rock for:
  - Shelters for humans and equipment.
  - Foundations for telescopes, research facilities, etc.
  - Storage capacity for materials and supplies, on surface and underground.
- Enables power generation:
  - Materials to produce solar power cells.
  - Materials to produce fuel cell reagents.
  - ^3He for nuclear fusion reactors.
- Leverages initial equipment.
  - Provides these materials for less mass than shipping finished products from Earth.



Requirements and Assumptions for Resource Extraction

- Additional Assumptions:
  - This roadmap may be the basis for future expansion, so the full range of eventual resources is included (gases, liquids, regolith, rock, waste, space, *etc*.)
  - Science Instruments and Sensors Capability will provide all instruments and sensors needed for Resource Assessment and subsequent operations.

- Requirements:
  - Piggyback Resource Assessment on missions to Moon and Mars
    - Complementary/supplementary to science goals.
    - Assessment provides crucial information for Resource Acquisition, Beneficiation, and Site Management.
  - Resource Acquisition requires
    - Power.
    - Dust control.
    - Access – robotic and/or human.
    - Material handling capabilities.
  - Resource Beneficiation requires
    - Same as Resource Acquisition, plus well-specified feedstock parameters.

Resource Extraction Commonality-Dependency With Other Capabilities

Products From Resource Extraction

- Raw materials for:
  - Propellants.
  - Fuel cell reagents.
  - System components.
  - Infrastructure fabrication.

(for High-Energy Power & Propulsion; In-Space Transportation; Advanced Telescopes & Observatories; Telecommunications and Navigation; Robotic Access to Planetary Surfaces; Human Planetary and Landing Systems)

- Waste re-use.
- Shelter excavation.
- Raw materials for life support.

(for Human Health and Support Systems)

Products To Resource Extraction

High-Energy Power & Propulsion
- Power for startup.
- Mobile/high-density power sources.

In-Space Transportation
- Access to Resource Extraction sites.
- Delivery of products.
- Delivery of parts, supplies, etc.

Advanced Telescopes & Observatories

Telecommunications and Navigation
- Mobile equipment navigation.
- Fast communication among systems components.

Robotic Access to Planetary Surfaces
- Surface mobility.
- Robotic access to Resource Extraction sites.

Human Planetary and Landing Systems
- Human access to Resource Extraction sites.

Human Health and Support Systems
- Enabling human presence on- and near-site.

Resource Extraction Commonality-Dependency With Other Capabilities

Products From Resource Extraction

- Raw materials for:
  - Propellants.
  - Fuel cell reagents.
  - System components.
  - Infrastructure fabrication.
- Increased sample and measurement density for science studies.

Products To Resource Extraction

Human Exploration Systems and Mobility (9)
- Human interfacing with Resource Extraction systems.

Autonomous Systems and Robotics (10)
- Autonomous and robotic systems for all phases of Resource Extraction.

Transformational Spaceport and Range (11)
- Equipment, parts, supplies, etc. delivery.

Scientific Instruments and Sensors (12)
- Resource Assessment data.

Advanced Modeling, Simulation, & Analysis (14)
- Resource formation models.
- Mining and reclamation method evaluation.
- Resource delivery and distribution models.
- Granular material performance models.

Systems Engineering Cost & Risk Analysis (15)
- Extraction system analyses.

Nanotechnology and Advanced Concepts (16)

Resource Extraction Interdependency with other ISRU Elements

ISRU Element Products To Research Extraction

Material Handling & Transportation
- Product shipment to customer
- Supplies delivery

Surface Construction
- Site preparation
- Logistics
- Infrastructure

Surface Manufacturing
- Spare parts

Product Storage & Distribution
- Propellants
- Buffer gases

Unique Testing and Certification
- Material performance models and tests
- Equipment/system performance tests

Resource Extraction

- Resource Assessment
- Resource Acquisition
- Resource Beneficiation
- Site Management

Products From Resource Extraction

All
- Site and region characterization for science and engineering

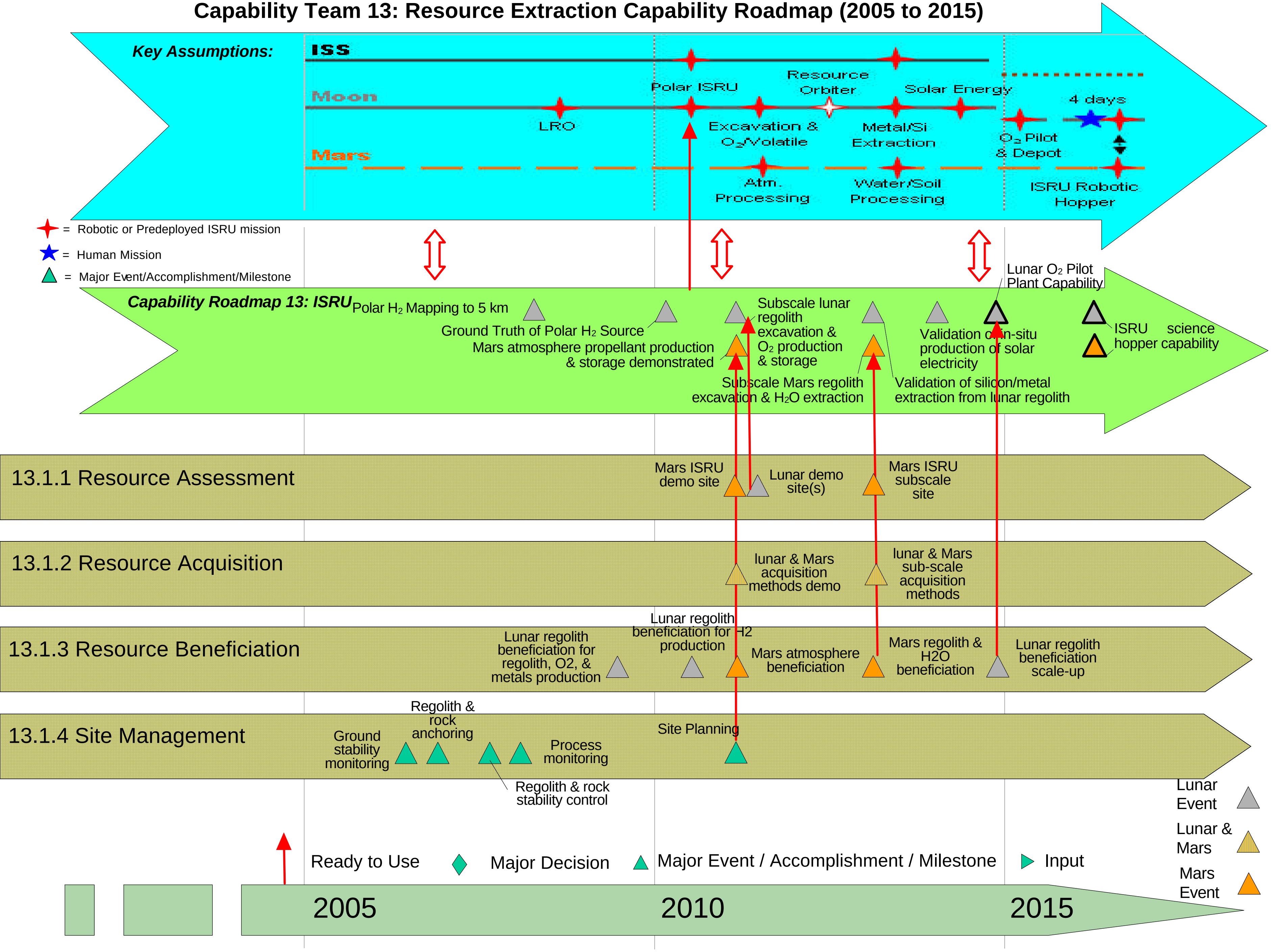
Resource Processing
- Feedstock

Surface Manufacturing
- Feedstock

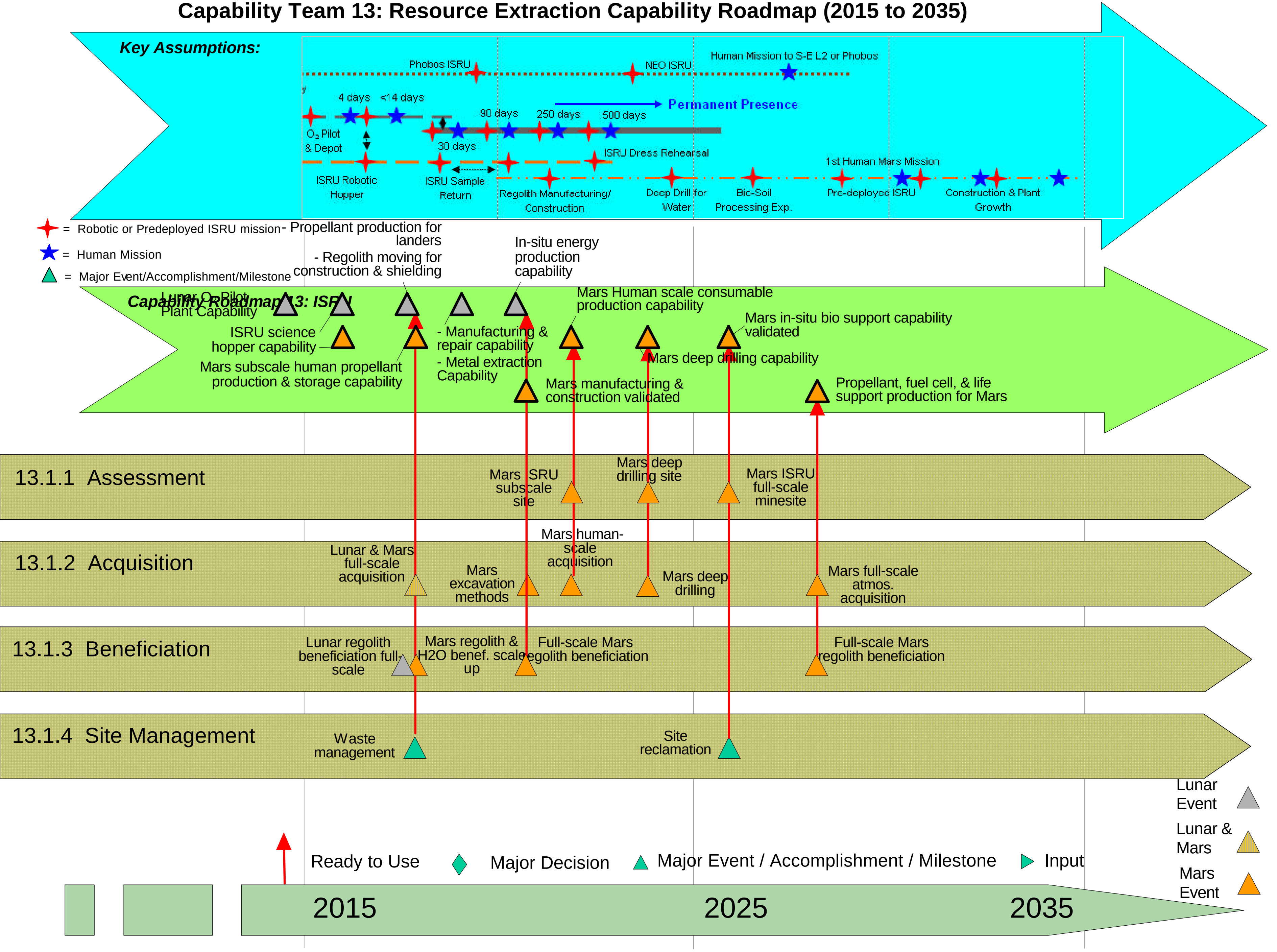
Product Storage & Distribution
- Ready-to-use gases and liquids

Surface Construction
- Ready-to-use construction materials

Capability Team 13: Resource Extraction Capability Roadmap (2005 to 2015)



Capability Team 13: Resource Extraction Capability Roadmap (2015 to 2035)



Current State-of-the-Art for Capability 13.1 Resource Extraction

- Some sub-capabilities have been demonstrated:
  - Scooping of regolith samples on the Moon and Mars.
  - Coring of regolith samples on the Moon.
  - Grinding and analysis of rock samples on the Moon and Mars.
  - Mars atmosphere capture and separation
    - Cryo-coolers demonstrated on satellites for long duration (Mars conditions).

- The present capabilities of terrestrial Resource Extraction include:
  - Semi-automated drilling/boring, fragmentation, excavation, and transportation of rock, both underground and on the surface.
  - Semi-automated pre-processing of gases, liquids, and solids into forms suitable for further processing, manufacturing, or direct use.
  - Production rates from a few liters/day to 200,000+ tonnes/day.
  - Successful operations:
    - from 4,600 m elevation to 3,800 m depth in the crust, and on the sea bottom;
    - in locations accessible only when the ground freezes, when it thaws, or when artificially refrigerated;
    - from the centers of cities to the remote tundra;
    - within and beneath rivers, lakes, and oceans.

Maturity Level – Capabilities for 13.1 Resource Extraction

Team 13: In-Situ Resource Utilization

Assess

Acquis

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Manage

Capability	Key Technologies or Sub-Capabilities	Readiness Assessment		
		CRL	R&D3	Need Date
Prospecting and Delineation	Field Sampling Technologies	1-7	I	2007
	Mapping Technologies	1-7	III	2006
	Remote Geophysical Surveying Technologies	1-7	III	2005
	In Situ Geophysical Survey Technologies	1-7	III	2007
	Sample Analysis Technologies	1-7	III	2006
Prospecting, Delineation, and Development	Drilling Technologies	1-7	III	2007
	Human & Robotic Transportation Technologies	1-7	III	2010
	Pit and Trench Excavation Technologies	1-7	III	2008
Development	Tunnel/Shaft Excavation Technologies	2	III	2025
	Atmospheric Extraction Methods	2	II	2020
	Borehole Liquid & Gas Extraction Methods	2	III	2024
	Surface Extraction (Mining) Methods	1	II	2016
	Underground Extraction (Mining) Methods	1	II	2030
	In Situ Extraction Methods	1	III	2012
	Gas Collection Technologies	2	II	2016
	Dust Mitigation/ Control Technologies	0	IV	2012
	Granular materials performance models	0	III	2007
all Resource Acquisition capabilities	Human&Robotic Transportation Technologies	1-7	III	2010
	Continuous Materials Handling Technologies	2	II	2015
	Cyclic Materials Handling Technologies	3-7	III	2010
	Dust Mitigation/ Control Technologies	0	IV	2012
	Process Monitoring Technologies	1-4	III	2012
Atmospheric Gases Resource Acquisition	Atmospheric Extraction Methods	3	II	2020
Atmospheric Gases, Underground Liquids and Gases Resource Acquisition	Liquid and Gas Containment Technologies	3	II	2007
	Gas Collection Technologies	2	II	2016
Underground Liquids and Gases Resource Acquisition	Borehole Liquid & Gas Extraction Methods	1	III	2024
Underground Liquids and Gases, Regolith, and Rock	Drilling Technologies	1-7	III	2007
Regolith and Rock Resource Acquisition	Surface Extraction (Mining) Methods	1	II	2016
	Underground Extraction (Mining) Methods	1	II	2030
Regolith and Rock Resource Acquisition, and Excavated Openings as Product	Regolith & Rock Fragmentation Technologies	1	III	2008
	Regolith and Rock Excavation Technologies	1-2	III	2009
	Regolith and Rock Transport Technologies	1	II	2008
	Pit and Trench Excavation Technologies	1-7	III	2008
	Granular materials performance models	0	III	2007
Mixed Materials Resource Acquisition	*In situ* Extraction Methods	1	III	2012?

Maturity Level – Capabilities for 13.1 Resource Extraction

Assess
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Capability	Key Technologies or Sub-Capabilities	Readiness Assessment		
		CRL	R&D3	Need Date
Excavated Openings as Product	Tunnel/Shaft Excavation Technologies	2	III	2025
	Pit and Trench Excavation Technologies	1-7	III	2008
all Resource Beneficiation capabilities	Sample Analysis Technologies	1-7	III	2006
	Process Monitoring Technologies	1-4	III	2012
	Dust Mitigation/ Control Technologies	0	IV	2012
Beneficiation Change of Phase	Gas-Liquid Phase Change Technologies	1-3	II	2015
	Solid-Plasma Phase Change Technologies	1	III	?
	Solid-Gas Phase Change Technologies	1-3	II	2015
	Solid-Liquid Phase Change Technologies	1-3	II	2015
Beneficiation Particle Size Change	Solids Comminution Technologies	1	III	2014
	Solids Agglomeration Technologies	0	IV	?
Beneficiation Separation	Gaseous Separation Technologies	3	III	2017
	Liquid Separation Technologies	2	III	2017
	Granular Solids Physical Separation Technologies	1	III	2014
	Granular Solids Chemical Separation Technologies	1	III	2014
Separation and Internal Materials Handling	Granular materials performance models	0	III	2007
Internal Materials Handling	Liquid and Gas Containment Technologies	3	II	2009
	Continuous Materials Handling Technologies	2	II	2015
	Cyclic Materials Handling Technologies	3-7	III	2010
Site Planning, Monitoring	Mapping Technologies	1-7	III	2006
	Remote Geophysical Surveying Technologies	1-7	III	2005
	In Situ Geophysical Survey Technologies	1-7	III	2007
	Sample Analysis Technologies	1-7	III	2006
Site Planning, Monitoring, Site Reclamation	Field Sampling Technologies	1-7	II	2007
Transportation and Storage	Human&Robotic Transportation Technologies	7	III	2010
Anchoring	Soil Anchoring Technologies	3	III	2008
	Rock Anchoring Technologies	2	III	2009
Anchoring, Ground Stability Control, Site Reclamation	Granular materials performance models	0	III	2007
Ground Stability Control	Ground Stability Control Technologies	2	III	2012
Ground Stability Control, Monitoring	Ground Stability Monitoring	2	II	2012
Waste Management, Site Reclamation	Pit and Trench Excavation Technologies	1-7	III	2008
Monitoring	Process Monitoring Technologies	1-4	II	2012
Monitoring, Site Reclamation	Drilling Technologies	1-7	III	2007

Maturity Level – Technologies for 13.1 Resource Extraction

Team 13: In-Situ Resource Utilization

Assess

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Technology	Capability Applications	Readiness Assessment		
		TRL	R&D3	Need Date
Mapping Technologies Remote Geophysical Survey Technologies	Prospecting and Delineation, Site Planning, Monitoring	2-9 9	III III	2005 2005
Human & Robotic Transportation Technologies	all Resource Assessment capabilities, all Resource Acquisition capabilities, Transportation and Storage	5-9	III	2008
Pit and Trench Excavation Technologies	all Resource Assessment capabilities, Waste Management, Site Reclamation	2, 6-9	III	2005
Drilling Technologies	all Resource Assessment capabilities; Underground Liquids and Gases, Regolith, and Rock Resource Acquisition; Monitoring and Site Reclamation	2, 6-9	III	2005
In Situ Geophysical Survey Technologies	Prospecting, Delineation, Site Planning, Monitoring	6-9	III	2005
Field Sampling Technologies	Prospecting, Delineation, Site Planning, Monitoring, Site Reclamation	9	I	2006
Sample Analysis Technologies	Prospecting and Delineation, all Resource Beneficiation capabilities, Site Planning and Monitoring	9	III	2005
Dust Mitigation/ Control Technologies	Development, all Resource Acquisition capabilities, all Beneficiation capabilities, and Dust Control	1-5	IV	2007
Atmospheric Extraction Methods	Development, Atmospheric Gases Resource Acquisition	6	II	2015
Borehole Liquid & Gas Extraction Methods	Development, Underground Liquids and Gases Resource Acquisition	6	III	2019
Surface Extraction (Mining) Methods Underground Extraction (Mining) Methods	Development, Regolith and Rock Resource Acquisition	6 6	II II	2005 2025
In Situ Extraction Methods	Development, Mixed Materials Resource Acquisition	6	III	2007
Tunnel/Shaft Excavation Technologies	Development, Rock Resource Acquisition, Excavated Openings	6	III	2020
Gas Collection Technologies	Development; Atmospheric Gases, Underground Liquids and Gases Resource Acquisition	6	II	2011
Granular materials performance models	Development; Regolith and Rock Resource Acquisition, and Excavated Openings as Product; Beneficiation Separation and Internal Materials Handling; Site Management, Anchoring, Ground Stability Control, Site Reclamation	1-4	III	2005
Process Monitoring Technologies	all Resource Acquisition and Beneficiation capabilities	2-6	III	2007
Continuous Materials Handling Technologies Cyclic Materials Handling Technologies	all Resource Acquisition capabilities, and Beneficiation Internal Materials Handling	2, 6 6-9	II III	2020 2005
Liquid and Gas Containment Technologies	Atmospheric Gases, Underground Liquids and Gases Resource Acquisition, Internal Materials Handling	6	II	2005
Regolith & Rock Fragmentation Technologies Regolith & Rock Excavation Technologies Regolith & Rock Transport Technologies	Regolith and Rock Resource Acquisition, and Excavated Openings as Product	6 6 6	III III II	2005 2006 2005
Gas-Liquid Phase Change Technologies Solid-Gas Phase Change Technologies Solid-Liquid Phase Change Technologies Solid-Plasma Phase Change Technologies	Beneficiation Change of Phase	8 6-8 6-8 1, 8	II II II III	2010 2010 2010 ?
Solids Comminution Technologies Solids Agglomeration Technologies	Beneficiation Particle Size Change	1-6 1-6	III IV	2009 ?
Gaseous Separation Technologies Granular Solids Chemical Separation Technologies Granular Solids Physical Separation Liquid Separation Technologies	Beneficiation Separation	1-6 1-6 1-6 1-6	III III III III	2012 2009 2009 2012
Ground Stability Control Technologies Ground Stability Monitoring	Ground Stability Control Ground Stability Control, Monitoring	2, 6 6	III II	2007 2007
Soil & Rock Anchoring Technologies	Anchoring	2, 6	III	2005

Metrics for 13.1 Resource Extraction

- Performance metrics for
  - Resource Assessment:
    - Speed of data collection.
    - Speed of data analysis.
    - Accuracy of results.
    - Precision of results.
  - Resource Acquisition, Resource Beneficiation, and Site Management:
    - Material throughput (volumetric or mass flowrate).
    - Production rate of system output.
    - Equipment/system working life.
    - Mean time between component failures.

- Normalized to:
  - Launch mass required to initiate.
  - Launch mass required to maintain.
  - Power/energy requirements.
  - Human effort/time required.

- Performance sensitivity to:
  - Environmental operating conditions
  - Other operating conditions:
    - Remote-from-tech-support operation
    - Tele-operation
    - Autonomous operation

Funding in Place for 13.1 Resource Extraction

- Regolith Characterization Instrument Suite
  - USACE Cold Regions Research and Engineering Lab, Honeybee Robotics, Applied Research Assoc, University of Arizona, Los Alamos National Lab, several NASA Centers
- Lunar Construction Equipment Concepts
  - Caterpillar, Honeybee Robotics, Dartmouth College, several NASA Centers
- Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE)
  - Northern Center for Advanced Technology, Colorado School of Mines, Lockheed-Martin, Boeing, Orbitec, several NASA Centers
- ISRU for Human Exploration - Propellant Production for the Moon and Beyond
  - Lockheed-Martin
- current SBIR projects:
  - Low-energy Planetary Excavator (LPE), Orbitec
  - Sample Acquisition for Materials in Planetary Exploration (SAMPLE), Orbitec
  - Collection and Purification of Lunar Propellant Resources, Technology Applications, Inc.

Gaps and Risks for 13.1 Resource Extraction

- **Gaps:**
  - Products and target materials – better definition required:
    - Extraction method depends on detailed resource information.
    - Extraction and beneficiation also depend on detailed product specifications.
  - Current data useful only for prospecting – better resolution required.
  - Unknown mass/mission constraints – precise architecture required.
  - Lunar and martian granular materials behavior poorly understood.
  - Effects of lunar and martian environments on equipment technologies:
    - Required capabilities are common to all environments.
    - Only the technologies needed to achieve these capabilities vary.
- **Risks:**
  - Prospecting uncertainty: "You don't know what you're dealing with until you already have."
  - System reliability.
  - Effects of lunar and Mars environmental conditions.
  - Political uncertainty.
  - Terrestrial experience in resource extraction is broad and deep, but translating these capabilities to the ISRU mission is new.

ISRU Capability Element 13.2
Material Handling and Transportation

Presenter:
Kurt Sacksteder/NASA GRC
Dale Boucher/NORCAT

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Government: Other

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Industry

- Jim Richard, Northern Center for Advanced Technology
- Klaus Heiss, High Frontier
- Larry Clark, Lockheed Martin Corp.

Academia

- Leslie Gertsch, University of Missouri, Rolla
- Brad Blair, Colorado School of Mines

Description
13.2 Material Handling and Transportation

- The Material Handling and Transportation sub-element describes capabilities for the handling of native resource materials within and transportation between ISRU devices
  - Including devices for the harvesting, processing, inter-stage transfer and storage of these materials,
  - including raw and beneficiated resources, and intermediate and final product materials that may be solid, liquid, vapor or multi-phase.

- This capability addresses the challenging environments of space
  - Lunar partial gravity, hard vacuum, temperature extremes, etc.
  - Martian partial gravity, low atmospheric pressures and temperatures, wind, dust etc.
  - Asteroids, Phobos, Deimos, “micro” gravity, hard vacuum, temperature extremes.

Attributes
13.2 Material Handling and Transportation

- Short distance movement of materials using fixed devices including augers, conveyors, cranes, plumbing, pumps, etc.

- Long distance movement of materials using surface vehicles including wheeled, tracked or rail-based; flight vehicles including aircraft or rocket propelled hoppers; plus the roads or other infrastructure needed for them.

- Resource material in various stages of added value including raw resources (regolith, atmosphere, etc.) and intermediate to finished products (cryogenic propellants, I-beams, etc.); materials requiring environmentally-controlled containment; and materials whose movement may be affected by the cold/vacuum/low-gravity space environment.

- Cross platform features including power and fueling; mechanisms and container seals; sensors and artificial intelligence; and strategies for logistics and system reliability.

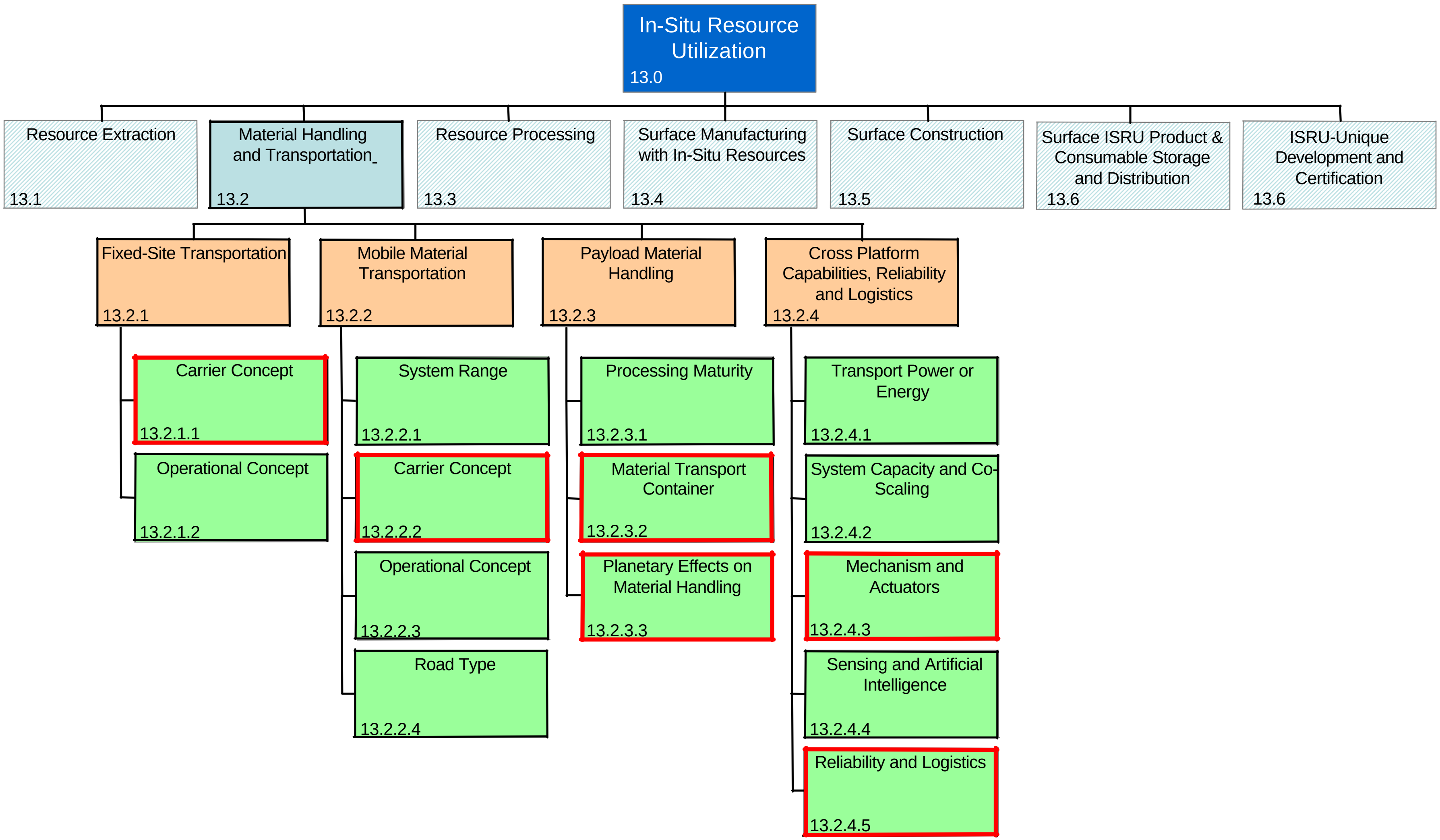
13.2 Material Handling and Transportation

The capabilities in this sub-element will enable:

- Manipulation of ISRU materials independent of the specific technology chosen for resource collection, processing, or storage.
- Collecting and processing quantities of resource materials beyond the capability of a small integrated demonstration device.
- Independent siting of resource collection, processing, storage and customer assets.
- Establishment of human or robotic operations at desirable Lunar and Martian surface locations independent of the location of essential in-situ resources.

13.2 Material Handling and Transportation CBS

Team 13: In-Situ Resource Utilization



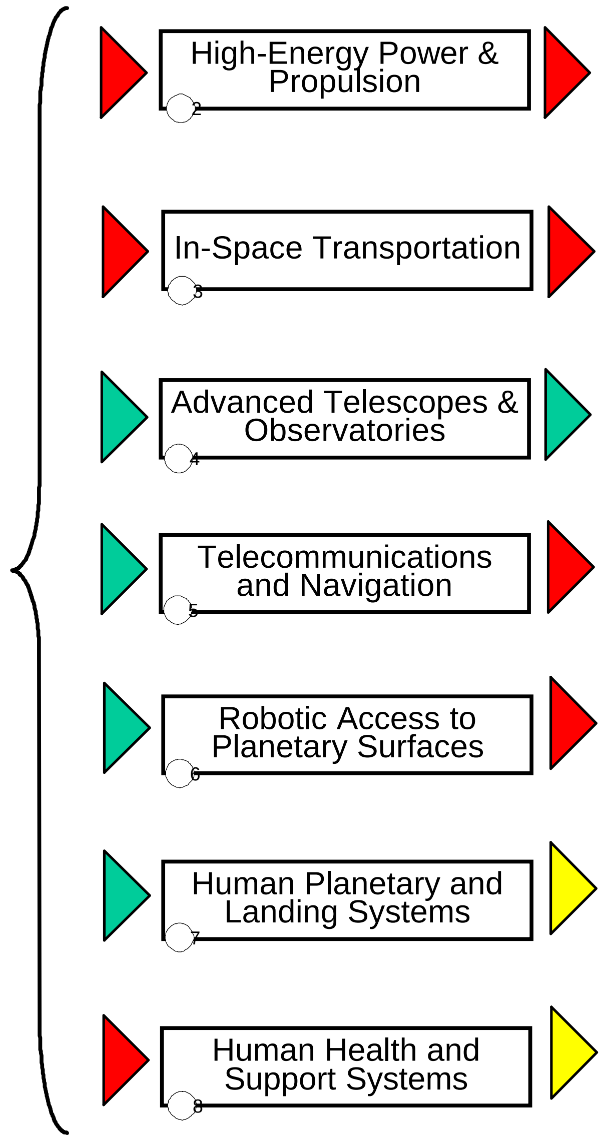
Requirements /Assumptions
13.2 Material Handling & Transportation

- Capabilities in MH&T are introduced over time according to the ISRU-Intensive Mission Architecture:
  - Demonstrations: Integrated systems – primarily material handling
  - Early operations: Material handling and local transportation
  - Later operations: Material handling and long-range transportation
- Substantial “High Energy Power…” is needed before ISRU produced surface power is available. ISRU is eventually self-sufficient, then delivers power system consumables to customers.
- Mobile transportation requires substantial “…Surface Mobility” capability for common vehicle chassis and ISRU compatible motive power.
  - MH&T provides specific functional capability on the common chassis.
  - ISRU eventually delivers fuel to surface mobility customers.
- MH&T capability includes “material handling” for other ISRU elements.
- This element supports the delivery of stored ISRU products (e.g. cryogenic propellants) in coordination with ISRU sub-element 13.6.

Material Handling and Transportation Commonality-Dependency With Other Capabilities

Products From Material Handling & Transportation

- Delivery and transfer of:
  - Propellants/oxidizer
  - Life support consumables and buffer gases
  - Fuel cell reagents
- Logistics system



Products To Material Handling & Transportation

- Power to startup short and long distance transport and environmental control in shipping containers.
- ISRU fuel compatible power/prop. sys.

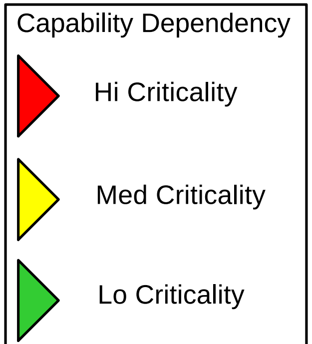
- Delivery of MH&T assets (infrastructure, parts and supplies.)
- Delivery in space of ISRU products.
- ISRU propellant compatible systems

- Vehicle location and navigation
- Low bandwidth command and control

- Pre-positioning of MH&T assets
- ISRU fuel compatible power/prop. sys

- Pre-positioning of MH&T assets
- ISRU fuel compatible power/prop. sys.

- ISRU compatible air/water/solid reclamation/recycling systems



Material Handling and Transportation Commonality-Dependency With Other Capabilities

Team 13: In-Situ Resource Utilization

Products From Material Handling & Transportation	Capability	Products To Material Handling & Transportation

• Delivery and transfer of:
  • Propellants/oxidizer
  • Life support consumables and buffer gases
  • Fuel cell reagents
• Logistics system
	Human Exploration Systems and Mobility (9)	• Reconfigurable transportation platforms compatible with ISRU Ops.
		• ISRU fuel compatible power/prop. sys.

	Autonomous Systems and Robotics (10)	• Autonomous and robotic systems for many aspects of MH&T. • ISRU fuel compatible power/prop. sys.
	Transformational Spaceport and Range (11)	• Delivery of MH&T infrastructure, parts and supplies. • ISRU fuel compatible power/prop. sys.
• Mobility and in-situ data resource	Scientific Instruments and Sensors (12)	• Transportation hazard identification. • MH&T device status/integrity (pipes, roads, rail, augers, containers, etc.)
• Models, simulations, & engineering data of material behavior in low temperature/ pressure/ gravity • Logistics of terrestrial MH&T system operations	Advanced Modeling, Simulation, & Analysis (14)	• Model/simulate material behavior in low temperature/pressure/gravity (granular media, multiphase fluid, etc.) • Logistics of MH&T system operations
	Systems Engineering Cost & Risk Analysis (15)	• Strategies for scaling up operation capability
	Nanotechnology and Advanced Concepts (16)	• Low temp/press lubricants

Material Handling and Transportation Interdependency with other ISRU Elements

Team 13: In-Situ Resource Utilization

ISRU Element Products To Material Handling and Transportation

Resource Extraction
- Material Handling and Transportation Requirements
- Compatible Material Transfer Interfaces

Resource Processing
- Material Handling and Transportation Requirements
- Compatible Material Transfer Interfaces

Surface Manufacturing
- Spare parts

Surface Construction
- Road Building
- Infrastructure

Product Storage & Distribution
- Cryogenic Fluid Transportation Containment and Equipment
- Compatible Material Transfer Interfaces

Unique Development and Certification
- Equipment/system performance tests in relevant environments

Material Handling and Transportation

- Fixed Site Transportation
- Mobile Material Transportation
- Payload Material Handling
- Cross Platform Capabilities, Reliability and Logistics

Products From Material Handling and Transportation

Resource Extraction
- Material Handling Capability
- Delivery of extracted feedstock

Resource Processing
- Material Handling Capability
- Delivery of Processing Feedstock
- Delivery of Processing Products

Surface Manufacturing
- Delivery of Manufacturing Feedstock
- Delivery of Manufactured Products

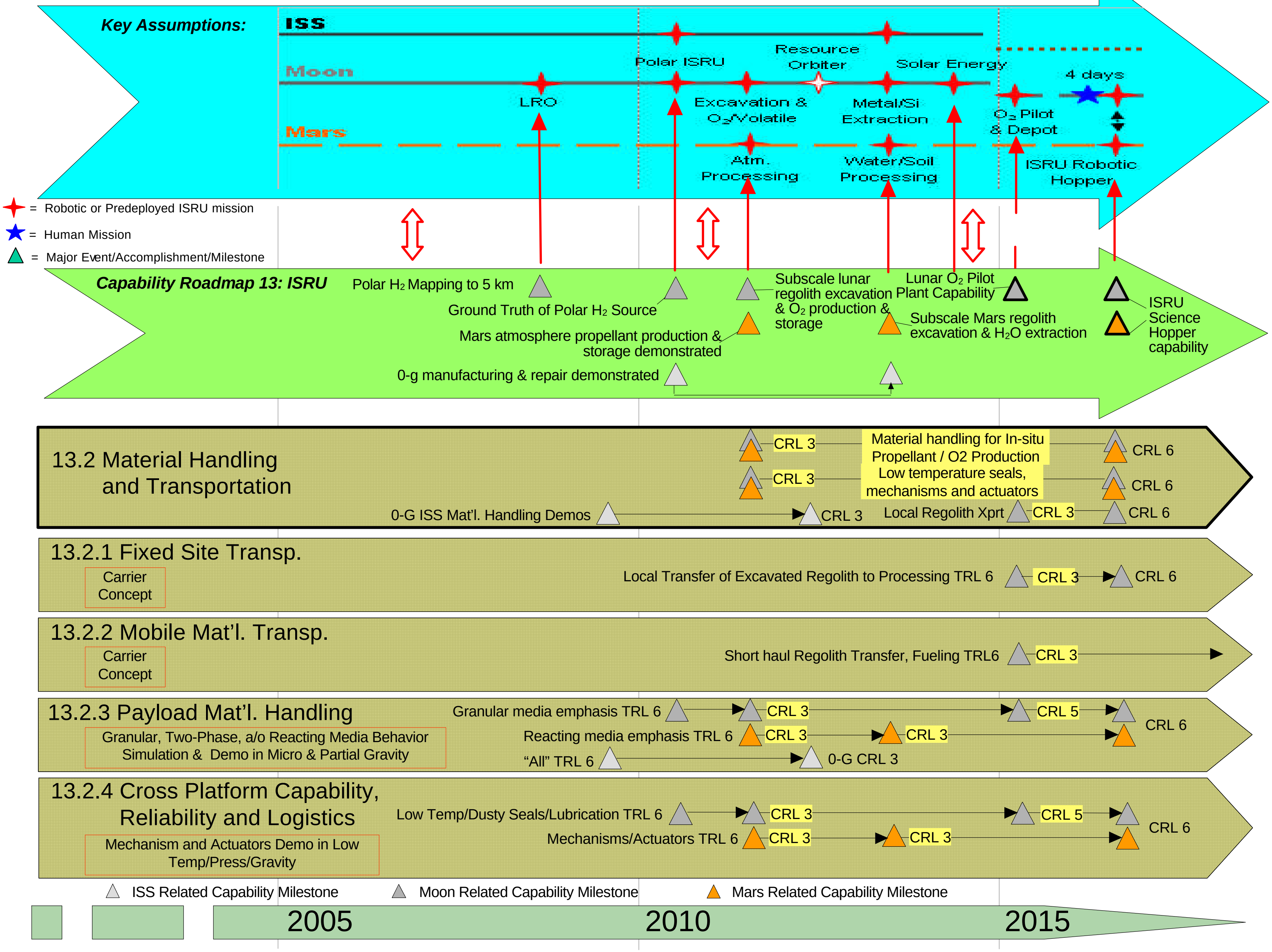
Surface Construction
- Delivery of Construction Feedstock

Product Storage & Distribution
- ISRU product delivery to storage
- Mobile product delivery to user

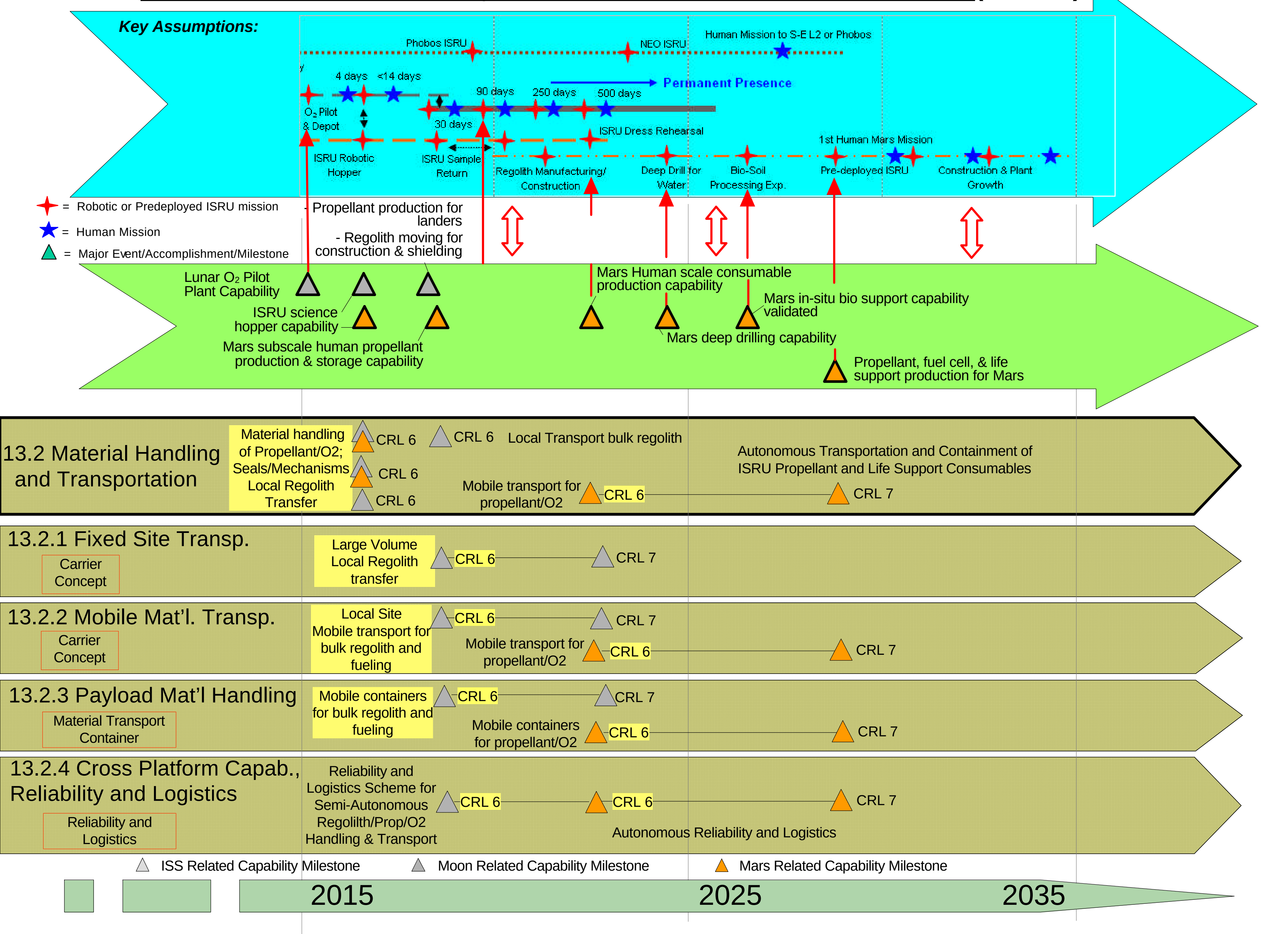
Unique Development and Certification
- Testing Requirements

All ISRU Elements
- ISRU Resource and Product Logistics
- Fuel, supplies and parts delivery

13.2: (ISRU) Material Handling and Transportation Capability Roadmap (2005-16)



13.2: (ISRU) Material Handling and Transportation Capability Roadmap (2005-16)



Current State of the Art:
13.2 Material Handling & Transportation

- Extra-terrestrial experience in handling and transporting native materials is very limited:
  - Apollo samples were manually manipulated for encapsulation and return to Earth. Considerable problems with dust and seals stays.
  - Some Apollo samples were transported in small containers aboard the Lunar rover vehicle.
  - Martian surface samples were/are robotically manipulated for limited analysis and disposal, Viking, MER, etc.

- Terrestrial experience in material handling is ubiquitous, but translating these capabilities to the ISRU mission is outside existing knowledge:
  - Terrestrial handling of granular media is largely empirical and may not be scalable – reduced gravity, temperature and pressure; abrasive lunar regolith will amplify the uncertainties.
  - Technology for handling materials in ways that would be affected by the gravity level (e.g. multi-phase and non-isothermal fluids) has been largely avoided in space-based systems.
  - Operational approach to power consumption, reliability, logistics, etc. requires blending terrestrial experience with space realities.

Maturity Level
13.2 Material Handling and Transportation

Capability		Key Technology or Sub-Capability		Capability Readiness Assessment		
				CRL	R&D3	Need Date
13.2.1	Fixed-Site Transportation	13.2.1.1	Carrier Concept	0-1	III	2018
		13.2.1.2	Operational Concepts	0-1	III	2018
13.2.2	Mobile Material Transportation	13.2.2.1	System Range	0-1	II	2018
		13.2.2.2	Carrier Concept	0-1	III	2018
		13.2.2.3	Operational Concepts	0-1	III	2018
		13.2.2.4	Road Types	0-1	II	2018
13.2.3	Payload Material Handling	13.2.3.1	Processing Maturity	0-1	II	2012 - 2018
		13.2.3.2	Material Transport Containers	0-1	III	2016
		13.2.3.3	"Planetary" Effects on Material Handling	0-1	IV	2012
13.2.4	Cross Platform Capabilities, Reliability, Logistics	13.2.4.1	Transportation Power or Energy	0-1	II	2016
		13.2.4.2	System Capacity and Co-Scaling	0-1	II	2018
		13.2.4.3	Mechanisms and Actuators	0-1	IV	2012
		13.2.4.4	Sensing and Artificial Intelligence	0-1	III	2012 2018
		13.2.4.5	Reliability and Logistics	0-1	II	2018

Maturity Level
13.2 Material Handling and Transportation

Capability	Sub Capability		Key Technology or Sub-Capability		Capability Readiness Assessment		
					CRL	R&D3	Need Date
Fixed-Site Transportation	13.2.1.1	Carrier Concept	13.2.1.1.1	Conveyers	0-1	III	2018
			13.2.1.1.2	Augers	0-1	III	2018
			13.2.1.1.3	Pipes/Plumbing/Pumps	1	III	2014
			13.2.1.1.4	Crane	0-1	III	2018
	13.2.1.2	Operational Concepts	13.2.1.2.1	Human directed, in situ	0-1	III	2024
			13.2.1.2.2	Human directed, remote	0-1	III	2016
			13.2.1.2.3	Semi-autonomous	0-1	III	2024
			13.2.1.2.4	Fully autonomous	0-1	III	2024
Mobile Material Transportation	13.2.2.1	System Range	13.2.2.1.1	Planetary (pole to equator)	0-1	IV	>2030
			13.2.2.1.2	Site (20 km)	0-1	III	2018
			13.2.2.1.3	Plant (200 m)	0-1	III	2018
			13.2.2.1.4	Short-Haul (20 m)	0-1	II	2016
	13.2.2.2	Carrier Concept	13.2.2.2.1	Surface Vehicles	0-1	III	2024
			13.2.2.2.2	Flight Vehicles	0-1	IV	2030
	13.2.2.3	Operational Concepts	13.2.2.3.1	Human directed in situ	0-1	III	2024
			13.2.2.3.2	Human directed, remote	0-1	III	2024
			13.2.2.3.3	Semi-autonomous	0-1	III	2024
			13.2.2.3.4	Fully-autonomous	0-1	III	2024
	13.2.2.4	Road Types	13.2.2.4.1	Unimproved Terrain	0-1	II	2018
			13.2.2.4.2	Improved Road	0-1	III	2024

Maturity Level
13.2 Material Handling and Transportation

Capability	Sub Capability		Key Technology or Sub-Capability		Capability Readiness Assessment		
					CRL	R&D3	Need Date
Payload Material Handling	13.2.3.1	Processing Maturity	13.2.3.1.1	Raw Resource	0-1	II	2018
			13.2.3.1.2	Beneficiated Resource	0-1	II	2018
			13.2.3.1.3	Processed Consumable or Feedstock	0-1	II	2018
			13.2.3.1.4	Finished Products	0-1	II	2024
			13.2.3.1.5	Waste or Recyclable Material	0-1	II	2024
	13.2.3.2	Material Transport Containers	13.2.3.2.1	Open to environment	0-1	III	2018
			13.2.3.2.2	Enclosed/sealed	0-1	III	2018
	13.2.3.3	"Planetary" Effects on Material Handling	13.2.3.3.1	Gravitational Buoyancy	0-1	IV	2012
			13.2.3.3.2	Flow and stability of granular media	0-1	IV	2012
			13.2.3.3.3	Material properties in extreme environments	0-1	IV	2012

Maturity Level
13.2 Material Handling and Transportation

Capability	Sub Capability		Key Technology or Sub-Capability		Capability Readiness Assessment		
					CRL	R&D3	Need Date
Cross Platform Capabilities, Reliability, Logistics	13.2.4.1	Transportation Power or Energy	13.2.4.1.1	Power or Energy Loads	1	II	2012
			13.2.4.1.2	Power or Energy Sources	1	III	2012
			13.2.4.1.3	Waste Power or Energy	0-1	III	2024
			13.2.4.1.4	Duty Cycle	0-1	II	2016
	13.2.4.2	System Capacity and Co-Scaling	13.2.4.2.1	Capacity Growth with other Sub Elements	0-1	II	2016
			13.2.4.2.2	Scale-Up Extrapolations	0-1	IV	2016 2024
	13.2.4.3	Mechanisms and Actuators	13.2.4.3.1	Prime movers, motors, pumps	0-1	III	2014
			13.2.4.3.2	Material or container loading and unloading	0-1	II	2018
			13.2.4.3.3	Wheels, tracks, conveyors, cranes	0-1	III	2018
			13.2.4.3.4	Steering	0-1	III	2024
			13.2.4.3.5	Seals	0-1	IV	2012
			13.2.4.3.6	Lubrication	0-1	IV	2012
	13.2.4.4	Sensing and Artificial Intelligence	13.2.4.4.1	State Sensing	0-1	III	2012 2024
			13.2.4.4.2	Artificial Intelligence and Autonomy	0-1	IV	2024
	13.2.4.5	Reliability and Logistics	13.2.4.5.1	Dust related issues	0-1	IV	2016
			13.2.4.5.2	Mechanical cycling	0-1	II	2016
			13.2.4.5.3	Seals	0-1	II	2016
			13.2.4.5.4	Overloading	0-1	II	2016
			13.2.4.5.5	Vehicle mass versus durability	0-1	II	2016
			13.2.4.5.6	Payload Material/Product Flow Logistics	0-1	III	2016
			13.2.4.5.7	Fueling Logistics	0-1	II	2016
			13.2.4.5.8	Maintenance and Repair strategy	0-1	IV	2016

Metrics
13.2 Material Handling and Transportation

- MH&T Capability meets quantitative requirements of customers, e.g:
  - ISRU: Resource Extraction, Resource Processing, and Resource Storage and Distribution (Mass throughput, reliability, etc.)
  - Other: High Energy Power/Prop, Human Exploration/Surface Mobility, Robotic Systems
- Function and Reliability in the space environment
  - Redundancies established at the parts through system levels by the time of pilot plant capability demonstration
  - Mean failure rate less frequent than Earth replacement possibility
  - Power consumption less than 10% of total ISRU system in place
  - Capacity growth ahead of Resource Extraction growth
  - Logistics and Reliability system capability is semi autonomous by the time of pilot plant capability demonstration
- MH&T systems meet Total Throughput Mass/System Mass targets
  - <1 for early demonstrations
  - 10x for pilot plant demonstrations
  - 1000's x for operational systems

Each of these metrics is measurable directly or in comparison with parallel capability developments

Funding in Place
13.2 Material Handling and Transportation

- Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE)
  - Integrated material handling demonstration
- ISRU excavation project
  - Integrated material handling demonstration
- Dust Mitigation
  - Characterization and mitigation of very small regolith particles
- Isolated studies from the former NASA Physical Sciences Division
  - Characterizations of reacting systems, multi-phase flows, and granular media behavior in variable gravity environments.

Gaps, Risks and Strategies
13.2 Material Handling and Transportation

- The principal gaps in MH&T capability stem from the fact that material handling techniques in the Lunar/Martian environment cannot be extrapolated from extensive Terrestrial experience:
  - Handling of granular media in terrestrial environments is accomplished by engineering based largely upon experience, not fundamental principles.
  - Processes involving multi-phase, non-isothermal, or reacting fluids are affected by changes in gravitation level in ways that are predictable in only a few limited cases.
  - Energy intensive thermal and chemical processes requiring reliable mechanisms, seals, etc. have not been demonstrated.
- It follows that the principal risks lie in development efforts limited to Terrestrial environments which may lead to failures in deployed systems designed to operate autonomously for extended periods.
- A risk mitigating strategy requires early effort to establish fundamentally based design guidance for the operational environment.

ISRU Capability Element 13.3
Resource Processing

Interim Roadmap Status Report

Presenter:

William E. Larson

Resource Processing Roadmap Team

Co-Chairs

NASA: William E. Larson, NASA
External: D. Larry Clark , Lockheed Martin Astronautics

NASA

- Tom Cable
- Bob Green
- Chi Lee
- Diane Linne
- Dr. Dale E. Lueck
- Dr. Clyde Parrish
- Margaret Proctor
- Kurt Sacksteder
- Tom Simon
- Stephen Sofie
- Dr. Bruce Steinetz
- Tom Tomsik
- Judy Yen

Industry

- Ed McCullough, Boeing
- Eric Rice, Orbitec
- Dr. Laurent Sibille, BAE Systems
- Dale Taylor, Jim Steppan, Ceramatec
- Robert Zubrin, Pioneer Astronautics

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- Dr. Robert Ash, Old Dominion University
- Brad Blair, Colorado School of Mines
- Kriston Brooks, Battelle Memorial Institute
- Dr. Christine Iacomini, University of Arizona
- David C. Lynch, Sc.D, University of Arizona

Capability 13.3: Resource Processing

- Resource Processing Is The Set Of Capabilities Needed To Convert Raw Materials Found At An Exploration Destination In To Usable Products.
- Three Product Classes
  - Mission Consumables (e.g.. Oxygen, Fuel, Purified Water, Fertilizer…)
  - Feedstock for Manufacturing (e.g. Metals, Silicon, Plastics…)
  - Feedstock for Construction (e.g. Bricks, Glass, Fiberglass…)
- Resource Processing Receives It's Raw Materials From The Extraction And Transportation Elements.
- Resource Processing Will Deliver It's Finished Products To Either The Storage And Distribution (gases/liquids) Or Transportation Elements (barstock, I-beams, powdered metals)

Benefits of Resource Processing

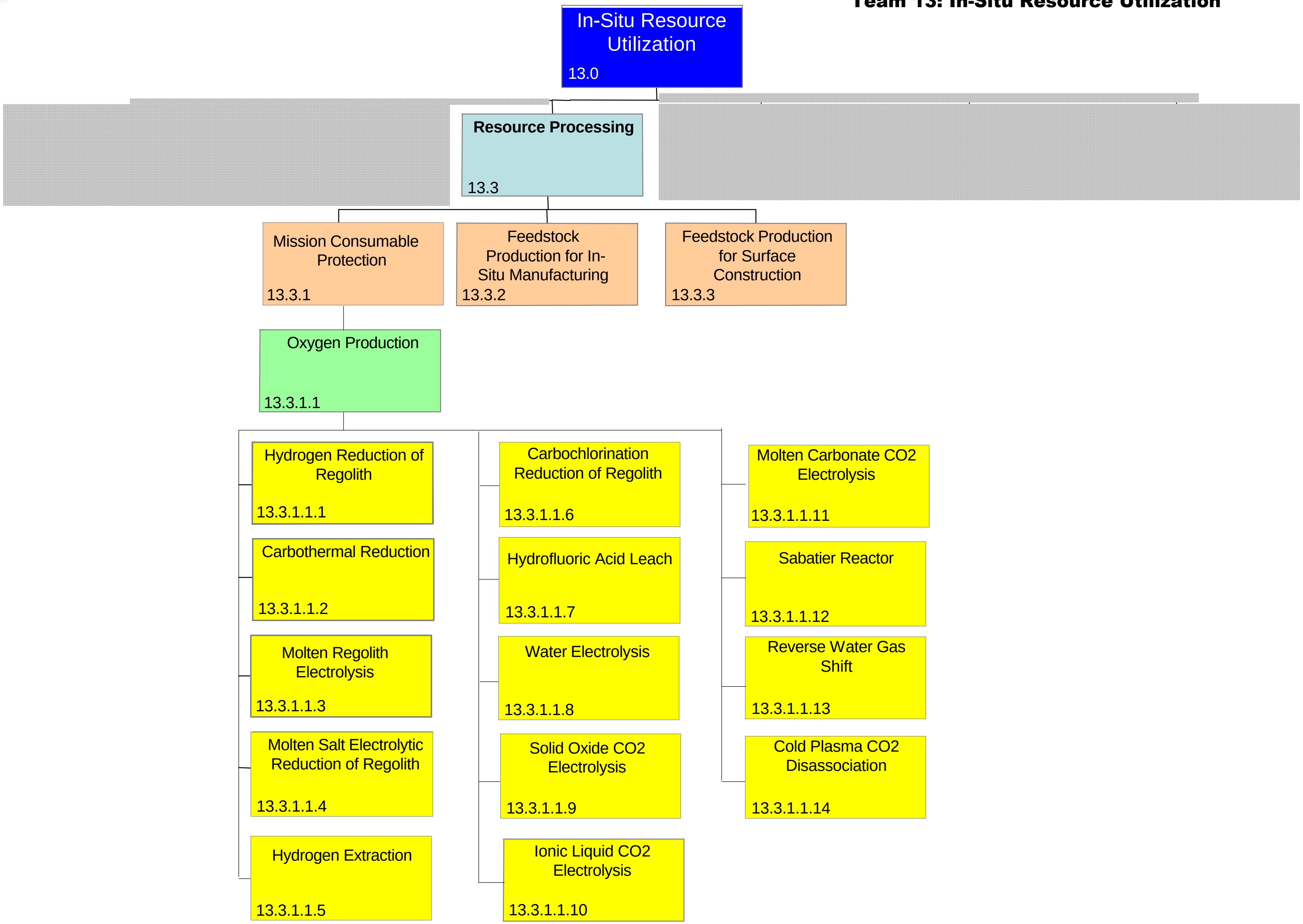
- Consumable Production Provides The Exploration Mission Significant Mass Savings.
  - Propellant and Oxygen Production Reduces Mass Between 3.5:1 And 5:1 On Human Mars Mission Depending On The Architecture.
  - e.g. ISS Required <u>2250 kg of Water This Year</u> To Provide Oxygen to Breathe And Water To Drink For An Average Crew Of 2.5
- Consumable Production Provides Overall Program Cost Reduction
  - Reduced Size Of Launch Vehicle Or Reduced Number Of Launches
  - Allows For The Development Of Reusable Transportation Assets
- Consumable Production Long Duration Robust Surface Mission Mobility
  - O2/H2 Production Allows Use Of Fuel Cell-based Refuelable Rovers
  - Habitat Life Support
- Provides An In-Situ Source Of Feedstocks For Manufacturing
  - Reduces Earth-based Logistics & Improves Safety.
- Enables Architectures That Would Otherwise Be Unattainable
- Enables Space Commercialization

Resource Processing

- In-Situ Resource Utilization 13.0
  - **Resource Processing** 13.3
    - Mission Consumable Production 13.3.1
      - **Oxygen Production** 13.3.1.1
      - **Propellant & Fuel Cell Reagent Production** 13.3.1.2 thru 13.3.1.8
      - Water Purification 13.3.1.9
      - Buffer & Science Gas Production 13.3.1.10 & 13.3.1.11
      - Bio-Support Feedstock Production 13.3.1.12
    - Feedstock Production for In-Situ Manufacturing 13.3.2
      - Chemical Regolith Beneficiation & Carbon Production 13.3.2.1 & 13.3.2.2
      - Metal Feedstock Production (iron, aluminum, alloys, etc..) 13.3.2.3 thru 13.3.2.5
      - Glass/Ceramic Feedstock Production (Silicon) 13.3.2.6 thru 13.3.2.8
      - Polymer/Plastic Feedstock Production 13.3.2.9
    - Feedstock Production for Surface Construction 13.3.3
      - Concrete/Bricks 13.3.3.1
      - Fiberglass 13.3.3.2
    - Common Critical Components 13.3.4

Resource Processing

Team 13: In-Situ Resource Utilization



Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov

Team Assumptions for Resource Processing

- Reusable Landers Will Land “Empty” And Be Refueled On The Surface
- Surface Mobility Systems Will Utilize In-Situ Produced Fuel Cells Reagents
- Long Term Missions Will Require The Production Of Manufacturing Feedstocks
- Permanent Presence On Other Planetary Bodies Will Require The In-Situ Production Of Construction Materials
- ISRU Systems Will Generally Be Predeployed By Robotic Missions And Will Operate Autonomously For Up to 500 days
- Robotic Mars Sample Return Missions (Direct Earth Return) Will Require The Production Of 1500kg Of Propellant
- Robotic Mars Sample Return (Orbital Rendezvous) Require 300kg Of Propellant
- Human Lunar Ascent Vehicles Will Require 20-30 Metric Tons Of Propellant
- Human Mars Ascents Vehicles Will Require ~50 Metric Tons Of Propellant
- Power systems will be available to supply the needs of ISRU systems even in the permanently shadowed craters of the moon.

Resource Processing Interdependency with other Capabilities

Team 13: In-Situ Resource Utilization

Products From Resource Processing	Capability	Capability Products To Resource Processing
• Propellant production • Fuel Cell Reagents	High-Energy Power & Propulsion	• Solar & nuclear power to support power-intensive ISRU activities
• Propellant production and pressurant/purge gases for lander reuse and in-space depots	In-Space Transportation	• ISRU-compatible propulsion • Electromagnetic launch systems for delivery of ISRU products
• Gases for Inflatable Structures	Advanced Telescopes & Observatories	
• Production of fuel cell reagents for rovers (vs solar arrays or RTGs for certain missions) • Propellant production for surface hoppers or large sample return missions	Robotic Access to Planetary Surfaces	• Pre-positioning & activation of ISRU assets
• Materials for Landing pads/plume debris shielding • Propellant production for lander reuse	Human Planetary Landing Systems	• Delivery of ISRU capabilities to sites of exploration

Resource Processing Interdependency with other Capabilities

Team 13: In-Situ Resource Utilization

Products From Resource Processing	Capability	Capability Products To Resource Processing
• Gases for inflation & buffer gases • Life support consumable production for backup • Fertilizer for plant growth • Materials for in-situ manufacturing	Human Health and Support Systems (8)	• Carbon-based waste products as resource for ISRU
• O_2 production for EVA & Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots	Human Exploration Systems & Mobility (9)	• Crew/robotics/rovers to perform ISRU surface activities
• Propellants & fuel cell reactants for surface vehicles	Autonomous Systems & Robotics (10)	• ISRU Compatable Robots/rovers Software & FD&R logic for autonomous operation
	Scientific Instruments & Sensors (12)	• Resource location & characterization information • Self Calibrating or Extended Calibration Life Sensors
	Nano-Technology (16)	• Nanotube catalysts for Microchemical Reactors

Resource Processing Interdependency with other ISRU Elements

Team 13: In-Situ Resource Utilization

ISRU Element Products To

Resource Extraction
- Regolith Excavation & Physical Beneficiation
- Regolith Volatiles Collection & Separation
- Atmospheric Gas Acquisition & Separation

Resource Transportation
- Surface mobility systems platforms for Raw Resource Transportation
- Surface mobility systems for Finished Product Utilization
- Surface mobility systems for Resource Processing "Waste" removal.

Surface Manufacturing w/In-Situ Resources
- Spare Parts for Resource Processing Systems
- Energy From PV Arrays

Product Storage & Distribution
- Stored Gases/Liquids as inputs to Resource Processing

Resource Processing

- Consumables
- Manufacturing Feedstock
- Construction Feedstock

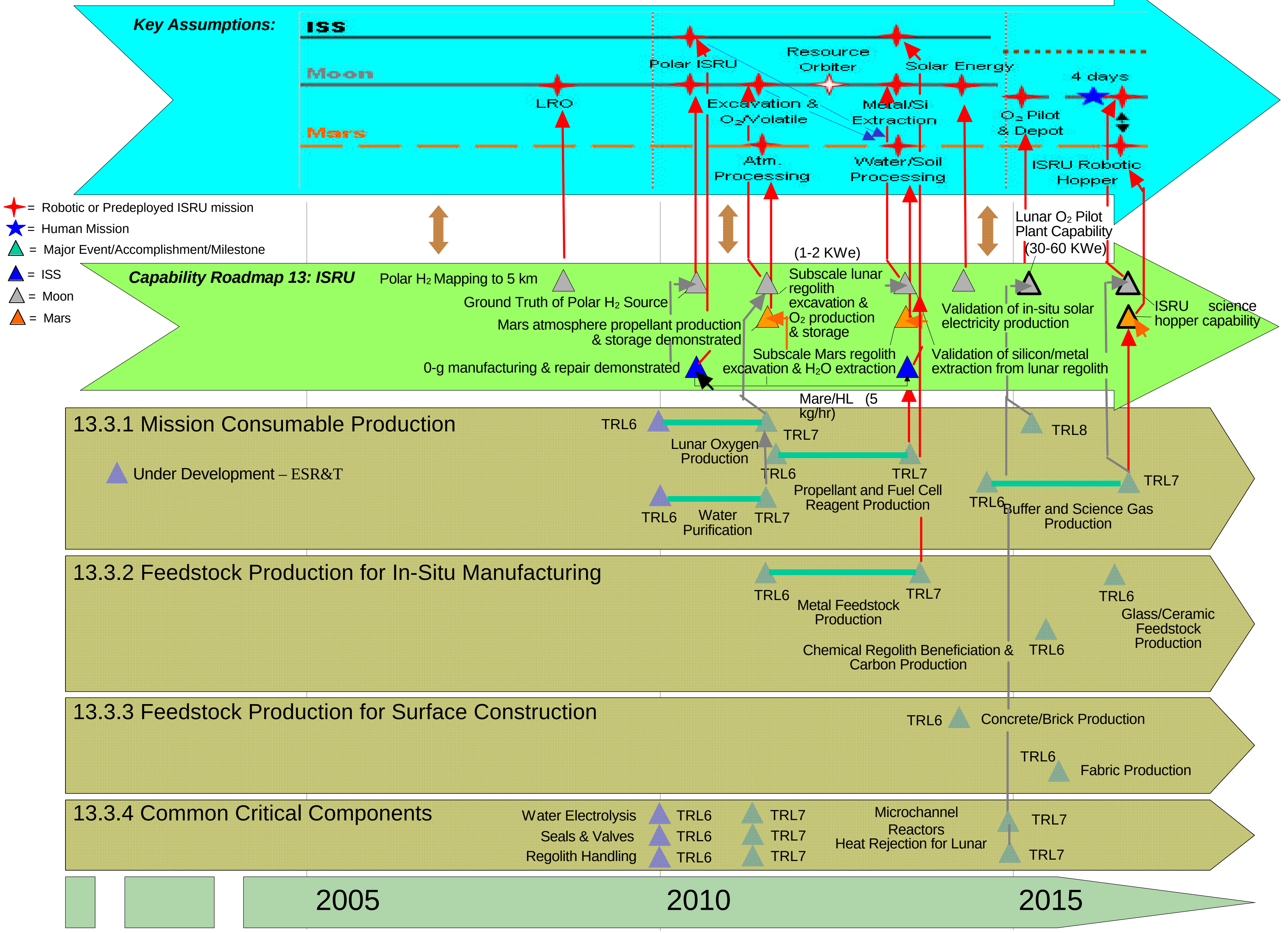
Products From Resource Processing

Product Storage & Distribution
- Oxygen for Life Support
- Oxygen for Propulsion
- Oxygen for Fuel Cells
- Fuels for Propulsion
- Hydrogen/Methane for Fuel Cells
- Buffer Gasses for Life Support
- Water for Life Support
- Ammonia for Cooling Systems

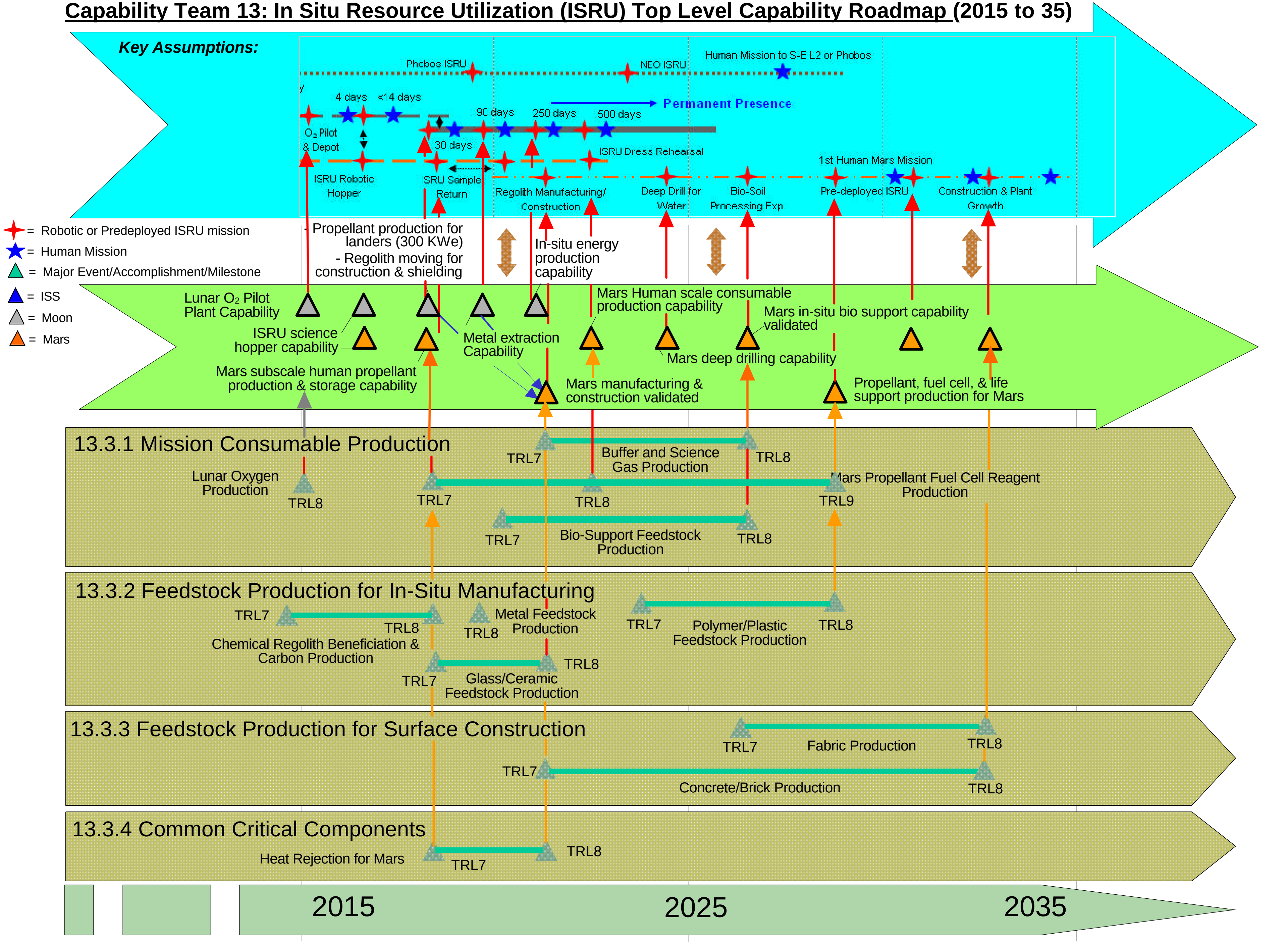
Surface Manufacturing w/ In-Situ
- Iron, Carbon Steel, Titanium & Aluminum for Manufacturing
- Carbon
- Plastics for Parts Manufacture
- Silicon for Electronics and Photovoltaic Arrays
- Glass for PV arrays

Surface Construction
- Ceramics for Construction Materials Fab (e.g. Bricks)
- Iron, Aluminum, and Steel for Habitat Construction
- Fiberglass for Composite Construction Materials
- Slag for Bricks
- Slag for Habitat Radiation Protection
- Slag for Nuclear Reactor Shielding

Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2005 to 16)



Capability Team 13: In Situ Resource Utilization (ISRU) Top Level Capability Roadmap (2015 to 35)



Current State-of-the-Art for Resource Processing

- Lunar ISRU Has A 30 Year History Of Laboratory Testing, But Little Development Money For Systems Level Development.
  - Majority Of Historical Work Is In O2 Production With Metals As A Byproduct Current TRL Is 3 At Best.
  - Reasonable Amount Of Research Has Been Conducted In The Production Of Silicon For Photovoltaic Arrays And Ceramics For Manufacturing But TRL For A Lunar Environment Still Low.

- Mars ISRU Has Had More Development Over The Last Decade But Focus Has Been Atmospheric Processing
  - O2 & Fuel Production CRL Estimate is between 2 and 3.
  - Several Technologies Have Been Developed As Sample Return-Scale Breadboards
    - RWGS, Sabatier, Solid Oxide Electrolysis, Methanol, Benzene
  - One Flight Experiment Has Been Developed, But Has Not Yet Flown
    - Mars In-Situ Propellant Production Precursor
  - Mars Metals Production At A Very Low TRL, But Will Share Reasonable Commonality with Lunar ISRU.

Maturity Level – Capabilities for Resource Processing

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assesment		
		CRL	R&D3	Need Date
Mission Consumables Production	*Oxygen Production*	3	*Mars I, Moon III*	Mars & Moon 2012
	Methane Production	3	*Mars I, Moon IV*	Mars 2012, Moon 2016
	Hydrogen Production	3	*Mars I, Moon III*	2016
	Powdered Metals for Propulsion	1	*IV*	2016
	Ethylene Production	2	*II*	Mars 2012, Moon 2016
	Methanol Production	2	*I*	Mars 2012, Moon 2016
	Carbon Monoxide Production	3	*I*	Mars 2012, Moon 2020
	Ammonia Production	1	*II*	Mars 2020 ?
	Water Purification	3	*I*	2014
	Nitrogen Production	3	*Mars I, Moon IV*	Mars 2012, Moon 2016
	Argon Production	3	*Mars I, Moon IV*	Mars 2012, Moon N/A
	Fertilizer Production	1	*Mars II, Moon III*	Mars 2020
Feedstock for Manufacturing	Carbon Production	2	*II*	Mars
	Iron & Iron Alloys	1-2	*III*	Moon 2014, Mars 2020
	Titanium Alloys	2	*III*	Moon 2014, Mars 2020
	Aluminum Alloys	2	*III*	Moon 2014, Mars 2020
	Silicon	3	*III*	Moon 2014, Mars 2020
	Glass	2	*I*	Moon 2014, Mars 2020
	Ceramics	2	*I*	Moon 2014, Mars 2020
	Plastics	1	*V*	2020?

Maturity Level – Capabilities for Resource Processing

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assesment		
		CRL	R&D3	Need Date
Feedstock for Construction	Concrete	2	*II*	Moon 2020
	Slag	2	*I*	2014
	Fabric	2	*II*	2020
Common Critical Components	Reaction Chamber Seals for High Vacuum, Dusty Environments	1	*III*	2012
	Product Shaping (Ingots, Bar Stock, Powdered Metal	1	*III*	2014
	High Efficiency Gas Separation	3	*III*	2012
	Hydrogen Drying	1	*I*	2016
	Oxygen Purification	1	*I*	2016

Maturity Level – Technologies Resource Processing

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Hydrogen Reduction of ilmenite	*Oxygen Production, Iron Production*	*Oxygen 4, Iron 3*	*Oxygen II, Iron III*	*O2 2012, Iron 2014*
Carbothermal Reduction of	*Oxygen Production, Iron Production*	*Oxygen 4, Iron 3*	*Oxygen II, Iron III*	*O2 2012, Iron 2014*
Molten Regolith Electrolysis	*Oxygen & Metal Production*	*2*	*V*	*O2 2012, Metal 2014*
Molten Salt Electrolytic Reduction of Regolith	*Oxygen, Iron, Aluminum, Titanium, Silicon Production*	*4*	*II*	*O2 2012, Metal 2014*
Carbochlorination reduction of anorthite and ilmenite	*Oxygen Production*	*2*	*IV*	*2012*
Hydrofloric Acid Leach	*Oxygen Iron, Silicon, Aluminum, Titanium & Glass Production*	*3*	*III*	*O2 2012, Metal 2014*
Solid Oxide CO2 Electrolysis	*Oxygen & Carbon Monoxide Production*	*4*	*III*	*2012*
Ionic Liquid CO2 Electrolysis	*Oxygen, Carbon Monoxide & Carbon Production*	*1*	*IV*	*2012*
Molten Carbonate CO2 Electrolysis	*Oxygen, Carbon Monoxide & Carbon Production*	*3*	*IV*	*2012*
Cold Plasma CO2 Disassociation	*Oxygen, Carbon Monoxide Production*	*3*	*II*	*2012*
Sabatier Reactor	*Oxygen & Methane Production*	*5*	*I*	*2012*
Reverse Water Gas Shift	*Oxygen, Water & Carbon Monoxide Production*	*4*	*II*	*2012*
Hydrocarbon Reformer	*Hydrogen Production*	*4*	*I*	*2012*
Liquid Water Electrolysis	*Oxygen Production*	*9*	*I*	*2012*
Gas Phase H20 Electrolysis	*Oxygen Production*	*5*	*II*	*2012*
Methanol Reactor	*Methanol Production*	*4*	*II*	*2012*
Fischer-Tropsch Reator	*Ethylene & Plastics Production*	*3*	*IV*	*Ethylene 2012, Plastics 2030*

Maturity Level – Technologies Resource Processing

Team 13: In-Situ Resource Utilization

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Haber Process	*Ammonia Production*	*4*	*II*	*2025*
Particulate Removal	*Water Purification*	*9*	*I*	*2015*
Deionization Bed	*Water Purification*	*9*	*I*	*2015*
Electrodialysis (Deionization)	*Water Purification*	*6*	*I*	*2015*
Distillation	*Water Purification*	*9*	*I*	*2015*
Hydrate Adsorption/Desorption	*Water Purification*	*7*	*I*	*2015*
Reverse Osmosis	*Water Purification*	*6*	*I*	*2015*
Ammonia Decomposition	*Nitrogen/Hydrogen Production*	*4*	*II*	*201*
Gas Separation Membranes	*Nitrogen, Argon & Carbon Monoxide Production*	*4*	*III*	*2012*
Cryogenic Gas Separation	*Nitrogen, Argon & Carbon Dioxide Production*	*4*	*II*	*2012*
Adsorption Gas Separation	*Nitrogen, Argon & Carbon Dioxide Production*	*4*	*II*	*2012*
Ammonia-based Fertilizer	*Fertilizer Production*	*4*	*II*	*2025*
Urea-based Fertilizer	*Fertilizer Production*	*4*	*II*	*2025*
Oxides of Nitrogen Fertilizer	*Fertilizer Production*	*4*	*II*	*2025*
Potassium-based	*Fertilizer Production*	*2*	*III*	*2025*
Phosphorus-based	*Fertilizer Production*	*2*	*III*	*2025*
Catalytic Decomposition of CO	*Carbon Production*	*2*	*III*	*2025*
Hydrochloric Acid Leach	*Iron, Aluminum, Silicon, Glass*	*4*	*II*	*2014*

Metrics for Resource Processing

- Summary of Resource Processing Metrics For Technology Trades
  - Rate of Production
  - Power Consumed vs. Mass of Product Produced
  - Mass of System vs. Mass of Product Produced
  - Mean Time Between Failure
  - Degree of System Autonomy
  - Reagent Recycling Near or At 100%

- Summary of Progress Metrics
  - All Component Technologies Are At TRL 4 At Least 6 Years Prior To Need Date
  - All Component Technologies Reach TRL 6 At Least 3 Years Prior To Need Date
  - Continuous Operation for 30 days 5 years before need date.
  - Continuous, Autonomous Operations in an Mission Simulated Environment for 1 year, 3 years before need date

Current Resource Processing Projects

- Microchannel In Situ Propellant Production System,
  - Battelle Memorial Institute, Richland, Washington
  - NASA: JSC, GRC; Oregon St. Univ., Colorado School of Mines
  - Methane and Oxygen Production from CO2
- ILMENOX,
  - British Titanium, London, England,
  - NASA: KSC; Florida Institute of Technology (FIT)
  - Oxygen Production from Lunar Regolith
- Integrated In-Situ Resource Utilization for Human Exploration – Propellant Production for the Moon and Beyond,
  - Lockheed Martin Astronautics, Littleton, Colorado
  - NASA:JSC, GRC, KSC; Hamilton Sunstrand, CO School of Mines, FIT, ORBITEC
- RESOLVE: Development of a Regolith Extraction & Resource Separation & Characterization Experiment for the 2009/2010 Lunar Lander,
  - NASA JSC, KSC, GRC, JPL; CO School of Mines, NORCAT, Boeing, ORBITEC
  - Lunar Oxygen Production & Hydrogen Extraction Experiment
    - Also supports Resource Extraction Sub-element

Technology Gaps for Resource Processing

- Reduction Of System Size, Microchannel Reactors Seem To Hold Great Promise
- Solid Oxide Electrolysis Of CO2 Struggles With Temperature Cycling Issues, Development A Workable Seal Between The Cell Stacks Is A Challenge That Must Be Met
- Systems Require The Development Of Seals That Can Work Repeatedly In A Low Temperature, High Vacuum, Abrasive Dust Environment.
- Many Of The Processes Involve Molten Materials, Designs To Handle This Molten Material Autonomously Are Not Trivial Exercises
- Improved Energy Efficiencies
- Understanding Of Reduced Gravity Effects On Processes
- Mixed Gas Stream Separation
- Chunks Of Pure Metals Have Been Produced, But They Are “Frozen” In The Slag, Not Separated Out.
- Significant Work Remains To Develop The Integrated Systems That Will Produce Final Feedstocks

Capability Development Strategy

- There Is No One "Best Solution" For Resource Processing.
  - One Technology May Trade Better Than Another Depending On The Architecture
- As Architecture Options Mature Trade Studies Will Be Used To Down Select To A Set Of Technologies That Have The Potential Meet Mission Requirements.
- These Technologies Will Be Developed To TRL 5 And Another Down Selection Will Occur.
  - Performance Metrics And Mission Requirements Will Be The Determining Factor.
- The Suite Of Technologies Will Be Flight Tested On Robotic Precursor Missions To Validate The Capabilities Readiness For Insertion Into The Critical Path For Human Missions.

Surface Manufacturing with In Situ Resources Element: ISRU Capability Roadmap Progress Review

Peter A. Curreri - NASA Lead
Edward D. McCullough – Boeing, External Lead
April 12, 2005

Surface Manufacturing with In Situ Resources Team

Co-Leads

NASA: Peter A. Curreri, NASA/MSFC
External: Edward D. McCullough, Boeing

Government:

- Ken Cooper, NASA MSFC
- Peter Curreri, NASA MSFC (Co-Lead 13.4.4)
- Melanie Bodiford, NASA MSFC
- Kevin McCarley, NASA MSFC
- Richard Hagood, NASA MSFC
- Ron King, NASA MSFC
- Lee Morin, State Department
- Mark Nall, NASA MSFC

NASA on-site contractors:

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- Scott Gilley, Tec-Masters, MSFC
- Jim Kennedy, TBE, MSFC
- Charles Owens, TBE, MSFC
- Julie Ray, TBE, MSFC (Lead 13.4.1,2,3,&6)
- Fred Rose, BD Systems, MSFC
- Yancy Young, TBE, MSFC

Industry

- Gary Rodriguez, sysRAND Corp. (Co-Lead 13.4.1,2,3,&6)
- Takashi Nakamura, Physical Sciences Inc.
- Charles O'Dale, Senomix Software
- Eric Rice, ORBITEC
- Rich Westfall, Galactic Mining
- Mark W. Henley, Boeing
- Edward McCullough, Boeing (Lead 13.4.5)
- David A. Rockwell, Raytheon
- Patricia Downing, Bechtel BSII Construction
- Nick Anstine, Bechtel BSII Construction
- Ronald Davidson, Guigne

Academia

- Allen Crider, U. of North Dakota
- Alex Ignatiev, U. of Houston (Lead 13.4.4)
- Ted Loder, Univ. New Hampshire
- John Moore, CSM
- Brad Blair, Colorado School of Mines
- Marvin E. Criswell, Colorado State University
- Mike Gaffey, Space Studies Department University of North Dakota

Capability 13.4: Surface Manufacturing with In Situ Resources

- Surface Manufacturing with In Situ Resources is a set of capabilities which enable repair, production of parts and integrated systems on the Moon and beyond using in situ resources.
- Six Surface Manufacturing Sub Capabilities are:
  - Additive Manufacturing (e.g. Free Form, Composites, CVD …)
  - Subtractive Manufacturing (e.g. Machining, E-Beam of Laser Cutting …)
  - Formative Manufacturing (e.g. Casting, Extrusion, Sintering, SHS …)
  - Locally Integrated Energy Systems (e.g. Photovoltaic Arrays, Solar Concentrators, Power Beaming, Power Storage …)
  - Locally Integrated Systems (e.g. Precision Assembly and Joining …)
  - Manufacturing Support Systems (e.g. Non Destructive Evaluation and Metrology)
- Surface Manufacturing receives it’s feedstock (barstock, I-beams, powdered metals) from the Resource Processing and with support from Transportation.
- Surface Manufacturing extends repair and spare parts services to all surface operations. It delivers expandable power for in situ resource extraction and processing, surface construction, and manufacturing.

Benefits of Manufacturing with In Situ Resources

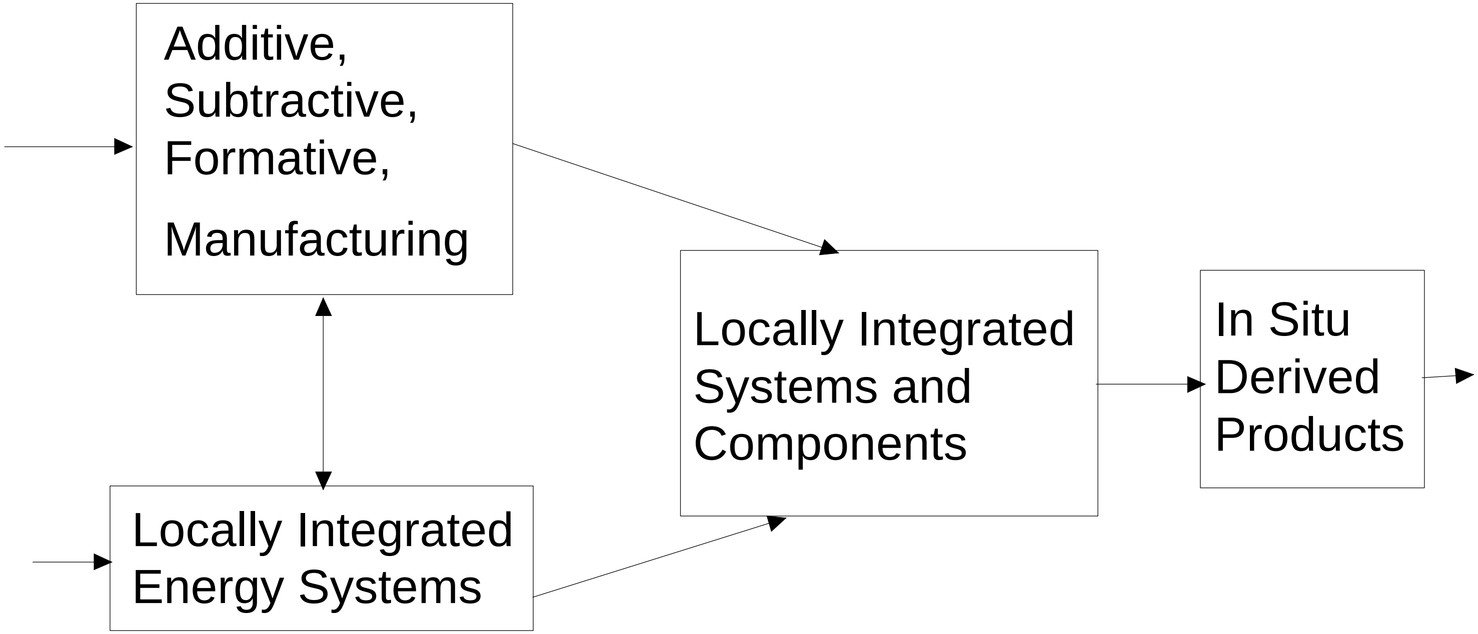
- In Situ Repair and Spare Parts Manufacturing
  - Enables the development of safe, self-sufficient, self-sustaining systems on the Moon and beyond.
  - Enables safe and timely recovery from system failures using in situ versatile manufacturing techniques (with design files from Terrestrial Design Centers) without long and expensive logistics from Earth.
- In Situ Manufacturing with In Situ Resources
  - Industrial Plant capable of manufacturing product mass orders of magnitude beyond the mass of the facility
  - Industrial Plant capable of manufacturing a second-generation Industrial Plant almost entirely (80% - 95%) from ISRU sources
- Surface Manufacturing of In Situ Energy Systems
  - Develop energy-rich environment in Space
  - Energy systems on the Moon and beyond to be expended for decreased cost for Increased production. For example a 1 MW solar cell system can be produced on the Moon with in situ resources for 1/10th the launch mass as a non in situ system.
- Enables large scale Space Commercialization and Development and safe low cost Human Exploration.

Surface Manufacturing w/ In-Situ Resources

Team 13: In-Situ Resource Utilization

- In-Situ Resource Utilization 13.0
  - **Surface Manufacturing with In-Situ Resources** 13.4
    - **Additive Manufacturing Techniques** 13.4.1
      - Free Form Fabrication 13.4.1.1
      - Composite Lay up 13.4.1.2
      - Chemical Vapor Deposition 13.4.1.3
      - Combustion Synthesis 13.4.1.4
    - **Subtractive Manufacturing Techniques** 13.4.2
      - Machining 13.4.2.1
      - E-beam/Laser Cutting & Ablation 13.4.2.2
    - **Formative Manufacturing Techniques** 13.4.3
      - Tape Casting 13.4.4.1
      - Powder Casting 13.4.4.2
      - Casting 13.4.4.3
      - Extrusion 13.4.4.4
      - Sintering 13.4.4.5
    - **Locally Integrated Energy Systems** 13.4.4
      - Photovoltaic Cell/Array Production 13.4.5.1
      - Solar Collector/ Concentrator Production 13.4.5.2
      - Rectenna/Power Beaming Production 13.4.5.3
      - Thermal Storage Media & System Construction 13.4.5.4
      - Battery Material/ Assembly Construction 13.4.5.5
    - **Locally Integrated Systems & Components** 13.4.5
      - Precision Assembly Capability 13.4.6.1
      - Geometric Situational Awareness 13.4.6.2
      - Precision Machining 13.4.6.3
      - Precision Joining/ Fastening 13.4.6.4
      - Precision Component Organization & Handling 13.4.6.5
    - **Manufacturing Support Systems** 13.4.6
      - Non Destructive Evaluation (NDE) 13.4.6.1
      - Metrology 13.4.6.2

Surface Manufacturing with In Situ Resources



Resource Processing Interdependency with other Capabilities

Team 13: In-Situ Resource Utilization

Products From Surface Mfg & Resources	Rating	Capability	Rating	Capability Products To
• Solar array and collector manufacturing & assembly • Rectenna fabrication for orbital power beaming • Thermal storage material production & fabrication	Red	High-Energy Power & Propulsion (2)	Red	• Solar & nuclear power to support power-intensive ISRU activities
• Parts and components for Lunar infrastructure	Green	In-Space Transportation (3)	White	
• Repair/replacement of reflector coatings • Shaping crater for collector • Power availability from ISRU fabricated solar cells	Red	Advanced Telescopes & Observatories (4)	White	
• Power beaming for power to robots	Yellow	Robotic Access to Planetary Surfaces (6)	Red	• Resource location & characterization information • Surface mobility system design & experience • Pre-positioning & activation of ISRU assets
• Repair, replace and fabricate system components	Yellow	Human Planetary Landing Systems (7)	Red	• Precision landing • Delivery of ISRU capabilities to sites of exploration
• Energy rich environment from ISRU fabricated solar cells • Materials for in-situ manufacturing	Red	Human Health and Support Systems (8)	Green	• Carbon-based waste products as resource for ISRU
• Spare parts produced on demand for mobility systems	Green	Human Exploration Systems & Mobility (9)	Green	• Crew/robotics/rovers to perform ISRU surface activities
• Energy rich environment from ISRU fabricated solar cells • Power beaming for power to robots	Green	Autonomous Systems & Robotics (10)	Red	• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation
• Energy rich environment from ISRU fabricated solar cells	Green	Scientific Instruments & Sensors (12)	Yellow	• Resource location & characterization information

ISRU Commonality-Dependency With ISRU Elements (13.4.1,2&3)

Team 13: In-Situ Resource Utilization

ISRU Element Products To Surface Manufacturing

- **Resource Transportation**
  - Surface mobility systems platforms for Raw Resource Transportation to In Situ Manufacturing
  - Surface mobility systems for Resource Processing "Waste" removal.
  - Mobile Material Transportation for Manufacturing
- **Resource Extraction**
  - Feedstock for In Situ Manufacturing
  - Metals, alloys, ceramic, and glass stock materials
- **Product Storage & Distribution**
  - Stored Materials for Surface Manufacturing
- **Locally Integrated Energy Systems**
  - Energy for In Situ Manufacturing

Surface Mfg and Resources

- Manufacturing Spare (iron, carbon, Al, Carbon, Titanium, Alloy, Plastic, glass etc.) Parts
- Manufacturing Heavy or Large Structures like beams, trusses and pilings
- Manufacturing added value added support infrastructure and tools like custom wrenches
- Repairing capability for existing systems
- Manufacturing of locally integrated systems

Surface Manufacturing with In Situ Resources Products To ISRU Elements

- **Resource Transportation**
  - Surface mobility systems for Finished Product Utilization
  - Manufactured payload material handling
- **Product Storage & Distribution**
  - Parts for Life Support
  - Parts for Propulsion
  - Parts for Fuel Cells
  - Parts for Cooling Systems
- **Locally Integrated Energy Systems**
  - Silicon parts for Electronics, Photovoltaic Arrays
  - Fibreglass parts
  - Glass parts for PV arrays
- **Surface Construction**
  - Ceramics Components for Construction Materials Fabrication
  - Iron, Aluminium, and Steel Parts for Habitat Construction
  - Fibreglass parts for Composite Construction Materials, Concrete Substitute, Structural Components, Pressure Vessels (Habitats)
  - Parts from Slag for Habitat Radiation Protection
  - Slag Parts for Nuclear Reactor Shielding

ISRU Element Products To → **Surface Mfg and Resources** ← Products From Surface Mfg & Resources

Locally Integrated Energy Systems

Resource Extraction
- Regolith Excavation & Physical Beneficiation
- Regolith Volatiles Collection & Separation
- Surface Preparation

Resource Transportation
- Surface mobility systems platforms for Raw Resource Transportation
- Surface mobility systems for Finished Product Utilization
- Surface mobility systems for Resource Processing "Waste" removal.

Resource Processing
- Raw materials for solar cell fab
- Raw materials for reflector/collector fab
- Raw materials for electronic parts fab
- Raw materials for thermal storage fav

Product Storage & Distribution
- Stored Gases/Liquids as inputs to Energy system fab

Solar Collectors /Reflectors →

Resource Extraction & Processing
- Energy for Extraction
- Energy for Construction
- Energy for Processing

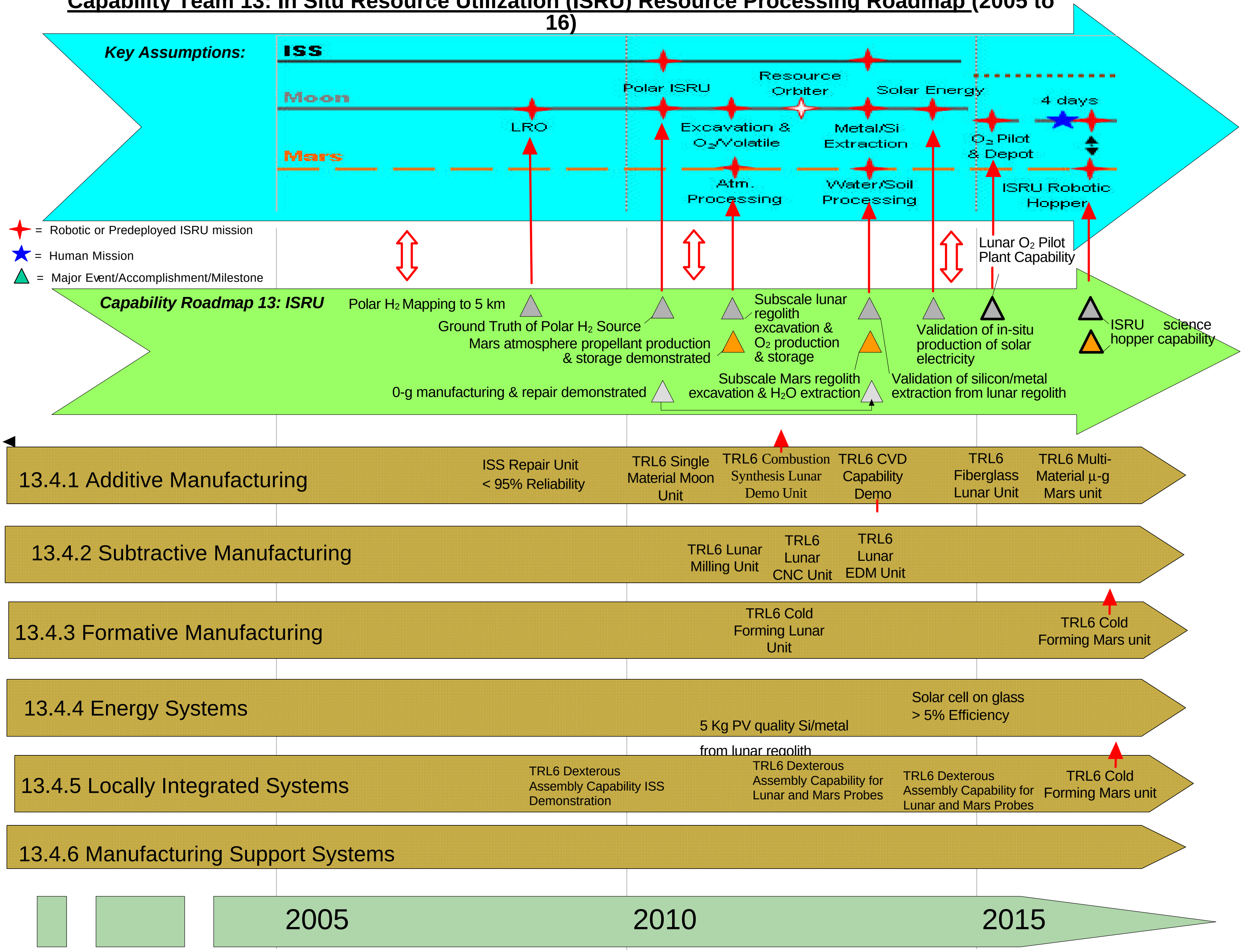
Silicon Solar Cells →

Product Storage & Distribution
- Energy for Life Support
- Energy for Propulsion
- Energy for charging for Fuel Cells
- Energy for Excavation
- Energy for Processing
- Energy for Construction

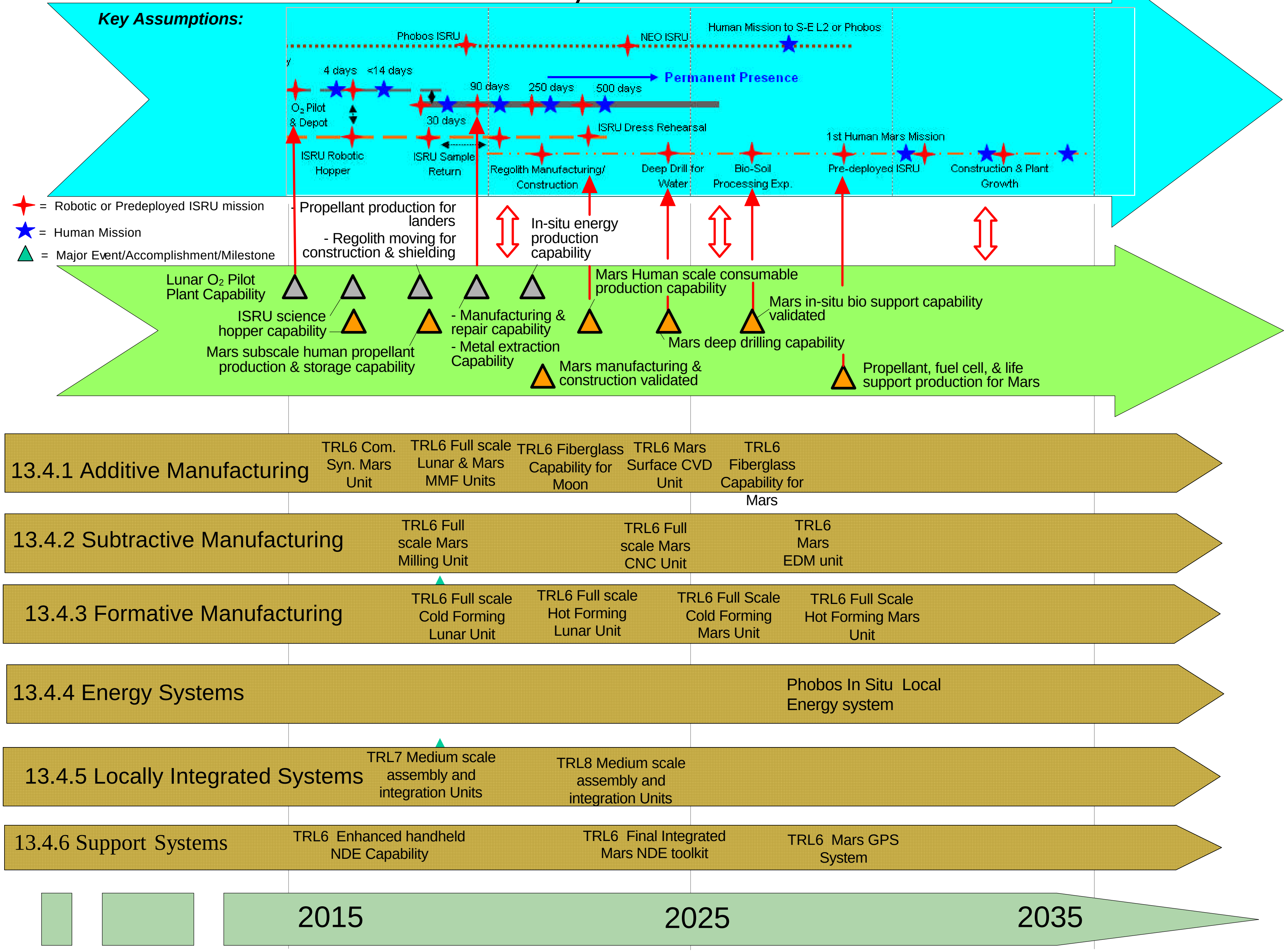
Power Beaming/ Thermal Storage →

Surface Construction
- Energy for construction
- Energy for Excavation
- Energy for processing

Capability Team 13: In Situ Resource Utilization (ISRU) Resource Processing Roadmap (2005 to 16)

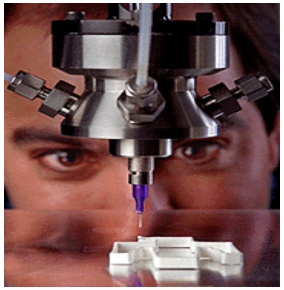


Capability Team 13: In Situ Resource Utilization (ISRU) Resource Processing Roadmap (2015 to 35)



Current State-of-the-Art for Surface Manufacturing with In Situ Resources

- Lunar Manufacturing with In In Situ Resources has over a 30 Years History mostly paper studies that 90% manufacturing materials closure can be obtained from lunar materials.
  – However, the necessary technologies in additive, subtractive and formative manufacturing, integrated systems, and solar cell production have a very high terrestrial state-of-the-art.
  – Extensive microgravity materials processing experiments have been done in space in Apollo, Skylab, and Spacelab and include welding, metals solidification, vapor deposition, glass fiber pulling, and Lunar equivalent vacuum molecular beam epitaxy crystal growth in the Wake Shield orbital facility.
- Mars Manufacturing with In Situ Resources also is mostly paper studies but Mars surface science indicates that near 100% of manufacturing materials closure can be obtained from Mars and Phobos materials.



Maturity Level – Capabilities
Surface Manufacturing with In Situ Resouces

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assessment		
		CRL	R&D3	Need Date
13.4.1 Additive Manufacturing	Solid Free-form Fabrication (SFF)	2	II	2006
	Chemical Vapor Deposition (CVD)	2	II	2015
	Fiberglass Fabrication	3	II	2015
	Combustion Synthesis	2	II	2015
13.4.2 Subtractive Manufacturing	Milling	2	II	2008
	CNC Lathe and CNC Turning	2	II	2009
	Electrical Discharge Machining (EDM)	2	II	2011
13.4.3 Formative Manufacturing	Cold Forming	2	II	2008
	Hot Forming	2	II	2015
13.4.4 Locally Integrated Energy Systems	Photovoltaic Cell/Array Production	3	II	2010
	Solar Collector/Concentrator Production	2	II	2020
	Power Beaming Construction	3	II	2030
13.4.5 Locally Integrated Systems & Components	Precision Assembly	3	III	2008
	Precision Machining	3	III	2008
	Precision Joining/Fastening	3	III	2015
	Precision Component Organization & Handling	3	III	2015
13.4.6 Manufacturing Support Systems	Non-Destructive Evaluation (NDE)	1	II	2012
	Metrology	1	II	2015

Maturity Level – Technologies
Surface Manufacturing with In Situ Resources

Capability	Key Technologies or Sub-Capabilities	Technology Readiness Assessment		
		TRL	R&D3	Need Date
13.4.1 Additive Manufacturing	Solid Free-form Fabrication (SFF)	4	II	2006
	Chemical Vapor Deposition (CVD)	2	II	2015
	Fiberglass Fabrication	2	II	2015
	Combustion Synthesis	4	II	2015
13.4.2 Subtractive Manufacturing	Milling	2	II	2008
	CNC Lathe and CNC Turning	2	II	2009
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	Solar Collector/Concentrator Production	2	II	2009
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	Precision Joining/Fastening	4	II	2011
	Precision Component Organization & Handling	4	II	2015
13.4.6 Manufacturing Support Systems	Non-Destructive Evaluation (NDE)	1	II	2012
	Metrology	1	II	2015

Metrics for Surface Manufacturing with In Situ Resources

- Summary of Surface Manufacturing Metrics For Technology Trades
  - Rate of Production
  - Power Consumed vs. Mass of Product Produced
  - Mass of System vs. Mass of Product Produced
  - Mean Time Between Failure
  - Degree of System Autonomy
  - Reagent Recycling Near or At 100%

- Summary of Progress Metrics
  - All Component Technologies Are At TRL 4 At Least 6 Years Prior To Need Date
  - All Component Technologies Reach TRL 6 At Least 3 Years Prior To Need Date
  - Continuous Operation for 30 days 5 years before need date.
  - Continuous, Autonomous Operations in an Mission Simulated Environment for 1 year, 3 years before need date

Technology Gaps for Surface Manufacturing with In Situ Resources

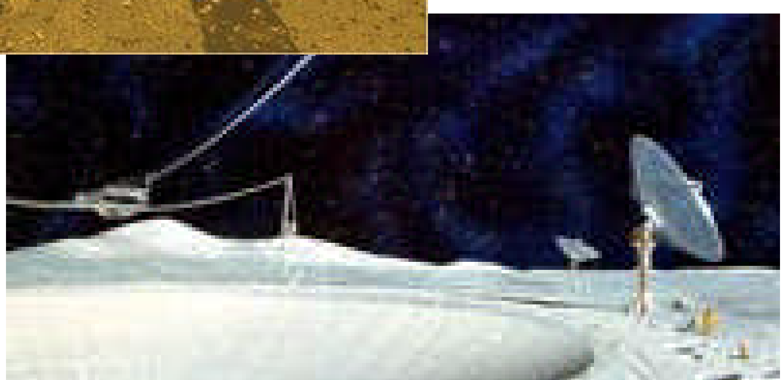
- Reduction of System Mass, for seed Manufacturing units.
- Although the systems will be human in-the-loop a maximum of autonomous and tele-operations must be developed
- Systems require the development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment.
- Many of the Processes Involve Molten Materials, Designs to Handle this Molten Material Autonomously Are Not Trivial Exercises
- Improved Energy Efficiencies
- Understanding Of Reduced Gravity Effects On Processes
- Mixed Gas Stream Separation
- Significant Work Remains To Develop The Integrated Systems
- Photovoltaic cell processes that utilize the lunar vacuum need to be improved to optimize the cell efficiencies.
- Interfaces must be developed between the extraction facilities and the production facilities.
- Methods must be developed for power management and distribution, metrology
- Systems must be designed “up front” that are repairable by in situ processes

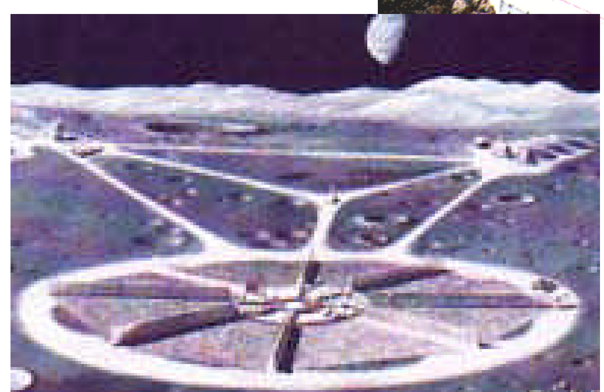
Capability Development Strategy

- Early tests of in situ extraction of metals and silicon enable many in situ surface manufacturing and energy options.
- Early tests of fabrication and repair methods using these in situ materials enable the design of in situ maintainable systems for the Moon and beyond. These systems enable affordable safe, self-sustaining, space systems.
- Early demonstration of In Situ produced energy on the Moon will provide options for energy growth on the Moon and beyond that will cost less per energy unit as the system grows
- Manufacturing and energy production on the Moon will enable lunar base growth at reduced cost and enable commercial development including the production of energy for use in space.
- Power beaming combined with in situ produced power will enable wireless transport of energy on the Moon and could be the basis for commercial Space Solar Power production.

ISRU Capability Element 13.5 Surface Construction

Kris Romig - NASA Chair
Dr. Eric Rice- External Chair
April 12, 2005





Co-Chairs

– NASA: Kris Romig, NASA/JSC
– External: Dr. Eric Rice, ORBITEC

Government: NASA

- Rob Mueller, JPL/KSC
- Joseph Casas, MSFC

Government: Other

- Darryl Calkins, USACE Cold Regions Research & Engineering Lab

Industry

- Mike Fiske, Morgan Research Corporation
- Regina Pope, Qualis Corporation
- Trygve Magelssen, Futron Corporation
- Nancy Lindsey, Futron Corporation

Academia

- Dr. Leslie Gertsch, University of Missouri-Rolla
- Brad Blair, Colorado School of Mines
- Javier Diaz, Colorado School of Mines
- Begona Ruiz, Colorado School of Mines
- Paul van Susante, Colorado School of Mines
- Prof. Jeffrey Taylor, University of Hawaii

Other/Critical Volunteers

- Most of the above are volunteer contributors
- Broad ISRU industry & academic community (Space Resources Roundtable & STAIF Conferences)

Capability 13.5 Surface Construction

- Surface Construction is a capability that is necessary throughout the spiral development of NASA's exploration vision
- Enabling for an extended human and robotic presence on any planetary surface
- Necessary for integration of surface assets

- Site Planning
- Surface & Subsurface Site Preparation
- Structure & Habitat Fabrication
- Radiation & Micro Meteoroid Debris Shielding
- Structure & Site Maintenance
- Landing and Launch Site Construction

Attributes 13.5 Surface Construction

- Site surveys and mapping
- Regolith construction material characterization
- Dust control and mitigation
- Moving of bulk regolith
- Grading of surfaces
- D-GPS like navigation capabilities
- Autonomous/telerobotic construction vehicles

Benefits of the 13.5 Surface Construction

- **Site Planning**
  - Site surveys & characterization of regolith for construction needs
  - Organization of emplaced and future surface assets
- **Surface & Subsurface Preparation**
  - Construction of science platforms (observatories)
  - Provides surface transportation infrastructures such as roads and landing/launch pads
  - Provides utility infrastructures for the site (utilidors)
  - Dust control and regolith stabilization
  - Increased accessibility to remote locations through transportation infrastructures
- **Structure & Habitat Fabrication**
  - Reduction of habitat mass launched from Earth
- **Bulk regolith shielding**
  - mitigates multiple threats simultaneously (radiation, thermal, debris)
- **Structure & Site Maintenance**
  - Maintainable and modifiable assets in place on lunar surface
- **Launch/Landing Pads**
  - Reduction of site degradation by flame and debris ejecta
  - Allows for closer proximity to current or future surface assets
  - Allows centralized location for propellant storage and refueling

13.5 Surface Construction

Team 13: In-Situ Resource Utilization

- In-Situ Resource Utilization 13.0
  - **Surface Construction** 13.5
    - **Site Planning** 13.5.1
      - Site Survey & Characterization 1.5.1.1
      - Architectural Layout & Master Planning 13.5.1.2
      - Civil Engineering Design 13.5.1.3
      - Geospatial Information System (GIS) Configuration Control Tool 13.5.1.4
    - **Surface & Subsurface Preparation** 13.5.2
      - Road Construction 13.5.2.1
      - Foundation Construction 13.5.2.2
      - Utilidor Construction 13.5.2.3
      - Terrain Shaping, Grading & Rock Clearing 13.5.2.4
      - Underground Structures 13.5.3.5
      - Soil Stabilization (Mars Dust) 13.5.3.6
    - **Structure & Habitat Fabrication** 13.5.3
      - Construction Techniques & Methods 13.5.3.1
      - In Situ Building Materials 13.5.3.2
      - Access & Handling Equipment 13.5.3.3
      - In Situ Robotic / Human Construction Equipment 13.5.3.4
    - **Radiation & Micro Meteoroid Debris Shielding** 13.5.4
      - Radiation Shelters 13.5.4.1
      - Shields for Nuclear Reactors 13.5.4.2
      - Micrometeoroid Shielding 13.5.4.3
    - **Structure & Site Maintenance** 13.5.5
      - Integrity & Preventative Maintenance 13.5.5.1
      - Waste Management 13.5.5.2
      - Facility Management 13.5.5.3
    - **Landing & Launch Site** 13.5.6
      - Landing/Launch Pads 13.5.6.1
      - Plume Debris Shielding 13.5.6.2
      - Exhaust Flame Management 13.5.6.4
      - Sheltered Propellant and Consumables Farms 13.5.6.5
      - Mars Lightning Protection 13.5.6.6

Surface Construction Interdependency with other Roadmaps

Team 13: In-Situ Resource Utilization

Construction Products To Other Capabilities	Roadmap	Capability Products To Construction
• Radiation shields for nuclear reactors • Power Cable Deployment • Power distribution layout	High-Energy Power & Propulsion (2)	• Solar & nuclear power to support power-intensive ISRU activities
• Landing/Launch Pads • Surface Support Infrastructure	In-Space Transportation (3)	• ISRU-compatible propulsion • Electromagnetic launch systems for delivery of ISRU products
• Shaping crater • In-situ construction and fabrication • Foundation design & preparation	Advanced Telescopes & Observatories (4)	
• Landing pads/plume debris shielding • Landing Site Characterization/Preparation	Robotic Access to Planetary Surfaces (6)	• Resource location & characterization information • Surface mobility system design & experience • Pre-positioning & activation of ISRU assets
• Landing pads/plume debris shielding • Landing Site Characterization/Preparation	Human Planetary Landing Systems (7)	• Precision landing • Delivery of ISRU capabilities to sites of exploration
• Habitat/shelter fabrication • Radiation shields from in-situ material • Micro Meteoroid Debris Shielding	Human Health and Support Systems (8)	
• Soil stabilization/dust control • Roadway infrastructures • Engineering properties of regolith	Human Exploration Systems & Mobility (9)	• Crew/robotics/rovers to perform ISRU surface activities
• Roadway infrastructures • Construction End Effectors and attachments	Autonomous Systems & Robotics (10)	• Robots/rovers to perform ISRU surface activities • Software & FDIR logic for autonomous operation
• Geospatial Information System (GIS) • Data fusion of regolith characteristics • Engineering properties of regolith	Scientific Instruments & Sensors (12)	• Instrumentation for resource location & characterization information

Surface Construction Interdependency with other ISRU Elements

ISRU Element Products To

Resource Processing
- Ceramics for Construction Materials Fab (e.g. Bricks)
- Iron, Aluminum, and Steel for Structure & Habitat Fabrication
- Fiberglass for Composite Construction Materials
- Slag for Bricks
- Slag for Habitat Radiation Protection
- Slag for Nuclear Reactor Shielding

Resource Extraction
- Regolith Excavation & Physical Beneficiation

Resource Transportation
- Surface mobility systems platforms for Raw Construction Resources
- Surface mobility systems for Finished Product Utilization
- Surface mobility systems for Resource Processing “Waste” removal.

Surface Manufacturing w/In-Situ Resources
- Spare Parts for Surface Construction Systems
- Manufactured parts for Structure fabrication

Product Storage & Distribution
- Stored Gases/Liquids as inputs to Surface Construction

Surface Construction

- Site Planning
- Surface & Subsurface Preparation
- Structure & Habitat Fabrication
- Radiation & Micro Meteoroid Debris Shielding
- Structure & Site Maintenance
- Landing & Launch Site

Products From Surface Construction

Site Planning →

All
- General site planning and characterization

Surface & Subsurface Preparation →

Resource Transportation
- Roadway infrastructure
- Soil stabilization dust control

Product Storage & Distribution
- Utilidors / Cable deployment/ piping
- Subsurface tank storage
- Foundation/soil stabilization for tank farms

Resource Extraction
- Roadway infrastructure
- End Effectors/ Attachments
- Granular overburden

Structure & Habitat Fabrication →

All
- Single and multifunctional structures

Radiation & Micro Meteoroid Debris Shielding →

All
- Radiation shielding for crew/equipment

Structure & Site Maintenance →

All
- General site & primary structure maintenance

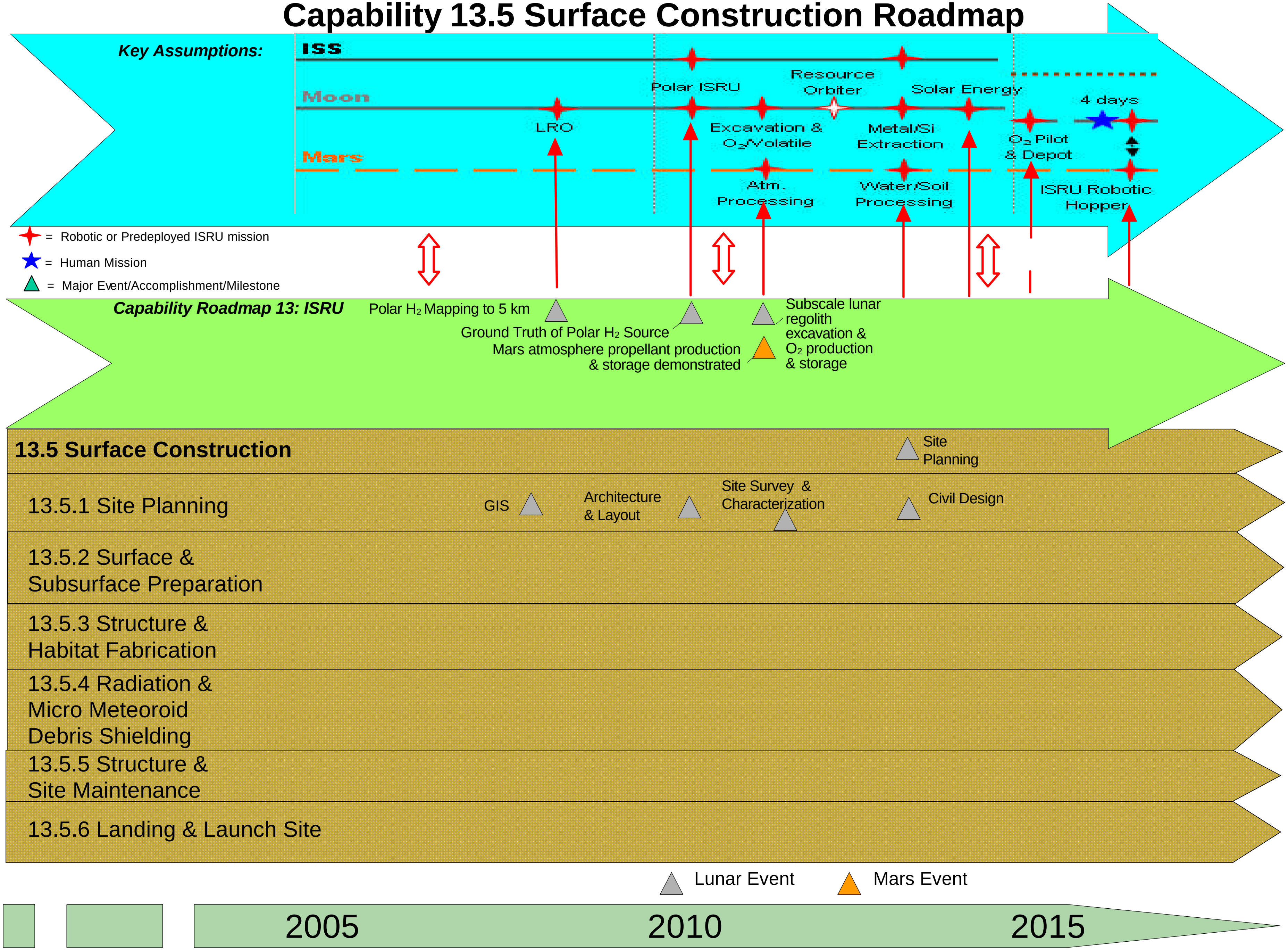
Landing & Launch Site →

Resource Transportation
- Landing & Launch site for off surface resource transportation

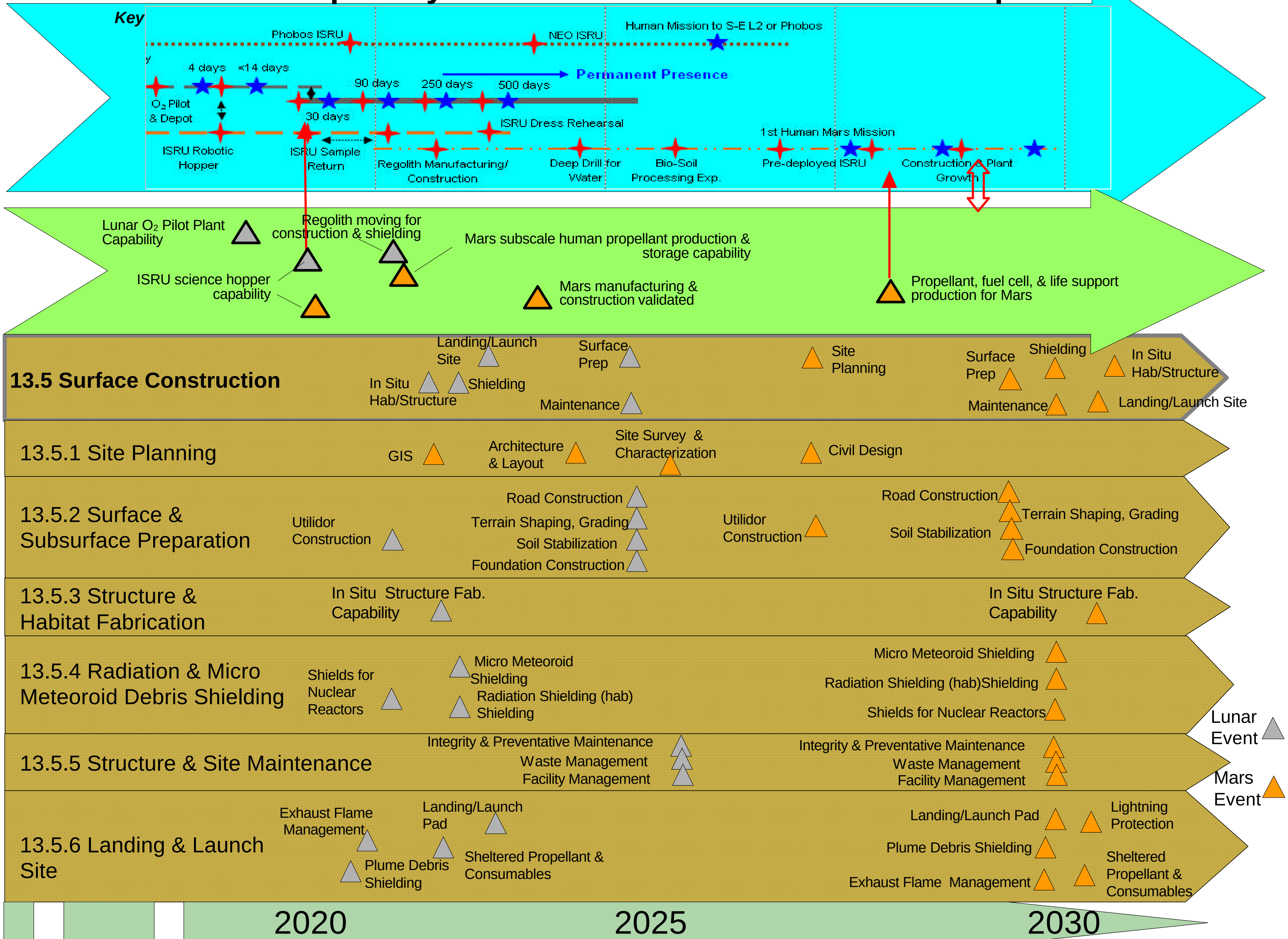
Requirements /Assumptions for Capability 13.5 Surface Construction

- **Additional Assumptions that the team used that drove the need for the capability:**
  - Lunar Base will be established at one location for staging to global Lunar access
  - Early Lunar missions (4 – 90 Days) will require minimal Surface Construction (Landing/Launch, Protection, Site Planning)
  - Later Lunar missions will be > 90 Days and evolve to commercial self sustainment with heavy emphasis on Surface Construction & permanent infrastructure
  - Government provides base infrastructure for Science / Commercial customers (McMurdo/South Pole Analogy)
  - Moon is a testbed and technology proving ground for Mars
  - Mars missions will also have a primary Mars base with Infrastructure

Capability 13.5 Surface Construction Roadmap



Capability 13.5 Surface Construction Roadmap



Current State-of-the-Art for Capability 13.5 Surface Construction

- **Site Planning**
  - Commercial Off the Shelf (COTS) GIS software available
  - Radar/Lidar automated mapping is available and proven (Shuttle/Mars/Venus)
  - Lunar / Mars Topography data sets are partially available
  - Some geophysical characterization is available (Apollo / Mars programs)
  - Lunar Regolith and properties available from Apollo program in the upper 2m, but lacking information at depth and at large spatial scales
  - Architecture & Civil engineering disciplines are mature for terrestrial applications
- **Surface & Subsurface Preparation**
  - Construction equipment (i.e., Bobcat, Caterpillar, Case, all- wheel steer loaders, excavators, work machines, backhoes, etc.)
    - terrestrial application @ TRL 9, Space @ TRL 1
  - Gravitometers, Transits, and Laser Surveying Equipment
    - terrestrial @ TRL9, Space @ TRL 1
  - GPS spatial control
    - terrestrial application @ SRL 9, Space @ TRL 1
  - Basaltic materials production TRL 1
  - Hand tools, concrete tools, screeds, power trowels, floats, etc.
    - terrestrial @ TRL9, Space @ TRL 2-9
- **Structure & Habitat Fabrication**
  - Many in situ-based or derived habitat construction methods have well-characterized terrestrial equivalents, including Commercial Off The Shelf (COTS) software
    - Water-based and waterless concretes
    - Sandbags
    - Blockmakers (compacted soil, carved rock, cast basalt)
    - Inflatables
    - Glass fiber and/or rods for concrete reinforcement or as structural elements
  - Lunar/Mars topography data sets are partially available
  - Some geophysical characterization is available (Apollo/Luna/Surveyor/Mars programs)
  - Lunar regolith and properties are available from the Apollo program
- **Radiation & Micro Meteoroid Debris Shielding**
  - Radiation, 25 rem/month (NASA's current Limit) achieved with 13cm of regolith or 5m to stop GeV particles, Solar Events mitigated by ~50-100 centimeters of regolith.
  - Meteoroids, 45.9 cm of regolith (~34cm AL) protects against impacts of 7 cm (1.76 x 10^{-10} impacts/m^2/yr)
  - Thermal, tests have shown under a few centimeters of regolith (2-4 x 10^{-6} W/cm^2) or in a lava tube produces a nearly constant -35°C and -20°C
  - MMOD concepts and hardware design for ISS currently exist (Aluminum/Kevlar/Nextel) (TRL 9)
  - Lead free protective garments are commercially available (vests, suits, gloves, etc)
- **Structure & Site Maintenance**
  - In space maintenance and repair are evolving disciplines. New advances in self-healing materials to reduce maintenance, improve reliability and reduce risk are currently being tested at the University of Illinois. The self-healing capabilities of certain polymers have been demonstrated at the laboratory level.
  - EVA and IVA repairs are regularly performed on the International Space Station
  - Tile repair tools and materials are being developed as part of return to flight activities for the the Space Shuttle
- **Landing & Launch Site**
  - Apollo style landings on the Moon showed ejecta occurred but did not threaten vehicle (23 metric Ton landed Mass)
  - Mars Viking, Pathfinder, MER missions show heritage but for small masses (1 metric Ton)
  - Huygens Probe landing on Titan
  - Extensive experience is available from Earth based spaceports.
  - Extensive experience with Earth based Propellant and consumables farms, but the mass, power, volume and reliability requirements are much more challenging for Moon/ Mars
  - JPL Skycrane type of devices may alleviate Landing/launch pad requirements

Maturity Level – Capabilities for 13.5 Surface Construction

Capability	Key Technologies or Sub Capability	Current CRL	Need Date	R&D3
Site Planning	Site Survey & Characterization	1	2014	II
	Architectural Layout & Master Planning	3	2010	I
	Civil Engineering Design	1	2014	I
	Geospatial Information System (GIS) Configuration Control Tool	3	2008	II
Surface & Subsurface Preparation (General)	Road Construction	1	2025	III
	Foundation Construction	1	2025	II
	Utilidor Construction	1	2020	I
	Terrain Shaping, Grading & Rock Clearing	1	2025	II
	Underground Structures	1	2030	III
	Soil Stabilization (Mars Dust)	1	2030	I
Structure & Habitat Fabrication	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	1	2025	II
	In Situ Building Materials	1	2025	I
	Access & Handling Equipment	1	2025	II
	In Situ Robotic / Human Construction Equipment	1	2025	III
Radiation & Micro Meteoroid Debris Shielding	Radiation Shelter (habitat, permanent)	1	2022	II
	Radiation Shields for Nuclear Reactors	1	2020	I
	Micro Meteoroid Shielding (habitat, permanent)	1	2022	I
Structure & Site Maintenance	Integrity & Preventative Maintenance	1	2025	III
	Waste Management	1	2025	III
	Facility Management	1	2025	II
Landing & Launch Site	Landing/Launch Pad	1	2022	III
	Plume Debris Shielding	1	2022	II
	Exhaust Flame Management	1	2021	III
	Sheltered Propellant & Consumable Farms	1	2022	I
	Mars Lightning Protection	1	2030	IV

Maturity Level – Technologies for 13.5 Surface Construction

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Autonomous Site Survey (Orbital /Surface)	Site Survey & Characterization	4	II	2012
Autonomous Geophysical Characterization (Orbital/Surface)	Site Survey & Characterization	4	IV	2012
Architectural Layout CAD Models	Architectural Layout & Master Planning	9	I	2009
Master Planning	Architectural Layout & Master Planning	9	I	2008
Civil Engineering Design CAD Drawings	Civil Engineering Design	5	I	2014
Standards for Planetary Civil Design	Civil Engineering Design	1	II	2008
Construction Methods and Schedules	Civil Engineering Design	2	II	2010
GIS/Configuration Control software	Geospatial Information System (GIS) Configuration Contrl Tool	9	I	2005
Planetary Data Sets	Geospatial Information System (GIS) Configuration Contrl Tool	6	II	2008
Bulldozers & Graders	Road Construction	1	II	2022
Backhoe/Excavators	Road Construction	1	II	2022
Bucket Loaders	Road Construction	1	II	2022
Stabilization techniques & equipment	Road Construction	1	II	2022
Dust Mitigation	Road Construction	1	I	2022
Regolith Crusher & conveyors	Road Construction	1	II	2022
Compactors	Road Construction	1	II	2022
Paving Machine	Road Construction	1	II	2022
Microwave sintering	Road Construction	3	II	2022
LGPS (Lunar GPS)	Road Construction	1	II	2022
Hand Tools	Road Construction	6-9	II	2015
Backhoe/Excavators	Foundation Construction	1	II	2022
Augers/Drilling/Piling	Foundation Construction	1	II	2020
Compaction equipment	Foundation Construction	1	II	2020
Microwave sintering	Foundation Construction	3	III	2022
Protective barriers	Foundation Construction	1	II	2020

Maturity Level – Technologies for 13.5 Surface Construction (2)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Blockout materials for pass through access for utilities	Foundation Construction	1	II	2020
Thermal barrier insulation	Foundation Construction	1	II	2020
Hand Tools	Foundation Construction	6-9	II	2015
Trenchers	Utilidor Construction	2	I	2016
Microwave Sintering	Terrain Shaping, Grading & Rock Clearing	3	III	2022
Bulldozers & Graders	Terrain Shaping, Grading & Rock Clearing	1	II	2022
Backhoe/Excavators	Terrain Shaping, Grading & Rock Clearing	1	II	2022
Horizontal Construction Equipment	Underground Structures	1	III	2026
Vertical Construction Equipment	Underground Structures	1	IV	2026
Precision Navigation/Control Equipment	Underground Structures	2	II	2026
Interlocking brick pavers	Soil Stabilization (Mars Dust)	1	II	2026
flexible mesh netting	Soil Stabilization (Mars Dust)	3	I	2026
Soil Stabilizers	Soil Stabilization (Mars Dust)	1	I	2026
Rigid Greenhouse	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	3	I	2021
Low Pressure Greenhouse	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	I	2021
Transparent Greenhouse Structure	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	III	2021
Rigidized Frames Inflatables	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	I	2021
Traditional Aluminum (ISS alloys)	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	9	I	2021
Carbon-based Composites	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	6	II	2021
Nanotube-based Composites	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	IV	2021
Transhab design (Kevlar-based)	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	5	II	2021

Maturity Level – Technologies for 13.5 Surface Construction (3)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Mod. Transhab design (Vectran)	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	4	II	2021
Inflatable Greenhouse	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	II	2021
Lava Tube or Cave formable inflatables	Constructions Techniques and Methods (self deployable, inflatable, robotic, human)	2	II	2025
In Situ Concrete	In Situ Building Materials	2	I	2021
Vertical Access Device	Access & Handling Equipment	1	II	2021
Scaffolding Functionality Device	Access & Handling Equipment	1	I	2021
Pallets	Access & Handling Equipment	1	I	2021
Cranes	Access & Handling Equipment	1	II	2021
Fork Lifts	Access & Handling Equipment	1	II	2021
Low Maintenance Construction Equipment	Access & Handling Equipment	2	III	2021
Stiff Legged Derricks	Access & Handling Equipment	1	II	2021
Jib Hoist	Access & Handling Equipment	1	II	2021
Robotic Brick Layer	In Situ Robotic / Human Construction Equipment	1	III	2021
In Situ Automated Forming System	In Situ Robotic / Human Construction Equipment	1	IV	2021
Robotic Construction Assistence	In Situ Robotic / Human Construction Equipment	1	III	2021
ISS heritage	Radiation Shelter (habitat, permanent)	9	I	2018
Polyethylene/nanotube structure	Radiation Shelter (habitat, permanent)	1	III	2018
Radiation Transport Modeling	Radiation Shelter (habitat, permanent)	3	III	2018
Lava Tubes	Radiation Shelter (habitat, permanent)	5	II	2018
ISS heritage	Radiation Shelter (habitat, permanent)	9	II	2018
Polyethylene/nanotube structure	Radiation Shelter (habitat, permanent)	1	III	2018
Radiation Transport Modeling	Radiation Shelter (habitat, permanent)	3	III	2016

Maturity Level – Technologies for 13.5 Surface Construction (4)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
Lava Tubes	Radiation Shelter (habitat, permanent)	5	II	2018
ISS heritage	Radiation Shelter (habitat, permanent)	9	II	2018
Polyethylene/nanotube structure	Radiation Shelter (habitat, permanent)	1	III	2018
Radiation Transport Modeling	Radiation Shelter (habitat, permanent)	3	III	2016
Bulk Regolith Radiation Shielding	Radiation Shelter (habitat, permanent)	3	I	2018
Bulk Regolith Radiation Shielding	Radiation Shields for Nuclear Reactors	3	I	2016
In-situ Processed Radiation Shielding Material	Radiation Shields for Nuclear Reactors	2	III	2016
Transhab design (Kevlar/Nextel)	Micro Meteoroid Shielding (habitat, permanent)	6	I	2018
Bulk Regolith Radiation Shielding	Micro Meteoroid Shielding (habitat, permanent)	3	I	2018
ISS design (Aluminum/Kevlar/Nextel)	Micro Meteoroid Shielding (habitat, permanent)	9	I	2018
Whipple Shields	Micro Meteoroid Shielding (habitat, permanent)	6	II	2018
Rigid structure (ISS epoxy patch)	Integrity & Preventative Maintenance	6	I	2021
Rigid (microwave-heated nanotube)	Integrity & Preventative Maintenance	1	III	2021
Erection and Environment Sealing	Integrity & Preventative Maintenance	3	II	2021
Systems monitoring / Remote sensing	Integrity & Preventative Maintenance	7	I	2021
Self-repairing systems (pipes)	Integrity & Preventative Maintenance	7	I	2021
Self-repairing systems (insulation)	Integrity & Preventative Maintenance	2	III	2021
automated response systems	Integrity & Preventative Maintenance	7	I	2021
Planetary Surface Containment Systems	Waste Management	2	I	2021
Salvaging	Waste Management	1	III	2021
Re-processing	Waste Management	1	IV	2021
Disposal	Waste Management	1	I	2021
non destructive testing and evaluation	Facility Management	2	I	2021

Maturity Level – Technologies for 13.5 Surface Construction (5)

Technology	Capability Applications	TRL/SRL	R&D3	Need Date
wireless structural systems monitoring / Remote sensing	Facility Management	7	I	2021
automatic shutdown / evacuation	Facility Management	5	II	2021
Learning systems	Facility Management	7	II	2021
Special regolith stabilizers/pavers	Landing/Launch Pad	1	II	2017
Pre-cast concrete slabs	Landing/Launch Pad	2	I	2017
Microwave Sintering	Landing/Launch Pad	1	III	2017
Autonomous Debris Clearing	Landing/Launch Pad	2	II	2017
Special regolith stabilizers/pavers	Plume Debris Shielding	3	II	2017
Bulk Regolith Shielding	Plume Debris Shielding	3	I	2017
Wire Mesh Containment	Plume Debris Shielding	3	I	2017
Special regolith stabilizers/pavers	Exhaust Flame Management	3	III	2016
Exhaust Deflectors/Containment	Exhaust Flame Management	3	IV	2016
Bulk Regolith Shielding	Sheltered Propellant & Consumable Farms	3	I	2017
Catenary Wire System	Mars Lightning Protection	1	I	2026
Electrostatic Shield	Mars Lightning Protection	1	V	2026
Mars Grounding System	Mars Lightning Protection	1	I	2026

Metrics for 13.5 Surface Construction

Technology	Current SOA (kg/day, W/kg, etc)	Goal (kg/day, W/kg, etc)
Autonomous Site Survey (Orbital /Surface)	meters	mm
Autonomous Geophysical Characterization (Orbital/Surface)	Orbital Mass Spec	Geo Mapping
Architectural Layout CAD Models	3D CAD Models	3D CAD Models
Civil Engineering Design CAD Drawings	3D CAD Models	3D CAD Models
Standards for Planetary Civil Design	Academic Papers	Design Standards
Construction Methods and Schedules	Concepts	Demos
GIS/Configuration Control software	GIS - COTS	GIS - Custom
Planetary Data Sets	Fractional Coverage	Global
Bulldozers & Graders	0 kg/hr	1000 kg/hr
Backhoe/Excavators	0 kg/hr	500 kg/hr
Bucket Loaders	0 kg/hr	500 kg/hr
Stabilization techniques & equipment	0 m^2	250 km^2
Dust Mitigation	0 m^2	250 km^2
Regolith Crusher & conveyors	0 kg/hr	TBD kg/hr
Compactors	0 m^2	250 km^2
Paving Machine	0 m^2	250 km^2
Microwave sintering	<5 cm	>15 cm
LGPS (Lunar GPS)	0 cm^2	10 cm^2
Hand Tools	Apollo	Effective
Backhoe/Excavators	0 kg/hr	500 kg/hr
Augers/Drilling/Piling	0 kg/hr	TBD
Compaction equipment	0 m^2	250 km^2
Microwave sintering	<5 cm	>15 cm
Protective barriers	0 m^2	250 km^2
Blockout materials for pass through access for utilities	>1m^2	>1m2
Thermal barrier insulation	0 w/m^2	TBD w/m^2
Trenchers	0 m deep	<.5 m deep
In Situ Concrete	0	100 m^3

Metrics for 13.5 Surface Construction (2)

Technology	Current SOA (kg/day, W/kg, etc)	Goal (kg/day, W/kg, etc)
Vertical Access Device	0	10 m vertical access
Scaffolding Functionality Device	0	10 m vertical access
Pallots	0	1000 kg
Fork Lifts	0	5,000 kg
Stiff Legged Derricks	0	5,000 kg
Jib Hoist	0	1,000 kg
Robotic Brick Layer	0	250 bricks/day
In Situ Automated Forming System	0	100 m^3
Robotic Construction Assistence	0	100 kg
Radiation Transport Modeling	25 rem/mo (EVA STD)	Earth-like conditions (~.36 rem/yr)
Lava Tubes	TBS	Earth-like conditions (~.36 rem/yr)
Polyethylene/nanotube structure	0	Earth-like conditions (~.36 rem/yr)
Bulk Regolith Radiation Shielding	25 rem/mo	Earth-like conditions (~.36 rem/yr)
In-situ Processed Radiation Shielding Material	TBS	No radiation contamination of Lunar environment
Bulk Regolith Radiation Shielding	As required by design	No habitat or personnel penetrations
Whipple Shields	As required by design	No habitat or personnel penetrations
Self-repairing systems (pipes)	0	repair within 80-90% of initial design characteristics
Self-repairing systems (insulation)	0	repair within 80-90% of initial design characteristics
Planetary Surface Containment Systems	0	100 M^3
Salvaging	0	80% of waste
Re-processing	0	60% of unsalvagable waste
Disposal	0	20% oi unsalvageble waste
automatic shutdown / evacuation	no automatic shutdown	automatic shutdown
Learning systems	0	self updating systems
Autonomous Debris Clearing	Ejecta	No Ejecta
Exhaust Deflectors/Containment	Uncontrolled Flame	Controlled Flame
Catenary Wire System	No Protection	Full Protection
Electrostatic Shield	No Protection	Full Protection

Gaps for 13.5 Surface Construction

- Insufficient scale and resolution of topography for the Moon and Mars for detailed site planning
- Immature architecture and civil engineering disciplines for non-terrestrial surface applications
- Design & testing of construction equipment for & in the lunar environment
- Automation of construction processes
- High tensile-strength lunar based concrete
- Understanding of regolith properties (mechanical/physical) at probable landing sites
- Dust mitigation & techniques to control
- Surface materials capable of wear resistance
- Pre-manned surface construction requires complex robotics and teleoperations
- Shielding can only be used to protect a lunar station and its inhabitants from the effects of the thermal, radiation, and meteoroid mechanisms. Other methodology is needed to combat atmospheric, magnetic field, and gravitational field mechanisms effects
- The most significant challenge of using lunar regolith as a shielding material is that the regolith material is not ready to be installed immediately. This means that the habitat/crew is not fully protected immediately
- Regolith is not pre-processed for immediate installation; it must be excavated, lifted, dumped, and controlled which requires time, positioning and additional tools and machinery (automate to minimize crew time required) be designed, tested, and deployed
- Additional structural analyses/ issues and habitat accessibility for exterior maintenance issues will need to be addressed if the regolith shield/barrier is dumped directly on a habitat
- Self-healing capabilities of materials should also be tested in similar environmental conditions to assess performance (i.e. tested on the ISS)
- In situ production of spares and parts (a demonstration mission is needed to test this capability)
- Very little known about Mars lightning /electrostatics and Mars weather details
- No landing/Launch pad has been built on other planetary surfaces

ISRU Capability Element 13.6 Surface ISRU Product and Consumable Storage and Distribution

Co-Chairs:
Dr. Robert Zubrin, Pioneer Astronautics
Robert G. Johnson, NASA KSC

Presenter:

Robert Johnson

Co-Chairs

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- Rob Boyle
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- Frederick Adams
- Dr. Martha Williams
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- Brekke Scholtens
- Eric Dirschka

Industry

- Rolf Baumgartner, TAI
- Scott Willen, TAI
- Larry Clark, Lockheed Martin
- Ray Radebaugh, NIST

Capability 13.6 Surface ISRU Product and Consumable Storage and Distribution

- Responsible for the efficient storage and distribution of all ISRU produced fluids and consumables to support mission success
  - Liquefaction of cryogenic products and maintenance of stores (LH2, LO2, LCH4, LN2, etc.)
  - Recycling and minimization of system losses
  - Storage of water (solid or liquid) and other earth storable fluids
  - Reagent storage for ISRU processes (if any)
  - Gas storage (buffer gasses and pneumatic uses)
  - Develop distribution options for wide variety of end users
    - Fixed service lines
    - Deployable service lines
    - Tanker trucks (In conjunction with ISRU transportation element)
    - Multi-use service station (rovers, astronauts, etc.)
    - Standardized user interfaces
  - **Integrated thermal management of ISRU systems**

Capability 13.6 Surface ISRU Product and Consumable Storage and Distribution

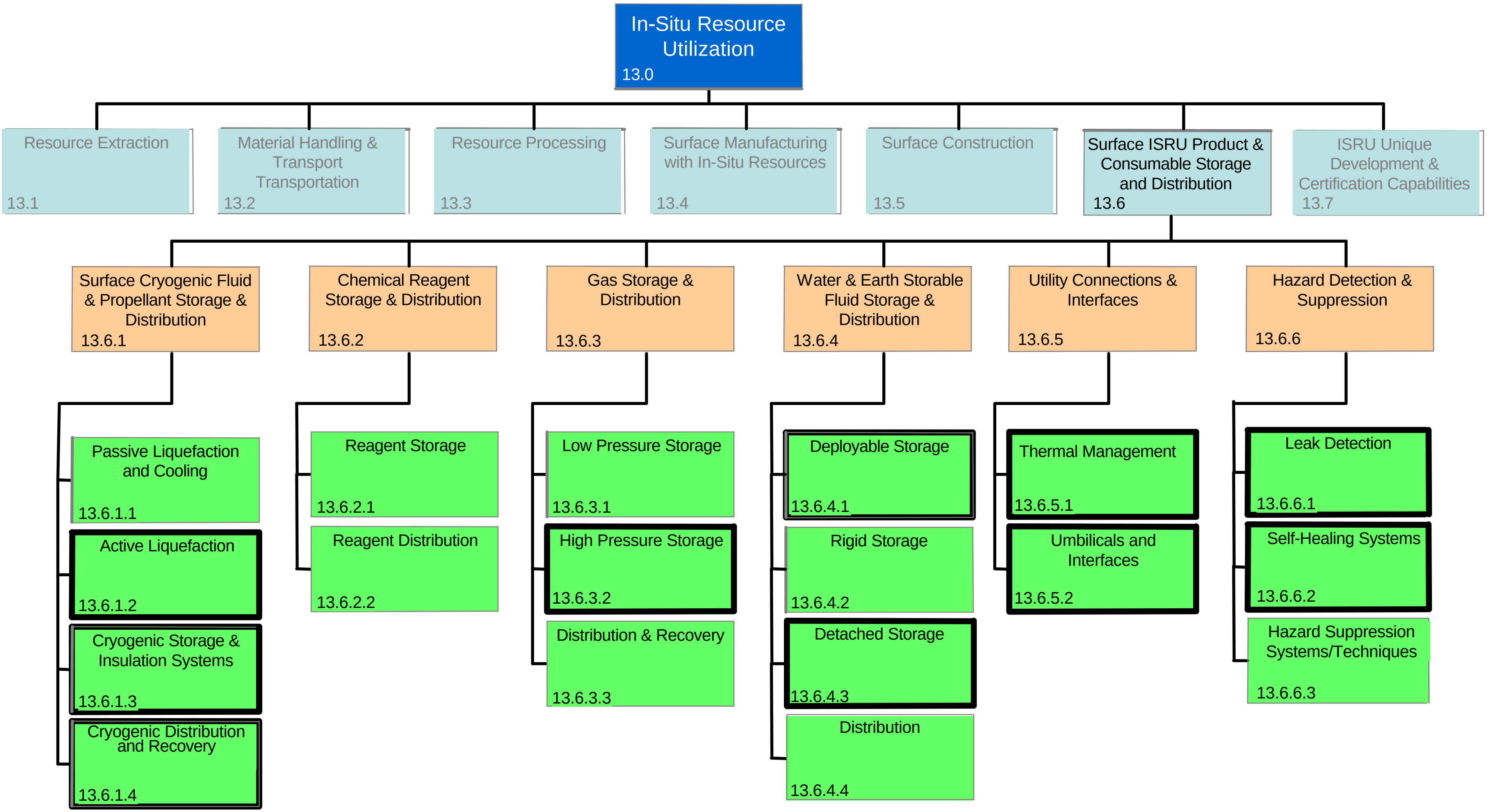
- Key attributes of Storage and Distribution Systems
  - High storage capacity to launch mass and volume ratio
  - Highly reliable systems (minimum repair and long service life)
  - Highly redundant, modular, interchangeable active components
  - Autonomous Control (minimum ground & flight crew involvement)
  - Energy efficient systems
  - Versatility - services many end users
  - Expandable to support increasing mission scenarios/larger bases
  - Robustness in harsh environment
  - Increases inherent safety level of exploration architecture

Benefits of the Capability 13.6 Surface ISRU Product and Consumable Storage and Distribution

- Provides redundant cache of life support consumables (oxygen, buffer gasses and water)
  - Safe Haven stores for ASARA exploration architectures
- Provides long term, zero loss storage of earth return propellants
- Manages and delivers propellant/reagents for increased surface mobility
  - Rovers, hoppers, EVA suits and devices
- Increases mission reliability by pre-positioned stores of earth return propellant
  - Reduced launch mass from earth
  - Smaller exploration vehicles
- Enables energy storage for long lunar night
- Provides thermal storage capability to support integrated thermal management system
- Integral part of extraterrestrial recycling center (fuel cell water cycle)

Surface ISRU Product and Consumable Storage and Distribution

Team 13: In-Situ Resource Utilization



Requirements /Assumptions for 13.6 ISRU Product Storage & Distribution

- ISRU supported missions and precursors will require storage and distribution capability – near term technology needs
  - Long production times (to minimize size and mass of production plants) require storage capacity
- Highly reliable, autonomous systems are needed to minimize crew workload and maximize safety and mission success probabilities
- Launch volume and launch mass are key parameters to keep launch rate and size of launch vehicles at an affordable level
- Small, modular systems that can be easily expanded and/or replaced are highly desirable for long term exploration success
  - Common hardware and subsystems are to be used where ever possible
- Technology development for storage and distribution is synergistic with In-space Transportation Propellant Depots but unique environmental conditions warrant separate development and demonstration
- ISRU intermediate products (bricks, I-beams) are stored at production facility until end user is ready for delivery by ISRU transportation element

ISRU Storage & Distribution Interdependency with other Capabilities

Team 13: In-Situ Resource Utilization

Products From Storage & Distribution	Capability	Capability Products To Storage and Distribution
• Fuel Cell Reactant Storage & Distribution • Propellant Storage & Distribution	High-Energy Power & Propulsion (2)	• Solar & nuclear power to support power-intensive ISRU activities
• Fluid storage and distribution for transfer to in-space depots	In-Space Transportation (3)	• ISRU-compatible propulsion • Electromagnetic launch systems for delivery of ISRU products
• Storage & Distribution of fuel cell reagents for rovers • Propellant storage & distribution for surface hoppers or large sample return missions	Robotic Access to Planetary Surfaces (6)	• Interface coordination for fluid transfer • Water by-products of rover fuel cells
• Propellant storage & distribution for lander reuse	Human Planetary Landing Systems (7)	• Interface Coordination for fluid transfer • Delivery of ISRU capabilities to sites of exploration
• Gases for habitat inflation & buffer gases • Life support consumable storage & distribution	Human Health and Support Systems (8)	
• Gases for science equipment • Propellants & fuel cell reactants for surface vehicles and aero-bots • O_2 & water distribution for EVA	Human Exploration Systems & Mobility (9)	• Interface coordination for fluid transfer • Water by-products of rover fuel cells
• Fluid storage & distribution	Autonomous Systems & Robotics (10)	• Robots/rovers to perform maintenance & repair • Software & Failure Detection and Repair logic for autonomous operation
	Scientific Instruments & Sensors (12)	• Highly reliable, self calibrating instrumentation and sensors

Storage and Distribution Interdependency with other ISRU Elements

ISRU Element Products To → **Storage & Distribution** → **Products To ISRU Elements**

ISRU Element Products To

Resource Extraction
- Raw or purified gases for storage

Resource Transportation
- Surface mobility for transporting tankers to end users
- Water by-products from rover fuel cells for recycling

Resource Processing
- All gaseous production for liquefaction and storage

Surface Manufacturing
- In-situ storage & distribution components

Surface Construction
- Initial deployment site prep
- Protection berm

Storage & Distribution

- Cryogenic Fluids
- Chemical Reagents
- Gases
- Water/Earth Storable Fluids
- Utility Connection & Interfaces
- Hazard Detection & Suppression

Products To ISRU Elements

Resource Extraction
- Fluids for extraction processes

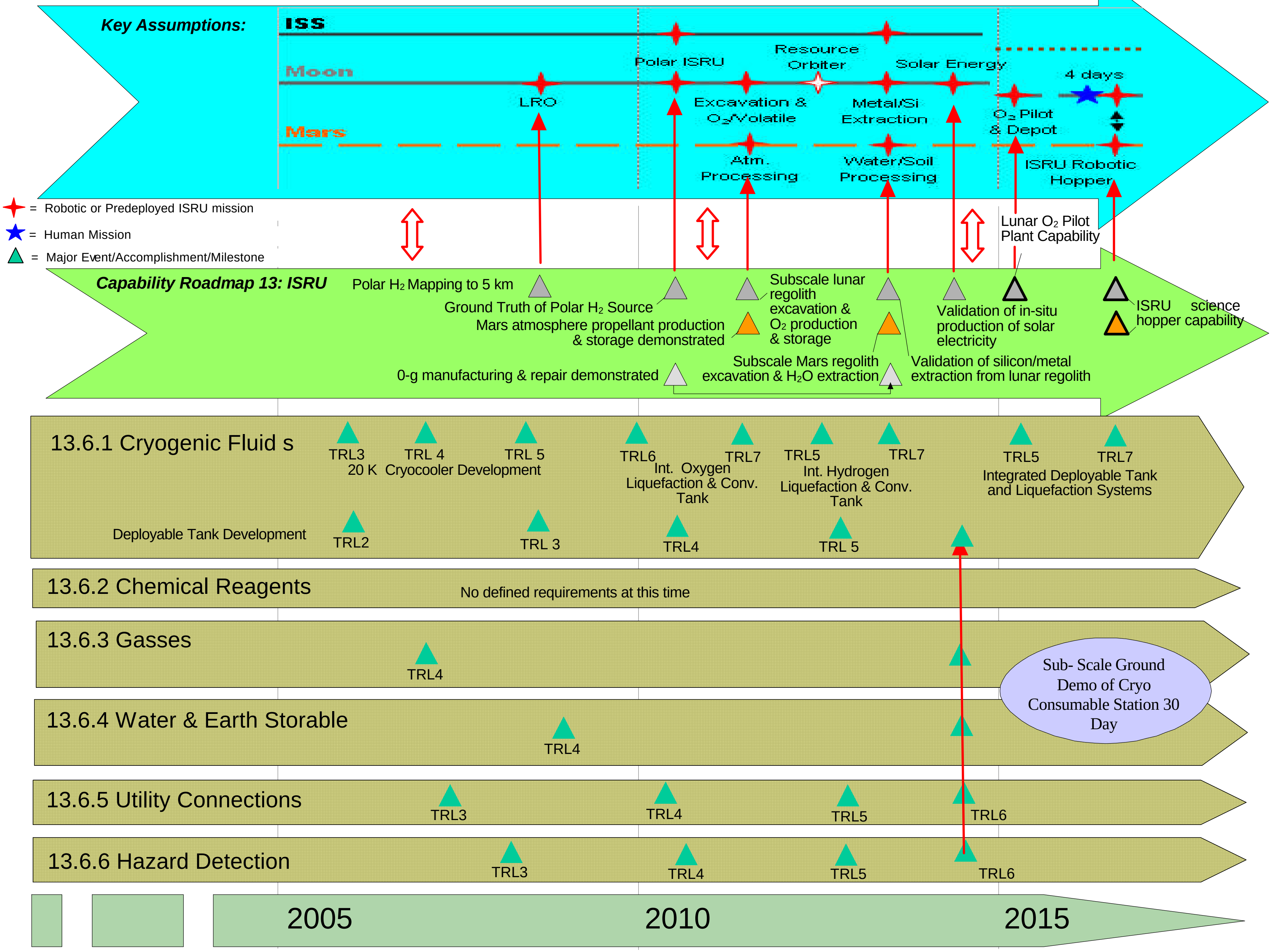
Resource Transportation
- Fluids for transportation vehicles

Resource Processing
- Process fluid replenishment
- Water for reprocessing

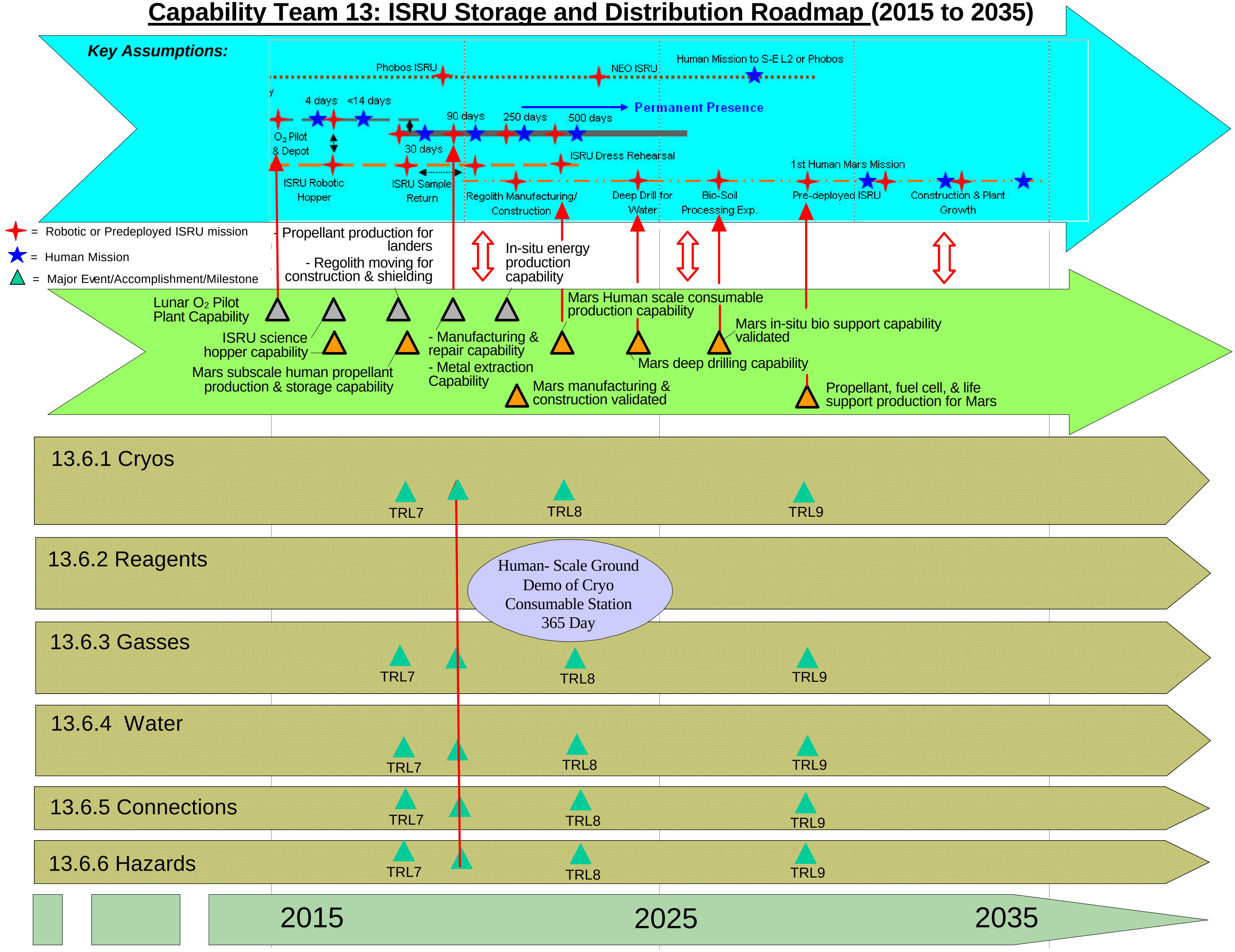
Surface Manufacturing
- Fluids for manufacturing processes

Surface Construction
- Fluids for construction vehicles & equipment

Capability Team 13: ISRU Storage and Distribution Roadmap (2005 to 2015)



Capability Team 13: ISRU Storage and Distribution Roadmap (2015 to 2035)



Liquefaction:

- Flight rated cryo-coolers are limited in size and capacity
  - Larger prototype 80K (LOX) systems are at a much higher level than 20K (LH2) systems
    - 10W, 80K Cryocoolers at TRL9, 100W at TRL5, 500W at TRL 2
    - 10W, 20K Cryocoolers at TRL2

Storage:

- Flight rated fixed systems are mature but do not have integrated liquefaction systems
  - Vacuum jacketed, cryogenic tanks, supercritical tanks and high pressure gas storage are fixed volume, heavy systems (shuttle PRSD and centaur propellant tanks)
- Low initial volume tanks are at TRL 2

Distribution/Transfer:

- Automatic Umbilicals are TRL 4/5
- Deployable cryogenic transfer lines are at TRL 2

System Health:

- Autonomous control of dynamic processes is TRL 2
- Leak Detection systems in vacuum and low pressure atmospheres TRL 2/3

Maturity Level – Capabilities for Storage and Distribution

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assessment		
		CRL	R&D3	Need Date
Cryogenic Fluid Storage and Distribution	*20K Cryocoolers, 100's of Watts cooling*	1	*III*	2012
	80K Cryocoolers, 100's of watts cooling	1	*II*	2010
	Low Launch Volume Cryogenic Storage Tank	1	*III*	2012
	Insulation systems	3	*II*	2012
	Long life compressors & motors	2	*II*	2016
	Deployable Transfer Lines	2	*III*	2016
	Portable Tanker Development	3	*II*	2014
	Low mass/volume components	2	*II*	2014
Gas Storage and Distribution				
	Low Pressure deployable	2	*II*	2014
	Sorption systems	1	*II*	2016
	Multi-phase systems	2	*II*	2016
	High Pressure deployable	2	*II*	2020
	Long life compressors & motors	2	*II*	2016
	Deployable high pressure lines	2	*II*	2020
	Portable Gas cylinder development	3	*II*	2014
	Low mass/volume components	2	*II*	2014
	Recovery Systems	2	*II*	2016

Maturity Level – Capabilities for Storage and Distribution

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assessment		
		CRL	R&D3	Need Date
Water and Earth Storable Storage & Dist.				
	Deployable Storage	1	*I*	2016
	Detachable Storage	1	*II*	2020
	Distribution System Development	2	*I*	2016
Utility Connections and Interfaces	Adv Thermal Management Systems	2	*II*	2016
	Adv Thermal Management Devices	2	*II*	2012
	Automated Umbilicals	2	*I*	2014
	Self-healing Seals	1	*II*	2014
	Low mass/volume Components	1	*II*	2014
	Long life Drive Motors	1	*II*	2016
Hazard Detection and Suppression	Point Sensor Development	2	*II*	2014
	Gas Chromatograph/Mass Spectrometer	1-2	*III*	2014
	Nano Sensors	2	*III*	2014
	Self-healing Systems	2	*III*	2014
	Hazard suppression systems	3	*III*	2014
	Halon Replacement	2	*II*	2014

Maturity Level – Technologies Storage and Distribution

Technology	Capability Applications	Readiness Assessment		
		TRL	R&D3	Need Date
20K Cryocoolers, 100's of Watts	*CFSD*	*2*	*III*	2014
80K Cryocoolers, 100's of watts cooling cooling	*CFSD*	*4*	*II*	2014
Low Launch Volume Cryo Storage Tank	*CFSD*	*2*	*III*	2014
Insulation systems	*CFSD*	*5*	*II*	2010
Long life compressors & motors	*CFSD, GSD*	*4*	*II*	2010
Deployable Transfer Lines	*CFSD*	*2*	*III*	2014
Portable Tanker Development	*CFSD*	*3*	*II*	2014
Low mass/volume components	*CFSD, GSD, UCI*	*3-6*	*II*	2014
Low Pressure deployable	*GSD*	*3*	*II*	2010
Sorption systems	*GSD*	*4*	*II*	2010
Multi-phase systems	*GSD*	*4*	*II*	2014
High Pressure deployable	*GSD*	*2*	*II*	2014
Deployable high pressure lines	*GSD*	*2*	*II*	2016
Portable Gas cylinder development	*GSD*	*5*	*II*	2014
Recovery Systems	*GSD*	*3*	*II*	2014

Maturity Level – Technologies Storage and Distribution

Technology	Capability Applications	Readiness Assessment		
		TRL	R&D3	Need Date
Deployable Storage	*WSD*	*4*	*I*	2014
Detachable Storage	*WSD*	*4*	*II*	2014
Distribution System Development	*WSD*	*4*	*I*	2014
Adv Thermal Management Systems	*UCI*	*2*	*II*	2020
Adv Thermal Management Devices	*UCI*	*2*	*II*	2020
Automated Umbilicals	*UCI*	*3*	*I*	2014
Self-healing Seals	*UCI*	*2*	*II*	2014
Long life Drive Motors	*UCI*	*4*	*II*	2014
Point Sensor Development	*HDS*	*3*	*II*	2014
Gas Chromatograph/Mass Spectrometer	*HDS*	*4*	*III*	2014
Nano Sensors	*HDS*	*2*	*III*	2020
Self-healing Systems	*HDS*	*2*	*III*	2020
Hazard suppression systems	*HDS*	*2*	*III*	2020
Halon Replacement	*HDS*	*4*	*II*	2014

Metrics for Storage & Distribution

- Summary of Storage & Distribution Metrics For Technology Trades
  - Mass of Commodity Stored/Launch Mass
  - Volume of Commodity Stored/Launch Volume
  - Thermal and Energy Efficiency of total system (input power/kg of propellant liquefied and stored/day)
  - Mean Time Between Failure of active components
  - Degree of System Autonomy (Ground controller manhours/week/kg of propellant stored)
  - Propellant Transfer Losses (kg lost/kg transferred)

Metrics for Storage & Distribution

- Summary of Progress Metrics (Same as Resource Processing)
  - All Component Technologies Are At TRL 4 At Least 6 Years Prior To Need Date
  - All Component Technologies Reach TRL 6 At Least 3 Years Prior To Need Date
  - Continuous Operation for 30 days 5 years before need date.
  - Continuous, Autonomous Operations in an Mission Simulated Environment for 1 year, 3 years before need date

Current Storage & Distribution Projects

Exploration Funded Projects

- Lockheed Martin has two Extramural Contract Awards
  - Integrated ISRU for Human Exploration - Propellant Production for the Moon and Beyond:
    - Liquefaction and storage of oxygen produced from lunar soil
    - Pulse tube cryocooler and lightweight, rigid tanks
  - High Energy Density Power System
    - High pressure gas storage for fuel cell reactants

- Several SBIR/STTR Phase II projects in recent years
  - Insulation systems
  - Cryocoolers
  - Valve technology
  - Automated umbilical
  - Gas detection sensors

Technology Gaps for Storage & Distribution

- 20K Cryocooler, space rated, 100's of watts cooling
- Deployable tanks and distribution systems for cryogenic fluids
- Deployable tanks and distribution systems for high pressure gas.
- Long life compressors and motors for extraterrestrial applications
- Large Scale liquefaction and long term storage of cryogenics with flight weight systems/components
- Autonomous control of dynamic processes
- Leak detection in open vacuum or low atmospheric environments
- No calibration required - sensors and instrumentation
- Self-healing systems development
- Improved Energy Efficiencies/Integrated Thermal Management

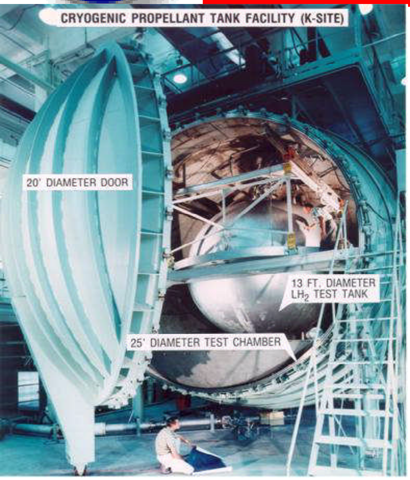
Capability Development Strategy
(Same as Resource Processing)

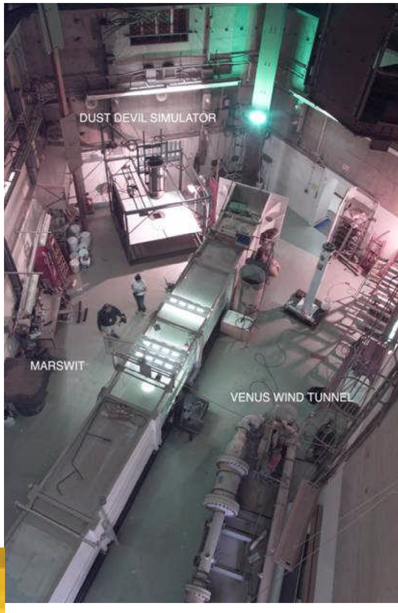
- There Is No One "Best Solution" For Storage and Distribution of fluids on the moon and Mars.
  - One Technology May Trade Better Than Another Depending On The Architecture

- As Architecture Options Mature Trade Studies Will Be Used To Down Select To A Set Of Technologies That Have The Potential Meet Mission Requirements.

- These Technologies Will Be Developed To TRL 5 And Another Downselection Will Occur.
  - Performance Metrics And Mission Requirements Will Be The Determining Factor.

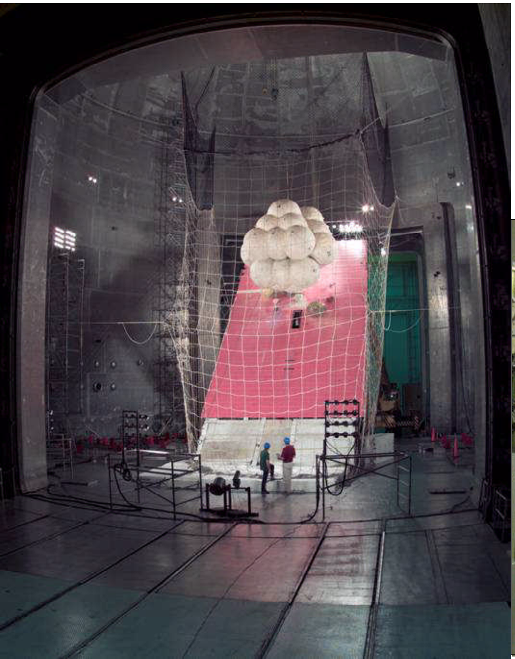
- The Suite Of Technologies Will be Flight Tested On Robotic Precursor Missions To Validate The Capabilities Readiness For Insertion Into The Critical Path For Human Missions.

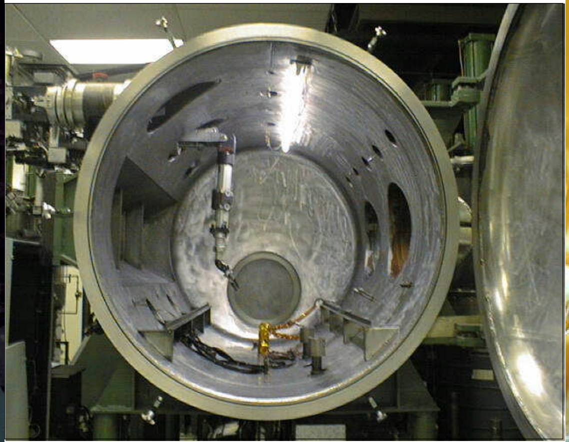




ISRU Capability Element 13.7
ISRU Unique Test and Certification

Diane Linne and Michael Downey
NASA Co-Leads





Unique Test and Certification Roadmap Element Team

Co-Chairs

NASA: Diane Linne
NASA: Michael Downey

NASA

- Phil Metzger
- Dr. Allen Wilkinson
- Robert Green
- Stan Starr
- ~15 NASA Facility Managers

Industry

- Larry Clark, Lockheed Martin Astronautics
- Dr. Laurent Sibille, BAE Systems

Academia

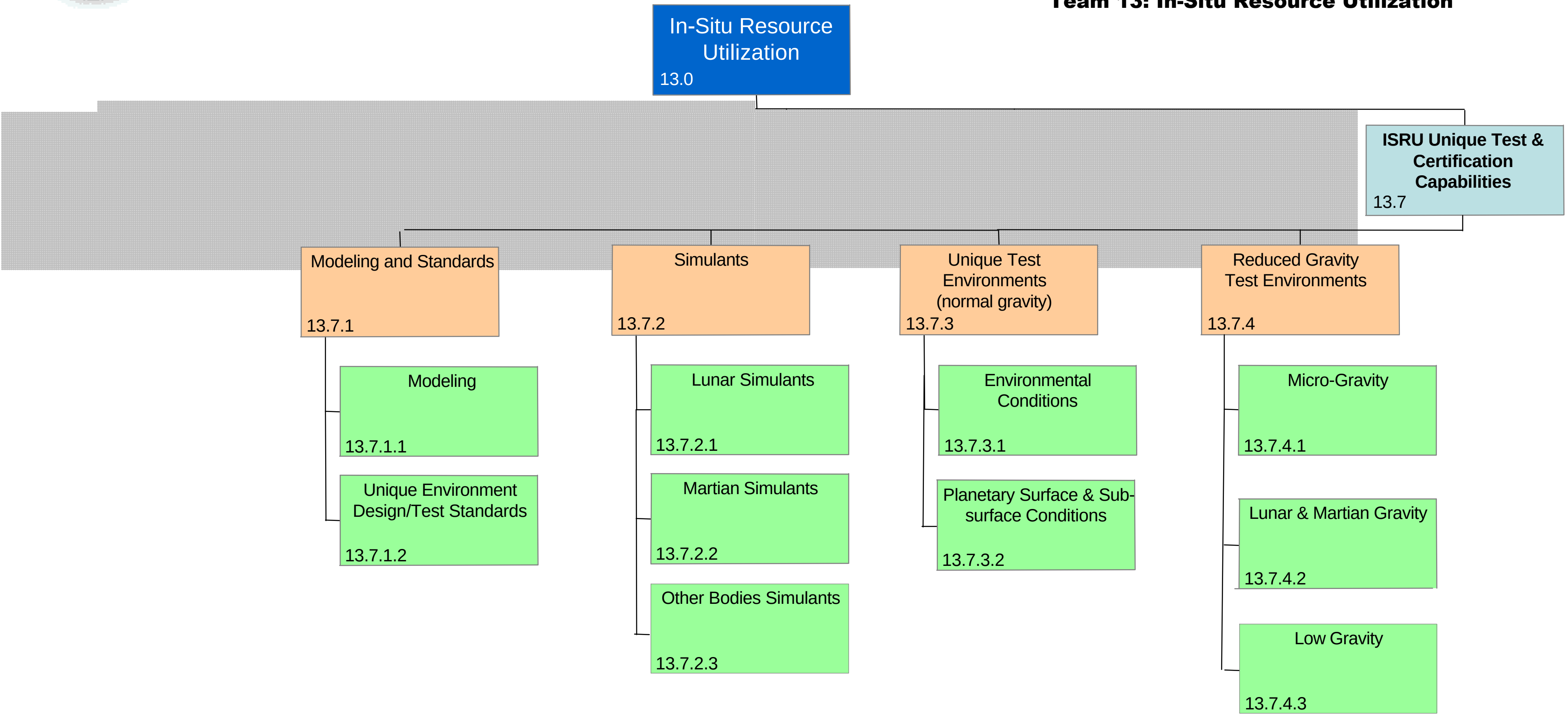
- Dr. Leslie Gertsch, University of Missouri-Rolla
- Brad Blair, Colorado School of Mines

Description of Capability 13.7: ISRU Unique Test and Certification

- Unique Test and Certification is the set of capabilities needed to support development, test, and certification of all of the ISRU technologies and capabilities
- Three Focus Areas
  - Modeling and Standards
    - extraterrestrial soil behavior and characterization models, ISRU component and system models
    - standardized procedures & guidelines for use of soil simulants, environmental testing, life/cycle tests, etc. for all elements
    - standardized set of metrics for modeling and technology comparisons
  - Simulants
    - Terrestrial geological materials (rocks, basalts, other minerals) selected for their similar characteristics to Lunar & Martian regolith, rock, and dust
    - Careful mixture of gases (and dust) to simulate Martian atmosphere
  - Unique Test Environments
    - Environmental simulation such as thermal extremes, low vacuum, thermal cycles, simulated atmosphere, dust, wind, radiation, surface and sub-surface conditions
    - Gravity simulation of micro-g, lunar & Martian gravity, low-g
- Unique Test and Certification receives unique or hardware-specific requirements definitions from the other six elements
- Unique Test and Certification provides to the other six elements the standard models, simulants, and environments required to design, develop, test and certify the ISRU hardware and systems

ISRU Unique Test & Certification Capabilities

Team 13: In-Situ Resource Utilization



Attributes of Unique Test and Certification

- Lunar regolith simulants
  - Root simulants (basalts, anorthite, pyroclastic glass) - grain size distribution match, dust portion below 20 microns
  - Derivative simulants - additions to root simulants
- Martian regolith simulants
  - Spectral match to Martian regions (for remote sensing, in-situ optical analysis)
  - Extremely low moisture content, absence of organics, DNA
  - H_2O_2 modified TiO_2 (simulates available Martian atm. oxidant produced by UV)
  - Airborne dust portion is magnetic
  - Regolith grains are weathered, contain no toxic metals
- Pressure and temperature environments
  - lunar day: 10^{-10} torr / 255 - 390 K
  - lunar night: 10^{-11} torr / 120 K
  - lunar poles: 10^{-11} torr / 40 K
  - Mars: 2.5 - 7.5 torr / 145 - 240 K
- Mars Wind: 300 km/hr

Benefits of Unique Test and Certification

- Modeling & Standards - Enables apples-to-apples comparisons between technologies
  - Concurrent development and validation of ISRU soil, component, and system models will reduce Design, Develop, Test & Evaluation (DDT&E) time and costs
  - Final flight validation by testing alone may not be possible
  - Common set of standards provided to all elements guides technology and capability development
- Simulants - ensures tests conducted on physical (excavation, transport, etc.) & chemical processes are relevant (i.e. properly address key driving forces & processes)
  - Avoid depleting existing collections of lunar and meteorite samples
  - Provide large quantities of materials to test and validate designs
  - Provide a substitute in the absence of Mars samples
  - Available for validating other flight hardware such as landers, habitats, EVA equipment, etc.
- Unique Test Environment
  - Careful simulation of the actual operating environment significantly reduces the risk of implementing ISRU technologies
    - example when environment not properly simulated: Apollo lunar dust environment caused detriment to astronaut health in cabin, severe space suit degradation
    - example when environment successfully simulated: Space Shuttle APU developed at 1 atm, but when original design was tested with proper ascent profile hardware exploded – because test was performed hardware could be redesigned before flight program
  - Much cheaper to test in simulated conditions on/near Earth than flight demos on moon/Mars
  - Allows post-test access to hardware for analysis and modifications

Team Assumptions for Unique Test and Certification

- The need for physically & chemically-accurate lunar and Martian regolith simulants is a unique requirement for the development of the ISRU Capability
  - Other capabilities may be interested in dust simulants for final qual tests
  - Simulant materials will evolve in time based on new data provided by science missions to the moon and planets
- The need for highly-accurate test environments will be a strong early need for the development of the ISRU Capability
  - ISRU uses the environment, while most other capabilities fight it or merely "live" with it
  - ISRU capability developers will need to define & develop this capability even though other capabilities may then want to utilize it
- In general, the surface manufacturing, surface construction, and storage and distribution elements will be using material already partially beneficiated & processed by the other ISRU elements
- Test will need to be performed at the discreet gravity levels that represent the moon and Mars
- Single identified set of test and certification capabilities (models, simulants, facilities) for all ISRU elements provides consistency & reduces costs

Unique Test and Certification Interdependency with other Capabilities

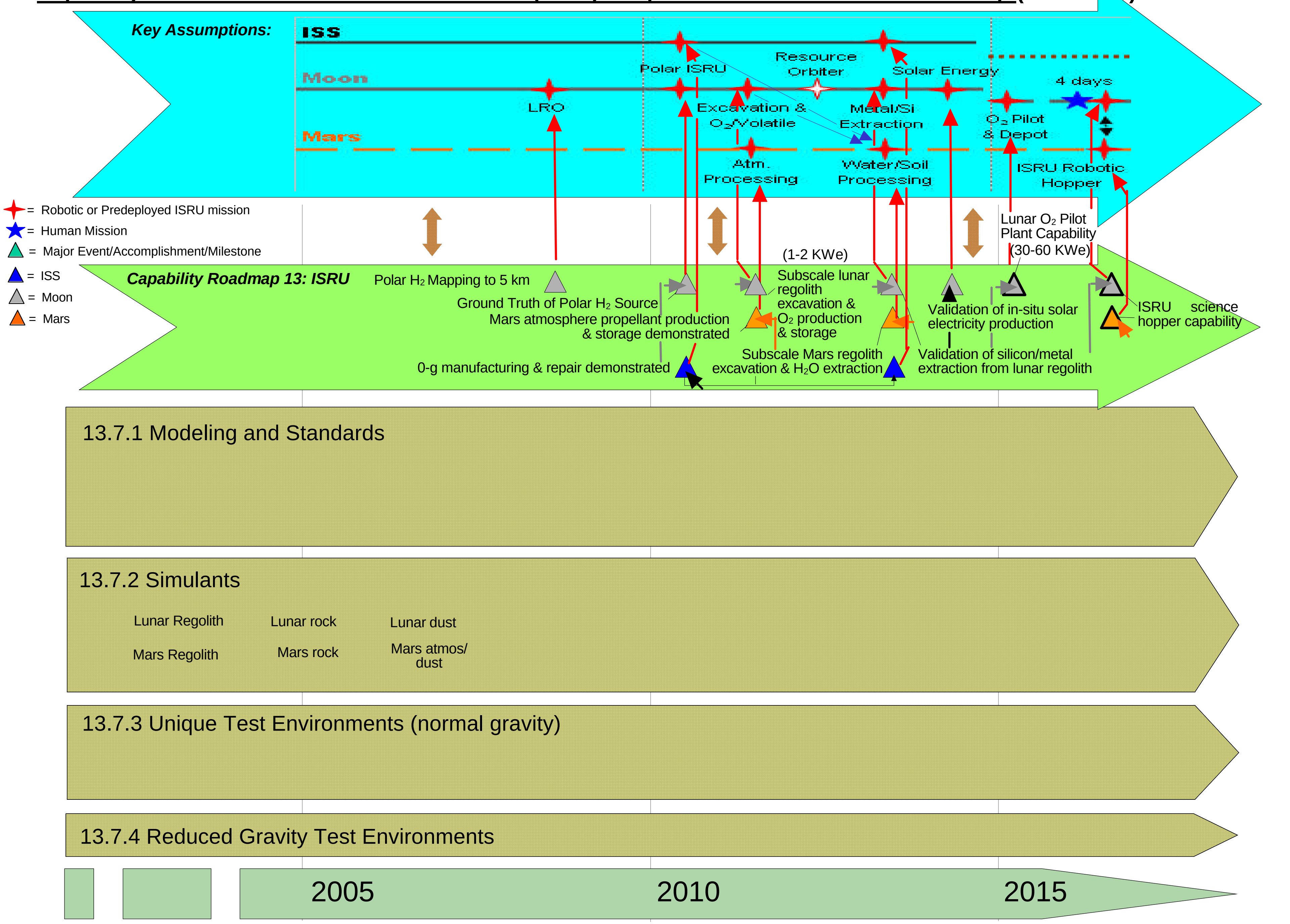
Products from Unique Test/Cert	Capability	Products to Unique Test/Cert
Unique Lunar and Mars test environment plus: • Simulants for solar array development	High-energy power and propulsion (2)	• Compact power for surface demos
• Long-term dust effects on ascent propulsion system operations • Soil mechanics models for rocket plume cratering analysis	In-space transportation (3)	
• Dust accumulation/removal on optics for surface telescopes	Advanced telescopes and observatories (4)	
• Soil mechanics for tire/soil interaction	Robotic access to planetary surfaces (6)	• in-situ measurement of soil properties • possible sample returns
• Long-term dust effects on spacesuits, life support systems, etc.	Human Health and Support Systems (8)	
• Long-term dust effects on mobility systems • Simulation/modeling of surface regolith/compactness for rovers	Human Exploration Systems & Mobility (9) Autonomous Systems & Robotics (10)	
• Opportunity to piggy-back on tests in unique environments	Scientific Instruments & Sensors (12)	• Advanced sensors and instruments for tests • Advanced sensors and instruments for robotic in-situ measurements
	Advanced modeling, simulation, analysis (14)	• Computational software technologies to support development of ISRU models • Infrastructure libraries and tools for science/engineering modeling

Unique Test and Certification Interdependency with other ISRU Elements

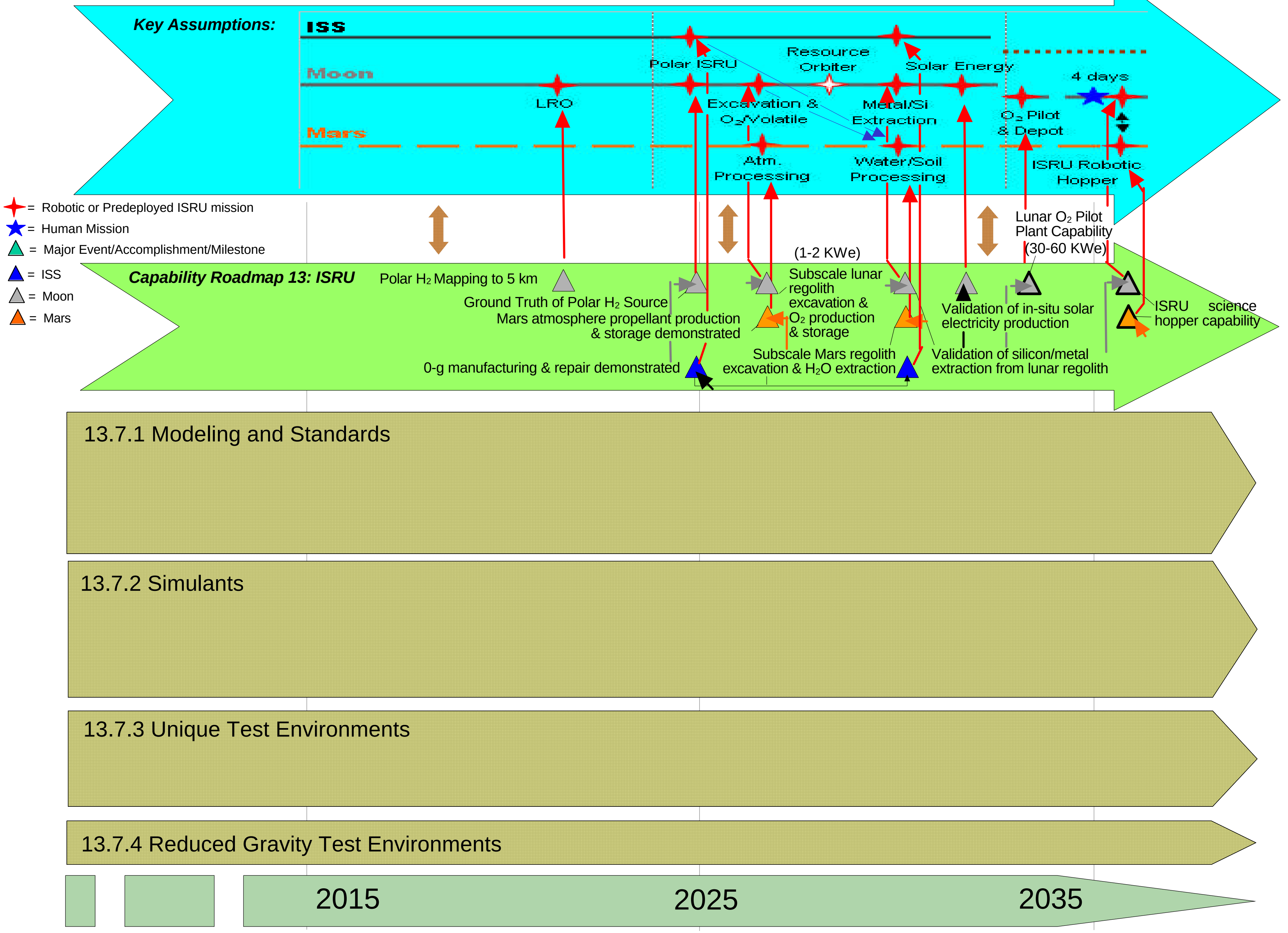
Team 13: In-Situ Resource Utilization

ISRU Element Products To	Unique Test and Certification	Products or Services From Unique Test and Certification
All Elements • Unique or hardware-specific requirements definition • Mission-driven requirements definition (e.g. length of time for tests)	Modeling and Standards Simulants Unique Test Environments - Normal Gravity Reduced Gravity Test Environments	**Resource Extraction** • All simulant types • Stratigraphy (layering simulation) • Test and certification environment **Material Handling and Transport** • All simulant types • Test and certification environment **Resource Processing** • All simulant types • Test and certification environment **Surface Construction** • Regolith and dust simulants • Test and certification environment **Surface Manufacturing w/ In-Situ** • Dust simulants • Test and certification environment **Product Storage & Distribution** • Dust simulants • Test and certification environment

Capability Team 13: In Situ Resource Utilization (ISRU) Unique Test and Certification Roadmap (2005 to 15)



Capability Team 13: In Situ Resource Utilization (ISRU) Unique Test and Certification Roadmap (2015 to 35)



Current State-of-the-Art for Unique Test and Certification

- Modeling and Standards
  - Regolith Characterization and behavior
    - extensive literature on modeling terrestrial soil mechanics
    - powder industry has elaborate bench-top to full process plant development process - extremely expensive and time-consuming process
    - Granular flow clogging is a common industrial problem with 'kick-the-chute' solutions
  - Component models of various fidelity developed by individual researchers to support very specific short-term studies and goals
    - primarily for chemical processing and storage components
  - System models
    - ISRU economic model in development by Colorado School of Mines - requires technical inputs for components
  - Design/Test Standards
    - ASTM and ASAE standards for (terrestrial) traction and soil mechanics

- Simulants
  - ~27,000 lbm of JSC-1 lunar simulant produced in early 1993 - no longer available
    - represents an average chemical composition between the highlands and mare regions of the moon
  - MLS1 lunar simulant (1987) - no longer available
  - FJS1 - lunar simulant - Japan - available in modest quantities
  - JSC Mars1 Martian simulant chosen for reflectance spectrum close to Mars bright areas
  - Atacama Desert Martian simulant chosen for very low organic concentrations

Current State-of-the-Art for Unique Test and Certification

- Lunar Test Environments
  - Complete thermal range available
  - Large chambers can reach 10^{-8} torr at best
  - Current best chambers identified so far offer mix of requirements, sizes, and capabilities
    - Largest at best pressure and temp (10^{-8} torr and 40 K (or other lunar temps)) is 4 m diameter (K-Site at NASA GRC-Plum Brook) - *but not currently rated for simulants (oil diffusion pumps)*
    - Largest at best pressure and temp ($5x10^{-7}$ torr and 80 K) that can *tolerate* simulants (cryopumps) is 7.5 m dia x 20 m (VF6 at NASA GRC) - *cannot control to other temps and has not actually tested with simulants*
    - Largest at best pressure and temp (10-6 torr and 80 K) that has used simulants and can vary/control temperature (Space Power Facility at NASA GRC - Plum Brook)
    - Largest at best pressure, temp (10^{-6} torr and 77 K) that has used simulants with remote manipulation capability is 2 m x 2 m x 3 m (Planetary Surface Environment Simulation facility at Lockheed-Martin)
- Mars Test Environments
  - Atmospheric gases have been simulated
    - JSC Mars Simulation Chamber (e.g.), 6.1 m diameter
    - typically 3-gas simulation (CO_2, Ar, N_2), but some have added O_2 and H_2O
  - JSC .6 m belljar simulation of atmosphere, wind, and Martian dust
  - Mars Wind Tunnel (NASA Ames) simulates winds/dust to 100 m/s, 1.2 m square by 16 m long - no thermal simulation
- Micro/partial gravity for short durations
  - Drop towers: 5.2 sec max for micro-g only, 1 m dia x 1.65 m high
  - Reduced-gravity aircraft: 20 sec micro-g, 30 sec lunar-g, 40 sec Martian-g, 50’ x 8’ x 6.5’ test hardware
  - Sounding rockets (5 - 6 mins, 1/2 m x 2 m test hardware)
- Micro-g for long durations
  - ISS glove-box (.9m x .5m x .4m (ave))
  - ISS integrated experiment racks (delivered to Station in May, 2007)
    - Combustion Integrated Rack: 0.4 m dia x 0.6 m; Fluids Integrated Rack: 1.1 m x .9 m x .5 m

Maturity Level – Capabilities for Unique Test and Certification

Capability	Key Technologies or Sub-Capabilities	Capability Readiness Assesment		
		CRL	R&D3	Need Date
Modeling and Standards	Regolith characterization and behavior - soil mechanics	1	*III*	
	Regolith characterization and behavior - granular flows	1	*III*	
	ISRU component models	2	*II*	
	ISRU system models	1	*II - III*	
	Unique environment design/test standards	1	*II*	
Simulants	Lunar regolith	3	*II*	
	Lunar rock	1	*II*	
	Lunar dust	1	*II*	
	Martian regolith	1	*III*	
	Martian rock	1	*II*	
	Martian dust	1	*III*	
	Martian atmosphere	4	*II*	
	Other Bodies	1	*III*	

Maturity Level – Facility Capabilities

Table is based on preliminary survey of facilities at NASA GRC, KSC, JSC, and ARC, and Lockheed-Martin - many more out there to evaluate (including more industry and DoD)

Test Condition	Requirement	Best Match Found So Far	Key Gaps (R&D3) to get to required condition
Lunar Day	10^{-10} Torr/255 - 390 K	$5x10^{-8}$ torr/ meets temp. requirement	Add helium pumping panels to get down to 10^{-10} torr (III)
Lunar Night	10^{-11} Torr/120 K	$5x10^{-8}$ torr / meets temp. requirement	Add helium pumping panels to get down to 10^{-11} torr (III)
Lunar Poles	10^{-11} Torr/40 K	$5x10^{-8}$ torr / meets temp. requirement	Add helium pumping panels to get down to 10^{-11} torr (III)
Mars (varies by day/night and winter/summer)	300 - 1000 Pa (0.044 - 0.145 psi)/145 - 240 K	several facilities meet pressure and temperature	
Mars Winds	300 km/hr (190 mph)	Meets wind, pressure, and simulants but not temp.	
Ability to accept simulants	dust (<20 microns) regolith (>20 microns)	demonstrated in 10-6 torr facility; possible in 10-7 torr facilities	Requires cryopumps (instead of oil diffusion pumps)
Reduced Gravity (specify g-level and max. time per test)	micro-g 1/6th Earth-g (moon) 0.38 Earth-g (Mars)	yes - long duration 30 seconds max 40 seconds max	Free-flying centrifuge facility for long duration (IV)

Maturity Level – Technologies Unique Test and Certification

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Quasi-static soils - predictive equations across wide conditions	Reg. characterization & behavior	2	II	
Quasi-static soils - relevant property identification	Reg. characterization & behavior	2	II	
Granular flows - equations of motion	Reg. characterization & behavior	1	III	
Granular flows - constituitive relations	Reg. characterization & behavior	1	III	
Granular flows - relevant property identificatio	Reg. characterization & behavior	2	II	
Ice composition and mechanics included in so models	Reg. characterization & behavior	1	III	
Root Simulant: Basalt-rich material representing Mare (lowlands) locations	Lunar regolith simulants	4	I	
Root simulant: Anorthite and feldspathic basal material representing Terrae (highlands) locations	Lunar regolith simulants	2	I	
Root simulant: Pyroclastic glass	Lunar regolith simulants	2	III	
Derivative simulant: Simulant materials specif to Lunar poles (ice and elemental concentrations)	Lunar regolith simulants	1	V	
Derivative simulant: Dust material (<20micron)	Lunar dust simulants	1	IV	
Derivative simulant: Impact-glass components added (agglutinates, microspheres)	Lunar regolith simulants	2	IV	
Derivative simulant: Nanophase metallic iron inclusions	Lunar regolith simulants	2	IV	
Derivative simulant; Specific mineral addition (e.g., olivine, ilmenite)	Lunar regolith simulants	3	I	
Derivative simulant: Volatile elements incorporation	Lunar regolith simulants	1	IV	
Derivative simulant: Specific chemical composition adjustments	Lunar regolith simulants	4	II	
Lunar rock properties simulations	Lunar rock simulants	1	IV	
Lunar rock simulants production, storage, & distribution	Lunar rock simulants	1	III	
Martian regolith physical properties simulation	Martian regolith simulants	2	III	
Martian regolith chemical properties simulatio	Martian regolith simulants	3	III	

Maturity Level – Technologies
Unique Test and Certification

Technology	Capability Applications	Readiness Assesment		
		TRL	R&D3	Need Date
Martian regolith mineralogical properties simulation	Martian regolith simulants	2	III	
Martian regolith simulants production, storage & distribution	Martian regolith simulants	3	III	
Martian rock physical properties simulations	Martian regolith simulants	1	V	
Martian rock chemical properties simulations	Martian regolith simulants	1	V	
Martina rock mineralogical properties simulations	Martian regolith simulants	1	V	
Martian rock simulants production, storage, & distribution	Martian regolith simulants	1		
Martian dust physical properties simulation	Martian dust simulants	4	III	
Martian dust chemical properties smulation	Martian dust simulants	2	IV	
Martian dust mineralogical properties	Martian dust simulants	2	V	
Martian dust simulants production, storage, & distribution	Martian dust simulants	1	II	
Martian atmosphere physical properties simulation	Martian simulants	4	I	
Martian atmosphere chemical properties simulation	Martian simulants	4	I	
Planetary moons properties simulations	Other bodies simulants	<1	V	
Asteroids properties simulations	Other bodies simulants	<1	V	
Comets properties simulations	Other bodies simulants	<1	V	

Technology Gaps for Unique Test and Certification

- Models and Standards
  - Detailed knowledge of the Martian regolith composition, fabric, microstructure
  - Role of tribo-charging and electrostatics
  - Ice composition and mechanics included in soil models
  - Basic physics of granular flows (static and dynamic equation equivalence of Navier-Stokes for fluids)
  - Traction, soil shear, granular mixing and separation issues in reduced gravity
  - Models that allow parametric sub-components performance inputs to identify effect on total component performance
  - End-to-end system models
  - Test protocols for use of simulants in component and system testing
- Simulants
  - Small fractions below 5 microns to adequately represent lunar dust
  - Anorthite mineral to represent ‘highlands’ regions (including polar regions)
  - Agglutinate fractions (represents up to 40% of typical lunar regolith mass)
  - Lunar rocks
  - Martian simulants for magnetic portion, rocks, <100 microns, chemical signature
- Unique Test Environments
  - Large chambers with vacuum levels below 10^{-8} torr (down to 10^{-11} torr - need actual requirement)
  - Vacuum chambers tolerant of simulants on large scale
  - Remote equipment to handle, distribute, charge, etc. simulants within vacuum chamber
- Reduced Gravity Test Environments
  - Capability for long-term simulation of reduced gravity (e.g. lunar or martian-g) – currently must send robotic demos to learn about and prove out reduced gravity capability
- Integrated Environments - thermal, vacuum, dust, *and* gravity

Unique Test and Certification Capability Development Strategy

- Modeling and Standards
  - Develop models with best existing data to aid in near-term trades
  - Structure initial models to allow continual updates of additional capability/technology definition as performance data becomes available
  - Develop standards for metrics across all ISRU elements
- Simulants
  - Develop root simulants for basalt-rich lowlands, anorthite and feldspathic basalt highlands, pyroclastic glass
  - Develop derivative simulants from mixture of roots to reflect mineralogical diversity of specific locations
  - Develop dust material simulants
  - Develop materials specific to lunar poles (ice and elemental concentrations)
  - Continually update simulant composition as additional information from science missions becomes available
- Designate some vacuum chambers as “dirty” facilities, others as “clean” facilities
  - Once dust and regolith simulants are introduced, may be difficult to clean back to level required for other Capability development (e.g. Adv Telescopes and Observatories)
- Tap into expertise in HSR&T (former microgravity) community to evaluate which technologies and processes from each element will be gravity-dependent
  - Determine whether micro-gravity will be sufficient/appropriate or whether actual gravity-level simulation is required

Metrics for Unique Test and Certification

- Modeling and Standards
  - Regolith characterization and behavior
    - predict standard soil mechanics indices ±10% (cone penetration, vane torsion, etc.)
    - Predict excavator torque and specific energy requirements ±10%
    - Predict vibration response of designed hardware in terrestrial environment ±10%
    - Predict flow rate, jamming power spectrum, energy spectrum required for unjamming ±20% compared to terrestrial hardware tests
  - Component and System models
    - Model matches existing hardware to ±5% on mass, power, useful output, recycling/resupply of consumables
    - Model successfully run by new user(s) with identical results
    - Number of components/capabilities included in system model
- Simulants
  - Validation of simulants by comparison to actual lunar samples or in-situ Martian measurements
  - Quality control process for simulant material to ensure batch-to-batch homogeneity
- Unique Test Environments
  - Vacuum and thermal matching
  - Tolerance to dirt (and willingness)
  - Size
  - Cost
  - Duration of reduced-gravity environment

ISRU For All Government (NASA, DOD, DOE, NOAA, Science) & Commercial Applications

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Fundamental Purpose For Commercializing ISRU

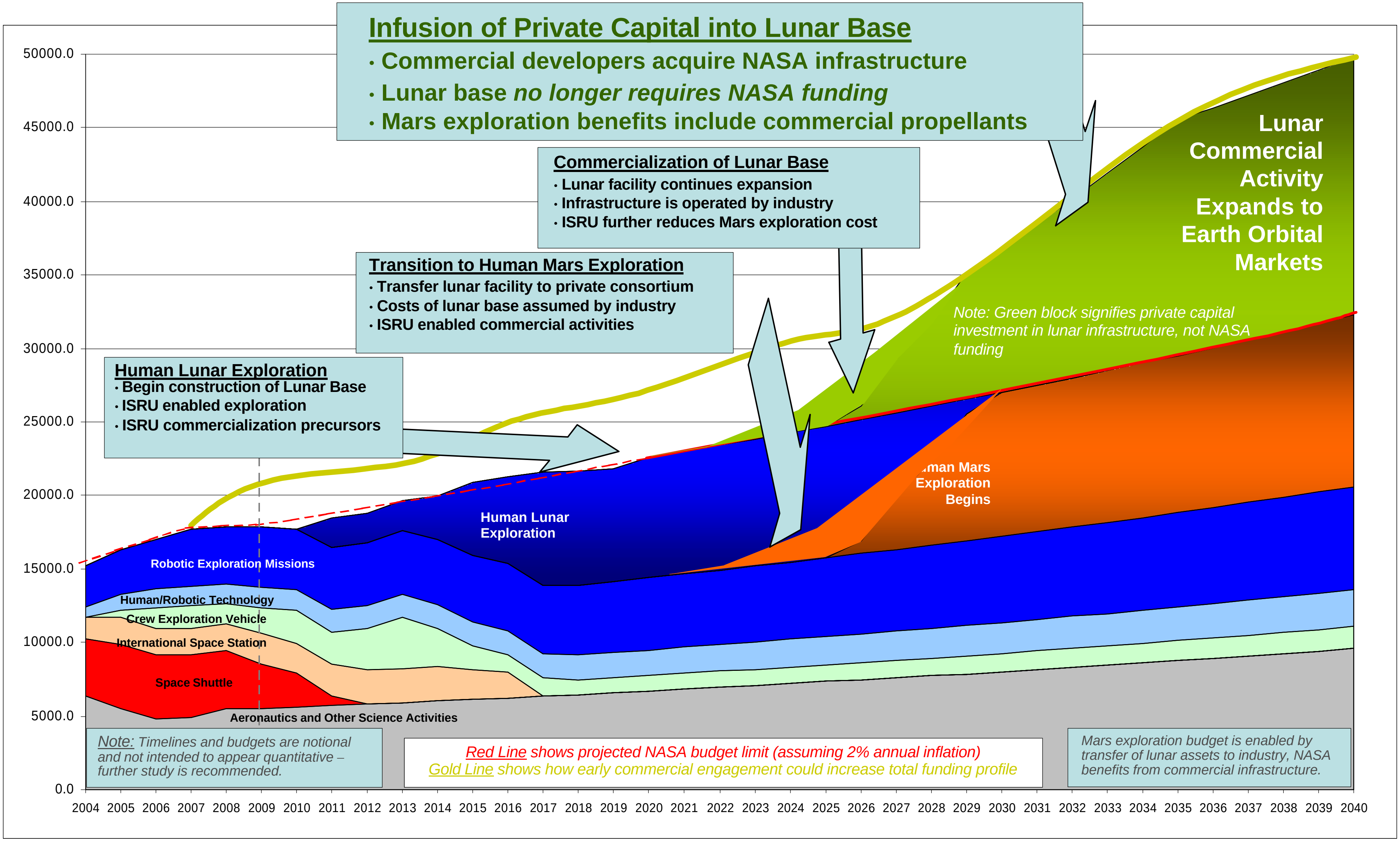
- NASA Guiding National Objective 4 (from NASA Strategic Plan, 2005)
  – Promote international and ***commercial participation*** in exploration to further U.S. scientific, security, and economic interests
- NASA Strategic Objective 17 (from NASA Strategic Plan, 2005)
  – Pursue ***commercial opportunities*** for providing transportation and ***other services*** supporting International Space Station and exploration missions beyond Earth orbit
- NASA Strategic Objective 18 (from NASA Strategic Plan, 2005)
  – Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve or ***increase the involvement of the U.S. private sector*** in design and development of space systems
- Unless the cost for Earth launch, in-space transportation, and planetary surface infrastructure and operations steadily decreases over time, 'sustained' and simultaneous human Moon and Mars operations will not be possible
  – Commercialization of government-developed technology and lunar infrastructure offers a rational pathway to sustainable exploration

Benefits of Commercializing ISRU

- Government-developed and operated ISRU can ***reduce cost and risk*** of human exploration compared to non-ISRU architectures, however further reductions in costs to government are possible if ISRU is 'commercialized'
- Money saved due to commercial ISRU and resulting infrastructure can support other aspects of the Space Exploration Program
  - Lunar ISRU commercialization can become a hand-off strategy, enabling human Mars exploration
- A partnership between industry and NASA can benefit both parties
  - NASA Benefits
    - Reduced operation costs and 'sustained' human exploration
    - Access to extensive terrestrial hardware and experience
    - Industry could steer technology development toward near-term market applications
    - Non-aerospace industries could provide additional congressional support
  - Industry Benefits
    - Anchor tenant and co-funding for technology and operations into emerging markets
    - Demos and ground/space laboratories to prove concepts and reduce risk for business plans and financing
    - Government support for favorable regulation
    - Reduced development costs and increase the likelihood of spin-off products and services

Lunar Commercialization Could Enable Budget for Mars

Team 13: In-Situ Resource Utilization



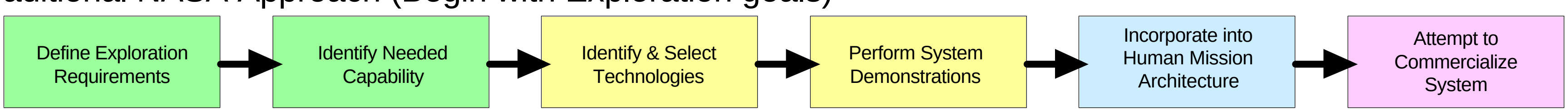
Approach to Commercializing ISRU

To ‘commercialize’ ISRU, markets besides NASA human exploration are required.

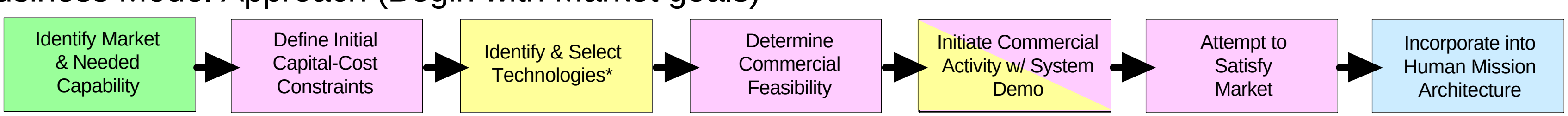
Note: Commercialization is **NOT** engaging a private company to design/build something where their main source of profit comes from the process and not the final product’s use.

- Identify ISRU capabilities that could be of benefit to multiple customers (Science, National Security, Public Interest, Economic Security)
- Identify impediments to commercialization (technology, policy/regulations, risk, etc.)
- Initiate NASA/Government activities to promote ISRU commercialization
  - Infrastructure, research & development, coordination, etc.
- The ‘Business Model’ will drive the Missions; Early Human exploration ISRU demonstrations could:
  - Develop and demonstrate technologies & operations to reduce risk
  - Business models can accelerate/defer ISRU demo prioritization and timing

Traditional NASA Approach (Begin with Exploration goals)



Business Model Approach (Begin with Market goals)



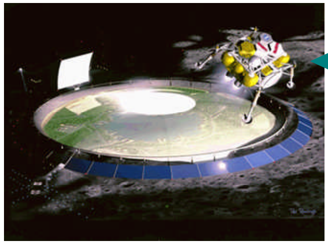
*Selection of Technology is based on optimum cost not performance

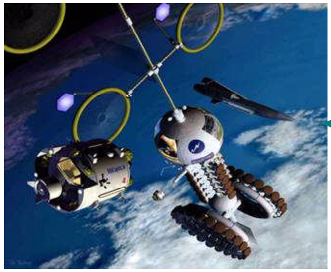
Market Identification

- Most Space Resources-related Exploration Applications have Commercial Potential
  - Propellants, consumables, power system elements, building materials, fabricated parts and higher-order manufactured items

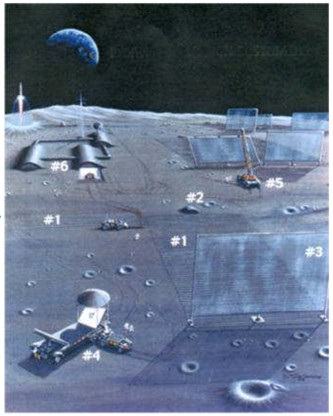
- Possible Market Areas for commercialized space ISRU in next 10 to 15 years
  - Science (NASA): lunar-based astronomical observatories
  - National Security (DOD, DOE):
    - Earth and space surveillance
    - Satellite refueling, space control, debris management
    - Eliminate dependence on foreign energy (power beaming, Helium-3, etc.)
    - Eliminate dependence on foreign strategic metals (NEOs)
  - Public Interest (NOAA): weather monitoring, Earth monitoring
  - Economy:
    - Space Commercial: communications & data, power, transportation, tourism/habitats
    - Earth Applications: mining, petrochemical, power, construction, powder, manufacturing

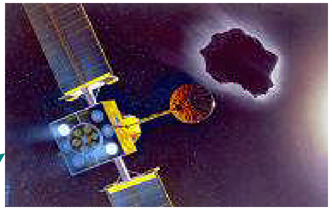
Near & Far Term Space Commercial Applications

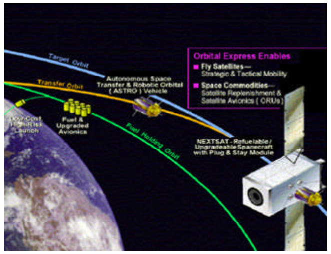




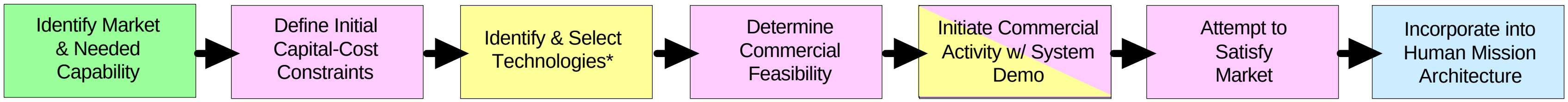
- **Remote Sensing**
  - Earth viewing
  - Astronomical observatories
- **Self-Sustaining Colonies**
  - Tourism
  - Resort construction & servicing
- **Power Generation**
  - Power beaming from lunar surface
  - Helium-3
- **Cis-Lunar Transportation & Propellant**
  At Earth-Moon L1 for following:
  - NASA Science & Human Exploration Missions
  - Debris Management
  - Military Space Control (servicing; moving, etc.)
  - Commercial Satellite Delivery from LEO, Servicing, & Refueling
  - Delivery of resources/products for Space Solar Power







Commercial Lunar Propellant Production Example



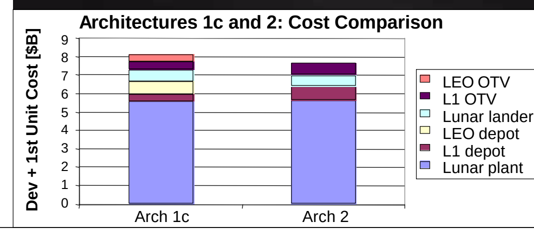
- Begin with projected Human Exploration requirements
  - Initial market: Propellant for Direct-return from Moon to Earth
  - Evaluate other markets and growth in production rate and infrastructure to enable propellant depot at Earth-Moon (EM) L1 for increased human exploration & other markets (i.e. LEO to GEO satellite transfer & DOD satellite refueling)
- Perform commercial propellant feasibility assessment based on Initial & long-term markets
  - Utilize NASA human lunar missions and ISRU-compatible transportation elements as 'anchor' for initial infrastructure on Moon
  - Evaluate growth in infrastructure and production required for E-M L1 propellant depot
- Select ISRU technologies & processes and propellant storage & transportation concepts based on projected demand and growth to obtain fastest return on investment
- Utilize NASA ISRU demonstration missions to reduce risk for complete commercial venture and provide initial capability

- Case Study: FY02 CSM/NExT Report on *Commercial Feasibility Assessment of Lunar Propellant Production*

Commercial Lunar Propellant Feasibility Study

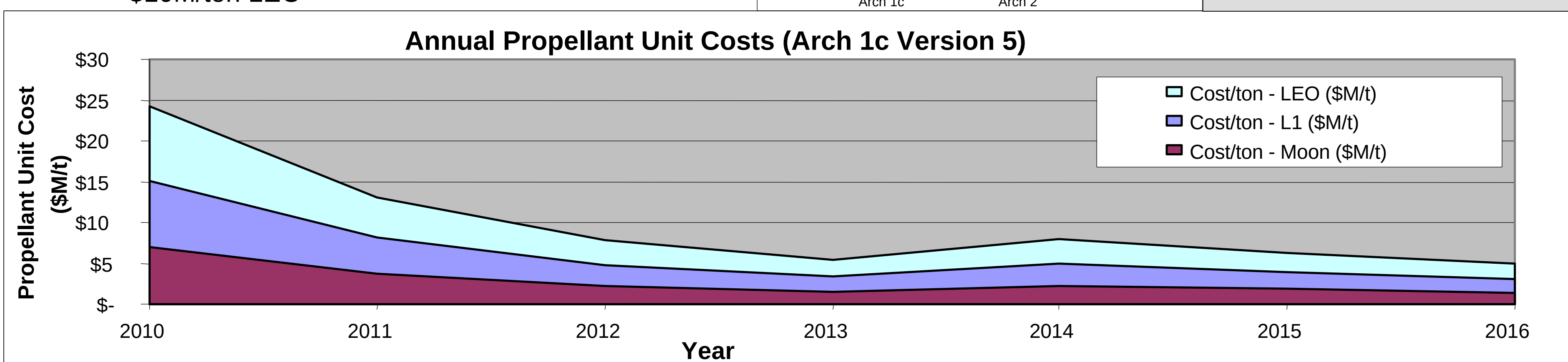
Project Description

- FY02 Study Funding provided by the NASA Exploration Team (NExT)
- Scope: Examine the ***commercial feasibility*** of lunar-based transportation fuel production and delivery
- Participants: JPL / CSM / CSP Associates, Inc.
- Assumptions
  - Water is produced on the Moon, along with the propellant needed to transport it to L-1 and LEO
  - Only *commercial infrastructure* is assumed (this study pre-dates the NASA Exploration Vision and does not consider human exploration)
  - Commercial infrastructure is deployed on lunar surface (ISRU plant), at L1 (fuel depot) and in LEO (fuel depot)
  - Hardware replacement at 10%/yr
  - Launch Costs: $90M/ton Moon, $35M/ton GEO, $10M/ton LEO



<u>Model Feasibility Conditions</u>

Zero non-recurring costs (DDT&E)
30% Production cost reduction
2% Ice concentration
2x Demand level (i.e., 300T/yr)
25% Price Increase



“Fort to City” Approach

- **Phase 1: Provide products/services to “Fort”: NASA Lunar surface human exploration**
  - Propellant production for lunar ascent: oxygen, fuel
  - Consumables for life support: oxygen, nitrogen, water
  - Power system growth: fuel cell consumables, solar energy (electric/thermal)
  - Site preparation & construction: berms, radiation shielding
- **Phase 2: Provide products/services to “Traders/Prospectors”: Other government & Earth-focused commercial activities**
  - Power generation: helium-3, power beaming to Earth, space solar power
  - Transportation:
    - Propellant production and delivery to Earth-Moon L1 for cis-lunar transportation, satellite servicing, and space control
    - Propellant & consumable production for surface transportation and hoppers
  - Surveillance: weather, ‘enemies’, surface & space astronomical and Earth observatories
- **Phase 3: Provide products/services to “Farmers”: Surface industry and tourists**
  - Surface power generation growth
  - Infrastructure Growth: habitats/shelters, roads, life support consumables

Path to Commercialization

- **Initiate NASA-Government Tasks to Enable Space Commercialization**
  - Demonstrations to validate concepts & build business case
  - Regulation reforms: tax incentives, property rights, liability, ITAR / export control
- **Utilize Multiple Methods for 'Commercializing' ISRU**
  - Traditional development BAA/Contracts
  - NASA Innovative Partnership Program (IPP)
  - Contract for 'services'
  - Government-Industry Consortiums (Comsat or Galileo)
  - Government-Industry "Infrastructure" Partnerships (railroad, air-mail, highways, etc.)
  - Prizes
  - Creation of Earth, LEO, and Lunar-based ISRU test & development laboratories
- **Establish a committee of representatives from NASA, industry, and academia**
  - Define the roles that NASA and Industry will have as space exploration matures.
  - Promote enactment of regulations and policy that enable short and long-term lunar commercialization goals
  - Initiate and establish policies, procedures and incentives to turn over Lunar infrastructure assets to industry so NASA can focus on exploring beyond the Moon.
  - Prioritize technology development & demonstrations which best meet goals of both reduced costs to NASA human exploration & space commercialization
  - Define scope and charter for Government-Industry Space Consortiums

➢ **Early engagement of NASA/commercial partnerships is required to maximize commercial benefits**

ISRU Commercialization Challenges

- **Financing**
  - Government funding for space is fairly flat
  - European Galileo project demonstrates industry-banks willing to invest when government is anchor tenant
  - Iridium, Space-X, Virgin Galactic, & Bigelow efforts demonstrate investment funding for commercial space activities are possible
  - Economic & market research can provide early feedback on commercial feasibility
- **Regulations & Policy**
  - International Agreements (Outer Space Treaty, Moon Treaty)
  - US Laws (Tax incentives, property rights, liability, ITAR / export control, etc.)
  - NASA policies, procurement and Industry cooperation infrastructure
- **Technical**
  - Level of maintenance & repair unknown
  - Uncertainty in resources
  - Uncertainty in performance and amount regolith excavation required
  - Sealing for regolith processing systems

➢ NASA as 'anchor tenant' can be catalyst, coordinator, and 'glue' to make commercialization of ISRU and space possible

Implementing ISRU Commercialization

Commercial Partnership Matrix

Activity	Outcome	Benefits to NASA/USG	Time Frame	Process	Key Assumptions
Partnerships for multi-use technology development	Leveraging off industrial development has demonstrated enormous savings to NASA	Reduced cost to develop ISRU technology and immediate public benefit from exploration	Currently in existence	NASA ISRU focused partnerships through the Research Partnership Centers	Continued need to leverage funding and maintain political support
Involvement of potential industrial developers in ISRU planning	Greater chance of successfully privatizing NASA's Lunar infrastructure	Lunar ISRU assets available for NASA use while freeing up funding for going to Mars	ASAP Since this can influence Lunar exploration architecture planning	Establishment of an industry working group to advise on architecture planning	Exploration beyond the Moon remains a priority for NASA
Prizes for ISRU development	ISRU system level demonstrations and potentially Lunar robotic ISRU demonstrations	Reduced cost of demonstrating ISRU technologies since NASA only pays for winners	ASAP for terrestrial demonstrations	Centennial Challenge announcement	Some ISRU is deemed beneficial to exploration
Establish a Comsat / Intelsat Type Federal Governenment Corporation (FGC)	Create organization that can sponsor research, coordinate ISRU efforts, and enter into long term, binding agreements with industry and other government organizations with more flexibility than NASA can	More efficient industrial ISRU development process that allows NASA to focus on exploration	ASAP (2007)	White House / ESMD works with Congress to establish a FDC for space resource development	Political support for this approach exists or can be created
Anchor tenancy agreements for future purchase of In-Situ Resources	Non-NASA / Government investment in ISRU production	Reduced cost to utilize In-Situ Resources and enhanced commercial space infrastructure	As soon as Lunar exploration architecture (ISRU requirements) is finalized	RFP for projected quantities of energy, gases, etc., needed for exploration	Significant In-Situ Resources are needed to support exploration
Homesteading & Property Rights	Enables independent commercial, market driven activities related to space exploration and development	Allows NASA exit strategy from Operations, enables Exploration focus	2007 - Jamestown Anniversary	Implement and expand the NASA 1958 Act	Progressive emergence of future market opportunities

ISRU Capability Team Wrap-up

ISRU Challenges

Maximize benefit of using resources, in the shortest amount of time, while minimizing crew involvement and Earth delivered infrastructure

- **Operation in severe environments**
  - Operation and interaction with dust (fine particles are invasive and highly abrasive)
  - Efficient excavation of resources in extremely cold (ex. Lunar permanent shadows), and/or micro-g environments (Asteroids, comets, Mars moons, etc.)
  - Methods to mitigate dust/filtration for Mars atmospheric processing

- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery (No crew for maintenance; Non-continuous monitoring)
  - Long-duration operation (ex. 300 to 500 days on Mars surface for propellant production)

- **High reliability and minimum (zero) maintenance**
  - High reliability due to no (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Development of highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Development of highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)

ISRU Challenges (Cont.)

- **Early mass, cost, and/or risk reduction benefits**
  - Methods for energy efficient extracting oxygen and other consumables from lunar or Mars regolith
  - Methods for mass, power, and volume efficient delivery and storage of hydrogen
  - Processing and manufacturing techniques capable of producing 100's to 1000's their own mass of product in their useful lifetimes, with reasonable quality.
  - Construction and erection techniques capable of producing complex structures from a variety of available materials.
  - In-situ manufacture of spare parts and equipment with the minimum of required equipment and crew training

ISRU Crosswalk of CRM Relationships

	1. High-energy power and propulsion	2. In-space transportation	3. Advanced telescopes and observatories	4.Communication & Navigation	5. Robotic access to planetary surfaces	6. Human planetary landing systems	7. Human health and support systems	8. Human exploration systems and mobility	9. Autonomous systems and robotics	10. Transformational spaceport/range technologies	11. Scientific instruments and sensors	12. *In situ* resource utilization	13. Advanced modeling, simulation, analysis	14. Systems engineering cost/risk analysis	15. Nanotechnology
1. High-energy power and propulsion	Same element											Critical			
2. In-space transportation		Same element										Critical			
3. Advanced telescopes and observatories			Same element									Moderate			
4. Communication & Navigation				Same element								Moderate			
5. Robotic access to planetary surfaces					Same element							Critical			
6. Human planetary landing systems						Same element						Critical			
7. Human health and support systems							Same element					Critical			
8. Human exploration systems and mobility								Same element				Critical			
9. Autonomous systems and robotics									Same element			Critical			
10. Transformational spaceport/range technologies										Same element		No Relationship			
11. Scientific instruments and sensors											Same element	Moderate			
12. *In situ* resource utilization												Same element	Moderate	Moderate	Moderate
13. Advanced modeling, simulation, analysis													Same element		
14. Systems engineering cost/risk analysis														Same element	
15. Nanotechnology															Same element

Same element (yellow)

Critical Relationship (dependent, synergistic, or enabling) (red)

Moderate Relationship (enhancing, limited impact, or limited synergy) (blue)

No Relationship (gray)

Examples of CRM Relationships

Team 13: In-Situ Resource Utilization

	2. In-space transportation	**Capability Flow & Criticality**	**12. In situ resource utilization**	Nature of Relationship
	Ascent /Descent Stages	←	Resource Processing, storage and Distribution	Propellant made on Moon/ Mars may provide significant mass savings
	Earth Departure Stage	←	Resource Processing, storage and Distribution	Propellant made on Moon may be used for Earth (L1) Departure Stage
	Earth Return Stage	←	Resource Processing, storage and Distribution	Propellant made on Mars may be used for Earth Return Stage

	8. Human exploration systems and mobility		**12. In situ resource utilization**	
	Sub-Topic or Subsidiary Capability	**Capability Flow & Criticality**	Sub-Topic or Subsidiary Capability	Nature of Relationship
	Crew Mobility - Surface Mobility Systems	→	Resource Assessment / Extraction	Geologists will require mobility to access resource areas for evaluation
	Refueling and fluids support systems	←	Surface Consumable & Product Storage and Distribution	Automated umbilicals will supply breathing air, propellants and purges
	Fuel Cell	←	Surface Consumable & Product Storage and Distribution	In Situ Produced Propellants can supply fuel cells for surface mobility

ISRU Interaction w/ Strategic Roadmap Activities

SR-#	Short	Full Name	Chartered Objective	In Situ Resource Utilization (ISRU)	Relationship
1	Moon	Robotic and Human Lunar Exploration	Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.		ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection
2	Mars	Robotic and Human Exploration of Mars	Exploration of Mars, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future		ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection
3	Solar System	Solar System Exploration	Robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.		Search for Solar System Resources
4	Earth-like Planets	Search for Earth-Like Planets	Search for Earth-like planets and habitable environments around other stars using advanced telescopes.		Not Applicable
5	CEV / Constellation	Exploration Transportation System	Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.		ISRU can reduce mass launched from Earth
6	Space station	International Space Station	Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space		In Space & In Situ manufacturing / In Situ Logistics and Repair Capability
7	Shuttle	Space Shuttle	Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the Space Shuttle to a new exploration		In Space & In Situ manufacturing / In Situ Logistics and Repair Capability
8	Universe	Universe Exploration	Explore the universe to understand its origin, structure, evolution, and destiny.		Not Applicable
9	Earth	Earth Science and Applications from Space	Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.		Not Applicable
10	Sun-Solar System	Sun-Solar System Connection	Explore the Sun-Earth system to understand the Sun and its effects on the Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.		Not Applicable
11	Aero	Aeronautical Technologies	Advance aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.		ISRU can provide propellants for planetary fliers
12	Education	Education	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the nation's scientific and technological capabilities.		Use ISRU principles to educate, inspire and motivate
13	Nuclear	Nuclear Systems	Utilize nuclear systems for the advancement of space science and exploration.		Utilize nuclear power for ISRU systems

ISRU State of Art (SOA)

- In all areas of ISRU, significant terrestrial capabilities & hardware exist
- Resource Extraction
  - Some sub-capabilities have been demonstrated, including scooping of regolith samples on the Moon and Mars, coring of regolith samples on the Moon, and grinding and analysis of rock samples on the Moon and Mars.
  - Significant work has been performed on acquiring and separating Mars atmospheric resources
- Material Handling & Transportation
  - Extra-terrestrial experience in handling and transporting native materials is very limited for Moon (Apollo samples were manually manipulated for encapsulation were transported in small containers aboard the Lunar rover vehicle and back to Earth) and Mars (samples were/are robotically manipulated for limited analysis and disposal by Viking, MER, etc.)
  - Terrestrial experience in material handling is ubiquitous, but translating these capabilities to the ISRU mission is outside existing knowledge:
- Resource Processing
  - Lunar ISRU has a 30 year history of laboratory testing, but little development money for systems level development.
  - Mars ISRU has had more development over the last decade but focus has been atmospheric processing
- Manufacturing with In-Situ Resources
  - Extensive microgravity materials processing experiments have been done in space in Apollo, Skylab, and Spacelab,
  - Paper studies show that 90% manufacturing materials closure can be obtained from lunar materials and 100% from Mars materials.
  - Feasibility efforts for fabrication of photovoltaic cells and arrays out of lunar derived materials have been performed

ISRU SOA (2)

- Surface Construction
  - Site planning: Lunar/Mars topography data sets are partially available, some geophysical characterization is available (Apollo/Mars programs), and Lunar regolith and properties for upper 2 meters is available from Apollo program
  - Structure & Habitat Fabrication: Many in situ-based or derived habitat construction methods have well-characterized terrestrial equivalents, and laboratory tests have been performed on lunar construction materials (waterless concretes, glass fibers and rods, sintered bricks, etc.)
  - Radiation protection: MMOD concepts and hardware design for ISS currently exist (Aluminum/Kevlar/Nextel)
  - Structure & Site Maintenance: In space maintenance and repair are evolving, self-healing materials are currently being tested , EVA and IVA repairs are regularly performed on the International Space Station, and tile repair tools and materials are being developed as part of return to flight activities for the Space Shuttle
  - Landing & Launch Site: Apollo style landings on the Moon showed ejecta occurred but did not threaten vehicle (23 metric Ton landed Mass)
- Surface Consumable/Product Storage & Distribution
  - Limited size and capacity cryo-coolers have flown (science instruments)
  - Cryogenic fluid storage systems has flown, but for limited durations and not with integrated liquefaction systems
  - Automatic and EVA fluid couplings have flown on ISS; Helium II coupling built but not flown
- ISRU Unique Test and Certification
  - Simulants: ~25 tons of JSC-1 lunar simulant produced in early 90's, and Martian physical simulant established and used in testing
  - Lunar and Mars environmental chambers exist to support ISRU development
  - Micro/partial gravity testing for short durations exist through use of drop towers (5.2 sec max), aircraft, and sounding rockets
  - Micro-g long duration testing might be possible through use of ISS glove-box (.9m x .5m x .4m) or ISS integrated experiment rack

ISRU Gaps

- Dust mitigation
- Low-gravity effects on solid material handling, processing, manufacturing, and construction
- Resource Extraction, Handling, & Transportation
  - Better definition of target material and resource information are required
    - Current data useful only for prospecting
    - Effects of Lunar and Martian environments on equipment technologies unknown
  - Lunar and Mars excavation, material handling, and transportation are very immature
- Resource Processing:
  - Development of seals that can work repeatedly in a low temperature, high vacuum, abrasive dust environment is required
  - Further processing technology development required to meet operating life goals and increase mass/power/volume efficiency of ISRU
  - Further integrated system build-up and testing required to meet packaging goals
  - Processing of manufacturing and construction feedstock is very immature
- Manufacturing
  - Development of power generation, management, and distribution from in-situ resources and feedstock is very immature

ISRU Gaps (2)

- Surface Construction
  - Scale and resolution for the moon and Mars for detailed site planning is insufficient
  - Architecture and civil engineering disciplines for non-terrestrial surface applications are immature
  - Tele-operation and/or automation of robotic construction processes is very immature
  - In situ production of spares and parts in space is very immature
- Surface Consumable/Product Storage & Distribution
  - High-capacity, long-life cryocoolers for cryogenic propellants
  - Deployable tanks and distribution systems for cryogenic fluids and high pressure gas.
  - Long life compressors and motors for extraterrestrial applications
  - Integrated, large scale liquefaction and long term storage of cryogenics with flight weight systems/components
  - Dust insensitive fluid couplings and leak detection in open vacuum or low atmospheric environments
- ISRU Unique Test & Certification
  - Granular material modeling requires a ‘mathematical breakthrough’ to accurately model all physical behaviors
  - Vacuum chambers and wind tunnels willing to allow introduction of simulants on large scale
  - Remote equipment to handle, distribute, charge, etc. simulants within vacuum chamber
  - Chambers with integrated test environments - thermal, vacuum/atmosphere, dust, and solar
  - Cost efficient long term environmental testing
  - Chambers to simulate permanently shadowed craters at lunar poles

ISRU Risks

- **Resource Risks** (due to incomplete prospecting)
  - Potential resource is not available
  - Resource not available at landing site
  - Resource is present, *BUT*
    - Form is different than expected (concentration, state, composition)
    - Location is different than expected (depth, distribution)
    - Unexpected impurities
- **Technical Risks**
  - Level of maintenance & repair unknown
  - Uncertainty in performance and amount regolith excavation required
  - Sealing for regolith processing systems .
  - System reliability.
    - More complex systems are more likely to fail and more difficult to fix.
    - Robustness and flexibility often conflict, though both are needed in new environments.
    - Scaling issues are non-linear and non-trivial.
    - Difficult to test with simulations; field experience required (more=better).
  - Effects of lunar and Mars environmental conditions.
- **Political uncertainty.**
  - Reliance on ISRU and resources seems to be a liability vs an asset by current mission planners
  - Many terrestrial resource extraction projects have been canceled due to changes in political climate.

ISRU Roadmap Team Recommendations

- Human mission architectures need to plan for use of ISRU products from start of planning
  - Can strongly influence mission phases, locations, and element designs to achieve maximum benefit of ISRU
  - Early investigation of Lunar and Mars resources, especially water can significantly change human exploration approach
- Piggyback resource assessment requirements and instruments on Science missions to Moon and Mars
  - Complementary/supplementary to science goals.
  - Assessment provides crucial information for all aspects of ISRU
- Early ISRU process demonstrations in relevant environment in logical and orderly progression
  - *Minimize risk and maximize benefits* of incorporating ISRU into mission architectures
  - Not all demonstrations need to be dedicated missions
- Maximize use of common technologies, hardware, and mission consumables between ISRU, propulsion, mobile power, life support, and EVA suit systems
- All systems must be designed “up front” for repairability or use of spare parts manufactured with in situ processes and resources
- Initiate government efforts to promote commercial development and use of ISRU

Summary/ Forward Work

- Make changes to roadmaps based on verbal feedback from NRC review
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for CRM Title capability
- Make changes to CRM Title roadmaps to ensure consistency with Strategic Roadmaps requirements
- Develop rough order of magnitude cost estimates for the CRM Title Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

NASA Transformational Spaceport and Range Capabilities Roadmap
Interim Review
to
National Research Council External Review Panel

March 31, 2005

Karen Poniatowski
NASA Space Operation Mission Directorate
Asst. Assoc. Administrator, Launch Services

Agenda

- Overview/Introduction
- Roadmap Approach/Considerations
  - Roadmap Timeline/Spirals
  - Requirements Development
- Spaceport/Range Capabilities
  - Mixed Range Architecture
- User Requirements/Customer Considerations
  - Manifest Considerations
  - Emerging Launch User Requirements
- Capability Breakdown Structure/Assessment
- Roadmap Team Observations
  - Transformational Range Test Concept
- Roadmap Team Conclusions
- Next Steps

National Space Transportation Policy

Signed December 2004

- National Policy Focus on Assuring Access to Space

  "The Federal space launch bases and ranges are vital components of the U.S. space transportation infrastructure and are national assets upon which access to space depends for national security, civil, and commercial purposes. The Secretary of Defense and the Administrator of the National Aeronautics and Space Administration shall operate the Federal launch bases and ranges in a manner so as to accommodate users from all sectors; and shall transfer these capabilities to a predominantly space-based range architecture to accommodate, among others, operationally responsive space launch systems and new users."

- ***NASA seeks to link the Transformational Spaceport and Range Capability Roadmap activity with the new National Space Transportation Policy direction as we develop a National Implementation Strategy***

Roadmap Tasking

The President's Commission on Implementation of the United States Space Exploration Policy Report Finding #4 states:

- *"The Commission finds that successful development of identified enabling technologies will be critical to attainment of exploration objectives within reasonable schedules and affordable costs."*
  - *"Transformational spaceport and range technologies – launch site infrastructure and range capabilities for the crew exploration vehicle and advanced heavy lift vehicles."*

NASA Capability Roadmap Charter, Phase 1:

- During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency.

- The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.

Roadmap Team Membership

- Karen Poniatowski, NASA HQ/Space Operations, NASA Chair
- Maj.Gen. (ret) Jimmey Morrell, Former USAF/AFSPC, External Co-Chair
- Col. Dennis Hilley, OSD/NII Space Programs, External Co-Chair
- Carole Flores, FAA, Manager, Licensing and Safety Division, Member
- Jim Costrell, NASA HQ/Space Operations/Space Communications, Member
- Jim Heald, NASA Kennedy Space Center, Member
- Bob Sackheim, NASA Marshall Space Flight Center, Member
- Bruce Underwood, NASA Goddard/Wallops Flight Facility, Member
- Tom Maultsby, Consultant, Member

Overarching Observations

- **The Transformational Spaceport and Range Capability Roadmap task is unique from other capability roadmaps, in that:**
  - NASA is one of many users of an existing capability
  - There is a broad diversity of current and potential providers of the capability: federal, state, commercial
  - NASA requirements are in various stages of identification and development
  - NASA Space Exploration related requirements may become a driver for new technology but those requirements are not yet matured
- **Key task is to identify NASA- unique requirements and any new technology that might be warranted to meet the Space Exploration Vision**
  - CEV requirements for human transport: Under definition
  - Cargo requirements for heavy lift transportation: Under trade studies considering evolution of existing shuttle and expendable systems as well as clean sheet approaches
  - Robotic requirements: e.g., Prometheus requirements under trade study and definition
- **Spaceport Roadmap will be driven by other strategic and capability roadmaps**
  - This roadmap's major output at this stage in the Space Exploration Vision definition will be a statement of capabilities and identification of potential paths for future technology investments
- **This is a continuous process and will need to be revisited as the Space Exploration requirements affecting public safety and customer needs at the launch site(s) evolve and mature**

Institutional Considerations

- Implementation of the Space Exploration Vision will involve the resources of NASA Centers , other government agencies (e.g., USAF) and state and emerging commercial capabilities

- Each NASA Center will likely have certain upgrades, improvements, and possibly responsibilities that will be seen as Space Exploration driven

- Affected organizations will want many of these met by the ranges as “common” requirements and will want them in the roadmap

- A challenge is to deal with the separate individual interests of institutions to operate in a “desired ideal end state” vs from the spiral/phased needs

- Investments in spaceport and range capabilities that support the general user community should be considered for institutional funding

- Customer-unique requirements should be expected to be funded by the customer

Roadmap Approach

- Assessed the national spaceport and range capabilities (Federal, state, commercial) with focus on USG investment options for space launch as well as test and evaluation
  - The bulk of Space Exploration-related launch activities will likely be on the U.S. east coast
    - CEV and potential heavy lift operations
  - Focus of this Roadmap is Earth-based range
  - Non-Earth-based concept (e.g., Lunar base) is downstream excursion for Spiral 3 horizon or beyond

- Solicited/Reviewed User issues/requirements drivers
  - Requirements will drive investment options

- Coordinated with Strategic Transportation Roadmap and Communications and Navigation Capability Roadmap
  - Preliminary definition of S&R Roadmap interface with the AFSCN, NASA Space Communications and launch requirements
  - Range requirements derived from that work

- Used existing national working group reports as technology references for investment considerations

- APIO guidance provided framework for Roadmap efforts

- The team defined two time periods: present to 2015 and 2015 to 2030

Issues in Conducting the Roadmap

- Defining the terms: Spaceport, range, transformational
- Priorities and sources of requirements that drive technology investments with measurable performance enhancements to end users
- Definition of the a Space Based Range and what it really implies
- How to relate the Advanced Space and Range Technology Reports technology development concepts to requirements
- Balancing individual institutional equities within the larger framework of Space Exploration

Definitions: Considerations

- There is no common purpose spaceport in existence today, although FAA has attempted to craft notional definitions
- Commercial spaceports in the future that could support space exploration are not excluded…..however focus in near term is on existing capabilities
- The quest for "Common user requirements" for the Federal launch bases or Centers that might support space exploration are extremely diverse and far from common at this time
  - The facilities and infrastructure that exist today have evolved based on requirements derived from common user needs at a launch site for spacecraft, vehicle operations and public safety
  - Mission specific requirements have to date been identified by the end-user and may or may not be permanently added to the common user structure
- Space exploration programs are not yet defined and will mature over time- this is especially true for Moon, Mars and Deep Space needs

Roadmap Definitions

- Primary functions of a “Range”:
  - Ensure public safety from hazardous operations
    - Ensure operational infrastructure/resources for launch support Telemetry coverage and launch communications
- “Spaceport” refers to collection of customer services/support at a launch site
  - Launch vehicle and Spacecraft processing, “customer” services and access, logistics, communications, etc
  - Launch countdown operations and contingency planning
  - Spacecraft and vehicle
  - Landing and Recovery operations
  - Institutional Infrastructure
- Federal Ranges today encompass a mix of Range and Spaceport functionality
- For purposes of this Roadmap assessment, the focus is centered on two primary requirements drivers:
  - Public Safety = Range
  - Customer support/service infrastructure = Spaceport

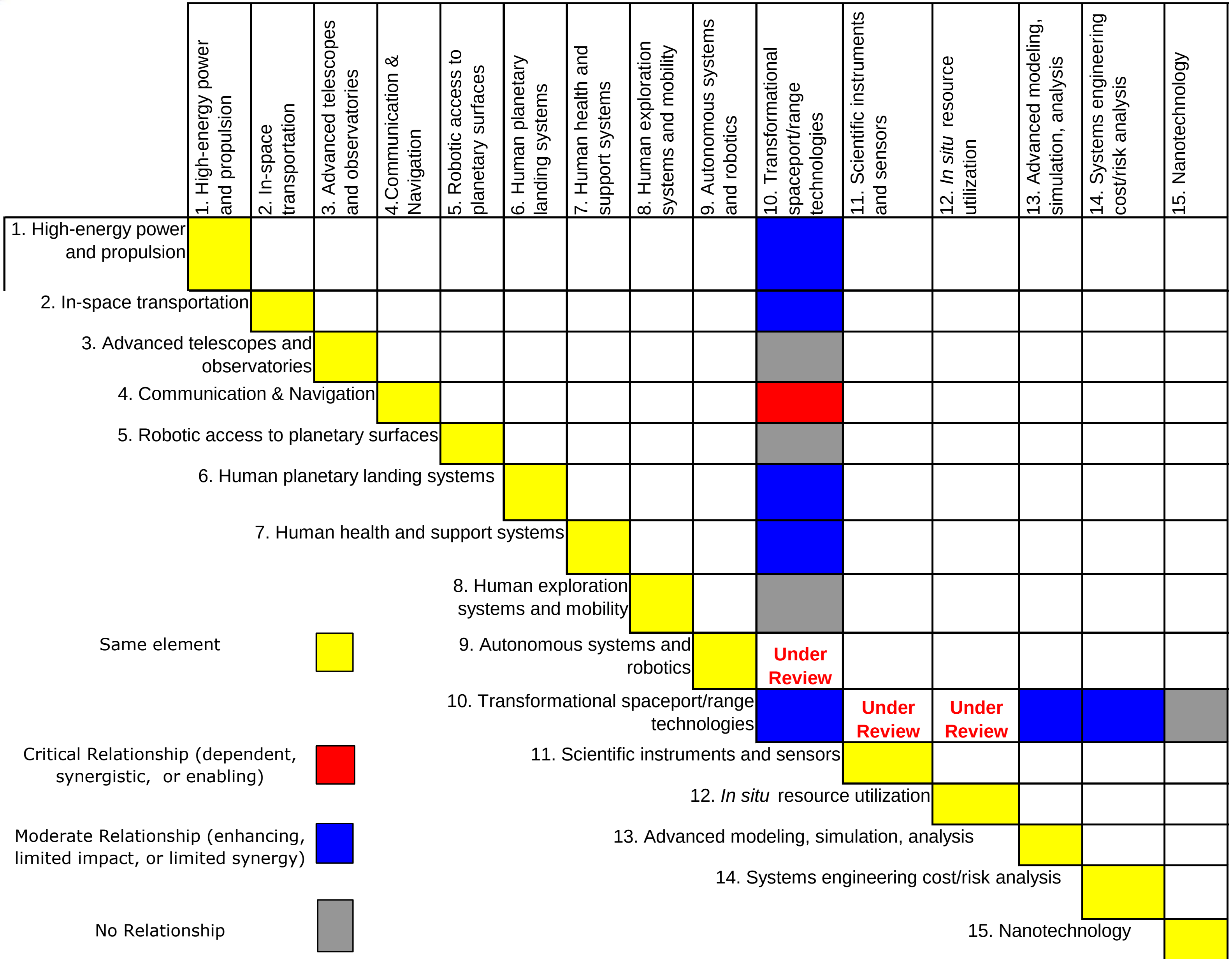
Transformational Definition

- Specific task focus was on "transformational" investments or actions to meet current and future requirements
  - Goal is to improve capabilities, safety, and performance of existing and future spaceports/ranges
  - Recognizing understanding of CEV and heavy lift requirements at the launch site and range are still evolving

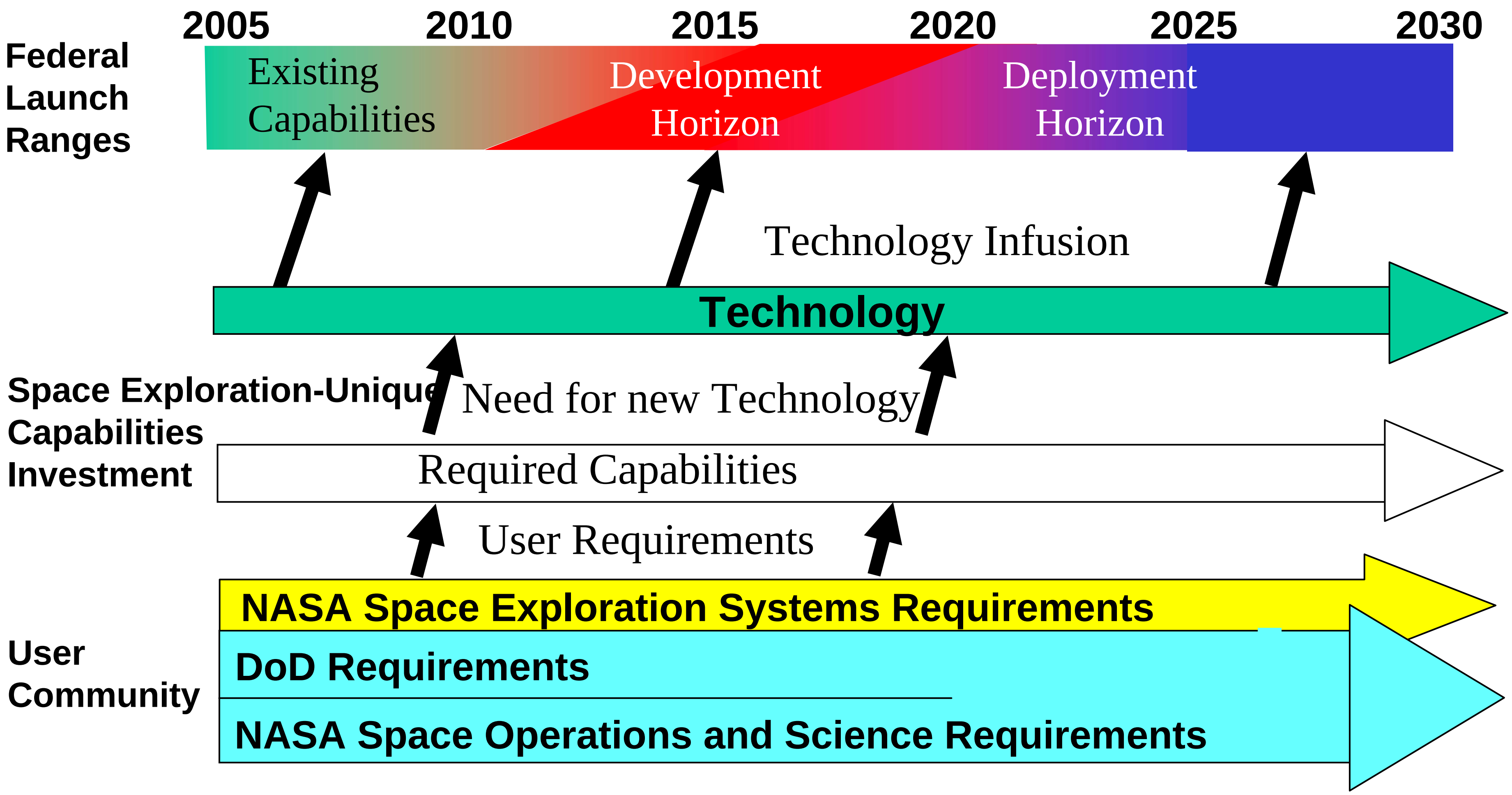
- Defined by Spaceport/Range Capability Roadmap Committee as:
  - Investments or actions that could lead to significant improvements in spaceport/range performance or capabilities, tied to current/future requirements
  - Actions that would increase range effectiveness

- The above could have affectivity in the near or long term

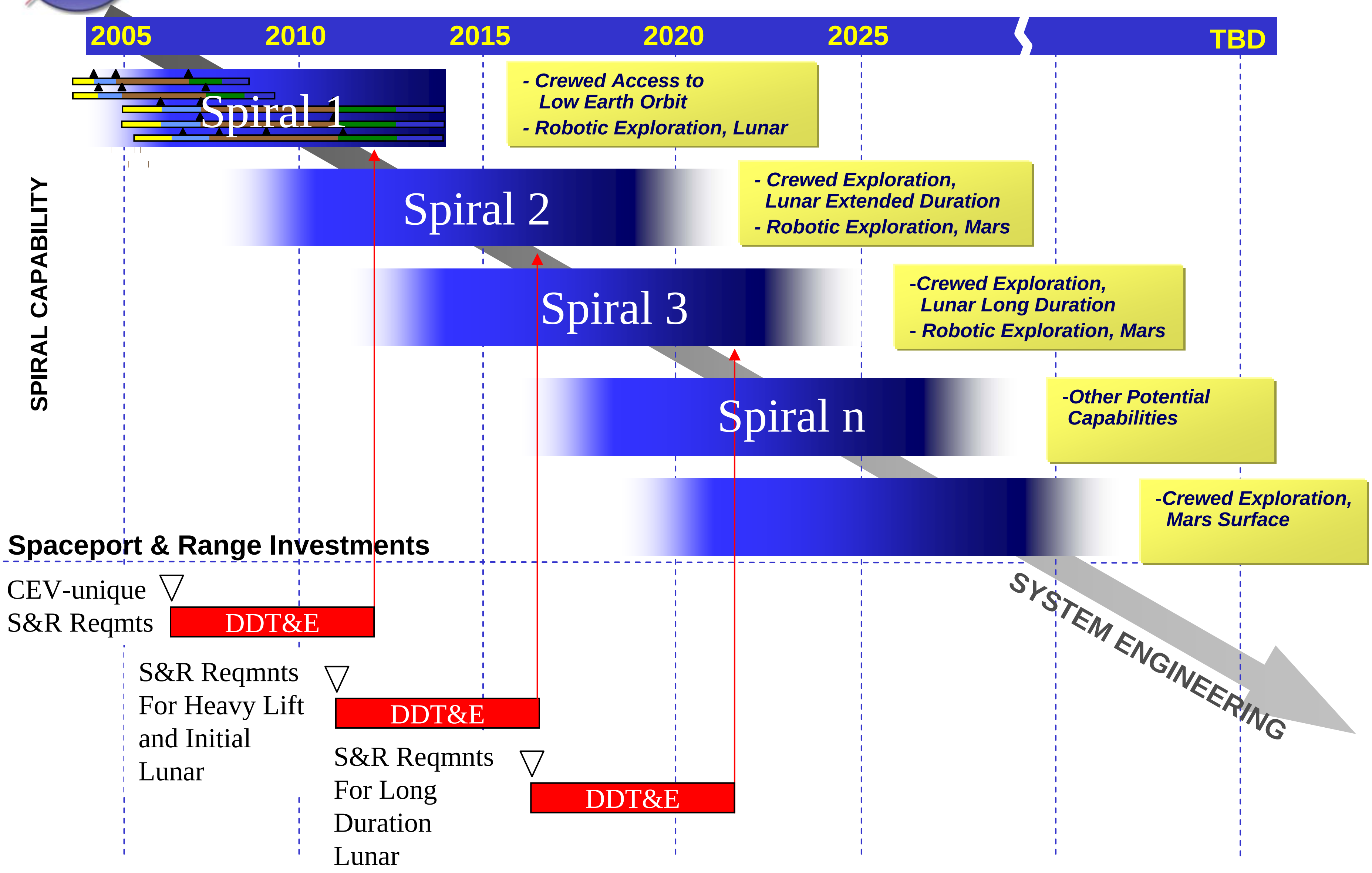
Crosswalk Matrix Ratings
Work In-progress



Roadmap Timeframes



S&R Capabilities Development relative to Space Exploration Spirals



Common Services and User Unique Requirements

- Historically, process has differentiated between what a range/launch site can best and should provide versus what the individual user should be expected to bring with the mission
  - Traditionally programs that require significant facility support or new infrastructure pay for the dedicated facility or capability on the range
  - This approach is likely best for support to the the Space Exploration initiative, considering fiscal reality
  - Also recognizes that these costs would never be supported in the range agencies' budgets – it would simply overwhelm the process

- Many functional common services are Rang operator's requirement to provide public safety and expand to support the users' needs for similar activity

- In all cases, requirements fall into the areas of either public safety or customer support

Technology Issues

- Some technology concepts today are not clearly driven by a stated firm specific mission or vehicle concept
- Need a link to requirements to enable development of a prioritization process of candidate technologies available
- The timeline for a presumed requirement continues to evolve
- Many technology concepts that might be feasible may not be attributable to "firm" requirements, but may be a need that makes sense from a multi-user standpoint.
  - Need to balance technology-push –vs- technology-pull
  - There is value in enabling (funding) technology R&D efforts for broad-based spaceport/range affectivity

ARTWG & ASTWG

Advanced Range Technology Working Group (ARTWG):

- Response to Presidential Directed OSTP & NSC Report, *“The Future Management And Use Of The U.S. Space Launch Bases And Ranges,”* February 2000
- Focus on next-generation range technologies
- MOA between NASA/Code M, and AF Space Command to jointly develop strategy
- Co-Chairs from NASA/KSC & AF Space Command

Advanced Spaceport Technology Working Group (ASTWG):

- Focus on next-generation ground processing technologies
- Chaired by NASA KSC, Vice Chair Executive Director Aerospace States Association

- Created forums for interchange among representatives from civil, commercial and national security sectors who have an interest in range and spaceport technology
  - Focused on new technology development
  - Emphasis on common needs and standardization
- Both forums have recently published reports which identify key capabilities and technologies for consideration as requirements for space exploration are developed

ASTWG and ARTWG Contributions to the Roadmap Process

- Both Working Groups have made a major contribution to enhancing the understanding of the functions and operations of both spaceports and ranges by providing forums for routine interchange
  - Sought to target mix of government ranges, range users, and commercial spaceports
  - Groups sought to identify broad range of candidate technologies that could improve ranges and spaceports

- Both Working Groups are formulating investment strategies based on notional business cases and cost-benefit analysis which can then be tied to specific requirements
  - Common user requirements
  - User unique requirements…Space Exploration

- Process to prioritize requirements within and across user communities and then link to achievable performance metrics is a necessary next step to focus future investments for civil and national security communities and commercial community as market demand warrants

Roadmap Requirements Development Discussion

- ARTWG and ASTWG framed all activities that occur as either a range or spaceport function
  - Useful construct for technology and planning discussions
  - Input needs tailoring for this Roadmap as ARTWG/ASTWG did not identify the lines of responsibilities between the USAF and NASA and the rest of the user community
  - Attempts to align commercially funded spaceports and Federally funded spaceports/ranges requirements as the same

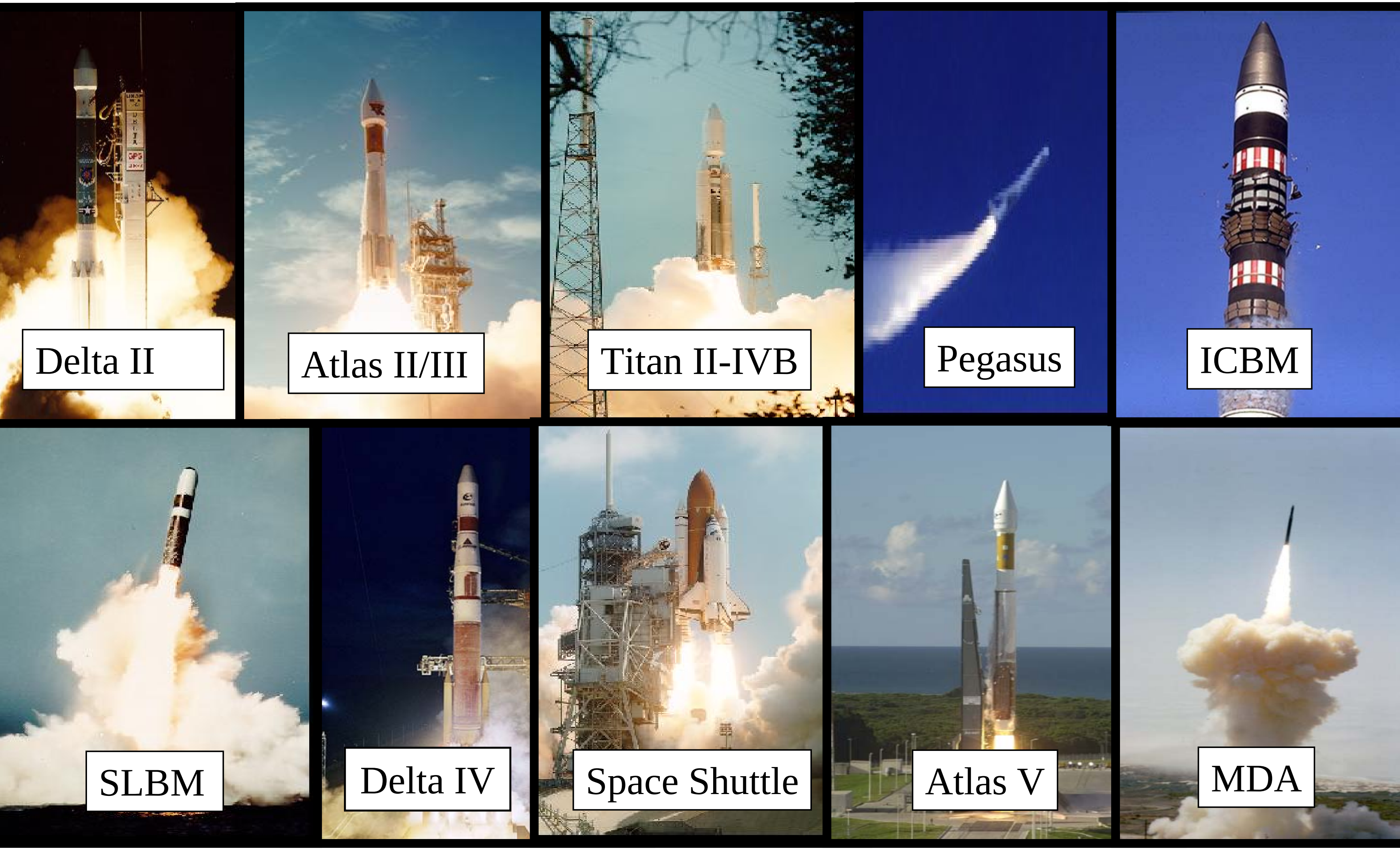
- "Commercial spaceport" roles in Space Exploration are expected but not definable at this time

- The roadmap assessment sought to identify where the highest capability pay offs exist for Federal ranges/launch sites with opportunities for application to other sites as appropriate downstream

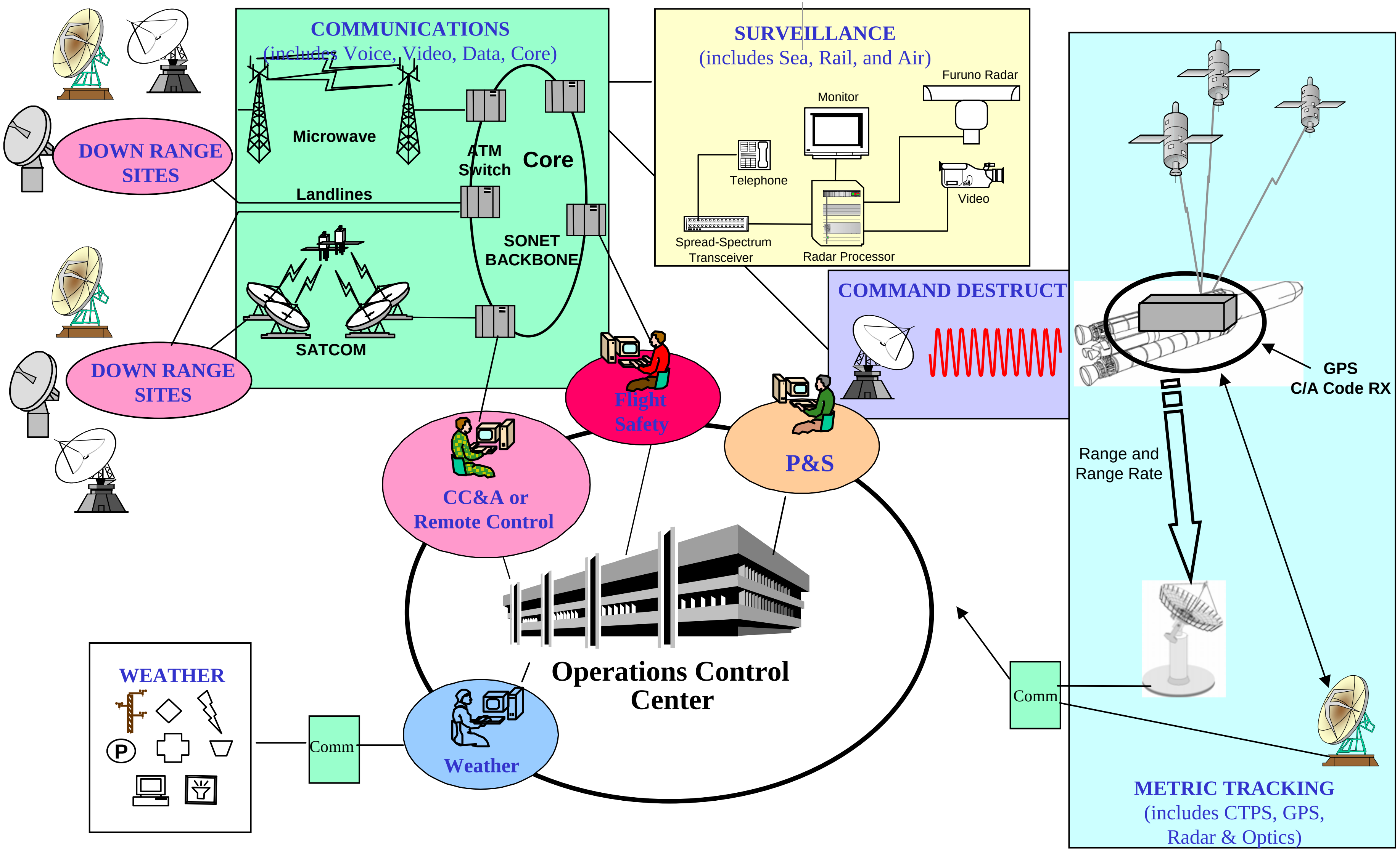
Current Ranges and Capabilities

National and Commercial

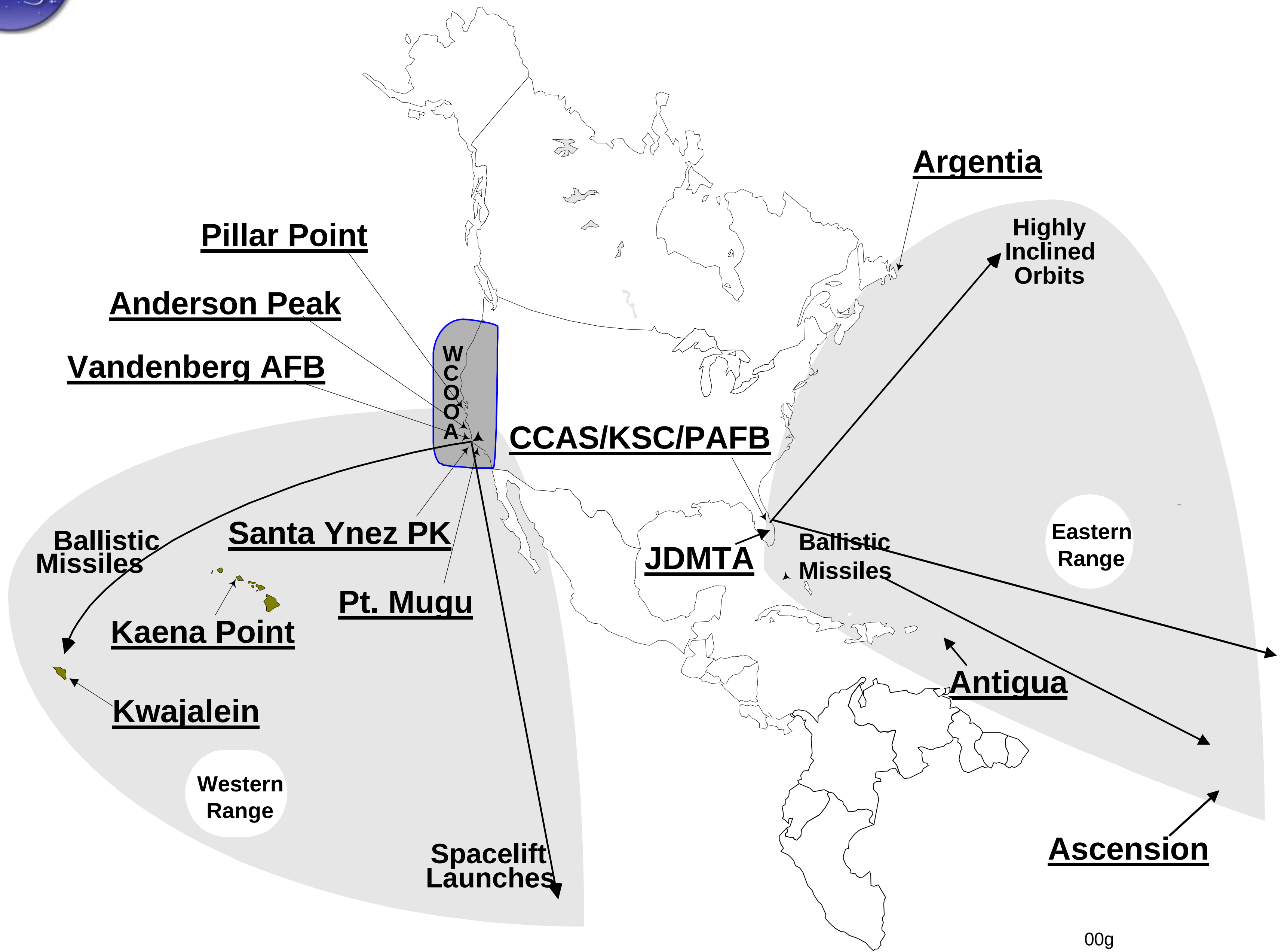
Examples of Launch Vehicles Supported



Current Federal Range Capabilities



Range Coverage



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Eastern Range
Space Launch Complexes and Payload Processing

- CCAS - Air Force
  - Titan Integrated Transfer Launch (ITL) Area
  - SLC 40 - Titan IV, IUS or Centaur
  - SLC 17 A&B - Delta II
  - SLC 41 - EELV (Atlas V)
  - SLC 37 - EELV (Delta IV)
  - Skid Strip - Pegasus
- CCAS - Navy
  - Complex 46 - Athena I/II
- KSC - NASA
  - Space Shuttle ITL Area
  - Complex 39 A&B - Space Shuttle
- Payload Processing
  - GPS, DSCS, SCIF

Western Range
Space Launch Complexes and Payload Processing

- Space Launch Complexes
  - SLC 4E - Titan IV, IUS or Centaur
  - SLC 4W - Inactive
  - SLC 2W - Delta II
  - SLC 3E - Atlas IIA/IIAS/IIIA, EELV (Atlas V)
  - SLC 3W – FALCON I
  - SLC 6 - EELV (Delta IV)
  - Pegasus

- Payload Processing
  - Astrotech
  - SSI @ IPF
  - Bldg.1610
  - Bldg. 836

Current Capabilities

NASA Wallops Flight Facility Range

Wallops Research Range Overview

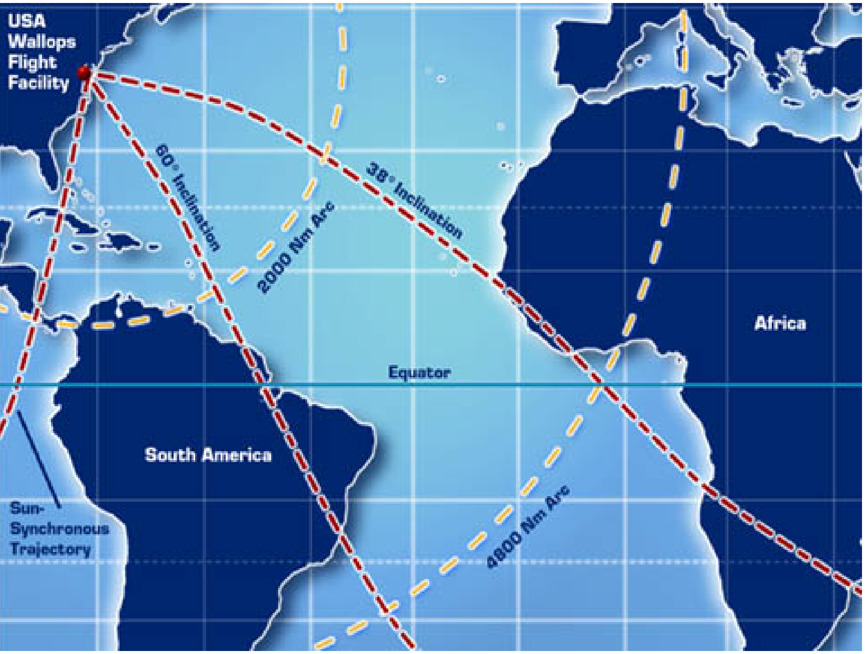
<u>Launch Areas</u>
- 2 Orbital Launch Complexes (active)
- 6 Suborbital Rail Launchers
- 3 Primary & 1 UAV Runways
- 3 Mobile Range Rail Launchers

<u>Processing Facilities</u>
- 2 Multi-Bay Hazardous Processing Facilities
- 5 Payload Processing Facilities

<u>Instrumentation</u>
- 1 Range Control Center & 1 Aeronautical Control Center
- 4 Fixed S-Band Telemetry Antennas
- 3 Fixed C-Band Tracking Radars
- 3 UHF Command Transmitters (redundant)
- 2 Ground & 1 Airborne Surveillance Radars
- Optical/Video
- Communications
- Weather Measuring & Forecasting
- Range Timing
- Real-Time Data Processing

<u>Mobile Range Capabilities</u>
- 3 Rail Launchers
- 2 Range Control/Transmitter Systems
- 1 UHF Command System
- 5 S-Band Telemetry Antennas
- 3 C-Band Radars
- 4 Power Generator Systems

Wallops Research Range Facts



- Range History
  - First Launch July 1, 1945
  - 15,000 total launches
  - 29 orbital missions
  - 600-700 Range events annually (all projects)
  - 35-50 launches annually
- Typical Range Limits
  - Azimuths: 90-160 degrees
  - Inclinations: 38-60 degrees
- Class of Vehicles Supported
  - Suborbital
  - Small Orbital (ELVs carrying payloads up to ~12,000 lbs.)
  - Experimental
- Nature of projects
  - NASA (Science, Technology, Education)
  - DoD (R&D, Targets)
  - Commercial

Current Capabilities

NASA Kennedy Space Center

KSC Space Shuttle Infrastructure

John F. Kennedy Space Center

- Facilities

Vehicle Assembly Building	8 Acre Footprint, 525' Tall
3 Orbiter Processing Facilities	30,000 SF Each
Launch Pads A&B	Fuel/Oxidizer Tank Capacity of 1.8 M Gal
Shuttle Landing Facility	15,000' Runway, 300' Wide
Operations Support Building	200,000 SF 1378 Ofc Space
Operations Support Building 2	189,000 SF 860 Office Space
Launch Control Center	230,000 SF 237 Office Space
4 LPS Control rooms	
Logistics Facility	3-story, 230,000 SF

- Facilities

NASA Shuttle Logistics Depot	8 bldg complex (Cape Canaveral)
Thermal Protection System Facility	2-story , 44,500 SF
Rotation Processing and Storage (RPSF) Facility	
PCC Facility	94,000 SF 235 Office Space
Launch Equipment Shop	On-site machine shop
Assembly and Refurbishment Facility	Managed by MSFC
Main Engine Processing Facility	
Hypergolic Maintenance Facility	
Parachute Refurbishment Facility	Managed by Marshall
Hangar AF	SRB/RSRM disassembly facilities
Hangar N & S	

KSC Space Shuttle Infrastructure

John F. Kennedy Space Center

- Support

- 300 Generators, 60 UPS Units, 156 Substations
- 30,000 Tons of Air Conditioning
- 40 Cranes, 183 Hoists, and 52 Elevators
- 500,000 Feet of Water Distribution Lines
- 440 Pieces of Heavy Equipment
- Over 170 Miles of Fiber Optic Cable
- Over 900 Fiber Optic Transmitters and 900 Fiber Optic Receivers
- LC-39 TV System Includes 166 Cameras, 9 Video Recorders, and Over
- 7770 Monitors
- 142,000 Items in Inventory
- 8,000 Issues Per Month

- Shuttle program funded facilities with current replacement value (CRV) >$1M is roughly $2.1B

- 50% of KSC real property with CRV of >$1M is dedicated Shuttle program or about $2.1B out of total $4.0B

Payload Processing

John F. Kennedy Space Center

Space Station Processing Facility (SSPF)

ISS elements are processed primarily in the 522,313 SF building

Additional Facility Capabilities:

O&C – Clean room warehouse mode

Supply Warehouse #1 – Shared facility provides warehouse storage for Flight Spares

Supply Warehouse #2 – Warehouse storage for Flight Spares, GSE, facility support spares

Aerospace Technician Shop

GSE Storage Facility

Vapor Containment Facility (VCF)

Additional Facility Capabilities:

Heavy Equipment Storage

Facilities O&M Building – Housing of Facility Technicians

Storage Building

Payload Support Building – Warehouse storage for Flight Spares, GSE, facility support spares

Apollo – Warehouse storage for bulk GSE

POL Shed – Provides paint, oil and lubricant storage

Payload Processing

Payload Hazardous Servicing Facility (PHSF) - Processing of unique LSP payloads

Multi-Operations Servicing Facility (MOSB) - Administrative office space

Multi-Payload Processing Facility (MPPF) - Payload processing capability

<u>Additional Facility Capabilities</u>:

E&O (CCAFS) – Administrative office space

Hanger AE – Houses the LSP telemetry laboratory

RTG Facility – Provides capability to process special nuclear materials

Operation & Control (O&C) - Administrative office space for LSP personnel

Delta II Launch Pad

NASA Facilities at VAFB

Vandenberg

VLS Hazardous Processing – Class 100K Payload Processing Facility

SLC-2 Remote Launch Control Center (VLS)

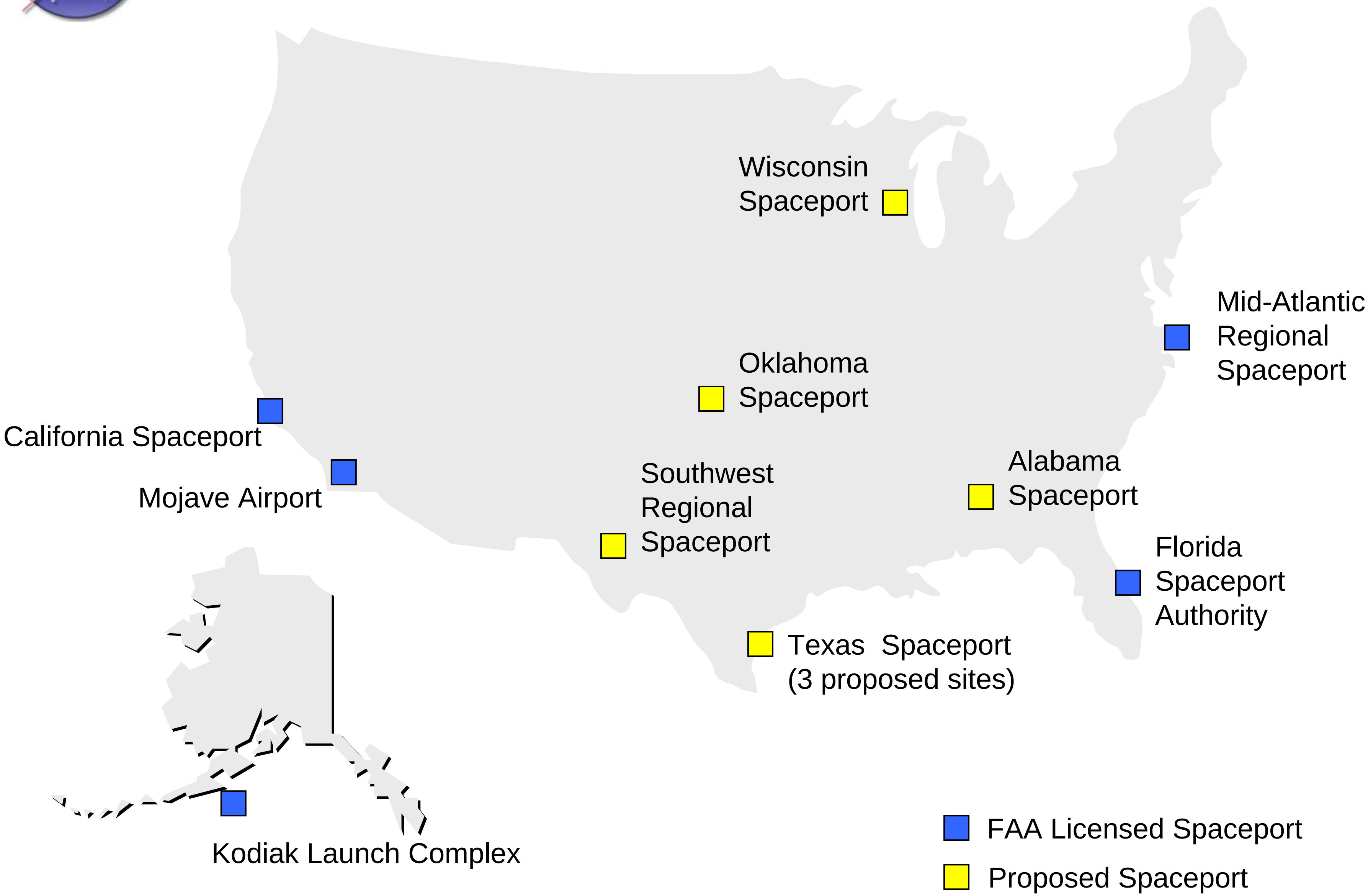
NASA VLS S/C – Mission Directors Center

NASA VLS S/C – Mission Directors Center

Current Capabilities

FAA Licensed Spaceports

Commercial Spaceports



Commercial Spaceports

- To date, approx. $165M has been invested into non-federal spaceports across the nation
- Primary investment funding is from State-level with some support from private and federal sponsorship.
- Contains infrastructure for processing a payload and commercial launch
  – Launch Pads and Runways
  – Infrastructure
  – Equipment
  – Propellants

Active Commercial Spaceports

- **Kodiak Launch Complex at Narrow Cape on Alaska's Kodiak Island, licensed in 1998**
  - LV and Payload Processing
    - Currently configured for Solid propellant launch
  - Total of 7 launches to date
- **California Spaceport, co-located at VAFB , licensed in 1996**
  - LV and Payload Processing
    - Currently configured for Solid propellant launch
      - Two Minotaur launches to date
    - Plans in-place to support liquid-fueled vehicle configurations
  - Launch azimuths ranging from 220° to 160°
- **Florida Spaceport Authority, co-located at Cape Canaveral Air Force Station, licensed in 1997**
  - Owns and Operates RLV Hanger at KSC and SLC-46, among others
    - Currently configured for Solid propellant launch
      - Two Athena launches to date
      - Supports suborbital launches for academic and research
  - Launch azimuths ranging from 47° to 110°
- **Mid-Atlantic Regional Spaceport, co-located at Wallops Flight Facility , licensed in 1997**
  - LV and Payload Processing
    - Currently configured for Solid propellant launch
    - Pad 0-A – built for Conestoga LV
    - Pad 0-B – Universal Launch Pad
  - Plans in-place to support liquid-fueled vehicle configurations
- **Mojave Airport, licensed in 2004**
  - Three runways
  - Supports horizontally launched sub-orbital RLVs
  - Total of five launches to date

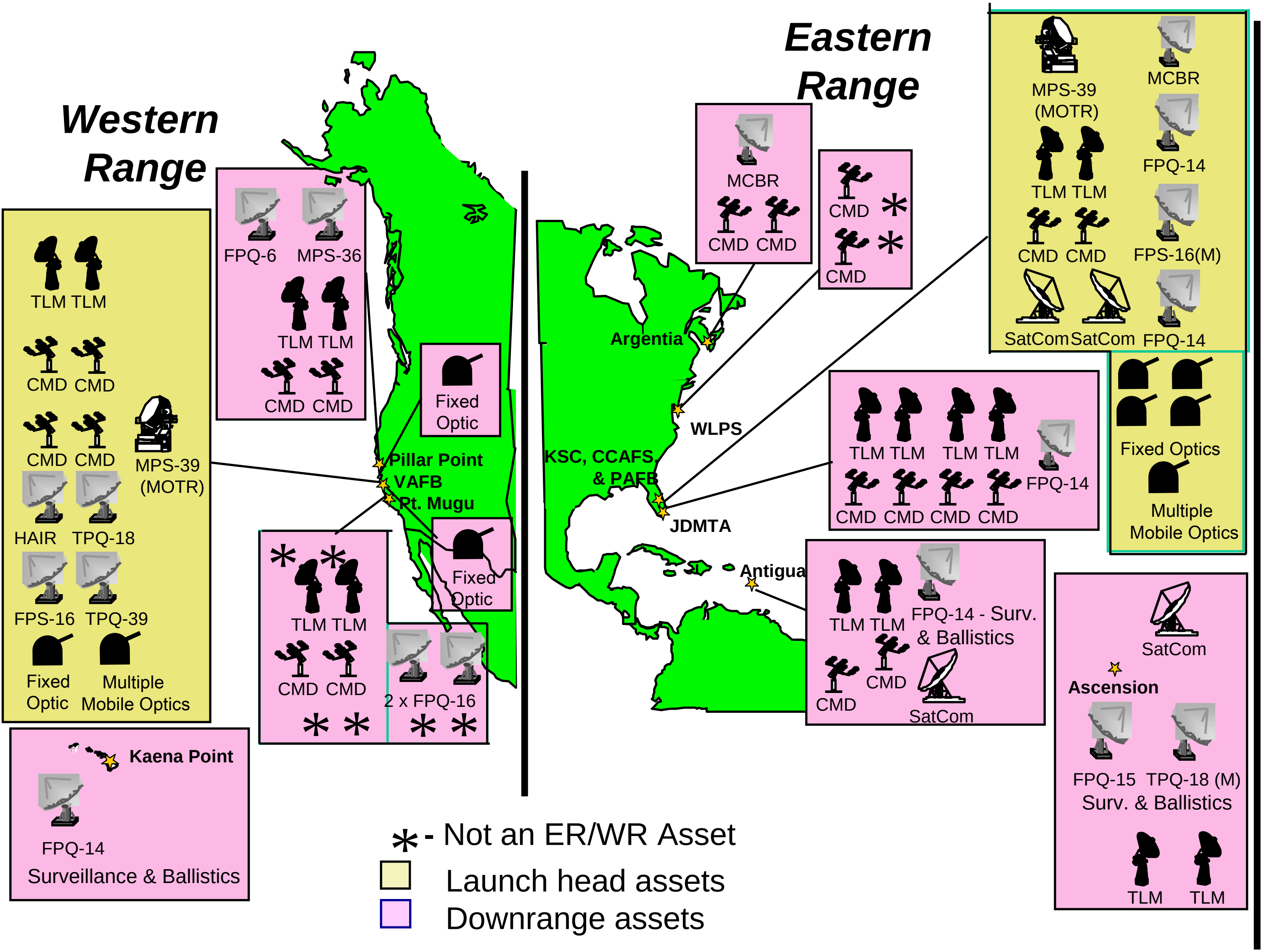
Potential Commercial Spaceports

- **Developing Spaceports**
  - **Southwest Regional Spaceport in Upham, NM**
    - Planned facilities: multiple launch complexes, runway, aviation complex, payload assy complex, cryogenic fuel plant
  - **Oklahoma Spaceport in Burns Flat, OK**
    - Current infrastructure: 13,500 runway, maint/repair hangars, rail spur
    - Planned service: support to horizontally-launched RLVs
  - **Wisconsin Spaceport**
    - Located on Lake Michigan
    - Have supported sounding rockets to altitude of 34mi
    - Host for Rockets for Schools
    - Seek to support orbital RLVs in the future
  - **Gulf Coast Regional Spaceport in Brazoria Co., Texas**
    - On-going safety analysis of different launch systems
    - Amateur Spaceflight Assn launched 12ft long rocket in 2003

- **Other Conceptual Spaceports**
  - Spaceport Alabama
  - South Texas Spaceport
  - West Texas Spaceport

Mixed Range Architecture

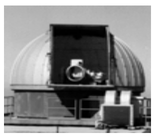
Current Launch and Test Range System Architecture



Typical Command Transmitter (6/10)*

Typical Tracking Radar (8/10)*

Typical S-band TLM Rcv Antenna (4/10)*



Typical Fixed Optic Site (3/4)*

Total # of Sites: 21/34*

*** (WR/ER totals)**

Range Instrumentation Architectures:
Fixed vs. Transportable vs. Space-Based

- Each architecture type has strengths, weaknesses, & optimal applications
  - Fixed/Ground-based:
    - Best suited for launch-heads & sites with continuous requirements
  - Mobile/Transportable:
    - Best suited to provide capabilities to limited use and/or mission unique launch sites (shared among multiple launch sites)
    - Provides gap-filling capabilities
  - Space-Based:
    - Best suited to provide down-range tracking & data, augmenting launch-head ground systems

- Ranges in the future are likely to use a combination of two or all three of these elements
  - Space-based data systems are expected to become a common feature of both established and emerging launch sites

Range Instrumentation Architectures:
Fixed/Ground-Based Instrumentation

- Fixed/Ground-based assets have traditionally been at the heart of the Range architecture

- Many Fixed/Ground-based assets have out-lived their intended design life and are expensive to replace/upgrade

- Due to the proven track record, Fixed/Ground-based assets will continue to compliment future Space-based architectures

- Typical Fixed/Ground-based assets include:
  - Down-Range Radar and Optical site
  - Communications antennae
  - Surveillance Radar at the Launch Site
  - Flight Control assets
  - Launch/Operations Control Centers

Range Instrumentation Architectures:
Space-Based Instrumentation

- Some space-based systems being fielded
  - GPS beginning to be used as a primary positional data source
  - TDRSS used for Space Shuttle
  - SATCOM for DoD applications
- Current federal technology developments expected to provide reliable, certified, & affordable space-based flight hardware within five years
- Space-based capabilities unlikely to fully replace launch-head ground systems
  - Data quality/latency & launch-area safety considerations pose constraints
- Implementing space-based flight hardware across the launch community would eliminate requirements for some existing down-range or deployed transportable instrumentation
  - Reduces fixed costs to Range-owners (costs passed on to customers)
  - Increases range responsiveness by eliminating time to deploy transportable systems

Range Instrumentation Architectures:
Mobile/Transportable Instrumentation

- Transportable ground-based capabilities are becoming increasingly attractive to space-launch community
  - Current state of technology enables instrumentation to be packaged in transportable containers
  - Provides ability to launch at non-established launch sites
  - Allows one set of instrumentation to support multiple locations

- National transportable range capabilities currently exist to provide full suite of traditional services required of space-launch missions, but…

- Significant opportunities remain to optimize designs to reduce quantity & size of containers, number of personnel deployed to the remote site, & increase capabilities
  - Developments offer reduced costs & improved responsiveness

Wallops Flight Facility Mobile Range Lessons Learned

- Mobile campaigns are not cheap! Logistics and personnel TDY costs can dominate traditional service costs
- Mobile campaigns do not afford the same level of service or redundancy as established ranges
- Remote sites often do not have needed reliable local services (telecommunications, power) adding cost, time, and risk to missions
- Much local coordination is needed for campaigns (air traffic, environmental, community interest)
- Mobile range equipment and personnel must be exercised regularly to be proficient
- Various organizations possess mobile range components, but few have full range capabilities
- Significant opportunities exist to improve the effectiveness of mobile range capabilities

Mobile Campaign Configuration for ELVs

<u>Launch Site</u>

- 1 - Mobile RCC w/command transmitters ***(6 personnel)***
- 1 – C-band radar system ***(2 personnel)***
- 1 – Telemetry van + 2 telemetry antennas ***(3 personnel)***
- 1 – Tracking camera ***(1 personnel)***
- 1 – Power generator system ***(1 personnel)***
- 1 – Fire console system ***(1 personnel)***
- 1 – Timing system ***(1 personnel)***
- 1- I&T Support Testing ***(2-3 personnel)***

<u>Downrange Site</u>

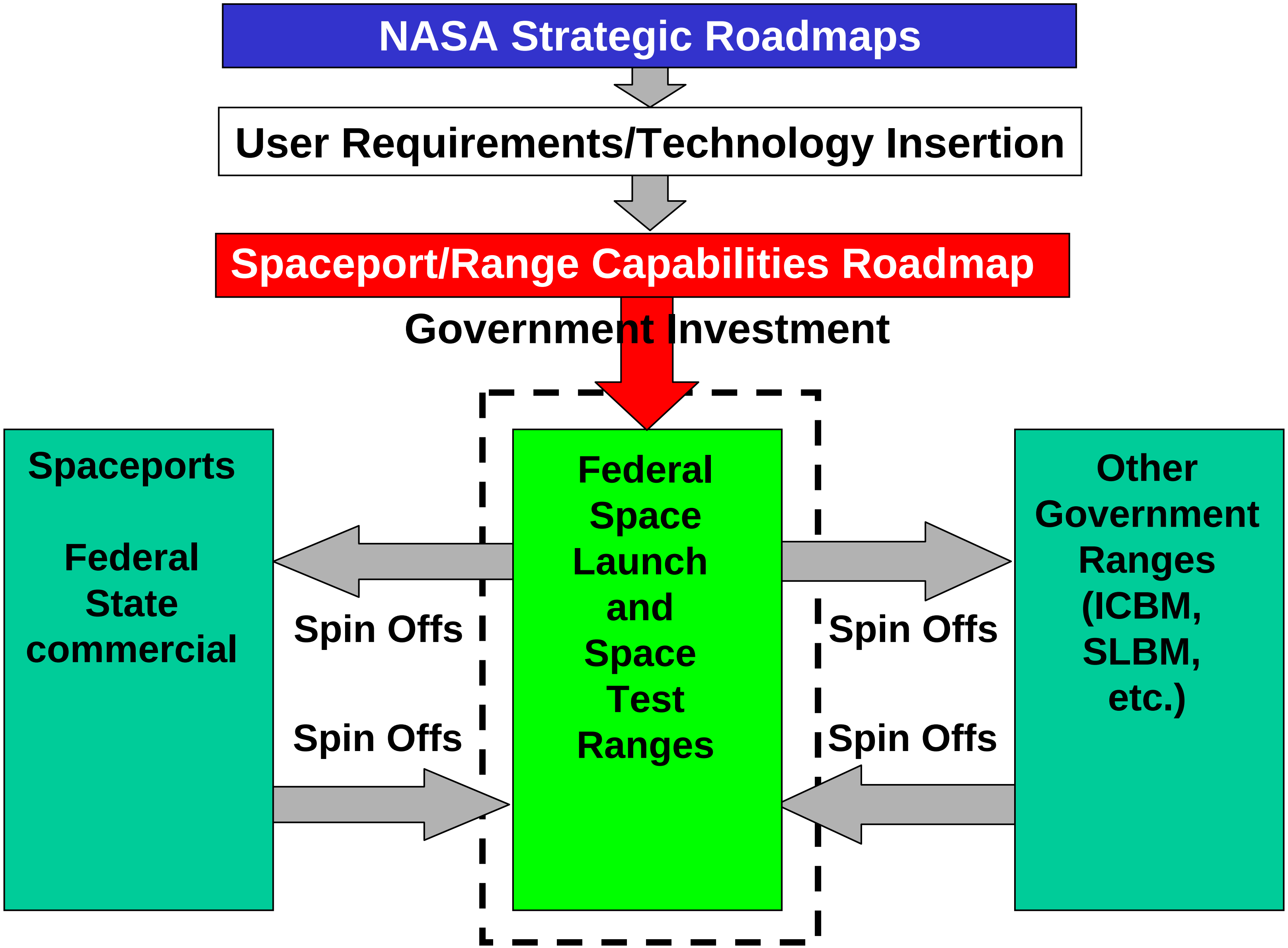
- 1 – Transmitter system ***(2 personnel)***
- 1 – C-band radar system ***(3 personnel)***
- 1 – Telemetry van + 1 telemetry antenna ***(2 personnel)***
- 1 – Power generator system ***(1 personnel)***

Note: ***(1) More than 1 downrange site may be needed for ELV missions***
(2) Requires personnel to carry out multiple functions (e.g., comm., PAO)

Requirements Focus

Explanation of Approach

Capabilities Roadmap Focus



Who Did We Talk To?

- USAF Ranges
- USAF Range Safety
- NASA Wallops Flight Facility
- NASA Mobile Range Assets
- FAA Licensing Office - Commercial Spaceports
- ARTWG/ASTWG/FIRST
- NASA Space Communications Office
- NASA Assessment of Emerging Space LV Range Needs
- Heritage Space LV Spaceport/Range Users – Boeing, LMCO, and Orbital
- NASA Spacecraft Spaceport/Range User
- MDA Range Users
- Navy Range Users
- NRO/Office of Space Launch

Team Assumptions

- Most Space Exploration activities assumed to require launch and processing support from federal facilities in Florida for CEV, heavy lift and intermediate and large class launch requirements
- Space Exploration requirements for the ranges involve:
  - Responsiveness (rapid turnaround) from tests, rehearsals or launches
  - Elimination of operational constraints imposed by Range such as launch azimuths and safety restrictions
  - Improved operational planning capabilities and approvals to support new missions. These include modeling, dispersions, break up analysis, and nuclear power systems
- Anticipate the USAF will continue to provide the basic capabilities for common user requirements and range/public safety at Eastern and Western Ranges for the foreseeable future
  - Includes scheduling, analyses, optics, telemetry, and communications
- Assume NASA will continue to provide spaceport customer services and institutional support at KSC and Wallops Flight Facility

Common Themes:2005-2015

- Public Safety
  - Simplify safety requirements for data and approvals
  - Real time weather support for all test and operations
  - Striking right balance between ground, mobile and space based assets
  - Enhanced flight termination systems and addition of satellite based assets for range tracking and telemetry
  - Improved air and sea surveillance
  - Improved mobile and transportable range assets
- Customer Services
  - Improvements in range turnaround for tests and operations
  - Higher volumes of data (i.e., continuous high-data rate communications)
  - Expanded and reserved frequencies for range operations
  - Improved digital equipment to support higher data rates
  - Improved scheduling and planning capabilities
  - Coordination of site enhancements impacts on users…PRIOR to implementation
  - Improved foreign national access and clearance
  - Lower cost of Launch Site/Range Operations

Common Themes:2016-2030

- Public Safety
  - Improved modeling for range safety(eg blast, toxic, re-entry)
  - Continuous Improvements in weather modeling and forecasting
  - Addition of IV&V for safety models
  - Expanded launch trajectories and azimuths
  - Enhanced capabilities for nuclear processing and storage

- Customer Satisfaction
  - Robust infrastructure for radars, optics and support equipment
  - Ability to conduct multiple parallel tests and operations
  - Increased launch window availability
  - Protect the availability of launch property at the launch head

Emerging Launch Vehicle Potential Spaceport/Range Needs

- **New emerging LV capabilities (e.g., DARPA FALCON, Space-X Falcon, Kistler) are intended to be low-cost access-to-space**
  - Generally smaller operations than heritage medium/heavy class LVs
  - Launch site operations and Range costs are larger percentage of overall service costs emerging companies are more sensitive to Spaceport/Range costs
  - Seek new technologies/capabilities to lower launch costs
    - Low Cost TDRSS Transceiver
    - Advanced Range Simulation
    - Mobile Fueling
    - Improved Surveillance

- **The emerging LV capabilities vary immensely in approach (e.g., liquid propulsion, solid rocket propulsion, air launch, etc.), which drives wide-range of needs at Spaceport/Range**
  - Spaceport:
    - Concrete Pad – “clean” pad
    - Lighting/Power
    - Access to site for transportable infrastructure
    - “Safe Crew” launch control area (bunker) or LCC
    - Payload encapsulation area
    - Portable assembly/stacking capability
  - Range
    - GPS/Range Tracking
    - Telemetry
    - Data and communications
    - Emergency vehicle support
    - Flight Trajectory assessment/range safety

Emerging Launch Vehicle Key Characteristics Range Considerations

Key Characteristic	DARPA FALCON Phase II A Contractors			
	Lockheed Martin Michoud	**SPACE-X**	**Microcosm**	**Air Launch**
Propulsion Concept	**Hybrid:** LOX/Rubber	**Liquid:** LOX/Kerosene	**Liquid:** LOX/Jet-A	**Liquid:** LOX/Propane
System Concept	Modular Simple vehicle and payload assembly and launch erection	Modular Simple vehicle and payload assembly and launch erection	Modular Simple vehicle and payload assembly and launch erection	Air drop & launch
Potential Launch Site	WFF	Kwajalein and/or Vandenberg	WFF	Any available/capable runways in the U.S., air launch from a C-17
Key Concept Of Operations	Simple Transporter/ Erector/Launcher Crane to erect full vehicle	Simple Transporter/ Erector/Launcher Crane to erect full vehicle.	Simple Transporter/ Erector/Launcher Crane to erect full vehicle plus extremely simple approach for all aspects of CONOPS	Drop launch from C-17 aircraft with simplified range tracking, safety, logistics & trajectory shaping and orbital mechanics

Emerging Launch Vehicles

Description of Potential Capability

- •Target small market to lift small payloads to LEO
- •1000 lb to 28.5 deg. Circular , 100 nm altitude
- •Target low recurring cost, less than$5M (20 launches/yr)
- •New launch operations/operationally responsive
  - •Reach alert status within 24 hours
  - • Launch within 24 hours
  - • Rapidly reconfigure launch systems to support higher launch tempo in a short time interval
- • Improved weather modeling, simulation, analysis, and prediction to reduce operations down time
- • Seek low cost vehicle processing infrastructure for new low cost launch vehicle

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Launch infrastructure and systems for new low cost small launch vehicles	U/R	U/R	Successful completion of development and first flight
a) Rapid turnaround of launch infrastructure b) Limited automated capability currently available for tracking, range safety & FTS	U/R	U/R	a) Increase processing speed, increase flexibility, decrease mission reconfiguration time b) Reduce cost associated with mission support
Weather Modeling Improved prediction capability to reduce false alarms	U/R	U/R	Reduce operations down time due to weather restrictions by a factor of 2

Current Capability

- • ICBM and Pegasus class launches range from $20-30M and assume low flight rates
- •Limited low cost/rapid turnaround, fully automated range capabilities currently available
- • Launch processing systems and pads are specific to launch vehicles based on larger heritage systems
- • Limited experience with launch mission manifests for rapid turnaround capability

Mission/Strategic Drivers

- • Multiple low-cost SLV's project readiness in 2008-2009
- •Targeted users: national security, civil, commercial, education, Amateurs (OSCAR satellites , etc.) low cost new technology demonstrations in-space
- •Potential low-cost approaches could be applied to future spiral(s) (10Klb or greater capability)

Manifest Considerations

Combined DOD, Current NASA, and Space Exploration Projections

NASA Launch Requirements

SCIENCE

- Robotic
    - Planetary Landers
    - Planetary Orbiters
    - Deep Space
    - Earth Observing
    - Sun-Earth Connection
    - Astrophysics
- Observatories

OPERATIONS

- ISS Crew
- ISS Assembly
- ISS Cargo
- ISS Partner Assets
- Space Communication
- Education payloads
- Reimbursable customers
- CEV Operations

SPACE EXPLORATION

- Robotic Precursors
- Technology Demonstrators
- Crew Exploration Vehicle(s)
- Project Prometheus
    - JIMO
- Moon/Mars cargo

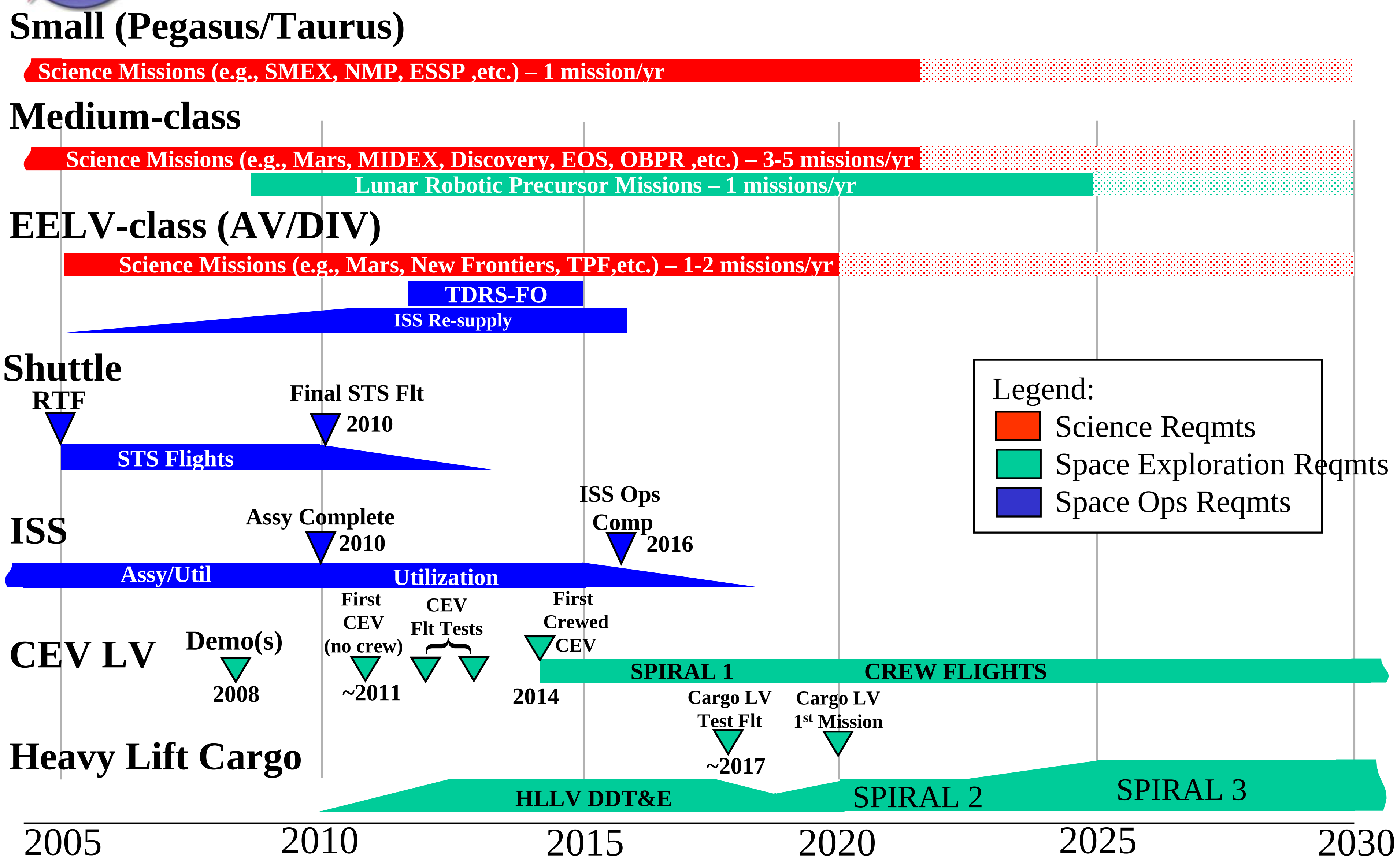
Access Considerations

- One of a kind science
- Nuclear propulsion
- Sensitive instruments
- Unique orbits
- Constrained launch periods
- Instantaneous launch windows

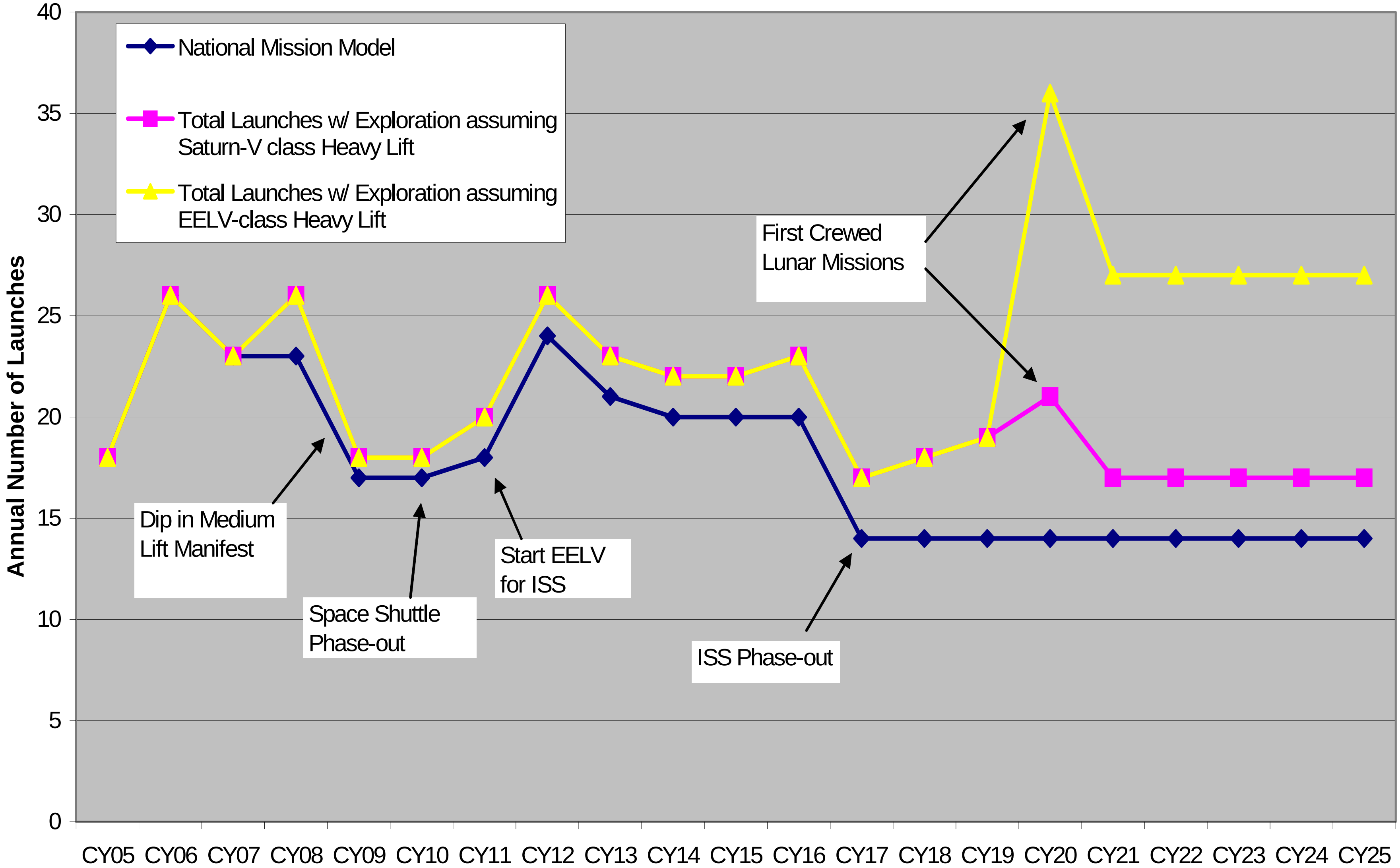
- Crew safety and health
- Crew logistics (food/water)
- Pressurized up and down mass
- Automated rendezvous & docking
- Moon/Mars operations

- Crew safety and health
- Crew logistics
- Automated rendezvous & docking?
- In space operations/assembly?
- Nuclear propulsion
- System of system approach

NASA Launch Requirements



Manifest Projections



Note: Totals above do not include emerging launch capabilities/market, nor does it include the missile-related T&E activities

Manifest Considerations

- NASA continues to pursue a Mixed Fleet Launch Strategy
  - Launch Services
    - Steady requirement for Small and Medium-class services projected
    - Modest use of Intermediate and large class (EELV)services
  - Space Shuttle
    - Complete ISS Assembly and retire Space Shuttle by end of 2010
  - International Launch Capability
    - Utilize foreign partner launch capability for international cooperatives
  - ISS cargo services, CEV and heavy lift requirements under review
    - Space Shuttle-derived, EELV-derived vehicle or new system in trade space
- DoD focus to consolidate all space payloads to EELV
  - Continue phase out of heritage systems
    - Titan IV targeted for end of 2005, Delta II targted for 2007/2008
  - Invest in sustainment of two EELV suppliers thru at least 2009
  - Meet small class requirement through use of refurbished ICBM assets
- DARPA FALCON Program offers potential for DOD operationally responsive lift needs and NASA science, education, technology needs

Manifests Considerations (continued)

- Space Exploration Heavy Lift Requirements
  - New Heavy Lift capability first use ~ 2016 timeframe
  - How much performance capability is required per flight?
    - Drives number and frequency of launches needed per planetary window
    - Drives In-space complexity
    - Launch System requirements may vary/evolve through Spiral development
  - Relationship between CEV and heavy vehicle is under review

- Unique Payload Processing Infrastructure Requirements
  - Facilities may need to be compatible with Nuclear power sources/propulsion
  - Oversized Spacecraft may require unique facilities
  - Unique transportation needs may exist
  - Seek synergy with TBD requirements with larger government user community

Manifest Considerations (continued)

- Continue to assess effects of a stagnant commercial market for foreseeable future
  - Domestic launch providers offering foreign services to obtain some market share
- New emerging launch capabilities and market continues to be unpredictable, hence affects on Roadmap have been to acknowledge and note
- Missile defense test and evaluation activities are not included in this assessment
- Flight rate and range testing volume do not pose an immediate concern as they fall within historical experience , need to monitor closely any potential increases in post 2015 timeframe as Space Exploration activities ramp up
- Expect that Space Exploration likely to dictate some requirements that drive transformational change, such as new human-rated systems and multi-launch scenarios in short duration planetary science window

Capability Breakdown Structure

Critical Capabilities Investment

Now through 2015

SPACEPORT AND CUSTOMER SERVICES:

1. Communications, command and control for Constellation
2. Improved commodities servicing next generation Personal Protective Equipment (PPE) (e.g. Advanced SCAPE)
3. Pad crew access
4. Human-related systems checkout and servicing
5. Egress and emergency systems
6. Launch infrastructure and systems for new vehicles
7. Rapid turnaround of launch infrastructure
8. Weather modeling for increased resolution and improved prediction capability

RANGE AND PUBLIC SAFETY:

1. Improved metric tracking for ground systems
2. Enhanced flight termination system
3. Improved broadband communications system
4. Space-based telemetry and range safety
5. Readily deployable mobile range assets
6. Improved surveillance for sea traffic in launch impact zone

INSTITUTIONAL:

1. Service based communications
2. Consolidation of communication systems
3. Data access & security

2015 and beyond

SPACEPORT AND CUSTOMER SERVICES:

1. Nuclear power and propulsion processing
2. Abort recovery operations for nuclear power and propulsion systems

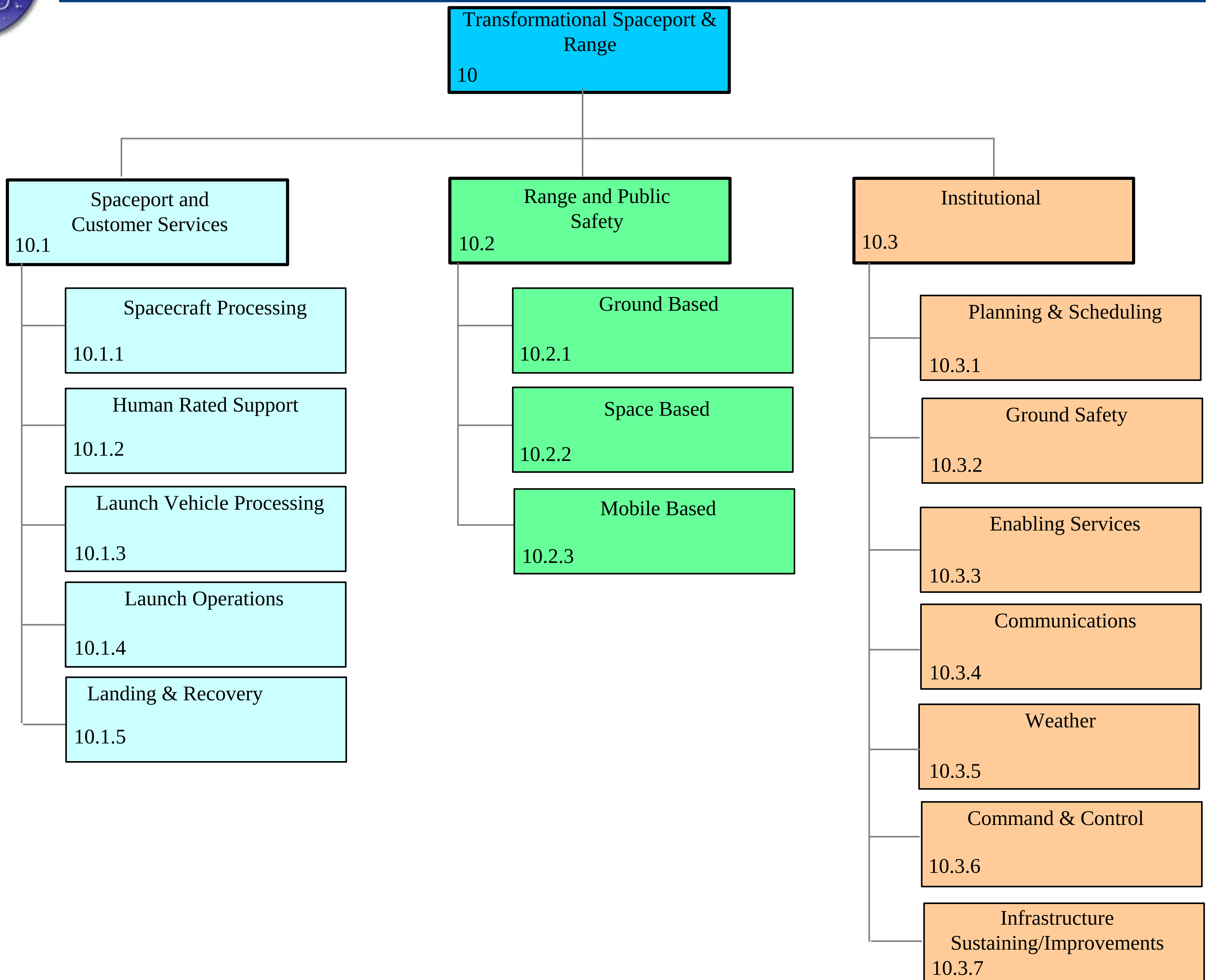
RANGE AND PUBLIC SAFETY:

(Decisions for additional capabilities needed to meet future requirements are TBD)

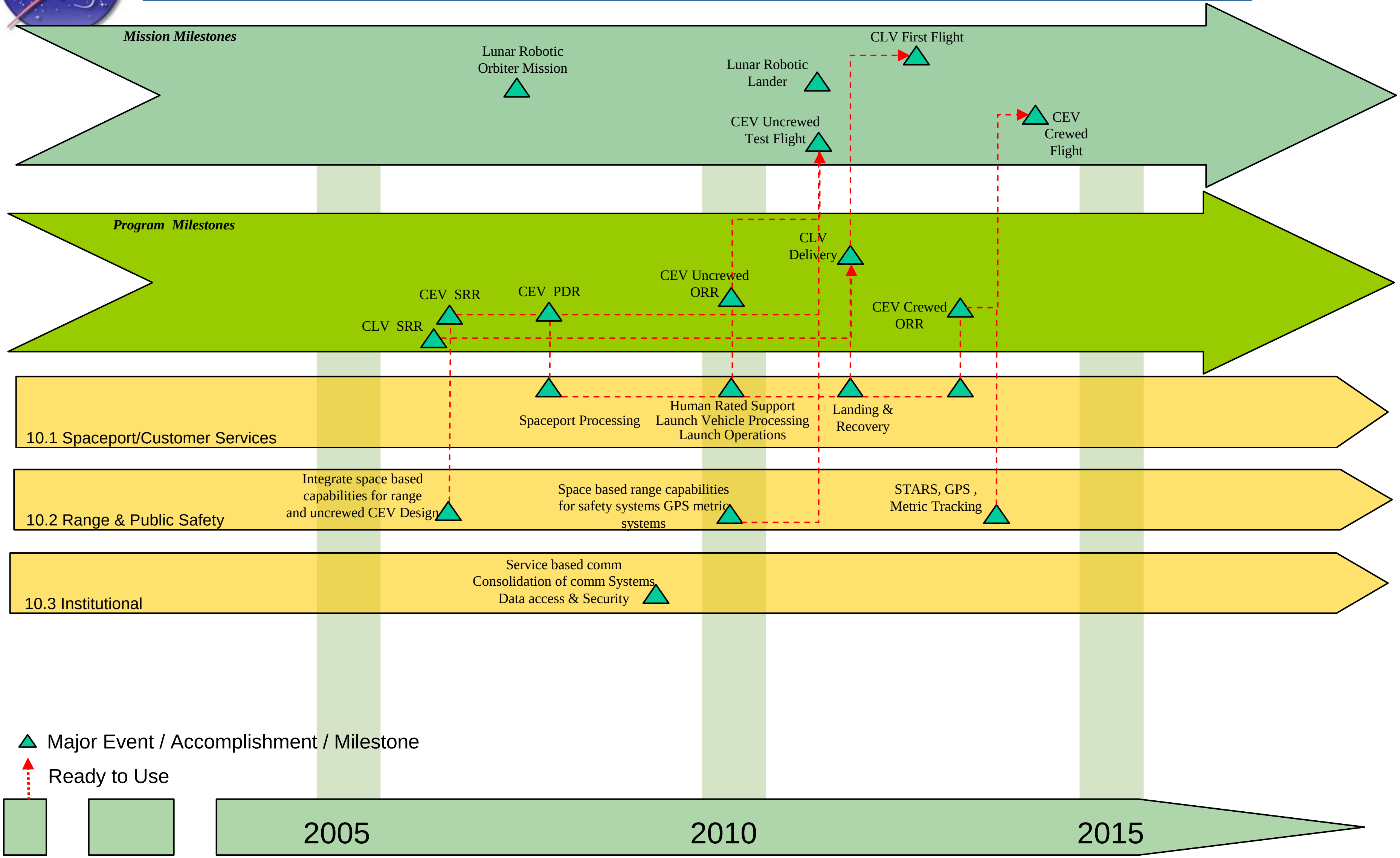
INSTITUTIONAL:

(Decisions for additional capabilities needed to meet future requirements are TBD)

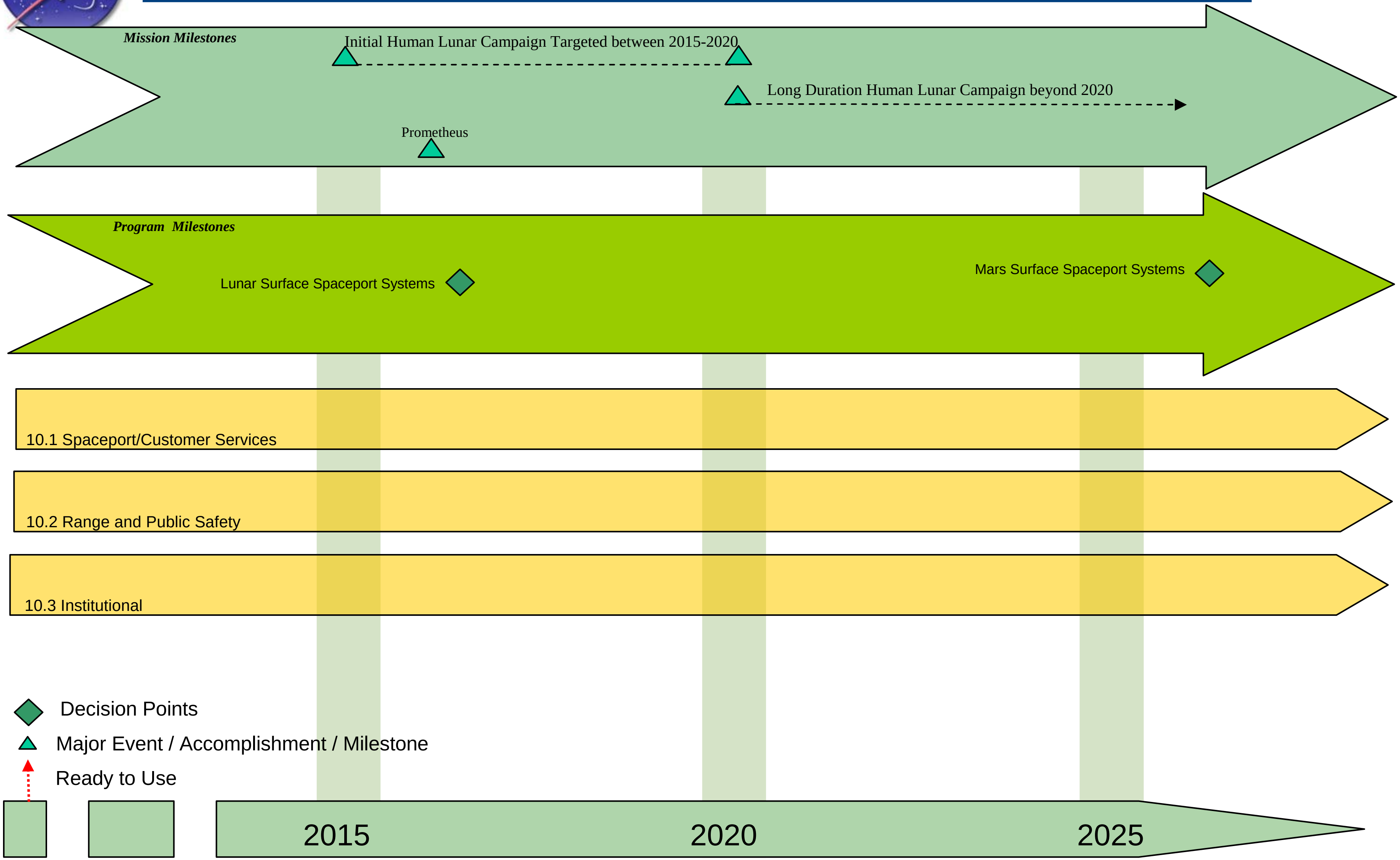
Capability Breakdown Structure



Transformational Spaceport & Range Roadmap Timeframe < 2015



Transformational Spaceport & Range Roadmap Timeframe > 2015



Capabilities Assessment Quad Charts

Description of Potential Capability

- Provides a general description of potential capabilities to meet future needs derived from postulated requirements in lieu of real requirements

Preliminary Gap Assessment

- Provides examples of individual capabilities
  - Preliminary assessment by KSC of the APIO Capability Readiness Levels (CRL)
  - Preliminary assessment of standard Technology Readiness Levels by ARTWG/ASTWG
  - KSC-proposed performance metrics
- Requires further analysis for link with still emerging Space Exploration priorities/requirements

Current Capability

- Provides general description of current capabilities, if applicable, and/or gap for the future

Mission/Strategic Drivers

- Identified Program Milestones

10.1.1 Spacecraft Processing

Description of Potential Capability

- Receive, test, service, integrate, and transport crewed and uncrewed spacecraft elements and integrate them to the launch vehicle. Specific capabilities include:
  - Distributed communications, command & control system using standard hardware, software, and interfaces for flight elements at dispersed sites, and also including standardized test equipment
  - Improved commodity servicing, associated leak detection, and system operations verification for preflight, launch, landing and recovery operations, next generation PPE for hazardous commodities
  - The capability to store, secure, process and test nuclear power and propulsion systems for flight hardware processing
  - Improved weather modeling, simulation, analysis, and prediction to reduce operations down time

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Communications, Command and Control for Constellation	2-3	5-8	Increase data volume and integration, decrease development and implementation costs. Increase speed and accuracy of fault detection and mitigation
Improved Commodities Servicing Next generation Personal Protective Equipment (e.g. Advanced SCAPE)	3-4	5-8	Improve standardization, decrease commodity loading times and improves safety and reliability
Nuclear Power and Propulsion Processing	2	5-8	Assure personnel and public safety, increase mission success Obtain required permits and certification
Weather Modeling a) Increase resolution of models (Space and Time) b) Improved prediction capability to reduce false alarms	4	a) 6 b) 4	a) With 500m resolution, initialize models with current weather data b) Reduce operations down time due to weather restrictions by a factor of 2

Current Capability

- Flight elements use different, individually tailored, communication, command, and control architectures throughout their life depending on their location (factory, launch site, in-space), and have unique interfaces for test, checkout, and servicing
- Hazardous commodity processing requires the use of manually operated equipment and SCAPE systems for personnel protection which are approaching the end of their useful life
- Experience with processing of nuclear power generation systems is limited to RTGs (no reactor experience or active conversion experience)

Mission/Strategic Drivers

- Communications, Command and Control systems available by uncrewed CEV ORR 2010
- Commodities Servicing systems available by uncrewed CEV ORR 2010
- The next generation personal protection equipment development must start as soon as possible to ensure replacement prior to end of useful life of current equipment
- Nuclear Power and Propulsion Processing systems available for Prometheus 2016
- Continuous improvements in weather modeling and forecasting
  - Increased launch window availability
  - Responsiveness (rapid turnaround) from tests, rehearsals and launches

10.1.2 Human Rated Support

Description of Potential Capability

- Provide crew support during launch operations, landing and recovery. Capabilities include :
  - Pad crew access capability to the spacecraft
  - Checkout and service specific systems supporting human rating e.g.: ECLSS; Air conditioning/revitalization; fuel cells; propulsion/attitude control; waste management; spacesuits; crew-related communication and data transmission.
  - Provide specific systems and capabilities for crew support and emergency egress and for abort/landing emergencies

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Pad Crew Access	5	9	Successful completion of design verification and operation readiness
Human-related systems checkout and servicing	5	9	Successful completion of design verification and operation readiness
Egress and Emergency systems	5	9	Successful completion of design verification and operation readiness

Current Capability

- Space Shuttle capabilities are planned to be phased-out in the 2010-2011 timeframe – TBD utilization for CEV
- Human rated vehicles require additional systems and ground support not required on non human rated pads
- Support to mission aborts or landing emergencies provided at multiple remote sites around the world.

Mission/Strategic Drivers

- Human-related systems available by crewed CEV ORR 2013
- Egress and Emergency systems available by crewed CEV ORR 2013
- Responsiveness (rapid turnaround) from tests, rehearsals or launches

10.1.3 Launch Vehicle Processing

Description of Potential Capability

- Vehicle processing infrastructure specific to any new advanced launch vehicle
- Rapidly reconfigure launch systems after a launch to support launch campaigns of many launches over a short period of time
- Improved weather modeling, simulation, analysis, and prediction to reduce operations down time
- Command & Control system compatible with 10.1.1

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Launch infrastructure and systems for new vehicles	1-2	8-9	Successful completion of readiness reviews
Rapid turnaround of launch infrastructure	1	5-7	Increase processing speed, increase flexibility, decrease mission reconfiguration time
Weather Modeling a) Increase resolution of models (Space and Time) b) Improved prediction capability to reduce false alarms	4	a) 6 b) 4	a) With 500m resolution, initialize models with current weather data b) Reduce operations down time due to weather restrictions by a factor of 2

Current Capability

- Launch processing systems and pads are specific to launch vehicles
- Limited experience with launch mission manifests for rapid turnaround capability
- Improved capability will reduce risk to schedule and mission assurance

Mission/Strategic Drivers

- Vehicle processing infrastructure specific to advanced launch vehicles must be verified operational prior to ORR for crewed CEV 2013
- Continuous improvements in weather modeling and forecasting

10.1.4 Launch Operations

Description of Potential Capability

- Improved systems, equipment and services for advanced launch vehicles and payloads
  - Next generation Personal Protective Equipment
- Improved weather modeling, simulation, analysis, and prediction for safer and less restrictive weather constraints
- Command & Control system compatible with 10.1.1

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Next generation Personal Protective Equipment	4	6	Decrease hazardous commodity servicing time, improve safety & reliability
Weather Modeling a) Increase resolution of models (Space and Time) b) Improved prediction capability to reduce false alarms	4	a) 6 b) 4	a) With 500m resolution, initialize models with current weather data b) Reduce necessary scrubs / delays due to weather restrictions by a factor of 2

Current Capabilities

- Existing Personal Protective Equipment for propellant loading are reaching the end of their useful life
- Improved capability will reduce risk of injury, loss of life and/or damage to flight hardware

Mission/Strategic Drivers

- The next generation personal protection equipment development must start as soon as possible to ensure replacement prior to end of useful life of current equipment
- Continuous improvements in weather modeling and forecasting
  - Increased launch window availability
  - Responsiveness (rapid turnaround) from tests, rehearsals and launches

10.1.5 Landing and Recovery

Description of Potential Capability

- Abort recovery operations for missions which include nuclear power and propulsion systems
- Recovery of crew after nominal mission and landing TBD depending on design
- Recovery of CEV and other spacecraft items TBD depending on design

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Provide nominal recovery for CEV uncrewed/crewed	4	7-8	Successful Completion of Crew Recovery and Vehicle safing Readiness Reviews
Abort recovery operations for nuclear power and propulsion systems	3	6-8	Public Safety

Current Capabilities

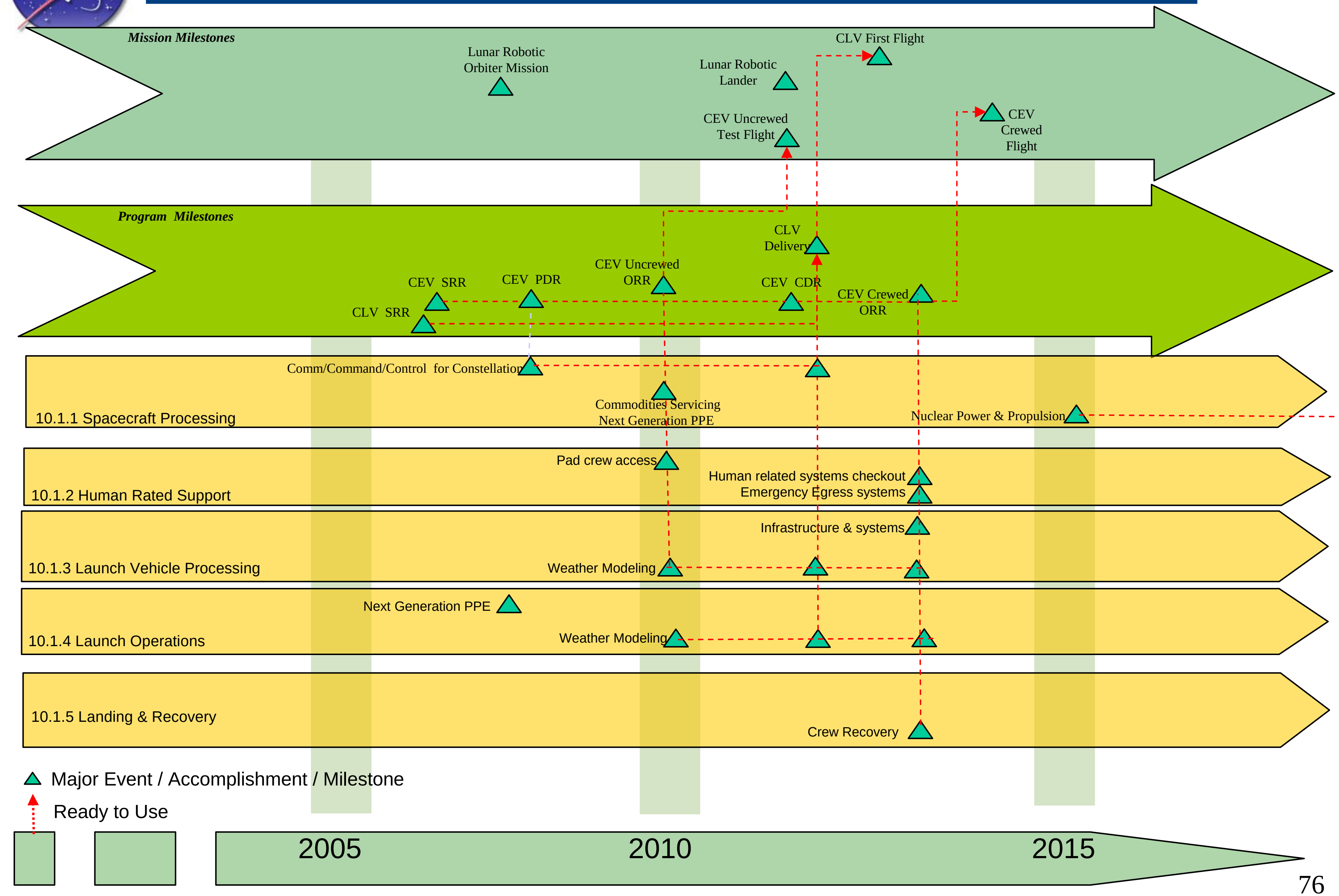
- Contingency plans to recover RTG
- Recovery of Orbiter (runway) and SRB's (ocean) for Shuttle missions
- Runway and turnaround Orbiter operations conducted at two prime sites plus several contingency and abort sites.
- Large amounts of support personnel and equipment at each landing site, and smaller (but significant) numbers of each at contingency and abort sites

Mission/Strategic Drivers

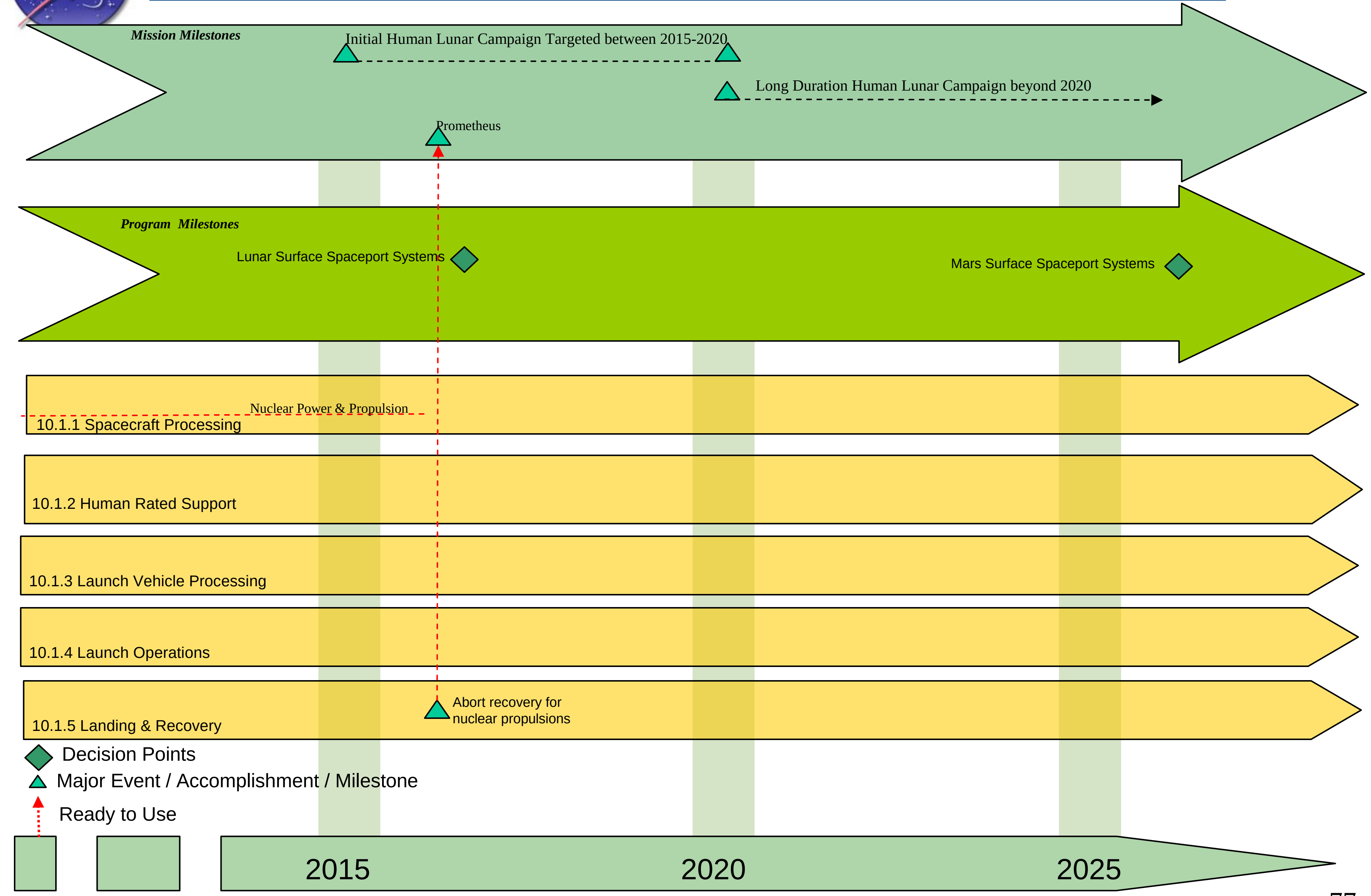
Potential Missions:

- Abort operation for nuclear power and propulsion for Prometheus 2016
- Recovery implementation planning for crewed CEV ORR 2013

10.1 Spaceport/Customer Services < 2015



10.1 Spaceport >2015



10.2.1 Ground-based

Description of Potential Capabilities

- Ground-based capabilities required:
  - Expand trajectories and azimuth improving metric tracking capabilities and continuous broadband communications from launch to orbital insertion

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Improved metric tracking for ground systems	3	6	Tracking accuracy and coverage

Current Capabilities

- Current system is fully functional for a limited set of launch azimuths and trajectories which relies on aging (1960s) technology and expensive ground-based assets
  - C-band radars
  - Optics
  - S-band telemetry
  - Flight termination system

Mission/Strategic Drivers

- Elimination of downrange C-band radars for metric tracking
- Space Exploration trajectories are TBD
- Responsiveness (rapid turnaround) from tests, rehearsals and launches

10.2.2 Space-based

Description of Potential Capabilities

- Enhanced flight termination system
- Provide continuous broadband communications from launch to orbital insertion
- GPS metric tracking to expand trajectories and azimuth
  - The Air Force is mandating GPS as the prime metric tracking solution

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
a) Enhanced flight termination system b) Improved communications e.g. Space-based Telemetry & Range Safety	5	6	Tracking pointing accuracy Instrumentation size and weight Data rates, data latency, bit error rate
Use of GPS for metric tracking	5	7	Tracking accuracy

Current Capabilities

- Limited use of space-based capabilities
  - TDRSS for communications
  - GPS for metric tracking is dependent on mobile or ground relays

Mission/Strategic Drivers

- 2006: Integrate space-based range capabilities with system requirements into uncrewed CLV design (CLV SRR)
- 2011: Support uncrewed CEV operation with space-based Telemetry

10.2.3 Mobile-based

Description of Potential Capabilities

- Readily deployable mobile range assets
- Augmentation of ground-based systems with an improved sensor suite on airborne or ship-based systems

Preliminary Gap Assessment

Capability	CRL	TRL	Metric
Readily deployable mobile range assets	6	7	Comparison with other range assets
Improved surveillance for air & sea traffic in launch impact zone	7	9	Integrated on board assets

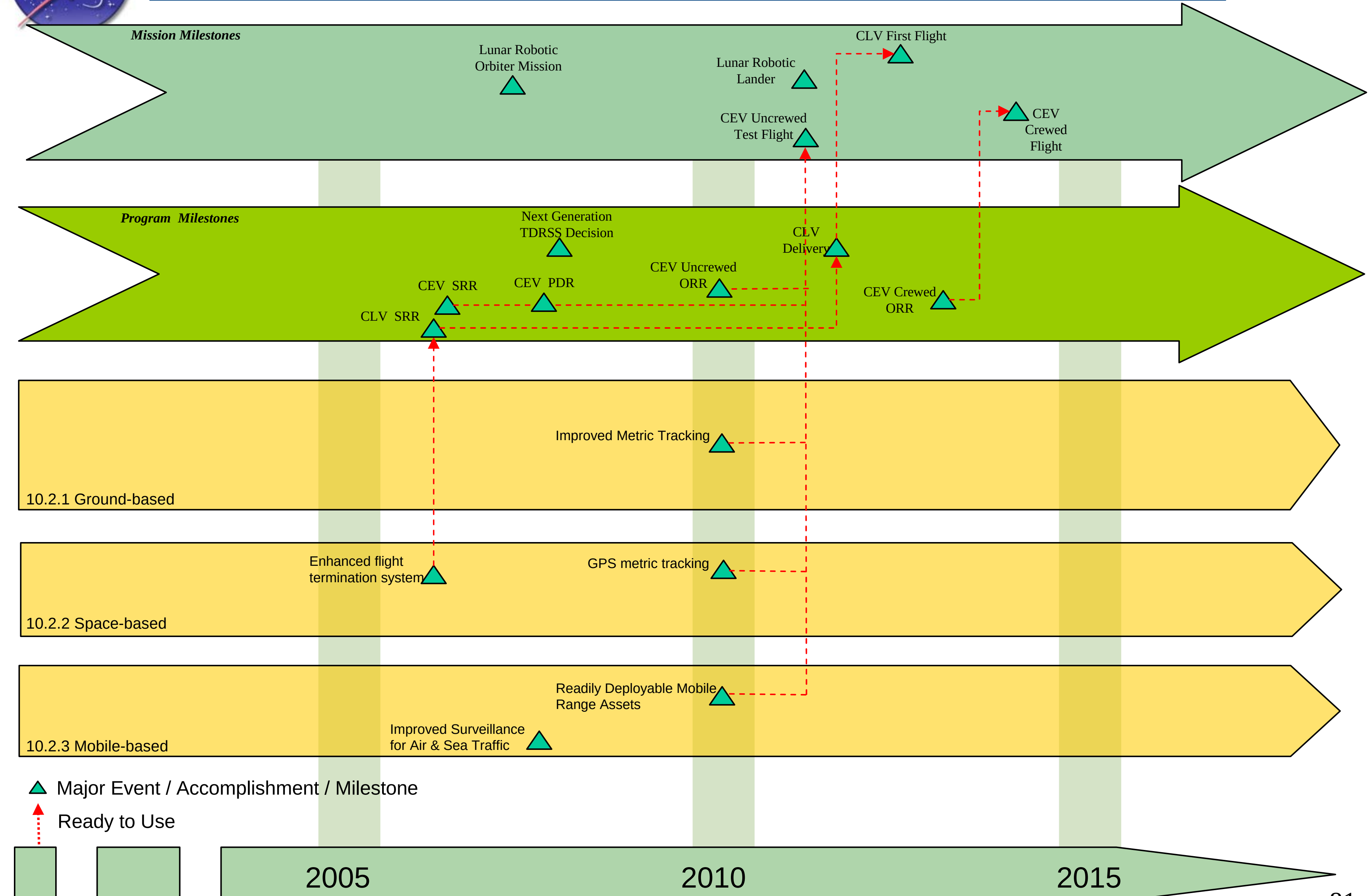
Current Capabilities

- Only a few mobile range assets (i.e., WFF, AFRL, WSTF). These are comprised of multiple trailers that need to be transported to remote sites at great difficulty, time, and expense
- Ground based systems augmented by a variety of airborne and ship-based systems

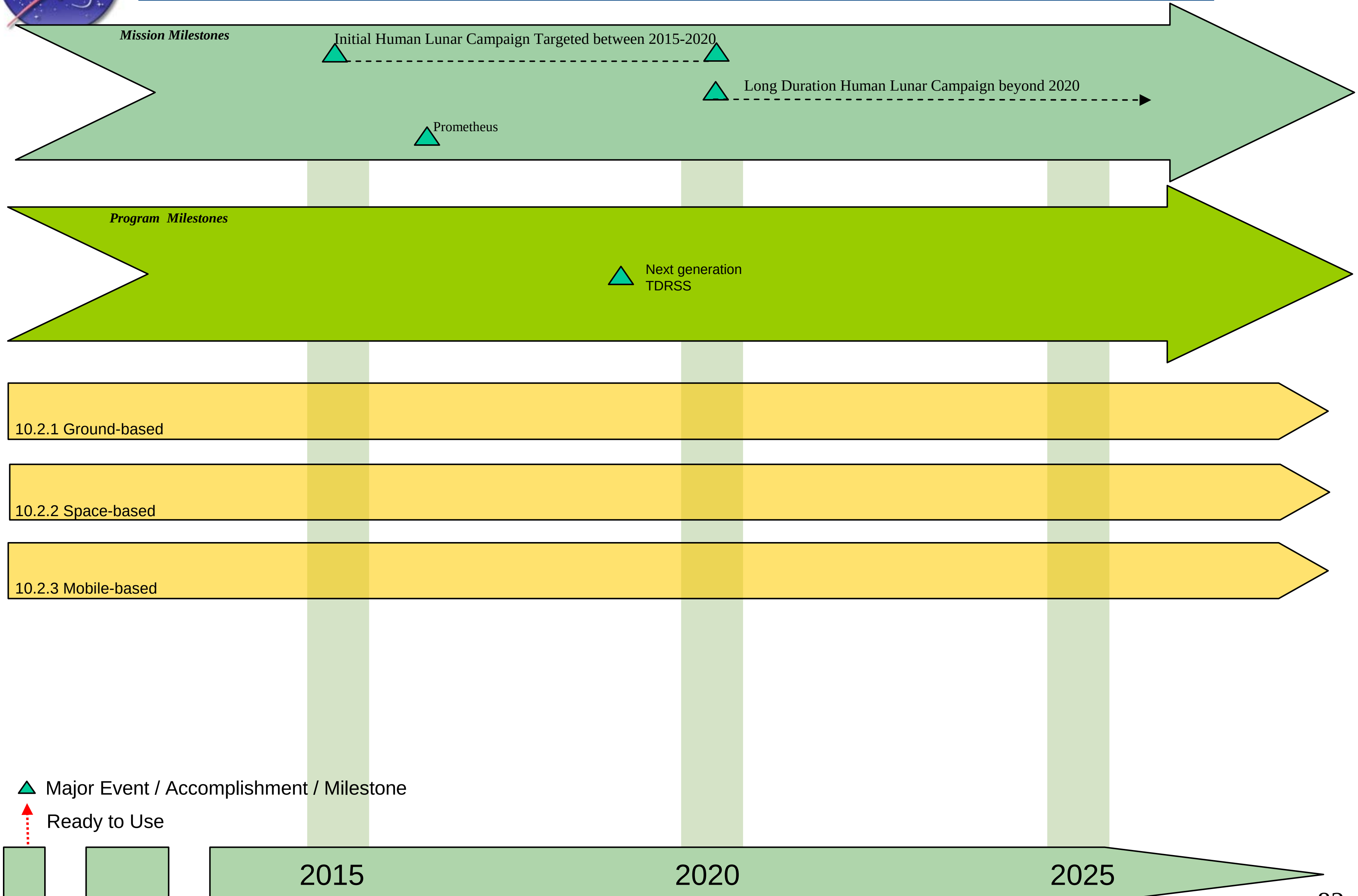
Mission/Strategic Drivers

- Provides improved ability to launch at non-established launch sites
- Improved public safety

10.2 Range and Public Safety < 2015



10.2 Range and Public Safety > 2015



10.3.4 Communications

Description of Potential Capabilities

- Transform from a system-based communications infrastructure to a service-based infrastructure; users subscribing to the network would receive user-specific service (access, permissions and functionality)
- Consolidation of communications infrastructure into a single carrier, maintaining compatibility with mission-specific communications
- Increase worldwide access to mission data while maintaining appropriate security

Preliminary Gap Assessment

Capabilities	CRL	TRL	Metric
Service-Based Communications a) Multi-vendor Volume	3	5	a) Provide on-demand comm. Coverage to authorized subscriber without dropouts b) Increase data rates 10x c) Automatic data collection and analysis services
Consolidated Communication Infrastructure a) Compatibility mission unique transition	3	6	Common protocols and media utilized for all comm. Systems
Data Access & Security a) Admin & Management	3	4	a) Web based access; encryptions and authentication of data b) QoS integrated info Mgmt of Global Information Grid

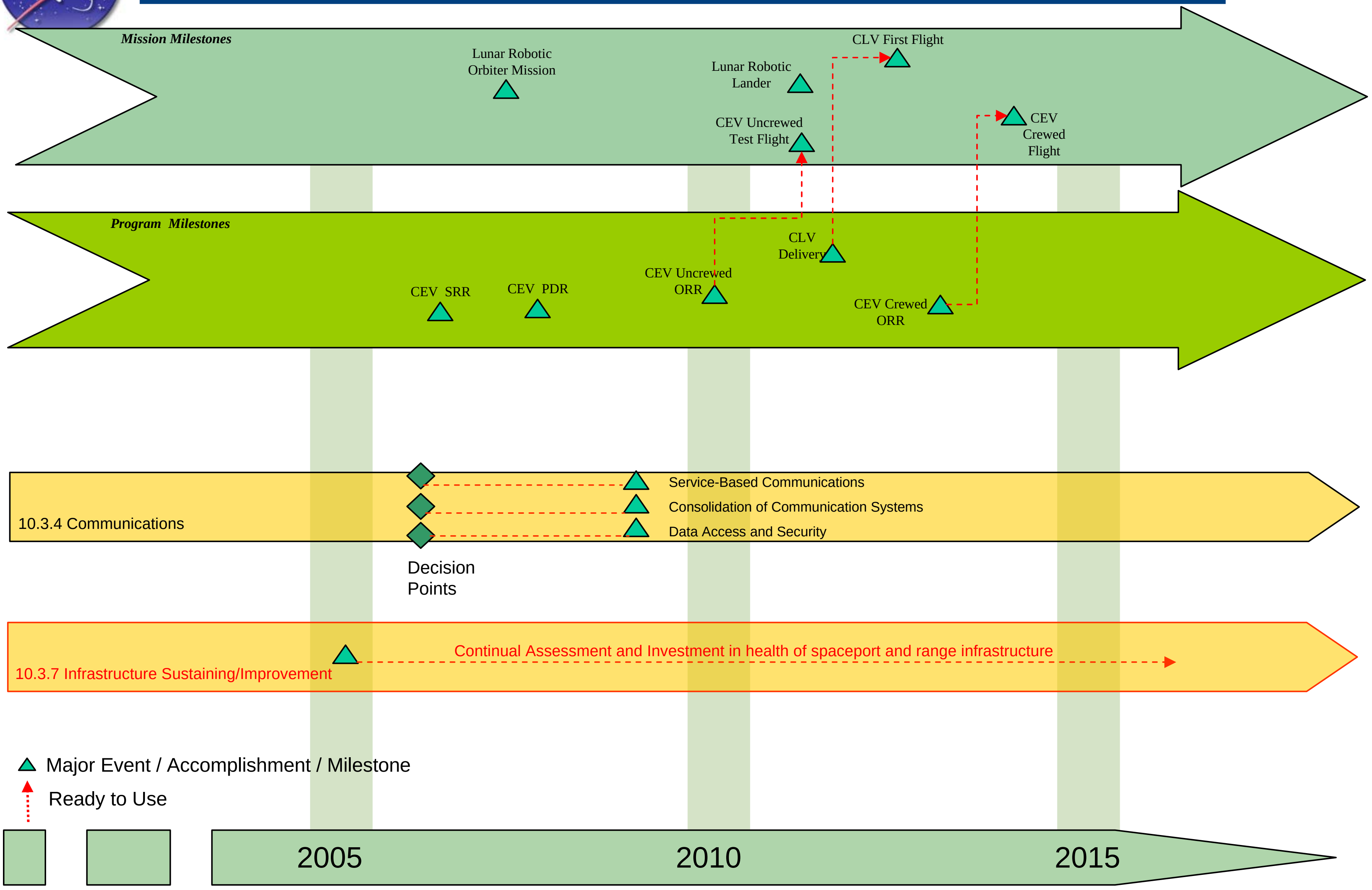
Current Capability

- All existing voice, video and data communication services are provisioned using dedicated systems, each with unique end instruments, cabling, distribution equipment, logistics spares, configuration management, and engineering. Separate unique systems required dedicated engineering, operations, system management and equipment spares resulting in increased costs
- Emerging communications technologies show promise that communications services can be provided from a common highly reliable, high bandwidth network capable of providing voice, video and data services. This approach significantly reduces the overall cost of designing, operating and maintaining communications capabilities while significantly increasing responsiveness and flexibility to the customer

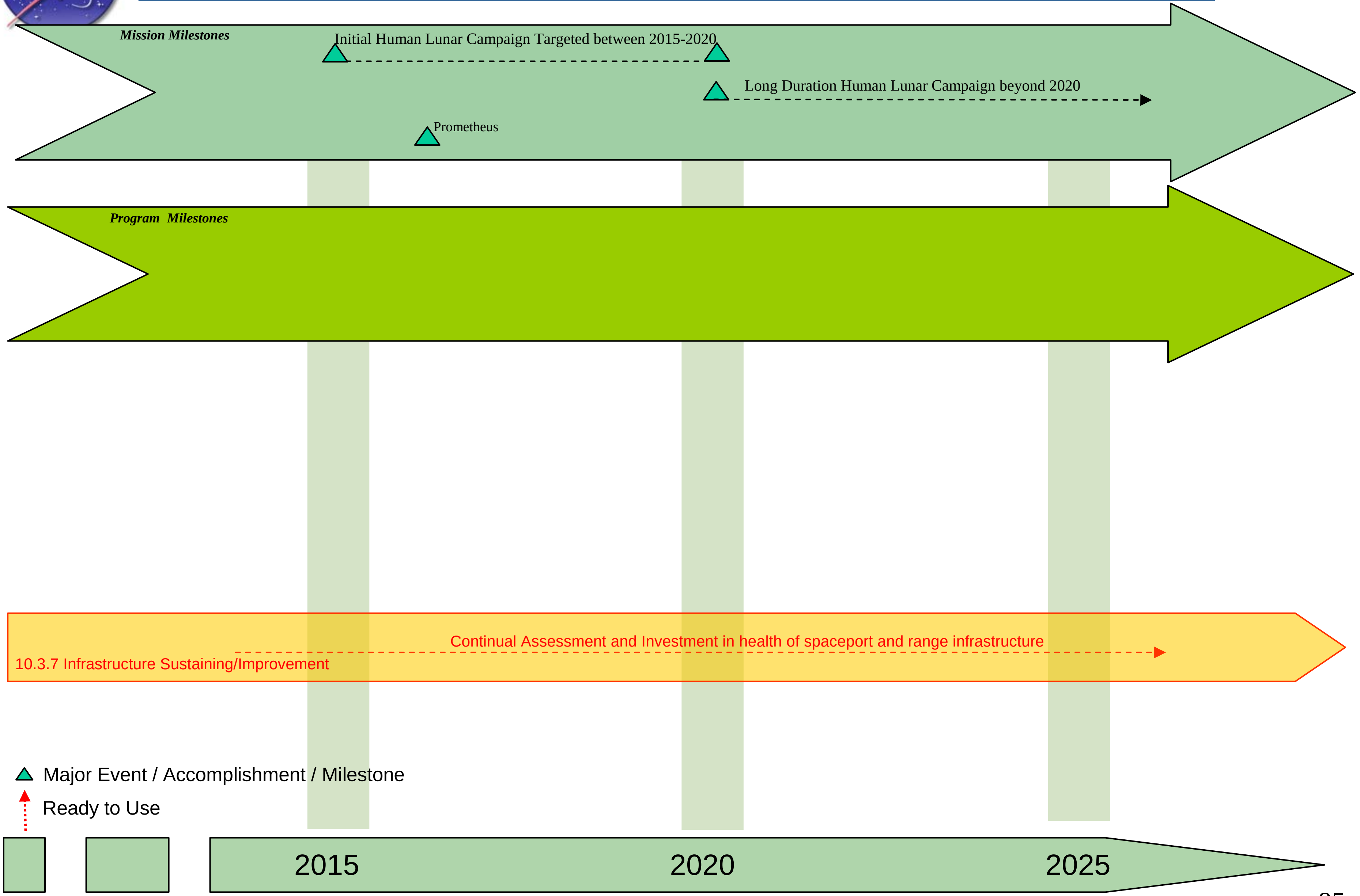
Mission/Strategic Drivers

- Improved services based communication infrastructure will allow rapid reconfiguration and provisioning of communications services to support element testing and daily operations at significantly reduced cost
- Provides high bandwidth mission or administrative voice, video and data streaming to any spaceport location in support to mission requirements.
- Provide 10GB/sec capability to all end users.

10.3 Institutional < 2015



10.3 Institutional >2015



Spaceport and Range Observations

Customer Satisfaction

- All Spaceports/Ranges have both common and unique needs as a result of their individual missions and customer base
  - Investments should be balanced on common needs as well as those carrying the highest national priority
- Improvement in turnaround times from test, development and launch activities should be area for continual improvement
  - Infrastructure : balance between sustaining current capability and new capability
  - Balance between resources constraints (people/funding) vs technology solutions
- Space-based communications capability should assume need for larger data volumes (e.g., power, antennas, etc.)
- Improved range and spaceport planning and scheduling capabilities should be implemented as part of continual improvement efforts
- Consistent with National Space Transportation Policy, all operators/users should seek to maximize use of commercial goods and services
  - eg satellite processing and general storage and support activities
- Reduced Spaceport and Range operations costs will continue to be a noble goal

Spaceport and Range Observations

Public Safety

- Models should be improved and true independent IV&V should be pursued
  - Weather prediction and safety calculations for blast and toxic
- Consider a center of excellence for models
- If a need is identified, development of models for nuclear generators and engines should be pursued
- Unique facilities to support nuclear activities may be needed as well

Observations on Non-technology Issues

The following items were identified during the Committee's deliberations and could be potential for forward-work for proposed Spaceport/Range Steering Committee:

- Launch Property at major federal ranges is becoming very scarce
  - Many demands for use and "ownership" exist
  - Likely not good planning to allow it to be reallocated to a single user before all space exploration requirements are known
- The FAA and the AF continue to work towards a joint safety regulation that could impact the commercial and government market place for rockets
  - Must preclude dual safety certifications
  - Must insure that additional costs not occur as a result of the dual/joint regulation environment
  - Need to include NASA in the dialogue
- Range encroachment, physical and RF, decrease the flexibility of operations
- Balance International participation with Homeland Security at Federal Ranges
  - Foreign entities access to Federal property
- Improvements needed to administrative accommodations at Spaceport for all users

A Transformational Thought

- The national ranges are crowded and becoming more so
- Design Test & Evaluation (DT &E) type range testing for range purposes is very difficult to fit in, can be risky, and precludes launch opportunities (RSA and other upgrades)
- Interplanetary windows could easily be impacted
- Basic capability exits to do these tests but it may not be the optimal method
- A range like Wallops Flight Facility may be best adapted to do range test and evaluation of new software or hardware for ranges
  - Test and transport of operational ranges for rapid insertion

Why a Wallops-Like Test Range Concept?

Wallops characteristics

- Lower overhead
- More schedule availability
- Aligns with existing Wallops culture & NASA-assigned mission
  - Focus on development activities & test missions
  - Can leverage existing NASA flight programs (e.g., Sounding Rockets) to provide low-cost technology demonstrations
  - Experience working with smaller users
  - Ability to demonstrate innovative approaches without compromising safety
- Experience in key transformational areas
  - Mobile range systems
  - Space-based and/or autonomous systems

What Might be Done on a Test Range for Ranges?

- Development of component systems like autonomous destruct or CRDs
- DT&E of common use range safety software and hardware
- DT&E of new common use hardware
- Test of new and truly mobile assets prior to operational range use and deployment
- Construction of other common user equipment
- Concept could include demonstration of key experimental flight system technologies that are best suited for a Test Range vs. Operational Range environment (e.g., prototype propulsion experiments, CEV crew-escape system demo, etc.)

Roadmap Conclusions

- Near-term Outlook:
  - Near term known mission requirements can be supported with current range and spaceports
  - There are areas that can be improved and/or life cycle costs that can be reduced once requirements identified and prioritized for investment

- Long-term Outlook
  - Transformational Spaceport and Range Roadmap has been focused on a requirements-driven approach with emphasis directed toward Program-unique and/or common user needs
  - Recommend the roadmap have careful review on a regular basis as the public safety and user requirements are identified and prioritized

Next Steps

- This Roadmap product is/should be a living document – this interim report is the initial step
- Committee will continue to refine requirements and develop investment strategies, using the best available customer milestones and data
- Report will be developed/submitted by June 2005
- NASA should continue to maintain a Spaceport/Range Steering Committee
  - Chaired by NASA HQ and co-chaired externally
  - Select membership by Centers and other stakeholders
  - Continued review of strategies for NASA investments into S&R capabilities and associated technologies as the Space Exploration initiative evolves

NRC Questions to be Answered

- Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

- Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

- Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

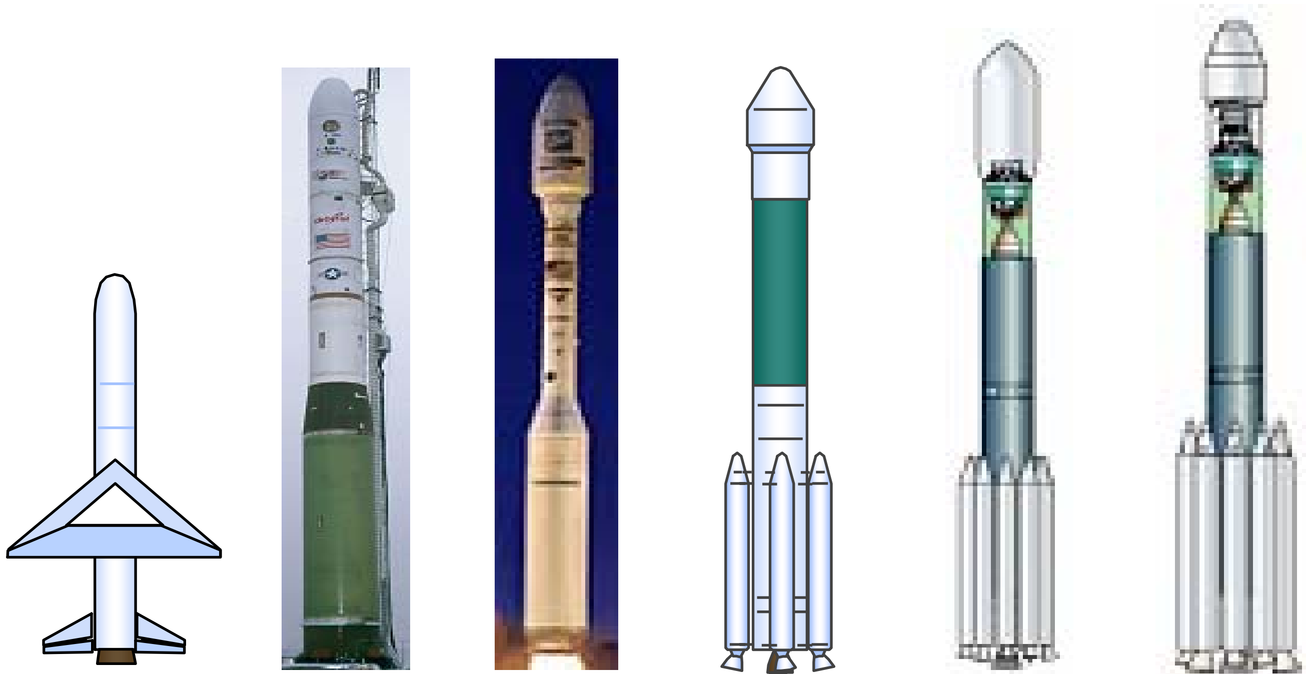
Acronyms and Abbreviations

AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AFSCN	Air Force Satellite Control Network
APIO	Advanced Planning and Integration Office (NASA)
ARD	Autonomous Rendezvous Docking
ARTWG	Advanced Range Technologies Working Group
ASTWG	Advanced Spaceport Technologies Working Group
CaLV	Cargo Launch Vehicle
CCAFS	Cape Canaveral Air Force Station
CDR	Critical Design Review
CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle
CoFR	Certification for Flight Readiness
CRD	
CRL	Capability Readiness Level
DARPA	Defense Advanced Research Projects Agency
DDT&E	Design, Development, Test and Evaluation
DoD	Department of Defense
ECLSS	Environmental Control/Life Support System
EDS	Earth Departure Stage
EELV	Evolved Expendable Launch Vehicle
FAA	Federal Aviation Administration
FAST	Flight Application of Spacecraft Technology
FIRST	Future Interagency Range & Spaceport Technologies
GB/Sec	Giga-Byte/Second
GPS	Global Positioning System
GSS	Ground Support Systems
HQ	Headquarters
IOC	Initial Operations Capability
ISS	International Space Station
IV&V	Independent Verification and Validation
KSC	Kennedy Space Center
LCC	Launch Control Center
LCN	Lunar Communications and Navigation
LSAM	Lunar Surface Access Module
LV	Launch Vehicle
MDA	Missile Defense Agency
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
ORR	Operation Readiness Review
OSD	Office of Secretary of Defense
OSHA	Occupational Safety and Health Administration
PDR	Preliminary Design Review
PPE	Personal Protective Equipment
QoS	Quality of Service
R&D	Research and Development
RF	Radio Frequency
RSA	Range Standardization and Automation
RTG	Radio-Isotope Thermal Generator
S&R	Spaceport and Range
SCAPE	Self-Contained Atmosphere Protective Ensemble
SCIF	Satellite Check-out and Integration Facility
SRB	Solid Rocket Booster
SRR	System Requirements Review
STARS	Space-based Telemetry And Range Safety
STS	Space Transportation System (aka Space Shuttle)
TBD	To Be Determined
TDRSS	Tracking and Data Relay Satellite System
T&E	Test and Evaluation
TRL	Technology Readiness Level
US	United States
USAF	United States Air Force
USG	United States Government
VAFB	Vandenberg Air Force Base
VPP	Voluntary Protection Program
WFF	Wallops Flight Facility
WSTF	White Sands Test Facility

SUPPLEMENTAL DATA

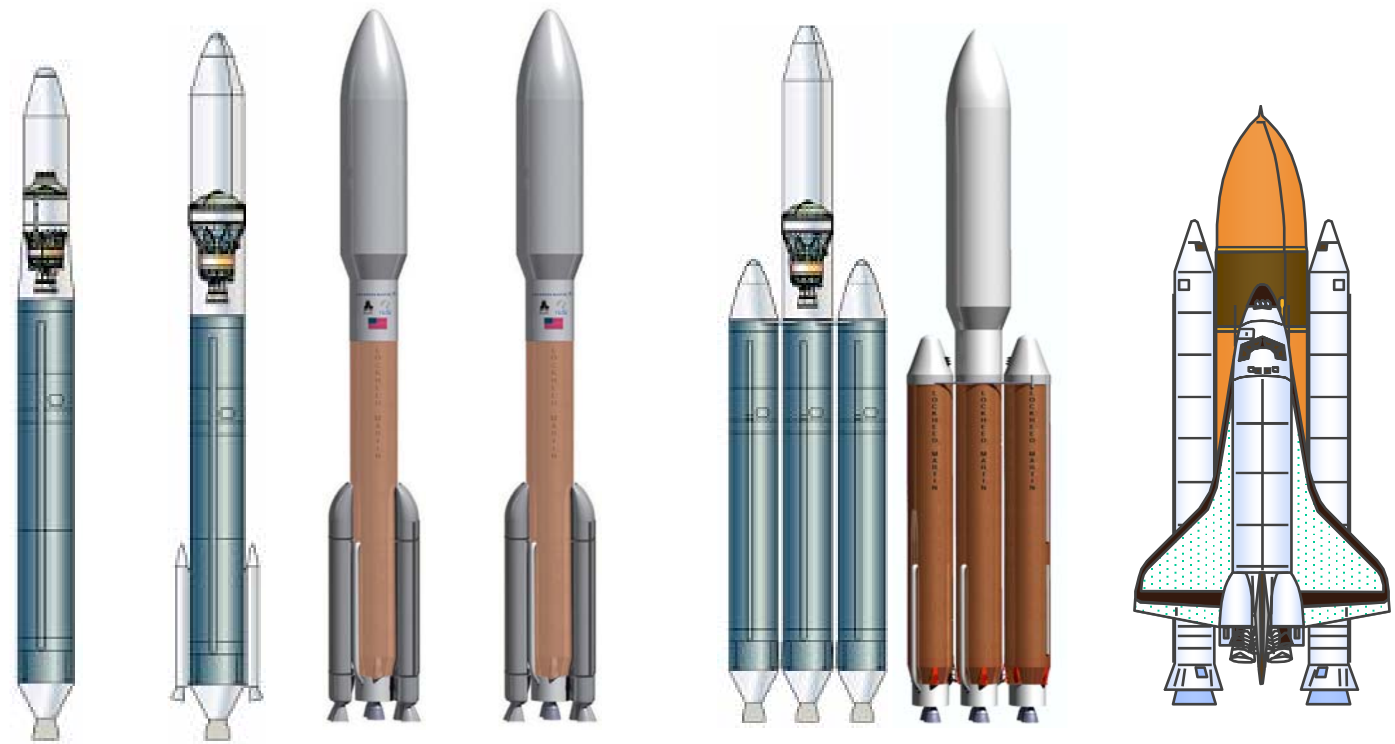
Not to be briefed, but in the package

Current Small US Launch Capability



Launch Vehicle	Pegasus	Minotaur	Taurus	Delta II 73XX	Delta II 79XX	Delta II 79XXH
Supplier	Orbital Sciences Corp.	Orbital Sciences Corp.	Orbital Sciences Corp.	Boeing	Boeing	Boeing
LEO (kg)	453	291	568	2,796	5,140	6,000
SSO (kg)	191	145	302	1,685	3,220	No WTR
ISS (kg)	350	N/A	455	2,435	4,440	5,200
GTO (kg)	N/A	N/A	N/A	1,000	1,870	2,100
High Energy C3=0	N/A	N/A	N/A	725	1,250	1,500
High Energy C3=10	N/A	N/A	N/A	600	1,000	1,300

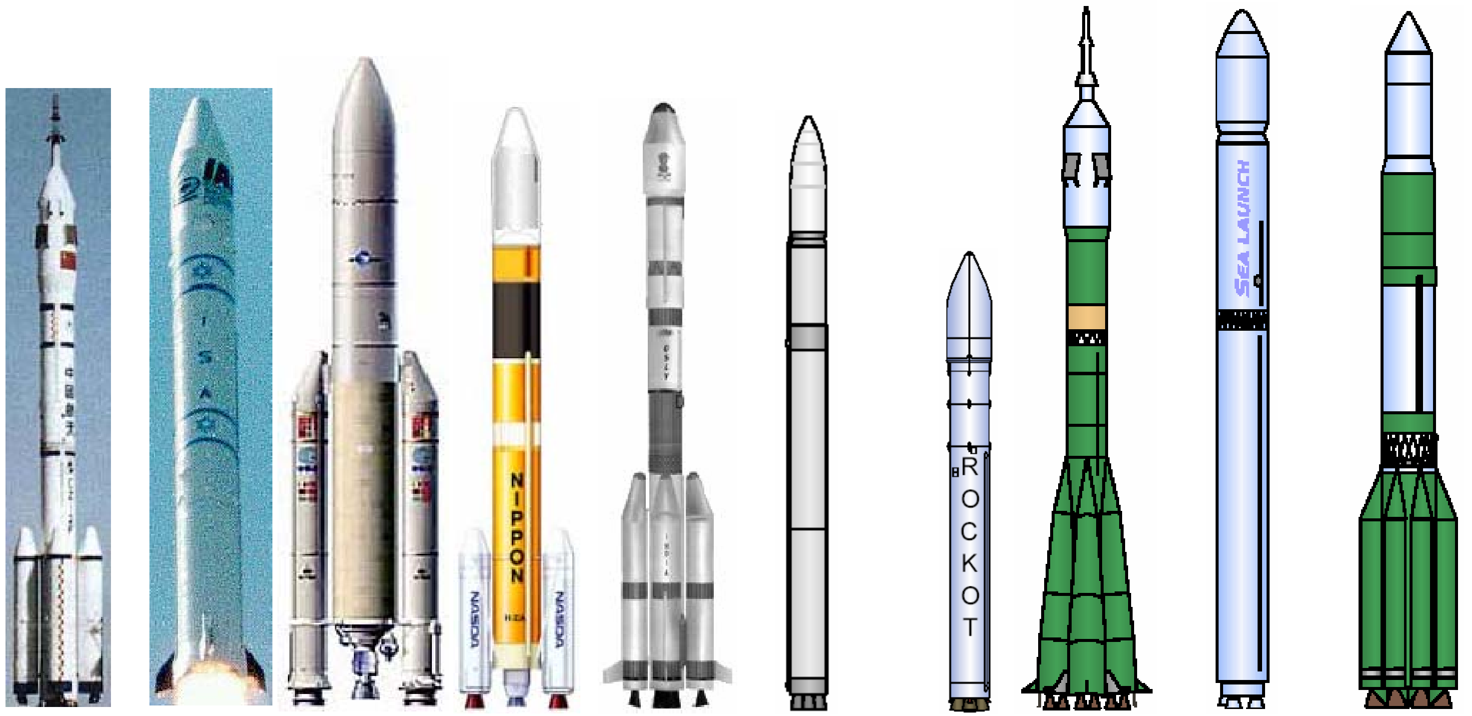
Current Large Class US Launch Capability



Launch Vehicle	Delta IV 4040	Delta IV 4450	Atlas V 50X	Atlas V 55X	Delta IV Heavy	Atlas V Heavy	Space Shuttle
Launch Service	Boeing	Boeing	LM	LM	Boeing	LM	NASA
LEO (kg)	8,600	13,100	9,540	18,000	23,165	U/R	22,600
SSO (kg)	6,300	9,600	No WTR	No WTR	21,040	No WTR	N/A
ISS (kg)	7,700	11,800	8,500	17,500	23,900	25,500	16,800
GTO (kg)	3,985	6,345	3,880	8,570	12,650	12,200	2200*
High Energy C3=0	2735	4,580	2680	6330	9305	9000	N/A
High Energy C3=10	2115	3,685	2150	5300	7810	7500	N/A

* Assumes IUS Upper Stage

Foreign Launch Capability



Pictures not to scale

Launch Vehicle	LM 2F	Shavit	AR 5	HII A	GSLV	Dnepr	Rockot	Soyuz	Zenit Sealaunch	Proton
Country	China	Israel	France	Japan	India	Russian	Russian	Russian	Russian	Russian
LEO (kg)	8,000	300	21,000	10,000	5,000	4,500	1,900	7,300	N/A	21,000
SSO (kg)	N/A	N/A	N/A	4,360	N/A	N/A	N/A	4,400	N/A	N/A
ISS (kg)	N/A	N/A	21,000	9,000	N/A	N/A	N/A	7,300	N/A	21,000
GTO (kg)	N/A	N/A	10,050	4,000	2,500	N/A	N/A	1,500	6,000	4,585
High Energy C3=0	N/A	N/A	6,000+	N/A	N/A	N/A	N/A	1,600	4,000	N/A
High Energy C3=10	N/A	N/A	5,500	N/A	N/A	N/A	N/A	1,200	3,000	N/A

Performance figures reflect publicly available advertised data
N/A = No known/advertised existing capability for respective trajectory

Crosswalk Matrix Ratings
Work In-progress

- Critical Relationships (Red):
  - Communications and Navigation Roadmap
    - Space-based assets for telemetry/tracking
- Moderate Relationships (Blue):
  - High Energy Power & Propulsion Roadmap
    - Potential unique launch site facilities/infrastructure needs for processing nuclear power sources/propulsion
  - In-space Transportation Roadmap:
    - Vehicle processing – pre-launch and launch
    - Telemetry/Tracking
  - Human Planetary Landing Systems Roadmap
    - Vehicle processing – pre-launch and launch
    - Telemetry/Tracking
  - Human Health and Support Systems Roadmap
    - Spaceport Infrastructure for crew pre-launch processing
    - Crew support equipment at launch site
    - Pad infrastructure (e.g., life support, comm, video, safety, etc.) for crewed vehicle
  - Advanced Modeling, Simulation, Analysis Roadmap
    - Modeling/Analysis for Range Safety (e.g., flight control ops, debris field analysis, expected casualty analysis, etc)
  - Systems Engineering Cost/Risk Analysis
    - Requirements Development, Design, Development of new Spaceport/Range Technologies

Wallops Mobile Range Mission Locations (Since 1983)

Full Mobile Range Missions/Campaigns

- Peru (1983) – ***Sounding Rocket Campaign***
- Fort Yukon, AK (1984)- ***Sounding Rocket Campaign***
- Fort Churchill, Canada (1983, 1984, 1989) – ***Sounding Rocket Campaigns***
- Sonde Stromfjord, Greenland (1985, 1988) – ***Sounding Rocket Campaigns***
- Woomera, Australia (1989, 1997) – ***Sounding Rocket Campaigns***
- Puerto Rico (1992, 1998) – ***Sounding Rocket Campaigns***
- Alcantara, Brazil (1994) – ***Sounding Rocket Campaign***
- Svalbard, Norway (1998, 2003) - ***Sounding Rocket Campaigns***
- Canary Islands (1997) – ***Pegasus ELV Mission***
- Kodiak, AK (2001) – ***Athena ELV Mission***

Partial Mobile Range Missions/Campaigns

- Poker Flat Research Range (Every 1-2 years) – ***Sounding Rocket Campaigns***
- Andoya, Norway (Every 2-3 years) – ***Sounding Rocket Campaigns***
- Kiruna, Sweden (Every 2-3 years) - ***Sounding Rocket Campaigns***
- Kwajalein Atoll (1990, 2004) – ***Sounding Rocket Campaigns***
- Midwest, USA (1998-1999) – ***X-33 Downrange Support***
- Coquina, NC (Every 1-2 years) – ***Wallops Downrange Support***

KSC Capabilities and Infrastructure

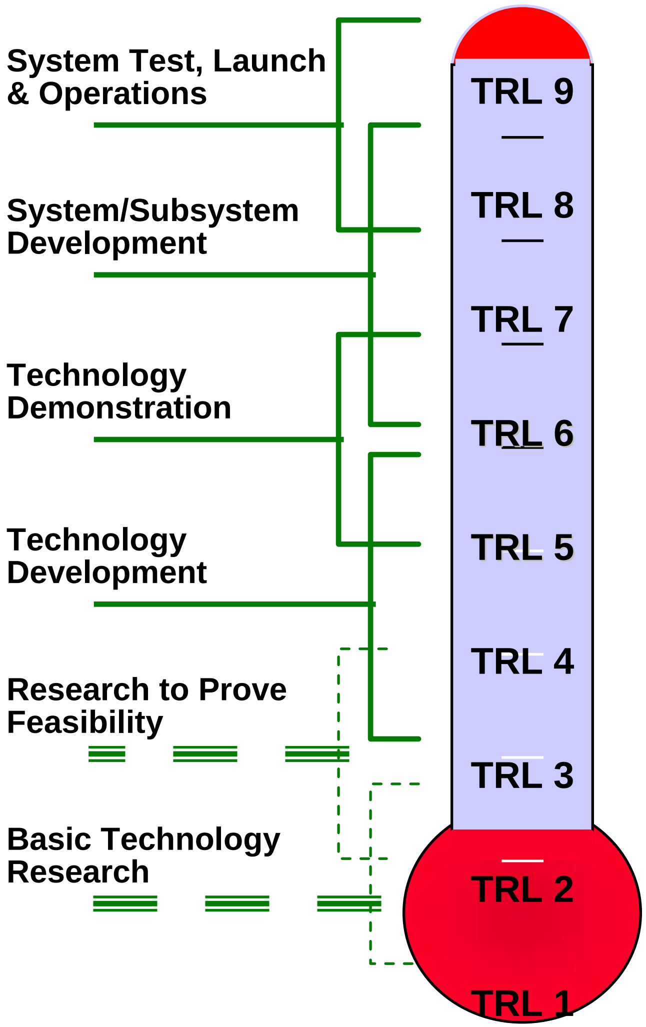
- 140,000 acres (218 square miles)
  - 70,000 acres of estuary deemed a system of National Importance
  - Located within confines of the Merritt Island National Wildlife Refuge and the Canaveral National Seashore
    - 6,800 acres for NASA activities
  - 27 State and Federally protected species, 11 of which are listed as threatened or endangered
- Over 7.2 million sq. feet of Building area
  - 3 fire stations
  - 2 medical facilities
- Utilities
  - 3 Central Cooling/Heating Plants
  - 2 Primary Substations
  - 270 miles of Electrical Distribution Lines
  - 60 miles of high pressure Helium/Nitrogen Pipelines
  - 46 miles of wastewater pipelines
  - 90 miles of water distribution pipelines
- Transportation
  - Shuttle Landing Facility (15,000 foot runway)
  - 540 miles of Roadway (paved and unpaved)
  - 2 Sea Docks
  - 40 miles of Railroad
  - 5 Major Bridges
- KSC Core Technical Capability (CTC) is comprised of the Center's multi-customer laboratories, critical competency sustenance and essntial technical services
  - CTC supports multiple enterprises and themes.

Approx. $4B Current Replacement Value

CTC Labs/Test Beds

- KSC Core Technical Capability (CTC) is comprised of the Center's multi-customer laboratories, critical competency sustenance and essential technical services.
  - CTC supports multiple Enterprises and themes
- Civil Service Labs/Testbeds
  - Metrology
  - Physical Test & Analysis
  - Chemical Test & Analysis
  - Development & Integration
  - Electrical Failure Analysis
  - Materials Failure Analysis
  - Bio-Medical
  - Telescience
  - Design Visualization
  - Real Time Control & Monitoring
  - Controls
  - Applied Physics
  - Electrostatics & Surface Physics Testbed
  - Launch Systems Testbed
  - Advanced Technology Development Center
  - Spaceport Processing Systems

TECHNOLOGY READINESS LEVELS



Actual system proven through successful mission operations

Actual system completed and qualified through test and demonstration

System prototype demonstration in a relevant environment

System/subsystem model or prototype demonstration in a relevant environment

Component and/or breadboard validation in relevant environment

Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Technology concept and/or application formulated

Basic principles observed and reported

Capability Readiness Levels

7 Capability Operational Readiness

6 Integrated Capability Demonstrated in an Operational Environment

5 Integrated Capability Demonstrated in a Relevant Environment

4 Integrated Capability Demonstrated in a Laboratory Environment

3 Sub-Capabilities* Demonstrated in a Relevant Environment

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

1 Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

* Sub-capabilities include Technologies, Infrastructure, and Knowledge (process, procedures, training, facilities)

National Research Council Dialogue to Assess Progress on

NASA's #13 In Situ Resource Utilization (ISRU) Capability Roadmap Development

General Background and Introduction

Rob Mueller

NASA Advanced Planning & Integration Office (APIO)

April 12, 2005

Agenda

Advanced Planning & Integration Office

- General Background and Introduction of Capability Roadmap
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

Advanced Planning & Integration Office

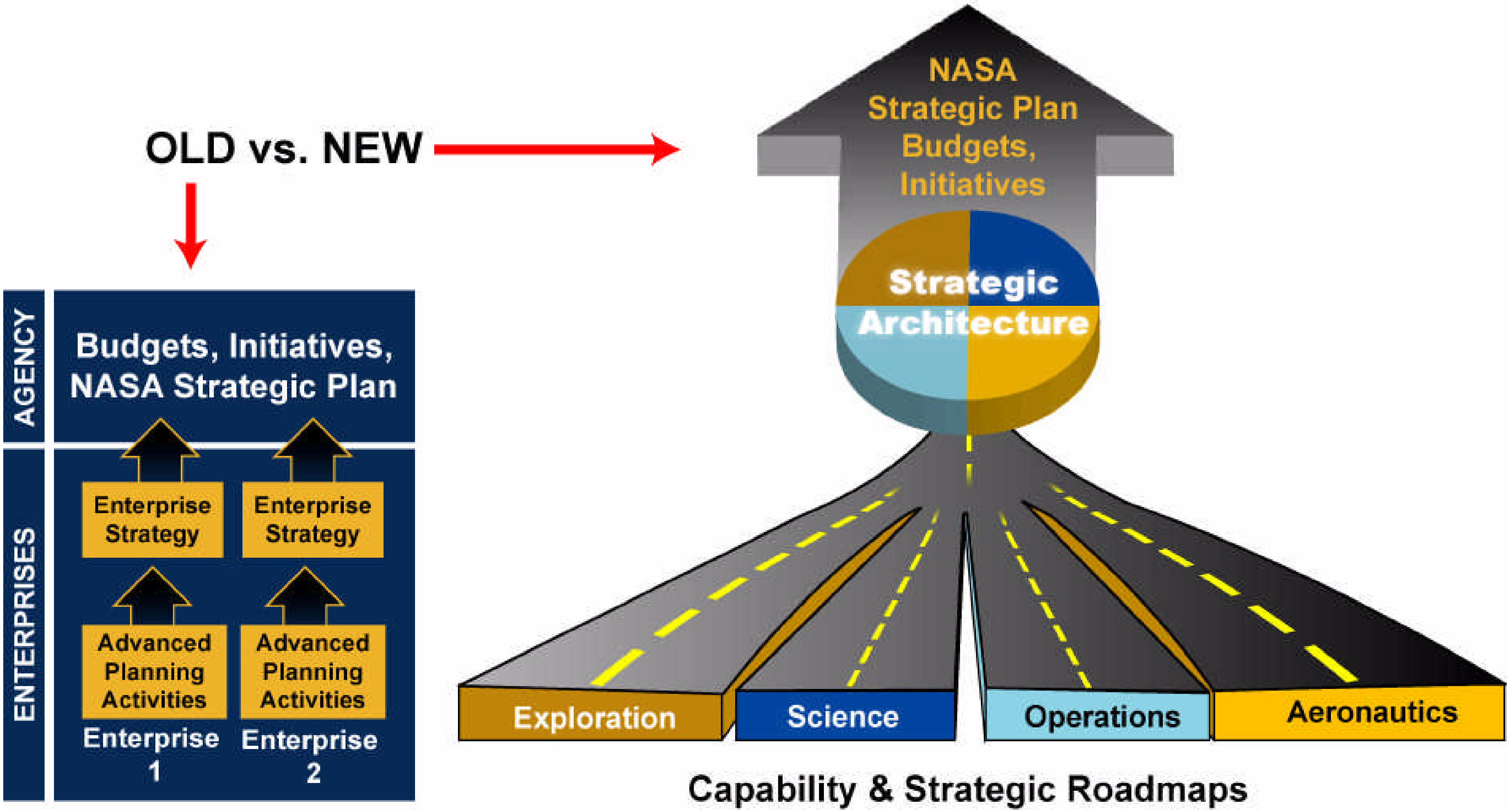
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

Agency Goals and Objectives

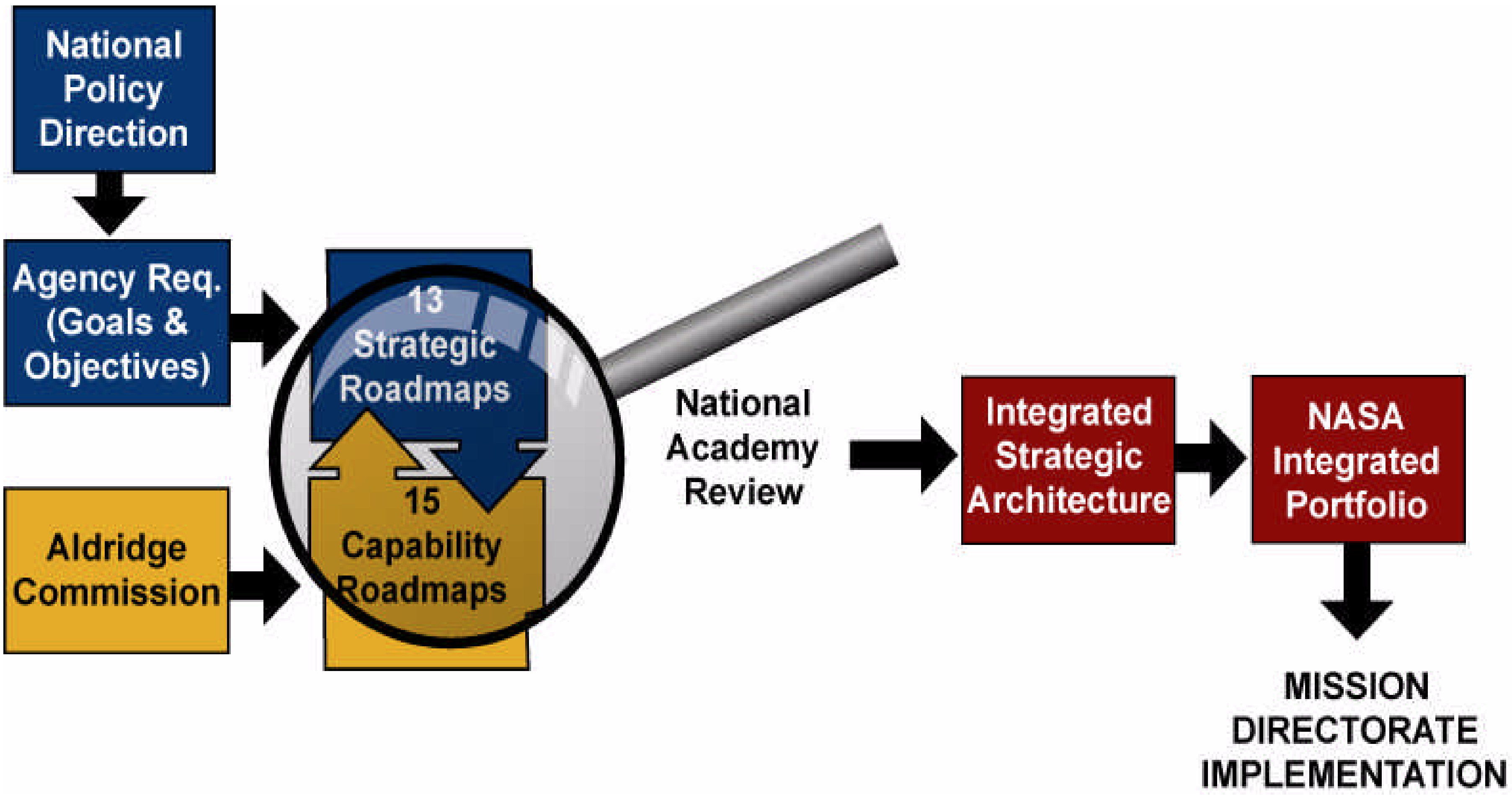
Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	Develop innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.	Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	Conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems. (SRM 9)
	Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)	Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)
	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)	

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

Advanced Planning & Integration Office

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (TBD)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

Advanced Planning & Integration Office

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

  - Broad human and robotic science and exploration goals, priorities, anticipated discoveries
  - High-level milestones, options, and decision points
  - Implementation approaches, suggested missions

Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
◤Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
◤Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators Also with Each Team

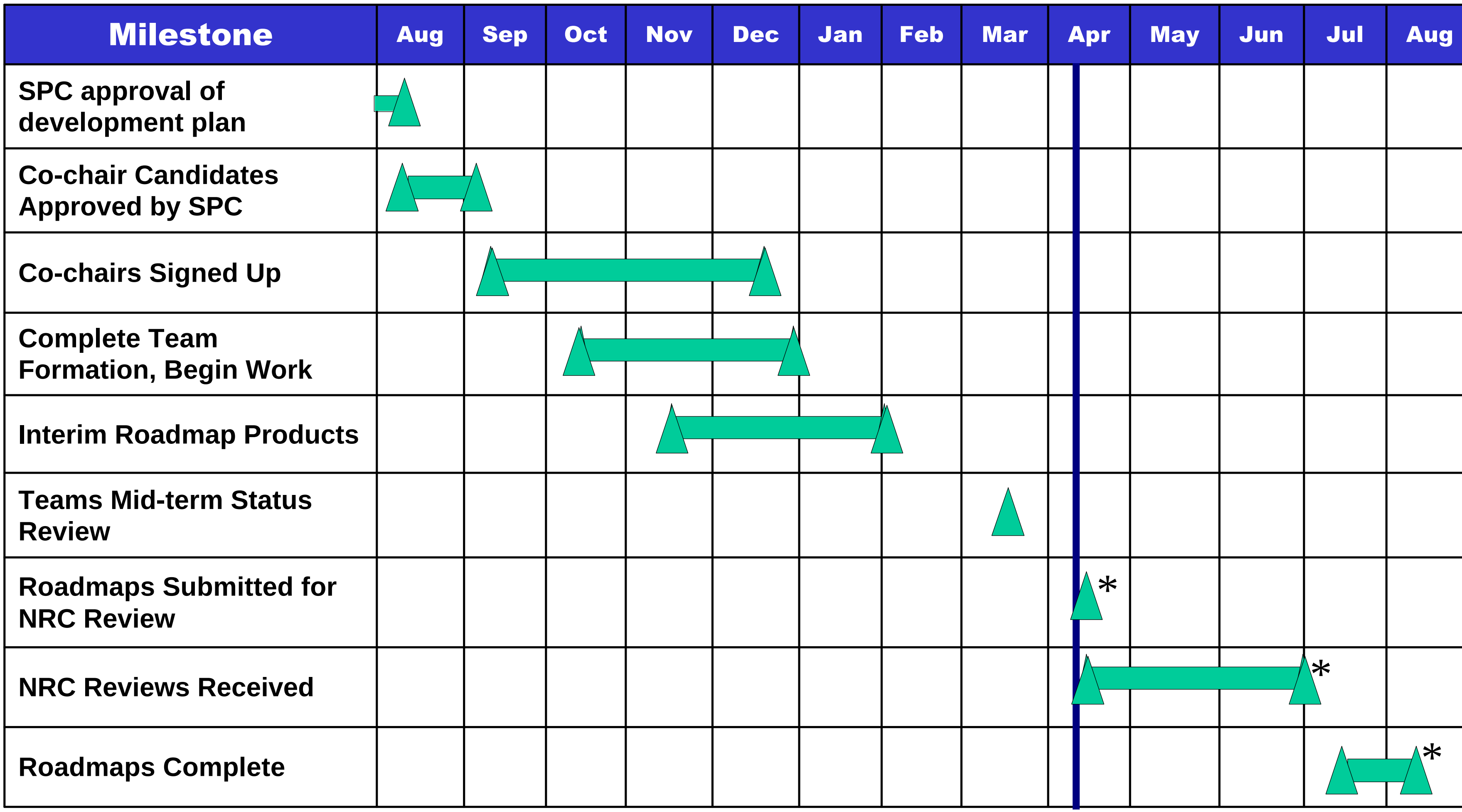
◤ = DoD Participation

Strategic Roadmaps - continued

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule

Advanced Planning & Integration Office



*Schedule under review.

Capability Roadmaps

- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

Advanced Planning & Integration Office

- NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.
- The capability roadmap development process will be accomplished in two phases.
  - Phase 1 will be the development of capability roadmaps and associated technical products.
    - During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.
  - Phase 2 will be the development of Investment Plans.
    - During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.

Process for Team Selection

Advanced Planning & Integration Office

- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**
    - **1/3 Industry**
    - **1/3 NASA & other Government Agencies**
    - **1/3 Academia**
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Capability	NASA chair	External chair
◤ High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
◤ In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
◤ Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
◤ Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
◤ Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators Also with Each Team

◤ = DoD Participation

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Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization (ISRU)	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

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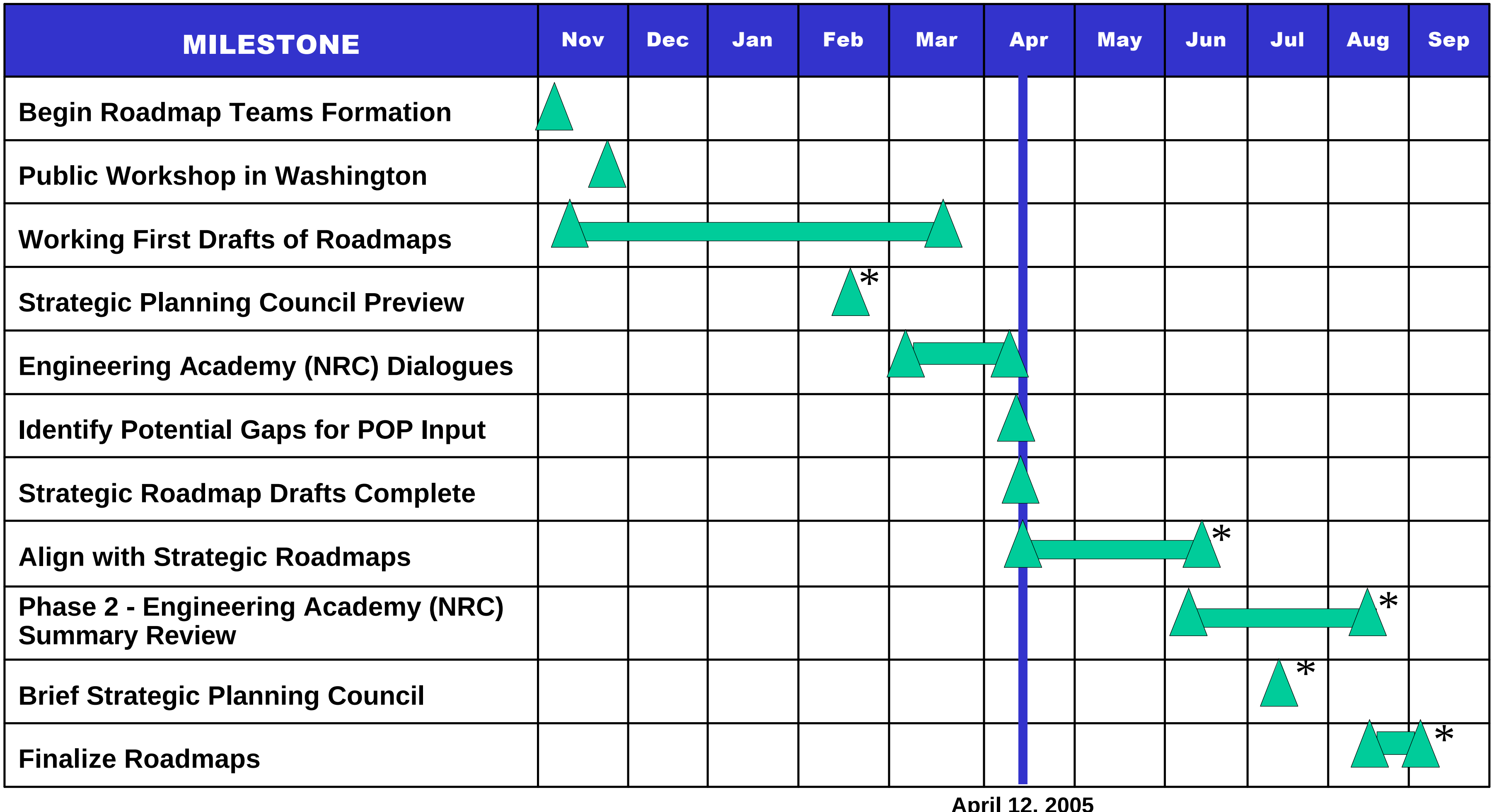

*Schedule under review.

Purpose of NRC Review

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

Technology Readiness Levels

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9 Actual System Proven in Operation

8 Actual System Qualified by Demonstration

7 System Prototype Demonstration in an Operational Environment

6 System/Subsystem Model or Prototype Demonstration in a Relevant Environment

5 Component and/or Breadboard Validation in a Relevant Environment

4 Component and/or Breadboard Validation in a Laboratory Environment

3 Analytical and Experimental Critical Functions Characteristic Proof-of-Concept

2 Technology Concept and/or Application Formulated

1 Basic Principles Observed and Reported

Capability Readiness Levels

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7 Capability Operational Readiness

6 Integrated Capability Demonstrated in an Operational Environment

5 Integrated Capability Demonstrated in a Relevant Environment

4 Integrated Capability Demonstrated in a Laboratory Environment

3 Sub-Capabilities* Demonstrated in a Relevant Environment

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

1 Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

Back-up charts

- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  - The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  - A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modelling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  - A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  - An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  - The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).

  -full scale flight articles
  -demonstration in appropriate operational 'envelope'
- **CRL 7: Capability Operational Readiness**
  - The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

ISRU Integration Crosswalk

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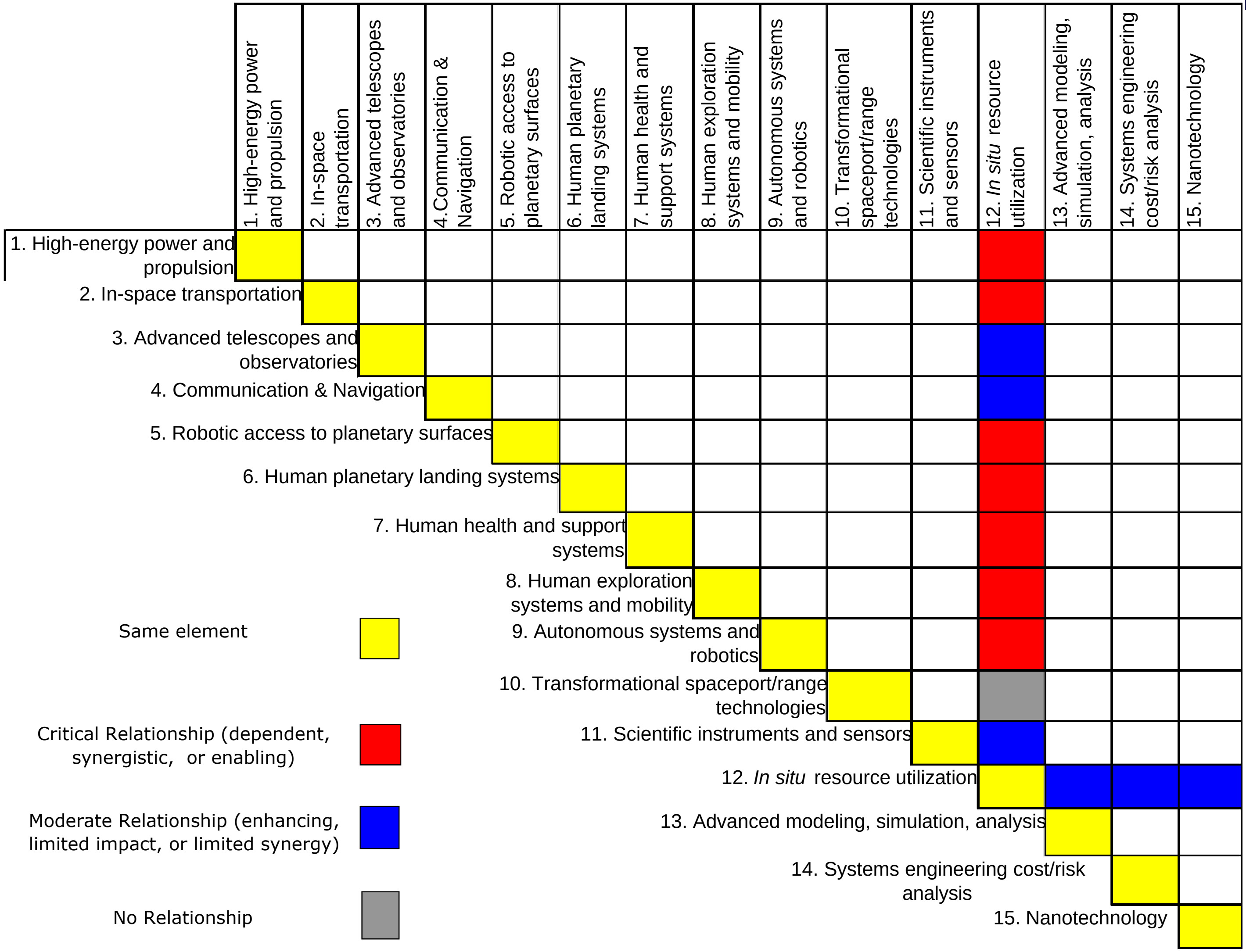


Crosswalk Details Example

	2. In-space transportation	**Capability Flow & Criticality**	**12. In situ resource utilization**	Nature of Relationship
	Ascent /Descent Stages	←	Resource Processing, storage and Distribution	Propellant made on Moon/ Mars may provide significant mass savings
	Earth Departure Stage	←	Resource Processing, storage and Distribution	Propellant made on Moon may be used for Earth (L1) Departure Stage
	Earth Return Stage	←	Resource Processing, storage and Distribution	Propellant made on Mars may be used for Earth Return Stage

	8. Human exploration systems and mobility		**12. In situ resource utilization**	
	Sub-Topic or Subsidiary Capability	**Capability Flow & Criticality**	Sub-Topic or Subsidiary Capability	Nature of Relationship
	Crew Mobility - Surface Mobility Systems	→	Resource Assessment / Extraction	Geologists will require mobility to access resource areas for evaluation
	Refueling and fluids support systems	←	Surface Consumable & Product Storage and Distribution	Automated umbilicals will supply breathing air, propellants and purges
	Fuel Cell	←	Surface Consumable & Product Storage and Distribution	In Situ Produced Propellants can supply fuel cells for surface mobility

SR-#	Short	Full Name	Chartered Objective	In Situ Resource Utilization (ISRU)	Relationship
1	Moon	Robotic and Human Lunar Exploration	Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.		ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection
2	Mars	Robotic and Human Exploration of Mars	Exploration of Mars, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future		ISRU for propulsion propellant, life support, mobility propellant, in-situ manufacturing, in-situ construction, radiation protection
3	Solar System	Solar System Exploration	Robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.		Search for Solar System Resources
4	Earth-like Planets	Search for Earth-Like Planets	Search for Earth-like planets and habitable environments around other stars using advanced telescopes.		Not Applicable
5	CEV / Constellation	Exploration Transportation System	Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.		ISRU can reduce mass launched from Earth
6	Space station	International Space Station	Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space		In Space & In Situ manufacturing / In Situ Logistics and Repair Capability
7	Shuttle	Space Shuttle	Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the Space Shuttle to a new exploration		In Space & In Situ manufacturing / In Situ Logistics and Repair Capability
8	Universe	Universe Exploration	Explore the universe to understand its origin, structure, evolution, and destiny.		Not Applicable
9	Earth	Earth Science and Applications from Space	Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.		Not Applicable
10	Sun-Solar System	Sun-Solar System Connection	Explore the Sun-Earth system to understand the Sun and its effects on the Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.		Not Applicable
11	Aero	Aeronautical Technologies	Advance aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.		ISRU can provide propellants for planetary fliers
12	Education	Education	Use NASA missions and other activities to inspire and motivate the nation’s students and teachers, to engage and educate the public, and to advance the nation’s scientific and technological capabilities.		Use ISRU principles to educate, inspire and motivate
13	Nuclear	Nuclear Systems	Utilize nuclear systems for the advancement of space science and exploration.		Utilize nuclear power for ISRU systems

National Research Council Dialogue to Assess Progress on

NASA's Advanced Modeling, Simulation & Analysis Capability and Systems Engineering Capability Roadmap Development

Jan Aikins

April 5-6, 2005

Agenda

- General Background and Introduction of Capability Roadmaps
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	1. Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	6. Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	7. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	8. Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	4. Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	9. Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	5. Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	10. Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

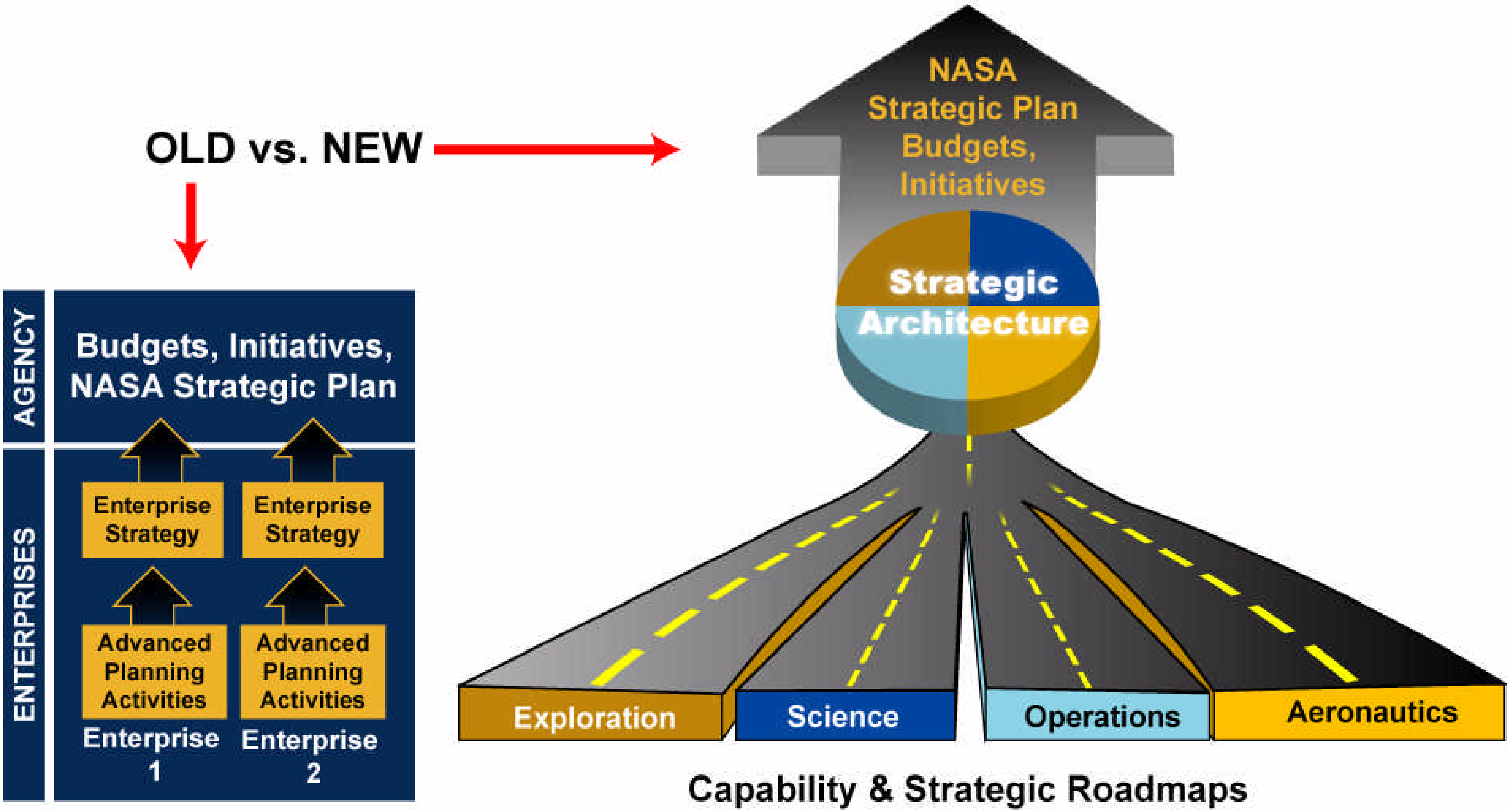
Agency Goals and Objectives

Advanced Planning & Integration Office

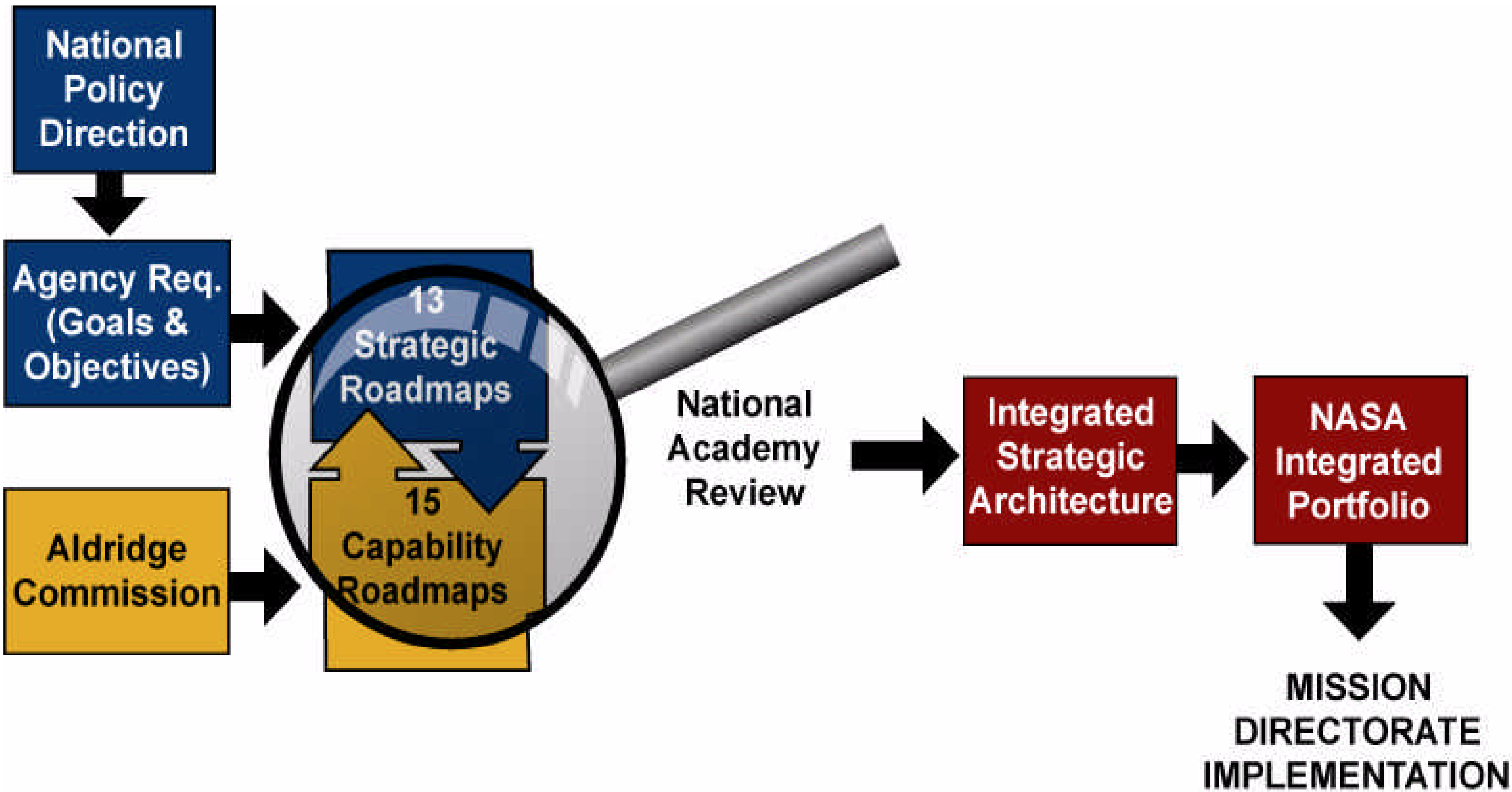
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	3. Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration.	4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	5. Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	11. Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	14. Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems. (SRM 9)	17. Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)
	12. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	15. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)	18. Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)
	13. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	16. Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	

Strategic Planning Transformation

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

Advanced Planning & Integration Office

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Charles Elachi)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

Advanced Planning & Integration Office

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

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- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

  - Broad human and robotic science and exploration goals, priorities, anticipated discoveries
  - High-level milestones, options, and decision points
  - Implementation approaches, suggested missions

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

= DoD Participation

Directorate and APIO Coordinators also with each team

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule

Milestone	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Plan Approved and Co-chairs Signed Up	▬	▬▲										
Complete Team Formation, Begin Work	▬	▬▲										
Interim Roadmap Products	▲▬	▬	▬	▲								
Teams Mid-term Status Review					▲							
Interim Roadmap Deliverable						▲						
First Synthesis Workshop							▲					
Roadmaps Submitted for NRC Review								▲				
NRC Reviews Complete								▲				
Second Synthesis Workshop								▲				
NAC Workshop										▲		
Integrated Strategic Architecture												▲

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Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Advanced Modeling Top-Level Crosswalk for Integration

Advanced Planning & Integration Office

Moderat Relationsh

No Relationshi

Critica Relationsh

	High Energy Power & Propulsion	In-space Transportation	Advanced telescopes & observatories	High-capacity telecom /information transfer	Robotic access to planetary surfaces	Human planetary landing systems	Human Health and support systems	Human exploration systems and mobility	Autonomous systems and robotics	Transformational Spaceport and Range	Scientific instruments/ sensors	Insitu resource utilization	Advanced modeling and simulation	Systems engineering cost/ risk analysis	Nanotechnology/ advanced concepts
High Energy Power & Propulsion															
In-space Transportation													???		
Advanced telescopes & observatories															
High-capacity telecom /information transfer															
Robotic access to planetary surfaces															
Human planetary landing systems													???		
Human Health and support systems															
Human exploration systems and mobility													???		
Autonomous systems and robotics															
Transformational Spaceport and Range															
Scientific instruments/ sensors															
Insitu resource utilization													???		
Advanced modeling and simulation															
Systems engineering cost/ risk analysis															
Nanotechnology/ advanced concepts															

Simulation & Modeling Capability Crosswalk

	1. High-energy power and propulsion	2. In-space transportation	3. Advanced telescopes and observatories	4.Communication & Navigation	5. Robotic access to planetary surfaces	6. Human planetary landing systems	7. Human health and support systems	8. Human exploration systems and mobility	9. Autonomous systems and robotics	10. Transformational spaceport/range technologies	11. Scientific instruments and sensors	12. *In situ* resource utilization	13. Advanced modeling, simulation, analysis	14. Systems engineering cost/risk analysis	15. Nanotechnology
1. High-energy power and propulsion	Same element	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
2. In-space transportation		Same element	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
3. Advanced telescopes and observatories			Same element	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
4. Communication & Navigation				Same element	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
5. Robotic access to planetary surfaces					Same element	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
6. Human planetary landing systems						Same element	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
7. Human health and support systems							Same element	Moderate	Moderate	Moderate	Moderate	Moderate	(light green)	Moderate	Moderate
8. Human exploration systems and mobility								Same element	Moderate	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
9. Autonomous systems and robotics									Same element	Moderate	Moderate	Moderate	Critical	Moderate	Moderate
10. Transformational spaceport/range technologies										Same element	Moderate	Moderate	Moderate	Moderate	Moderate
11. Scientific instruments and sensors											Same element	Moderate	Moderate	Moderate	Moderate
12. *In situ* resource utilization												Same element	(light green)	Moderate	Moderate
13. Advanced modeling, simulation, analysis													Same element	Critical	Moderate
14. Systems engineering cost/risk analysis														Same element	Moderate
15. Nanotechnology															Same element

Same element (yellow)

Critical Relationship (green)

Moderate Relationship (light cyan)

No Relationship (red)

Process for Team Selection

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  - **Small teams of 12 -15 members with participation from:**

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    1/3 NASA & other Government Agencies

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Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

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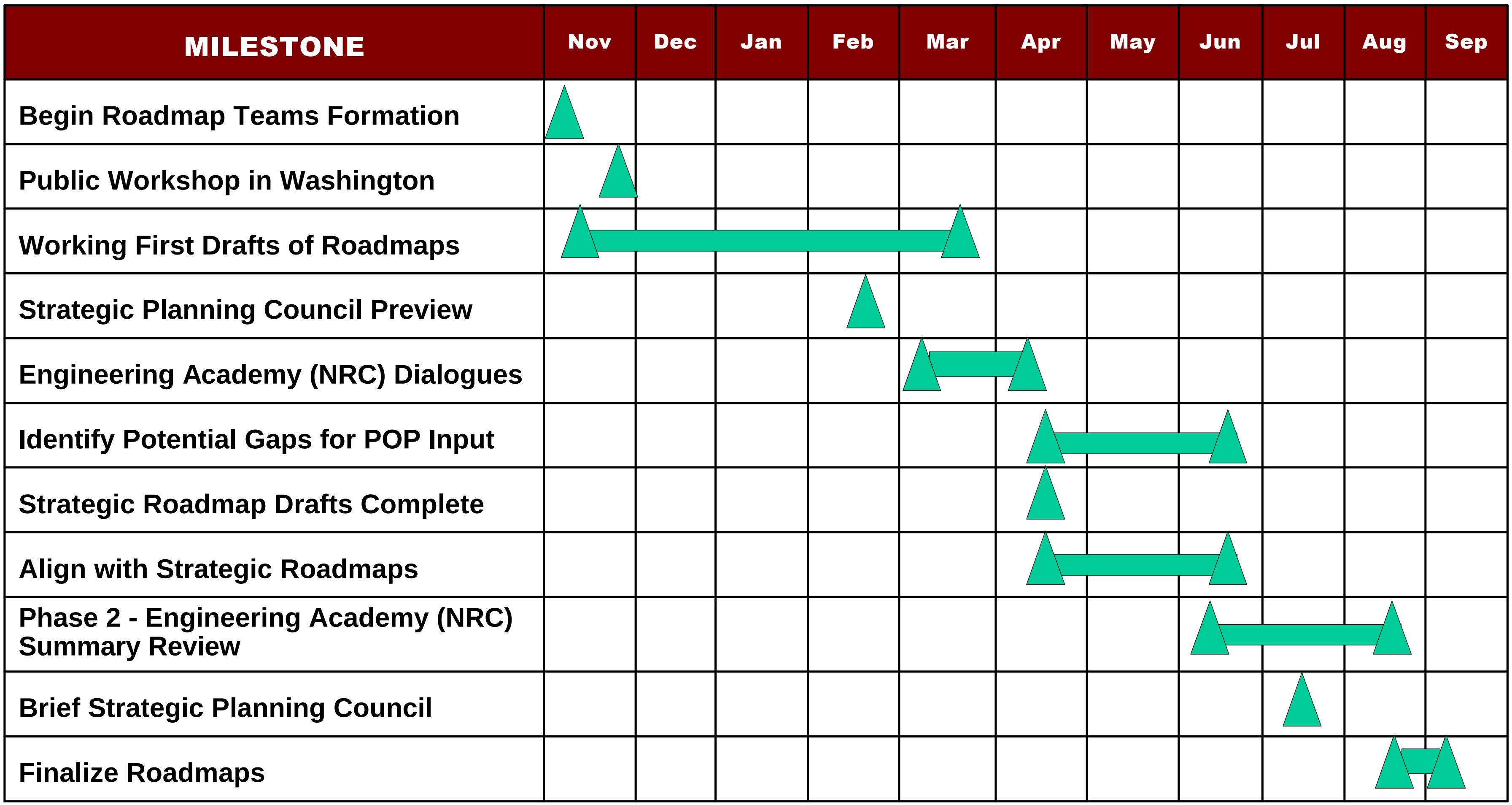

Purpose of NRC Review

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- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metrics for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate?

Technology Readiness Levels

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- **9** Actual System Proven in Operation
- **8** Actual System Qualified by Demonstration
- **7** System Prototype Demonstration in an Operational Environment
- **6** System/Subsystem Model or Prototype Demonstration in a Relevant Environment
- **5** Component and/or Breadboard Validation in a Relevant Environment
- **4** Component and/or Breadboard Validation in a Laboratory Environment
- **3** Analytical and Experimental Critical Functions Characteristic Proof-of-Concept
- **2** Technology Concept and/or Application Formulated
- **1** Basic Principles Observed and Reported

Capability Readiness Levels

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Level	Description
7	Capability Operational Readiness
6	Integrated Capability Demonstrated in an Operational Environment
5	Integrated Capability Demonstrated in a Relevant Environment
4	Integrated Capability Demonstrated in a Laboratory Environment
3	Sub-Capabilities* Demonstrated in a Relevant Environment
2	Sub-Capabilities* Demonstrated in a Laboratory Environment
1	Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

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Back-up charts

Capability Readiness Levels Defined

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- **CRL 1: Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified**
  - The Capability is defined in written form. The use/application of the Capability is described in a concept paper. The uses are speculative, and no proof or detailed analysis exists to support the concept. The constituent Sub-capabilities and requirements of the Capability are specified.
- **CRL 2: Sub-Capabilities* Demonstrated in a Laboratory Environment:**
  - A Proof-of-Concept analysis of the Capability is performed. Analytical and laboratory studies of the Sub-capabilities are performed to physically validate separate elements of the Capability. Analytical studies are performed to determine how constituent Sub-capabilities will work together.
- **CRL 3: Sub-Capabilities* demonstrated in a Relevant Environment:**
  - Sub-capabilities are demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - functionally equivalent flight articles
    - major system interactions identified
  - Limited analytical modelling of the integrated Capability can be performed.
- **CRL 4: Integrated Capability Demonstration in a Laboratory Environment**
  - A representative model or prototype of the integrated Capability is tested in a laboratory environment. Performance of the constituent Sub-capabilities are observed in addition to the Capability as an integrated system. are specified.
- **CRL 5: Integrated Capability Demonstration in a Relevant Environment**
  - An integrated prototype of the Capability is demonstrated with realistic supporting elements to simulate an operationally relevant environment (e.g. to the Capability).
    - of appropriate scale
    - actual flight articles
    - all system interactions identified
- **CRL 6: Integrated Capability Demonstration in an Operational Environment**
  - The Capability is near or at the completed system stage. This level represents the demonstration of an integrated Capability in an operational environment with representatives of the intended user organization(s).

  -full scale flight articles
  -demonstration in appropriate operational 'envelope'
- **CRL 7: Capability Operational Readiness**
  - The Capability has been proven to work in its final form and under expected operational conditions. This level represents the application of the Capability in its operational configuration and under "mission" conditions.

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Advanced Modeling, Simulation and Analysis (AMSA) Capability Roadmap Progress Review

Erik Antonsson
Tamas Gombosi
April 5, 2005

Agenda

Time	Topic	Speaker
7:30	Continental Breakfast	
8:00	Welcome and Review Process, Panel Chair & NRC Staff	
8:15	NASA Capability Roadmap Activity	Jan Aikins, NASA
8:30	14.0 Advanced Modeling, Simulation, and Analysis Overview	Erik Antonsson, JPL
	-Sub-Team Presentations-	
9:15	14.1 Scientific Modeling and Simulation	Tamas Gombosi, U. Mich
9:45	14.2 Operations Modeling	Ron Fuchs, Boeing
	– Break –	
10:45	14.3 Multi-Spectral Sensing (UV-Gamma)	Mike Lieber, Ball Aerospace
11:15	14.4 System Integration	Walt Brooks, NASA
	– Lunch –	
12:45	14.5 M&S Environments and Infrastructure	Mark Gersh, LMC
1:15	Co-Chair Summary	Tamas Gombosi, U. Mich
	– Break –	
2:15	Open Discussion	NRC Panel

Capability Roadmap Team

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Co-Chairs

NASA: Erik Antonsson, JPL
External: Tamas Gombosi, University of Michigan

Team Members

Government

Walt Brooks, NASA
Dave Bader, LLNL
Tsengdar Lee, NASA
Steve Meacham, NSF
Charles Norton, JPL
Carl Peterson, Sandia
Ricky Rood, NASA
Tom Zang, NASA

Industry

Karen Fucik, NGC
Ron Fuchs, Boeing
Mark Gersh, Lockheed-Martin
Mike Lieber, Ball
Irene Qualters, Merck

Academia

Dan Reed U. N. Carolina
John Rundle, UC Davis
Quentin Stout, U. Mich.

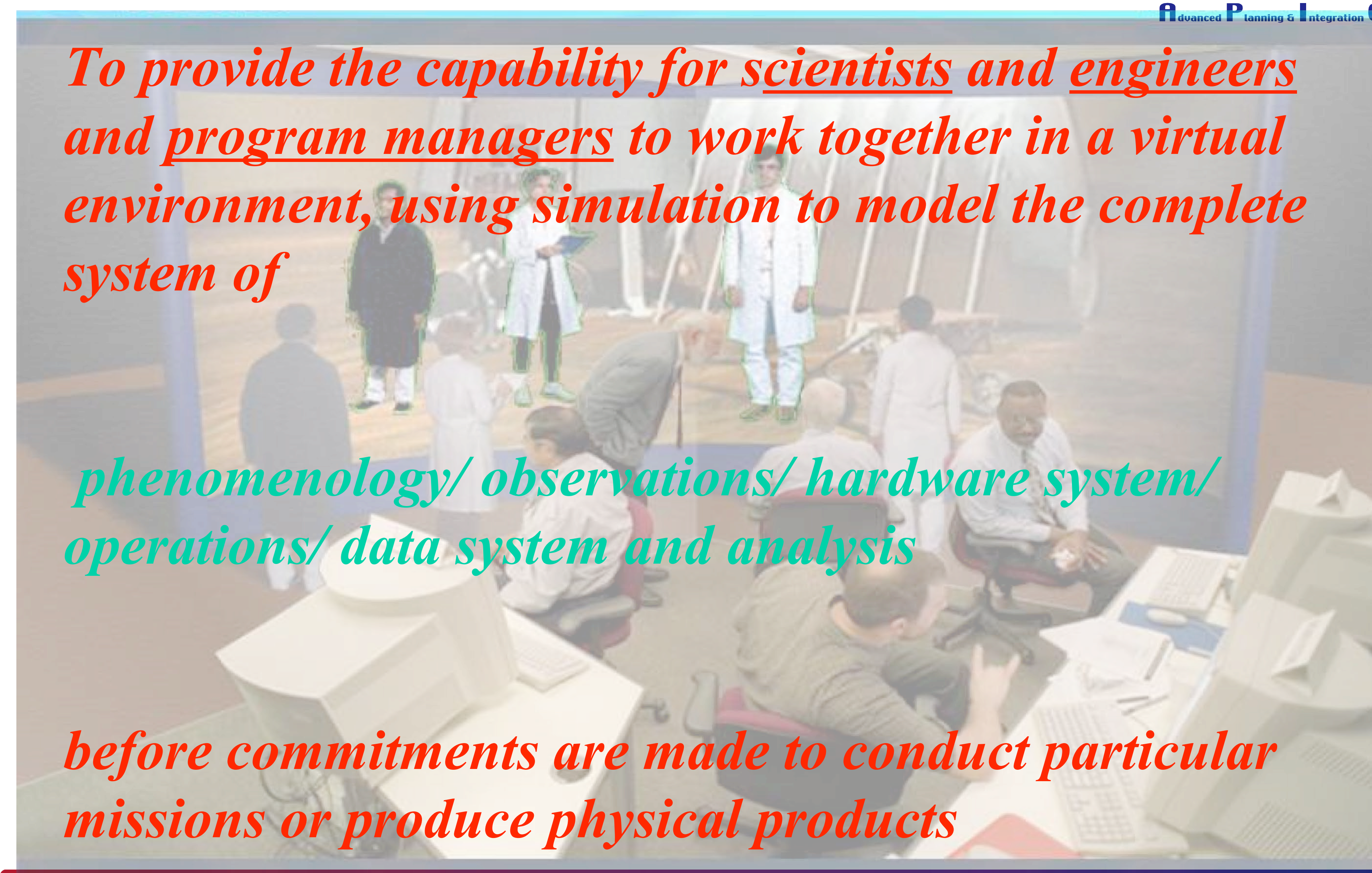
Coordinators

Directorate: Harley Thronson, SMD
APIO: Janice Aikins, ARC

Cross-team Coordinators

Systems Engineering CRM: S. Prusha, JPL
Nanotechnology CRM: P. Von Allmen, JPL

What is this all about?



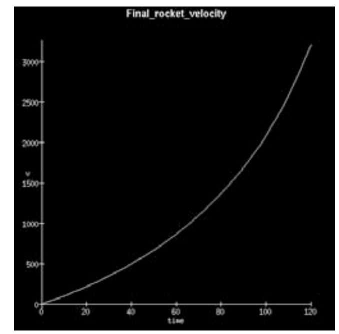
To provide the capability for <u>scientists</u> and <u>engineers</u> and <u>program managers</u> to work together in a virtual environment, using simulation to model the complete system of

phenomenology/ observations/ hardware system/ operations/ data system and analysis

before commitments are made to conduct particular missions or produce physical products

Terminology

What does 'modeling' mean ?

Real world behavior	Analytical model of real behavior	Numerical 'model' of analytical model	'Model' of performance
	$U_f = V_{ex} \ln (M_i / M_f) + U_i$	$U_i = 0$ $V_{ex} = 4000$ Mi = 1000 Δo 1 $\Delta U_n = VEX*\Delta M/M_n$ $M_{n+1} = M_n - \Delta M$ 1 END	
	Physicist	*(1) Numerical analyst/ (2) Project engineer*	*Project manager*

Answer: It depends on your experience/ background

Lesson 1: We must always check our semantics when we talk across disciplines

Capability Description

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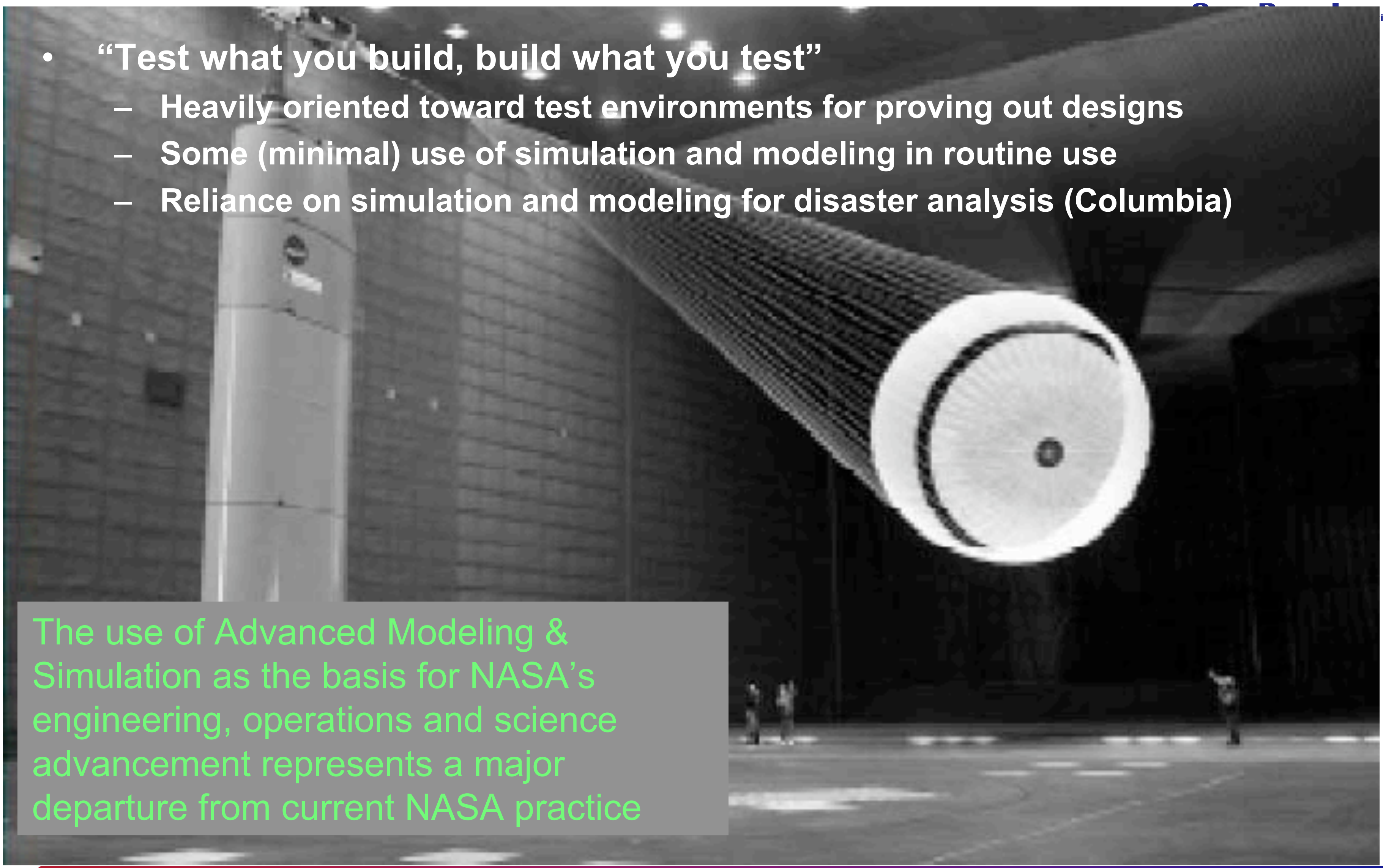
- The AMSA roadmaps include capabilities in Science modeling, Engineering modeling for Mission development, Operations modeling and Science Data analysis.
- Drivers for these roadmaps
  - The Vision for Space Exploration
  - The New Age of Exploration: NASA Strategic Objectives for 2005 and Beyond
  - A Journey to Inspire, Innovate, and Discover: President's Commission Report
  - Design Reference Missions
- These roadmaps present a new future technical paradigm for NASA
  - Invert [experiment primary / analysis and simulation secondary] relationship throughout NASA business
  - Focus on end-to-end systems modeling for increased efficiency
  - Provide viable approach to allow NASA to field aggressive new missions
- Roadmaps build on existing limited demonstration of capabilities
  - SIM use of IMOS
  - Earth Science Modeling Framework
  - Space Weather Modeling Framework

Current NASA Development Approach

- "Test what you build, build what you test"
  - Heavily oriented toward test environments for proving out designs
  - Some (minimal) use of simulation and modeling in routine use
  - Reliance on simulation and modeling for disaster analysis (Columbia)

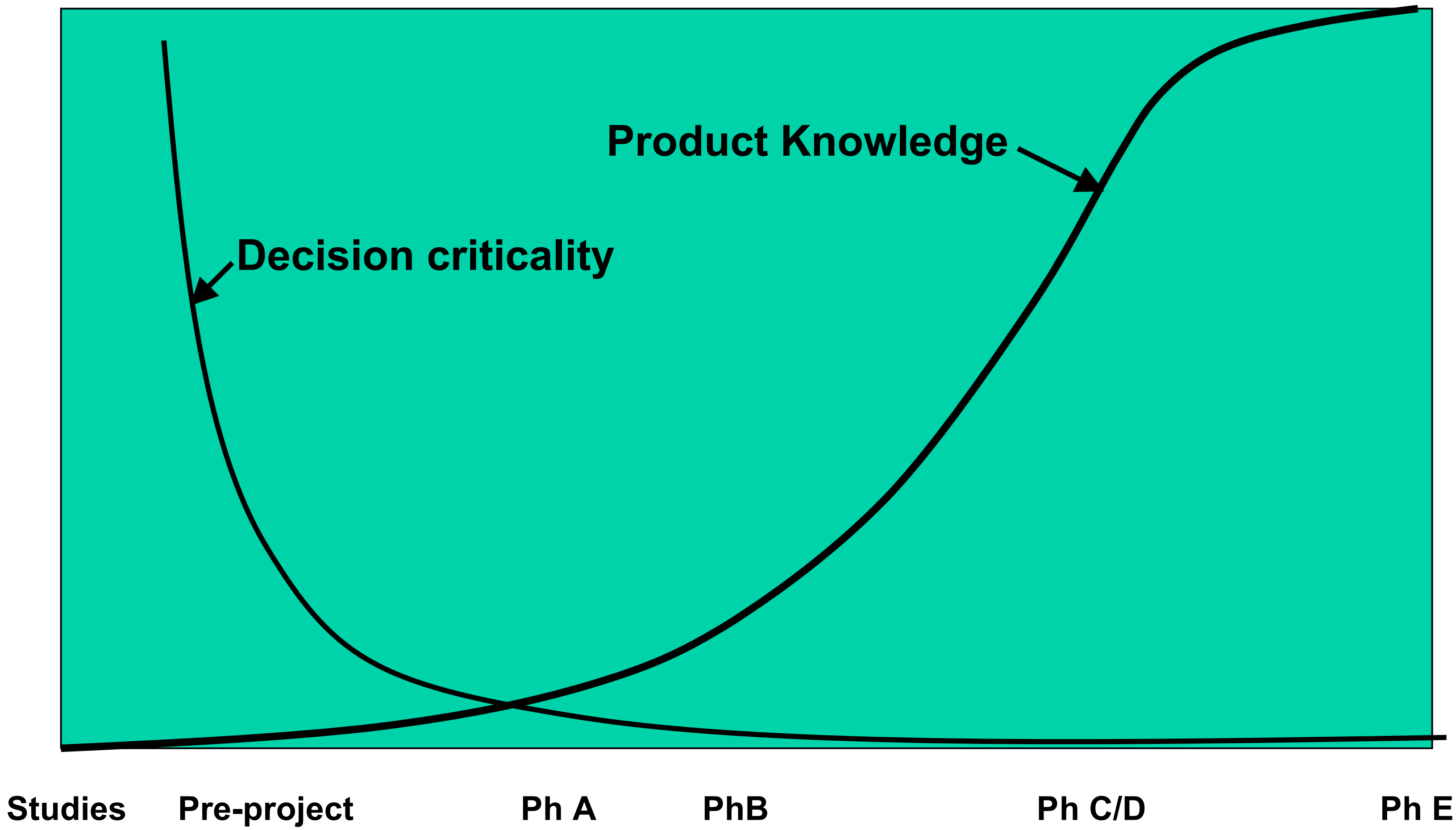


The use of Advanced Modeling & Simulation as the basis for NASA's engineering, operations and science advancement represents a major departure from current NASA practice

Some Specific Examples

- Engineering
  - Systems level (multidisciplinary) analysis is performed in early studies (pre-phase A / phase A)
    - Characterized by GSFC-IMDC, JPL-Team X, JPL-Team I
    - Based on table lookup, simple models
    - Point design
    - Exclusive of real technology input
  - Detailed design
    - Integration limited to COTS packages (e.g., TeamCenter)
    - IMOS (Integrated Modeling of Optical Systems) used widely within NASA
    - Virtually no handoff from Preliminary design
    - No link to operations
    - No feedback of engineering data for model validation
- Science
  - Some experimental coupling between Ocean Circulation and Atmospheric modeling
  - Coupling of the Sun, corona, energetic particles, heliosphere, magnetosphere and ionosphere
  - Some experiments with data assimilation in weather modeling

Project Characteristics
-- Current Practice --



So what? What's wrong with this situation?

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- NASA current approach is at the limit of fulfilling system design demands. Evidence:
  - Shuttle failures were not anticipated and were poorly understood until after disasters
  - Missions such as SIM (Space Interferometry Mission)
    - System performance requirements are EXTREME
    - Project has already recognized need for reliance on modeling
- Future missions, even more demanding, require simulation
  - Large apertures that cannot be deployed or tested in 1g
  - Ultra stable platforms requiring precision formation flying that cannot be tested except in space
  - Assessments of instrument performance from highly demanding vantage points (eg, earth from L1, L2) that cannot be tested except in space
  - Complex, inter-dependent systems of systems for missions such as human exploration of Mars

Resolution

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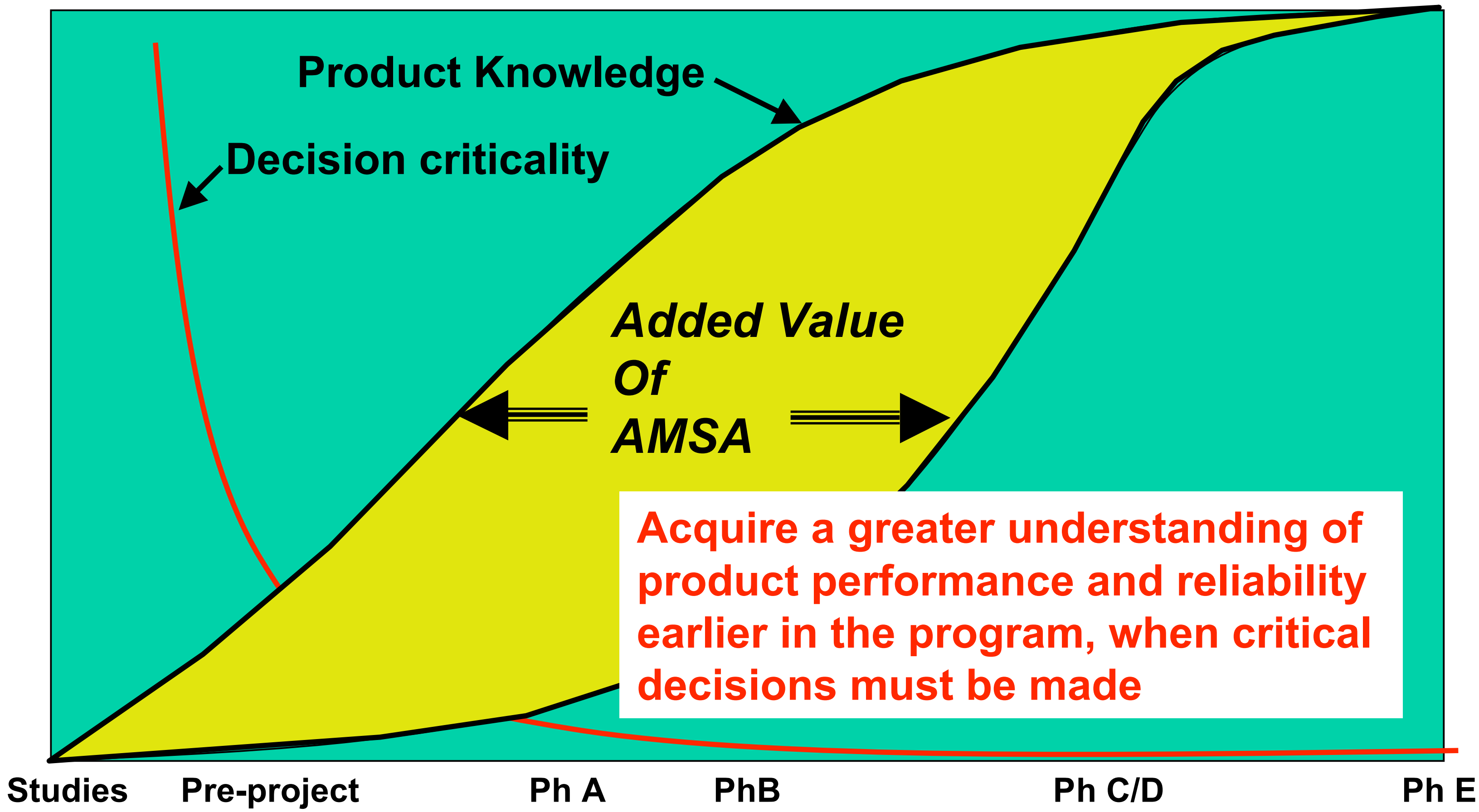
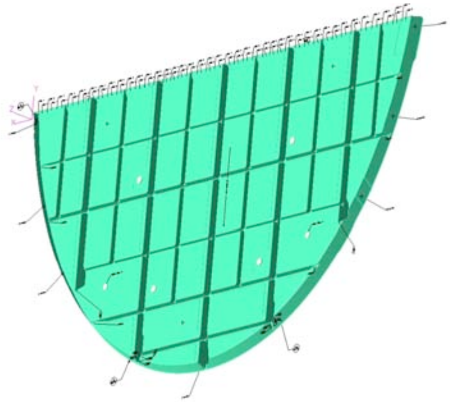
- Expand and complete an AMSA-based systems approach to science & discovery, engineering design, hardware development and mission operations
  - Such an approach has already demonstrated in pockets within NASA
  - Testing still plays an important role, but the use of Modeling and Simulation creates a *predictive capability* that NASA's test-based approach can never provide
- Follow the lead of private aerospace companies and other Federal Agencies in moving to simulation-based systems development

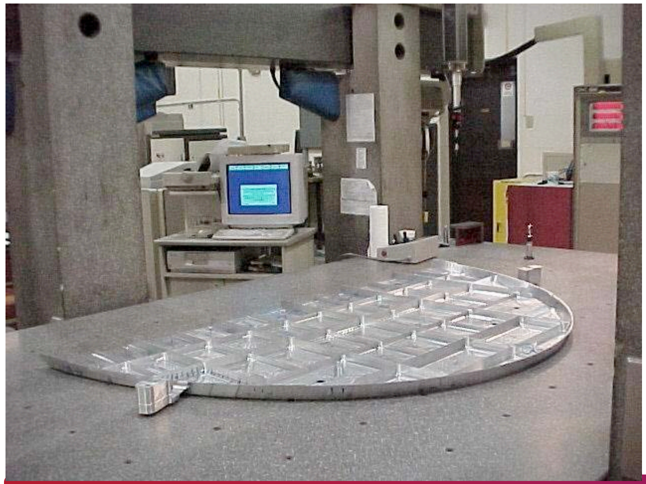
Project Characteristics
-- Desired Change --



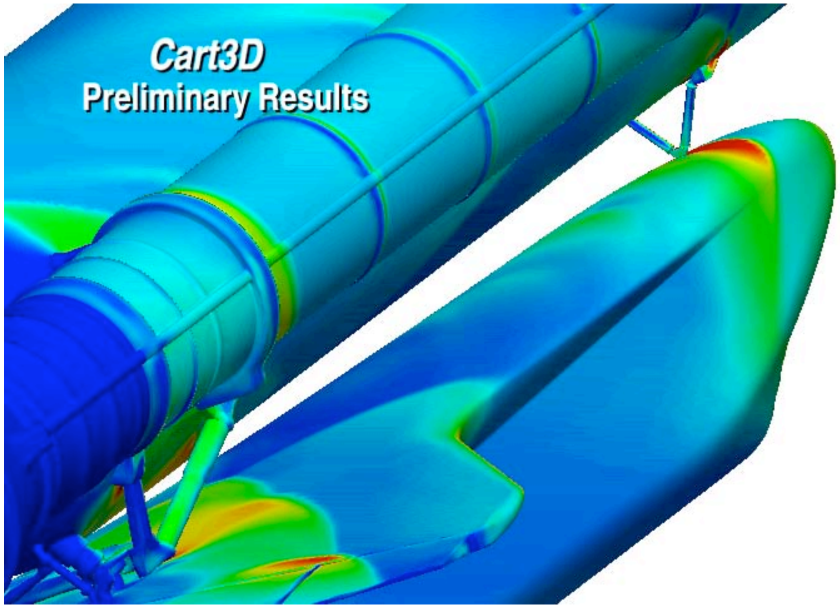
Specific examples

Boeing: Seeing and working with reality before it exists



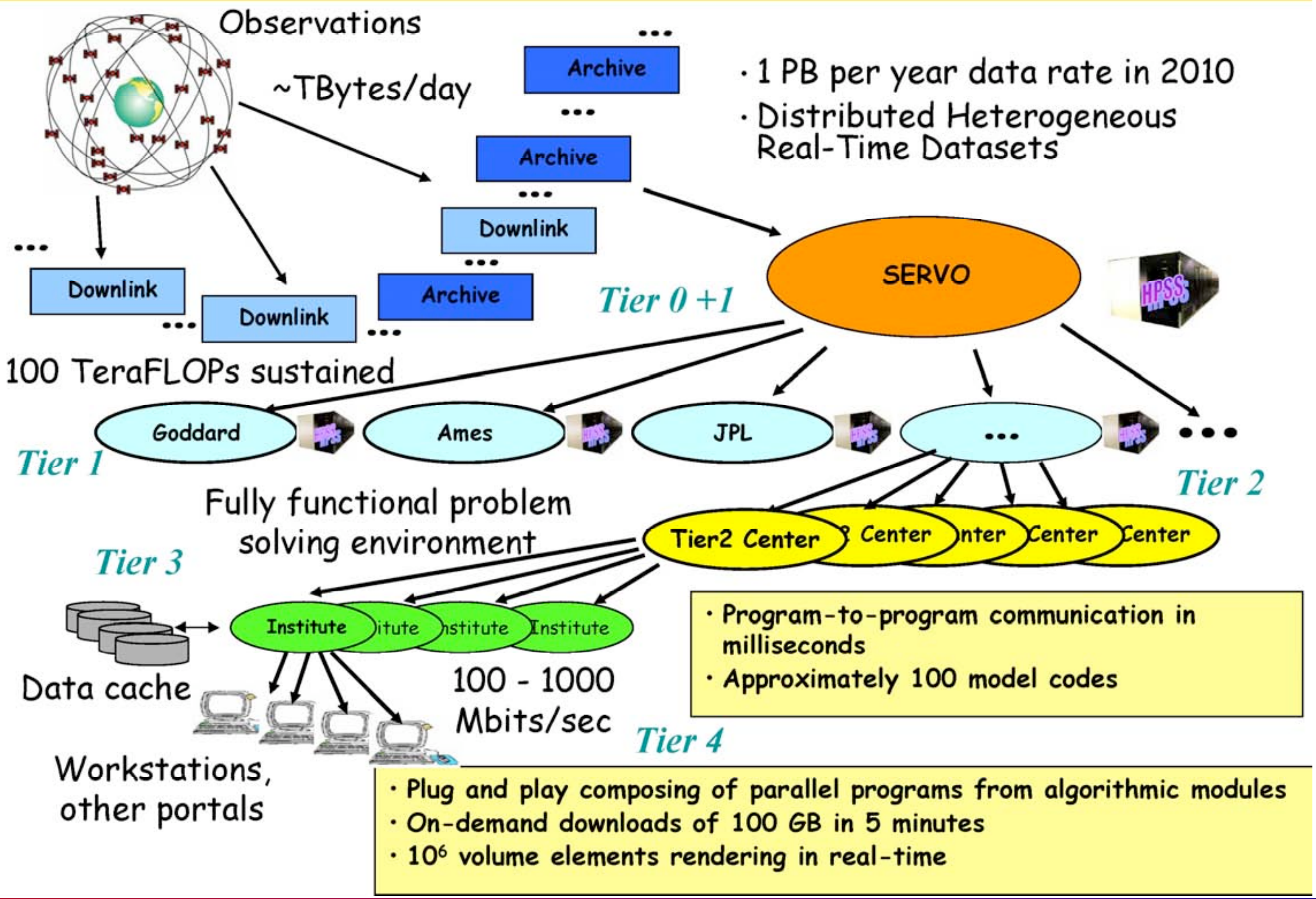


Ames Research Center: Columbia post-disaster analysis



Specific Examples- End-to end integration

Solid Earth Research Virtual Observatory (SERVO)



Summarizing: Situation Today

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Phenomenology modeling

Mission development

Structures | *Payload* | *C&DH* | *Comm* | *Power* | *Etc…*

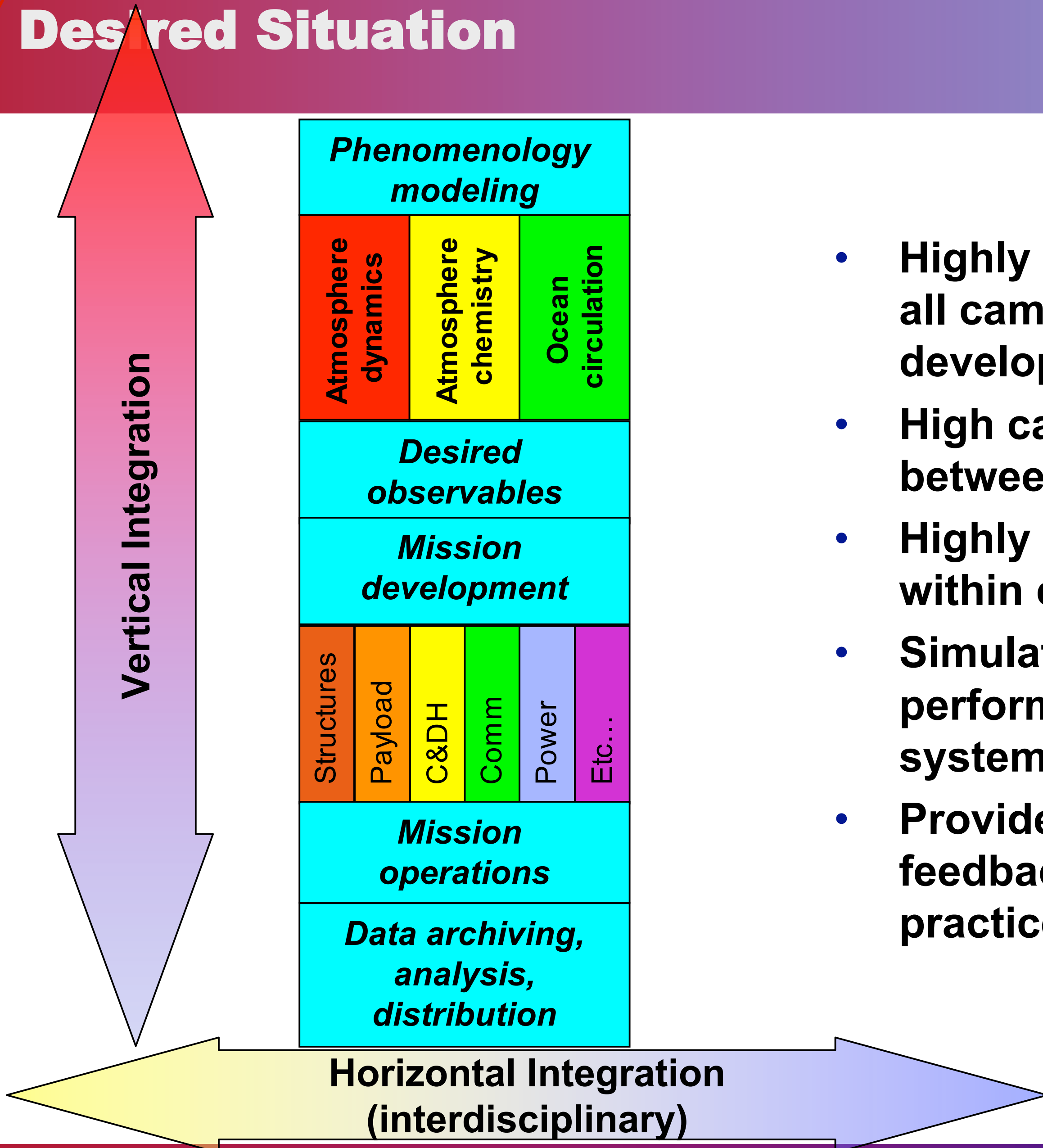
Data archiving, analysis, distribution

Mission operations

Characterized by

- **Camps of system development disconnected**
- **Limited AMSA capability within each camp**
- **Little to no feedback from practice to models for improvement**
- **"Test and hope for the best"**

Desired Situation



- Highly capable models in all camps of systems development
- High capability bridging between camps
- Highly integrated modeling within camps
- Simulate cradle-to-grave performance of entire system
- Provide deliberate feedback from flight practice to improve models

Our history, our future

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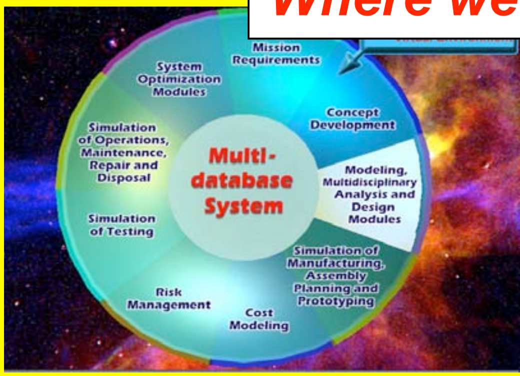
Where we're going



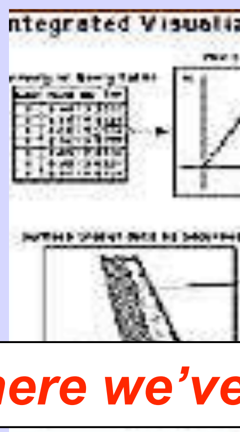
'Phenomenon to Data' system model

Digital Process

Today

Digital Mockup

Pre-CAD



Pre-CAD

3D-CAD

Where we've been

Summary

It is FAR better to simulate a system and crash it in a virtual environment

Than to

Build a poorly understood system and crash it in the real world

Top Level Assumptions

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- Fundamental ASSUMPTION: That commercial progress in High Capability Computing and NASA access to that resource will continue
  - Grid computing will become essential infrastructure
  - Continual exponential increases in computational power (especially via parallelism), communication bandwidth, and storage ca pacity (peta- to yotta- scale data storage)
- Problem complexity will increase and simplification must come from "system of systems" approach (c.f. increased complexity in aircraft industry)
- Delivery dates for AMSA depend on the specific AMSA application. Dates shown correspond to the driving missions launch dates. Actual AMSA need dates are shown in separate table.
- NASA cannot accomplish this program without partnering with other agencies and industry and academia to develop the key components
- Examples and terminology tailored to SMD missions can be applied similarly for exploration and aeronautics.

Capability Breakdown Structure

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14 Advanced Modeling, Simulation and Analysis

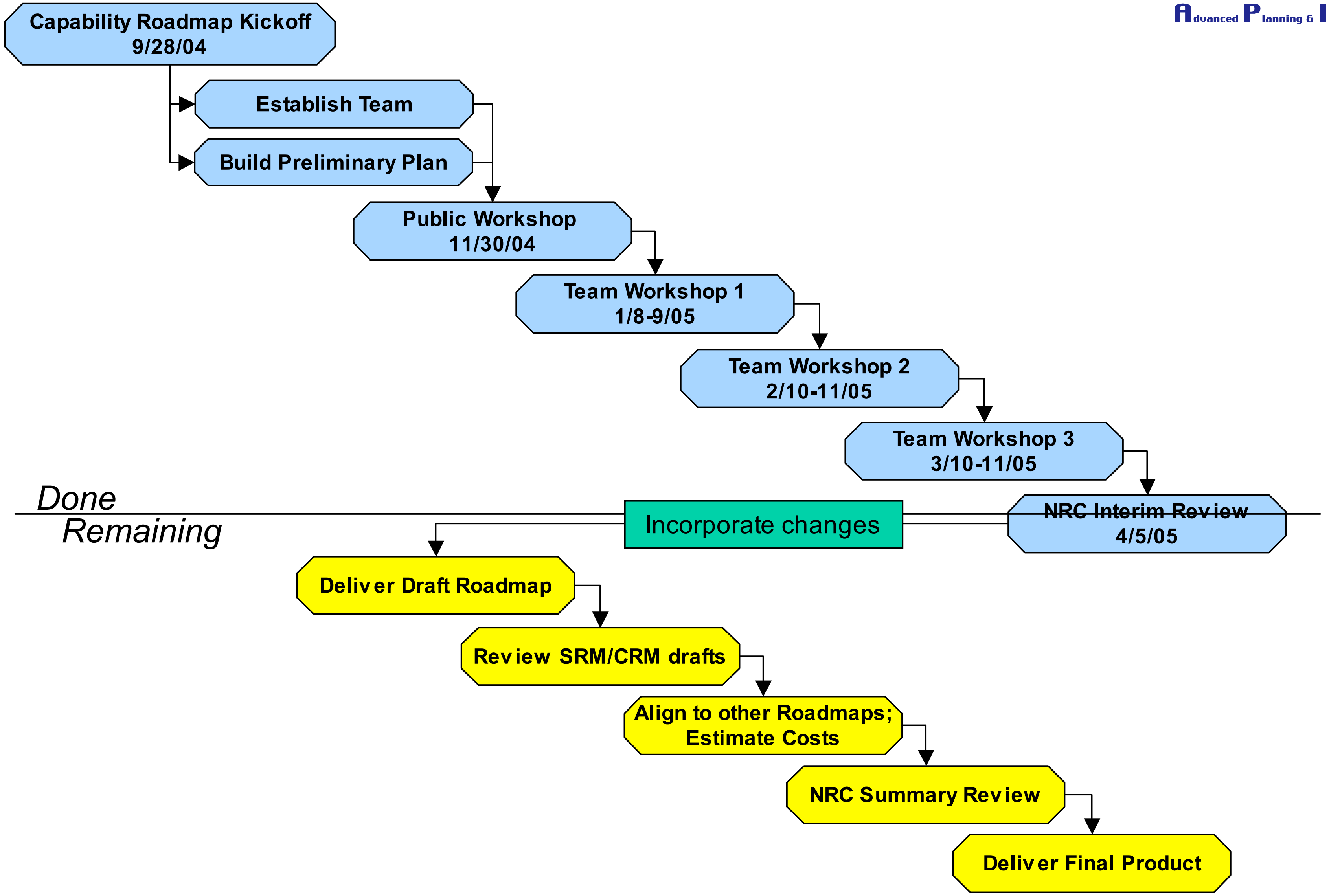
Chair: Erik Antonsson, JPL
Co-Chair: Tamas Gombosi, U. Mich.

- **14.1 Scientific Modeling** — Chair: T. Gombosi
  - 14.1.1 Simulate natural and anthropogenic phenomena
  - 14.1.2 Visualize simulation results
  - 14.1.3 Assimilate large data sets
  - 14.1.4 Distribute and mine large data sets
- **14.2 Operations Modeling** — Chair: R. Fuchs
  - 14.2.1 Requirements Development
  - 14.2.2 Mission Rehearsal
  - 14.2.3 Anomaly Resolution
  - 14.2.4 Human-System Interfaces
  - 14.2.5 Training
  - 14.2.6 Subsystem Validation
- **14.3 Engineering Modeling** — Chair: M. Lieber
  - 14.3.1 Large-scale systems modeling
  - 14.3.2 Anomalous behavior Models (ABM)
  - 14.3.3 Virtual test environments (VTS)
  - 14.3.4 Uncertainty models (UM)
  - 14.3.5 Robotics mfg/ Servicing models (RMSM)
  - 14.3.6 Visualization (V)
- **14.4 Integration** — Chair: W. Brooks
  - 14.4.1 V&V "OSSE"
  - 14.4.2 Standards and protocols
  - 14.4.3 Infrastructure Model migration
  - 14.4.4 Archive Data repository
- **14.5 M&S Environments & infrastructure** — Chair: E. Antonsson
  - 14.5.1 Verfication, Validation and Accreditation
  - 14.5.2 Software Engineering environments
  - 14.5.3 Simulation environments
  - 14.5.4 Integration Technology and processes
  - 14.5.5 End-to-end Integration & test

Roadmap Approach

- Advanced Modeling, Simulation and Analysis is a broad and diverse roadmapping topic with significant application challenges.
  - Practiced widely throughout the aerospace, defense, and educational sectors
  - Largely unstructured and uncoordinated, poorly documented, verified and validated
- Public input given high priority
  - 17 Presentations to team leads in Public Workshop; additional 31 white papers submitted but not presented
  - 25 Invited presentations to the full team during workshops.
- Team formation is critical element of roadmapping success
  - Team membership distributed throughout industry, academia, NASA and other government institutions, cross-cuts science, engineering and operations
  - Team-building practiced throughout with weekly telecons and 3 2-day workshops
- Additional reference material accumulated, reviewed analyzed, and archived
  - Design reference missions
  - Related reports sponsored by other agencies
  - Capability needs documents published within NASA
- Final roadmaps developed by sub-teams with membership appropriate to the members' expertise

Roadmap Process Steps



Current State-of-the-Art for Capabilities (1/2)

- Scientific Modeling and Simulation
  - Sophisticated Capabilities
    - Astrophysics
    - Earth Science
    - Space Physics
  - Significant developments in integrating using frameworks
    - Earth Science Modeling Framework
    - Space Weather Modeling Framework
- Operations Modeling and Simulation
  - Work-flow modeling, particularly for ground processing
  - Event tree/sequence generation for mission operations
  - Resource planning/scheduling for communications and other operations assets
  - "Purpose built training simulators"

Current State-of-the-Art for Capabilities (2/2)

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- Engineering Modeling and Simulation
  - Some use of M&S for technology investment decisions
  - Sophisticated disciplinary modeling capability, such as
    - Structures
    - CFD
    - Thermal
  - Limited numerical optimization capabilities
  - Limited multidiscipline integration
    - Preliminary design centers
    - IMOS (Integrated modeling for Optical Systems)
- System Integration
  - Limited integration between observables and science modeling:
    - Observing System Simulation Experiments (OSSE), primarily for weather
    - Solid Earth Research Virtual Observatory
  - No known integration between science, engineering and operations
  - Modeling and Simulation Environments and Infrastructure
  - State-of-capability in high performance computing (Columbia at ARC)
  - Largely COTS-based environments for software and simulation

Traceability Matrix

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- **All AMSA capability needs can be traced directly back to the following top-level strategic documentation**
  - **Design Reference Missions**
  - **The Vision for Space Exploration**
  - **A Journey to Inspire, Innovate, and Discover: President's Commission Report**
  - **The New Age of Exploration: NASA Strategic Objectives for 2005 and Beyond**
  - **NASA Enterprise Strategies**
  - **National Research Council Reports**

- **Traceability Spreadsheets were developed to establish, track, and communicate linkages between design reference missions, science measurement needs, and critical AMSA capabilities.**

Traceability Matrix (example)

Area	Mission	launch Date	Mission description	AMSA driver	AMSA impact (at a minimum)
ESS	Solar Orbiter	2014	• ESA Mission • 3-axis stabilized spacecraft will use VGA every third orbit to obtain an increasingly slanting solar orbit at 0.2 AU out of the ecliptic plane to heliographic latitudes of 30-38 degrees • Close approach every 5 months • Perihelion "Hover" period of orbit will allow imaging of solar storm buildup over several days	• Solar Electric Propulsion to be validated on ESA SMART-1 mission in 2003 • High temperature thermal management to accommodate solar intensity 25x than seen at Earth	electric propulsion modeling and thermal modeling
ESS	L-Band MEO InSAR Constellation	2014	Constellation of s//c in MEO to measure land surface topography. Interferometry for vector deformation measurement with global coverage.	Lightweight deployable radar antenna and structure (ex, deployable membrane, L-band, 10m x 40m area) with antenna flatness of lambda/20. Large aperture electronically scanning arrays -low mass (<2-4kg/sq-m structure + aperture + electronics) Pointing knowledge of approx. 0.01deg and control of approx. 0.05deg, free-flying satellite of 3000-15,000km elevation, repeat track to better than 100-200m accuracy.	End-to-end systems modeling; large aperture structure and deployment modeling
ESS	High Resolution CO2	2014	One spacecraft in LEO carrying laser absorption instrument	Autonomous narrowband (~100 kHz) optical heterodyne receiver control, using platform attitude feedback/control. Spacecraft attitude knowledge ~10 micro radians for updating the receiver bandwidth	Attitude control system modeling
ESS	MEO - Global Tropospheric Aerosols	2016	One s/c in MEO, Measure in five spectral bands from 180 GHz to 2.5 THz. Provide global coverage with horizontal resolution of 50 km. Provide vertical resolution of 1-3 km. Provide smart sensor response to atmospheric events.	Cryocooler for ~10 mW heat load at T=4 K, Antenna system for scanning Earth's limb with ~2 km vertical and ~20 km horizontal resolution at 200 GHz, and reflector surface accuracy of ~10 micrometers. 2.0-2.5 THz HEB radiometer with < ~2000 K noise temperature, >2GHz IF bandwidth. Antenna system with ~4x2 m primary reflector, with ~10 micrometer surface accuracy.	End-to-end systems modeling; large aperture structure and deployment modeling; thermal modeling
ESS	Wide Swath LIDAR	2017	One s/c in LEO carrying laser altimeter	Efficient dissipation of multi-kW heat loads on orbit.	thermal modeling
ESS	Quantum Gravity Gradiometer	2018	One s/c in LEO carrying the QGG instrument	Gravitational Reference Sensor with a test mass isolated to less than 1.E-15 m/s**2 rms over 100 seconds and a measurement system for providing a measure of the spacecraft position with respect to the test mass with accuracy of 1 nanometer rms over 100 seconds Micro-Thruster system to adjust the spacecraft position to stay centered on the test mass to within 1 nanometer rms over 100 seconds, with thruster requirement of 2-100 micro-Newton with step size 0.1 micro-Newton and noise less than 0.01 micro-Newton rms over 100 seconds.)	Attitude control system modeling; micro-propulsion modeling

Mission Drivers- examples and complete list

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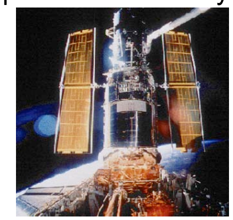
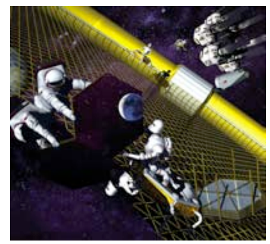
2010 SDO

Constellation-X

Large-Aperture UV/ Optical Observatory



Space Assembly



Mars manned

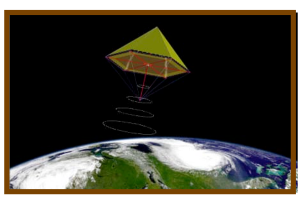
TPF-C

CEV

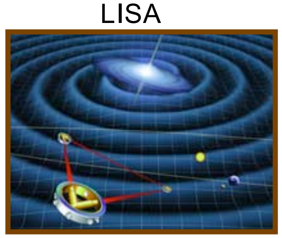
2015 lunar manned

GEO Global Precipitation

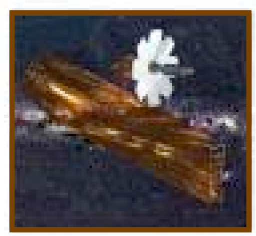
GEO/MEO InSAR



LISA



SAFIR



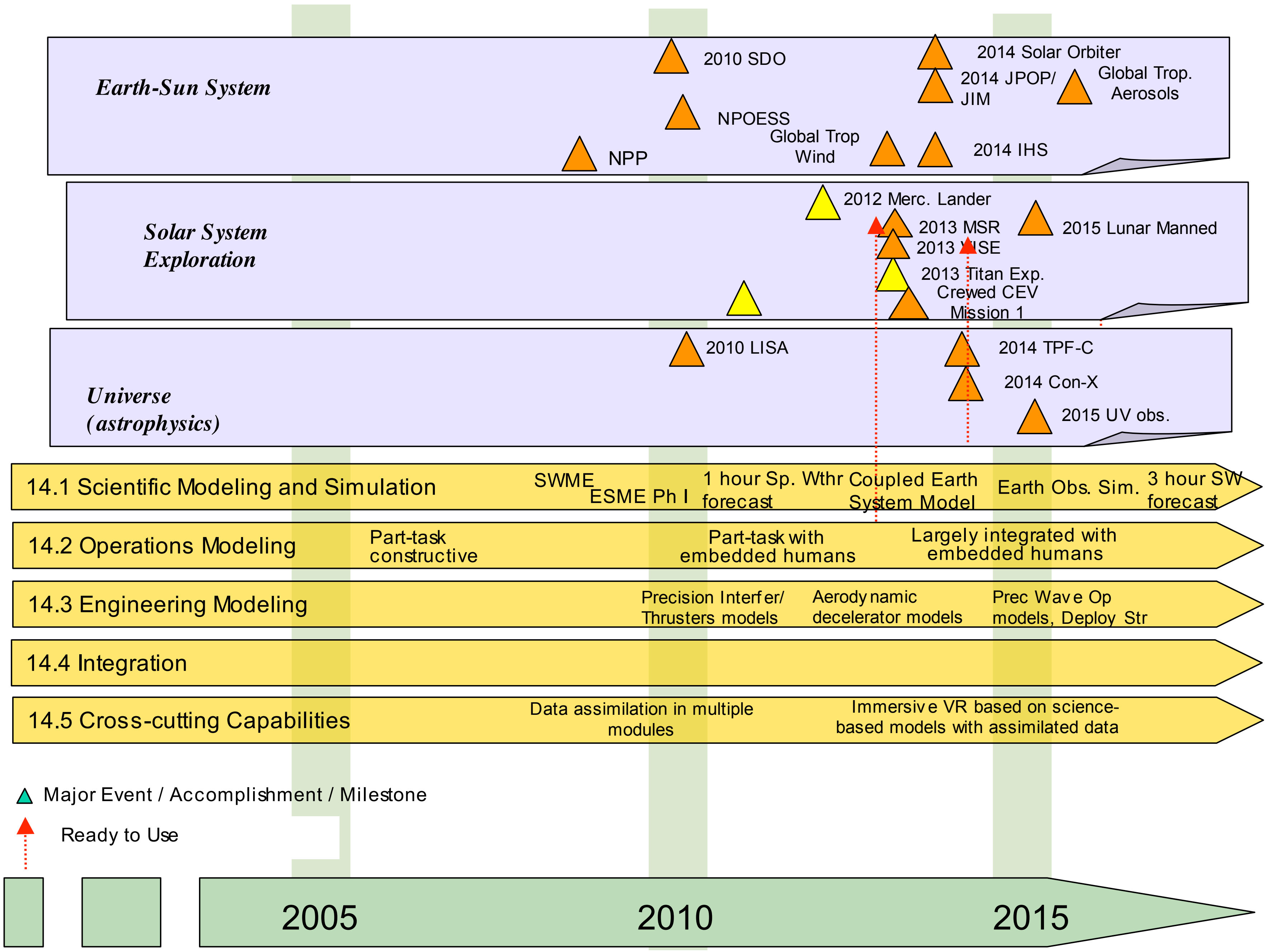
Planet Imager

2010 2020 2030

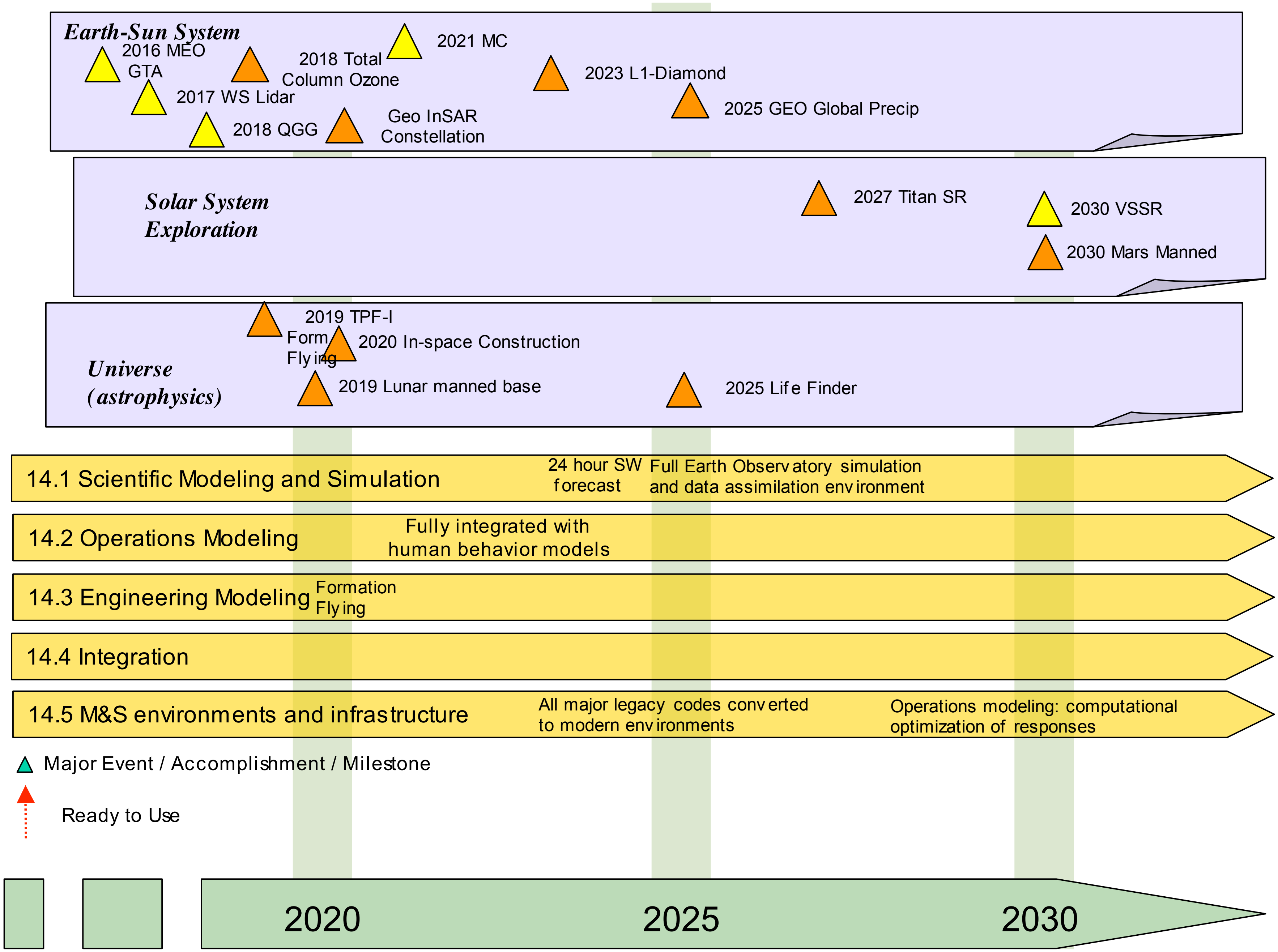
Full AMSA list

Mission	***Year***
NPP	2009
SDO	2010
NPOESS	2010
LISA	2010
Global Trop Wind	2013
MSR	2013
VISE	2013
Crewed CEV Mission 1	2013
Solar Orbiter	2014
JPOP/JIM	2014
IHS	2014
TPF-C	2014
Con-X	2014
Lunar Manned	2015
UV Obs.	2015
Global Trop Aerosols	2016
Total Column Ozone	2018
TPF-I	2019
Lunar manned base	2019
Geo InSAR Constellation	2020
IN-space construction	2020
L1-Diamond	2023
GEO Global Precip	2025
Life finder	2025
Titan SR	2027
Mars Manned	2030

Capability Team 14: Advanced Modeling, Simulation and Analysis Roadmap Team



Capability Team 14: Advanced Modeling, Simulation and Analysis Roadmap Team



Capability 14.1:
Scientific Modeling and Simulations

Speaker: Tamas Gombosi, Lead
Tsengdar Lee
John Rundle

Capability 14.1 Description : Science Modeling and Simulation

- The ability to simulate complex natural and anthropogenic phenomena, and to forecast and predict unanticipated outcome
  - M&S is a new instrument of learning and understanding new phenomena
  - Pursue integrated science models (ESMF, SWMF) to integrate science disciplines.
  - Anomaly detection in the environment
- The ability to visualize the results and outcomes of simulations
- The ability to assimilate (ingest) large data sets into simulations, and set the parameters for them
- The ability to mine large data sets for new and unexpected information from space mission data.

Capability 14.1: SM&S Motivation

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Exploration and discovery motivates looking in places that are previously unexamined.

Classic tools of exploration are telescopes, which look outwardly into space, and microscopes that look inwardly to finer and finer detail.

Simulations have become an indispensible tool for probing and exploring phenomena that are currently outside of our experience.

Models can be used to explore virtual environments of the moon, Mars and the space environment before we get there.

Capability 14.1: SM&S Benefits

New Vistas in Exploration - will lead to new kinds of science and generate new discoveries.

Measurements will rely on models – to capture, analyze, and characterize features of this environment for interpretation

Models were always part of NASA's culture of exploration

A New Paradigm - Recent major advances in computational capabilities allow numerical simulations to plan, conduct and analyze NASA missions.

Natural Systems are Complex - Simulations of the coupled earth-planetary models and the space environment are essential components of understanding and forecasting

Capability 14.1: Scientific Modeling & Simulation Requirements and Assumptions

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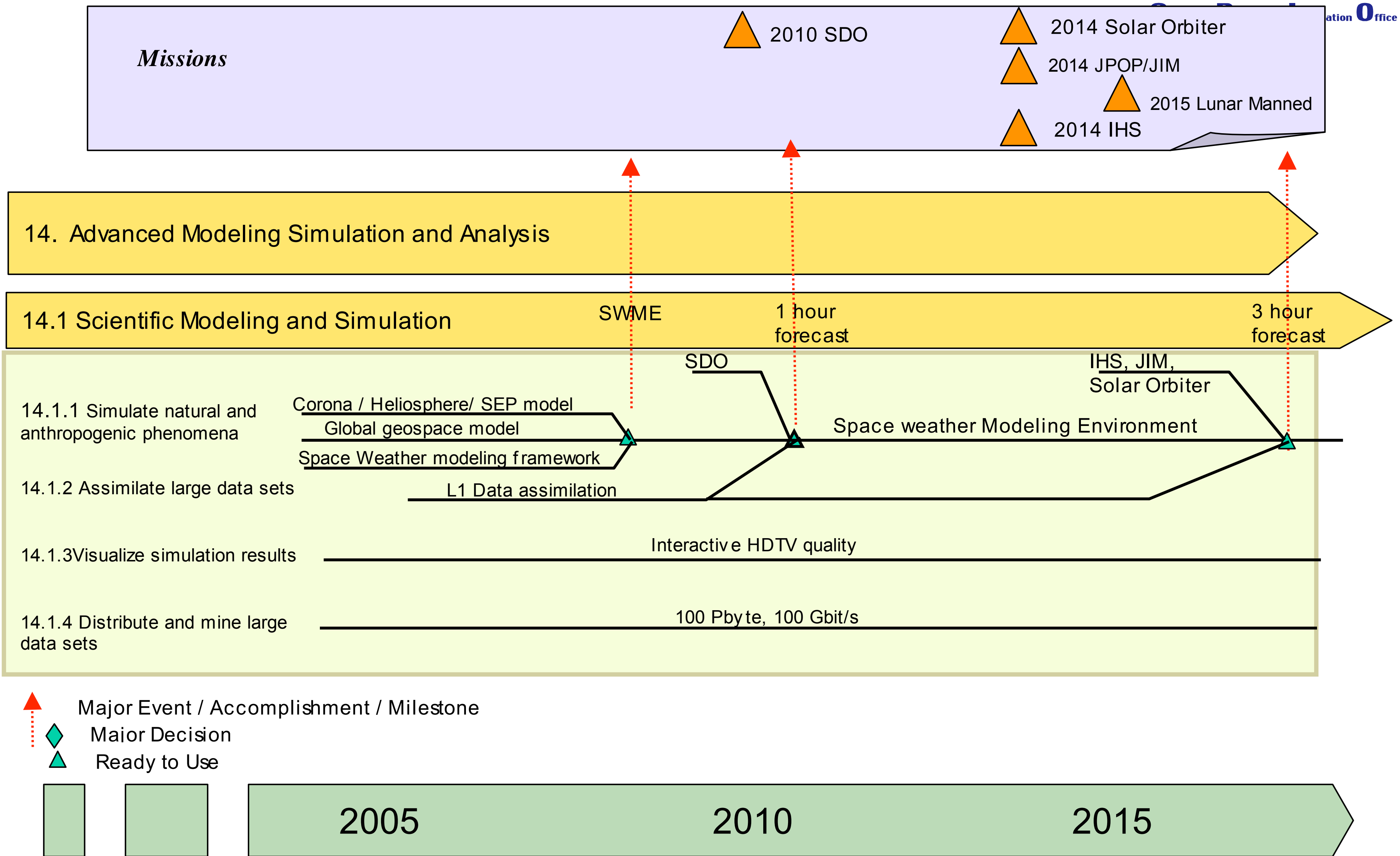
- What missions are driving the requirements?
  - NPP and NPOESS (2008, 2010)
  - InSAR Constellation and Global Precipitation Measurement missions (2014)
  - Solar Dynamics Observatory (2009)
  - Heliospheric Sentinels (2013)
  - Jupiter orbiters and Outer planets/Kuiper belt mission (~2017)
  - NGST (2015)
  - Robotic and human exploration of the Moon(2010-2020)
  - Robotic and human exploration of Mars (2010-2030)
  - Protostellar disks and planet formation mission, Saphir (2020+)
- Additional Assumptions that the team used that drove the need for the capability
  - We are presenting our best estimates for the science drivers, but we have not had a chance to coordinate with the strategic roadmaps yet.
  - VSE is interpreted in a broader sense
  - Grid computing will become essential infrastructure
  - Moore's law continuing and storage capacity will proportionally increase
  - Problem complexity will increase and simplification must come from "system of systems" approach (c.f. increased complexity in aircraft industry)

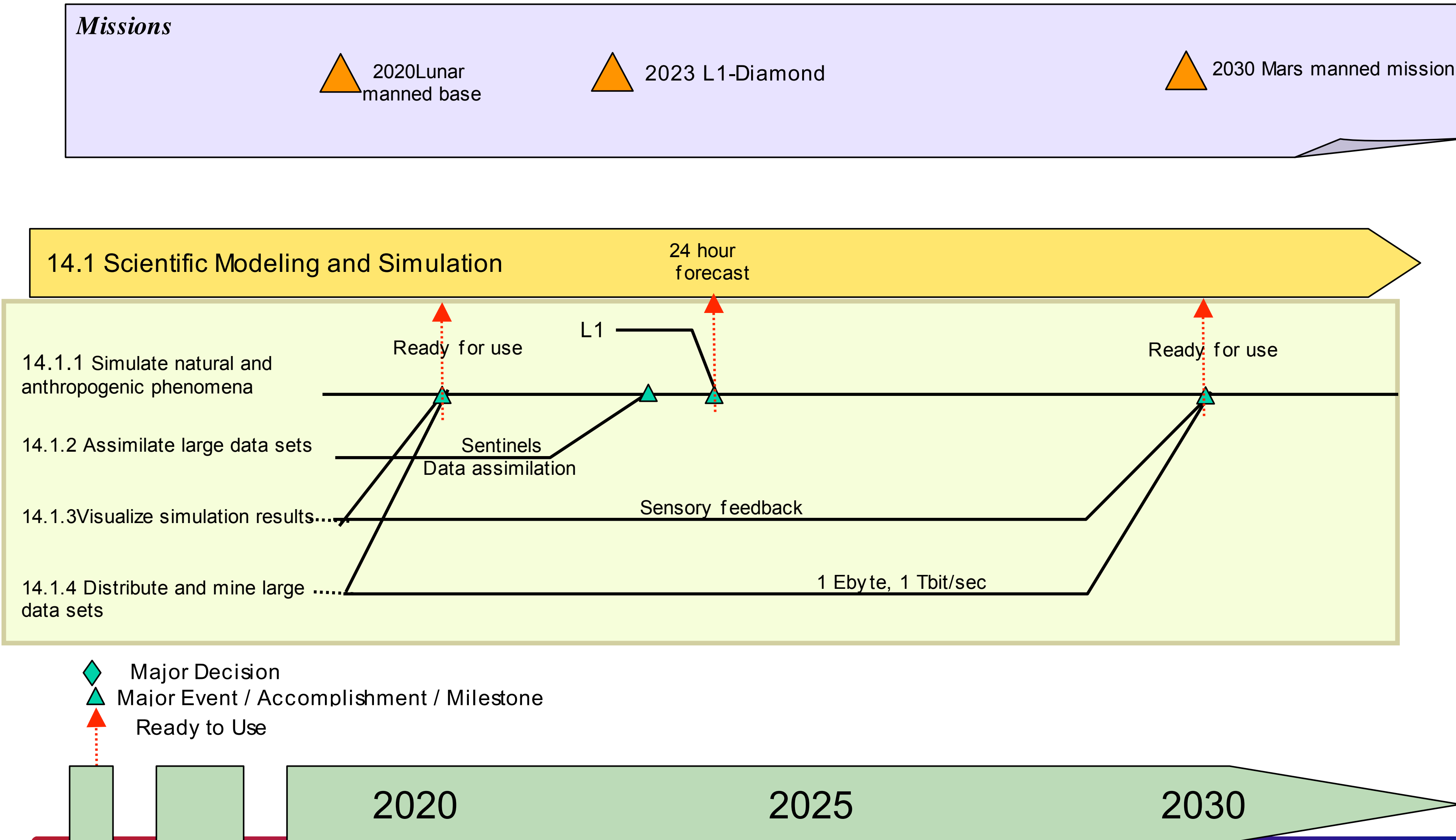
Capability 14.1: SM&S Current State-of-the-Art

- Simulation technology
  - Simulations: Routine simulations with ~10^6 cells
  - Computing resources: TFlops
  - Visualization: Routine visualization of all simulations and data via post-processing of simulations and data
  - Data volume: Store in federated data bases and distribute 10 Pbyte of data
- Science capabilities
  - Space: 0.25 Re, millions of computational cells; kinetic simulations with 1 billion particles
  - Atmosphere: 1 degree resolution for climate, 0.25 degree for weather simulations
  - Ocean: 0.1 degree resolution (Earth Simulator)
  - Solid earth: millions of interactions (Green's functions), fault length scales of several km
  - Astrophysics: Solve protostellar & planetary disk models with 3D MHD problems with 10 million cells and multiple species

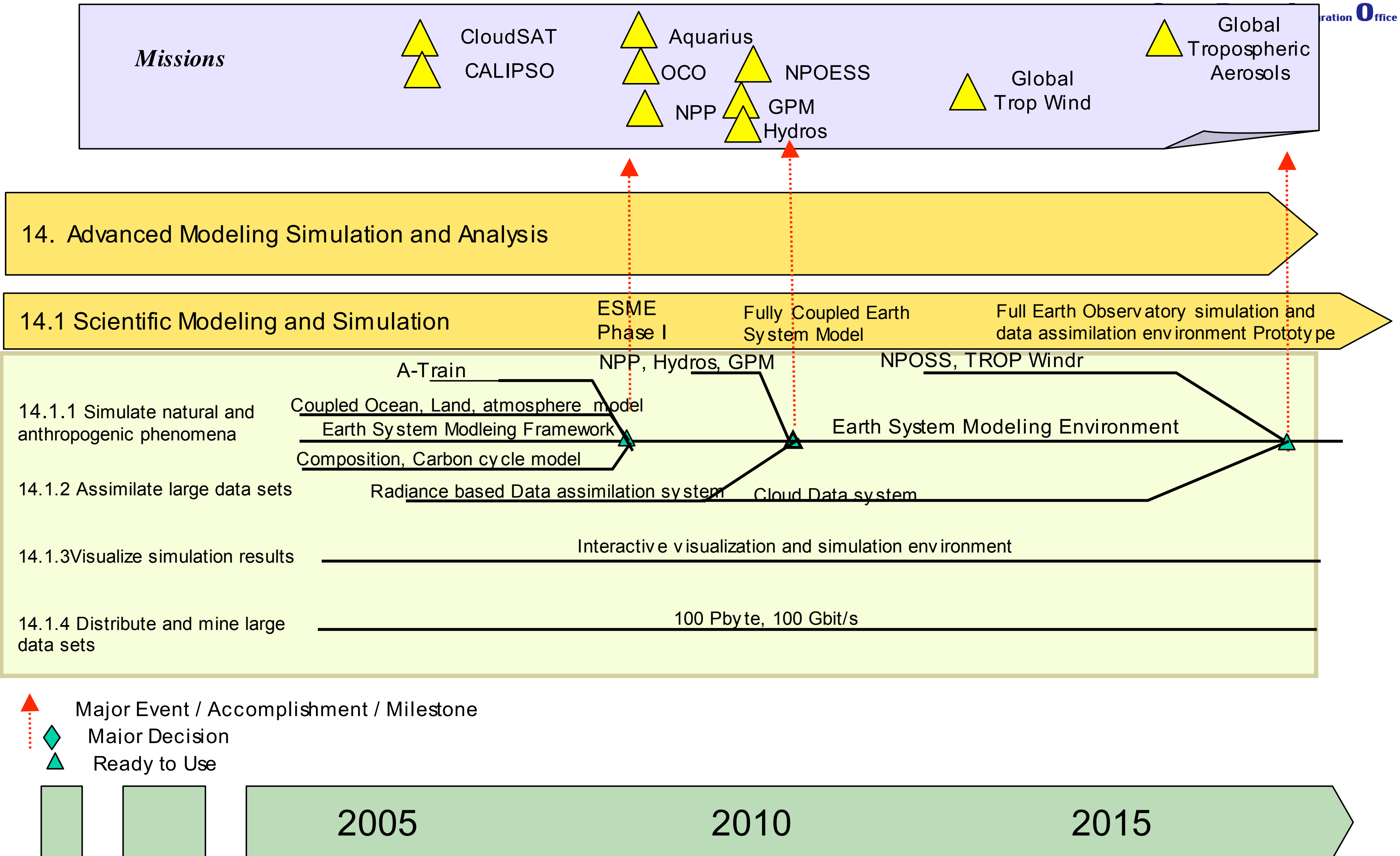
Capability 14.1: SM&S Space weather Roadmap



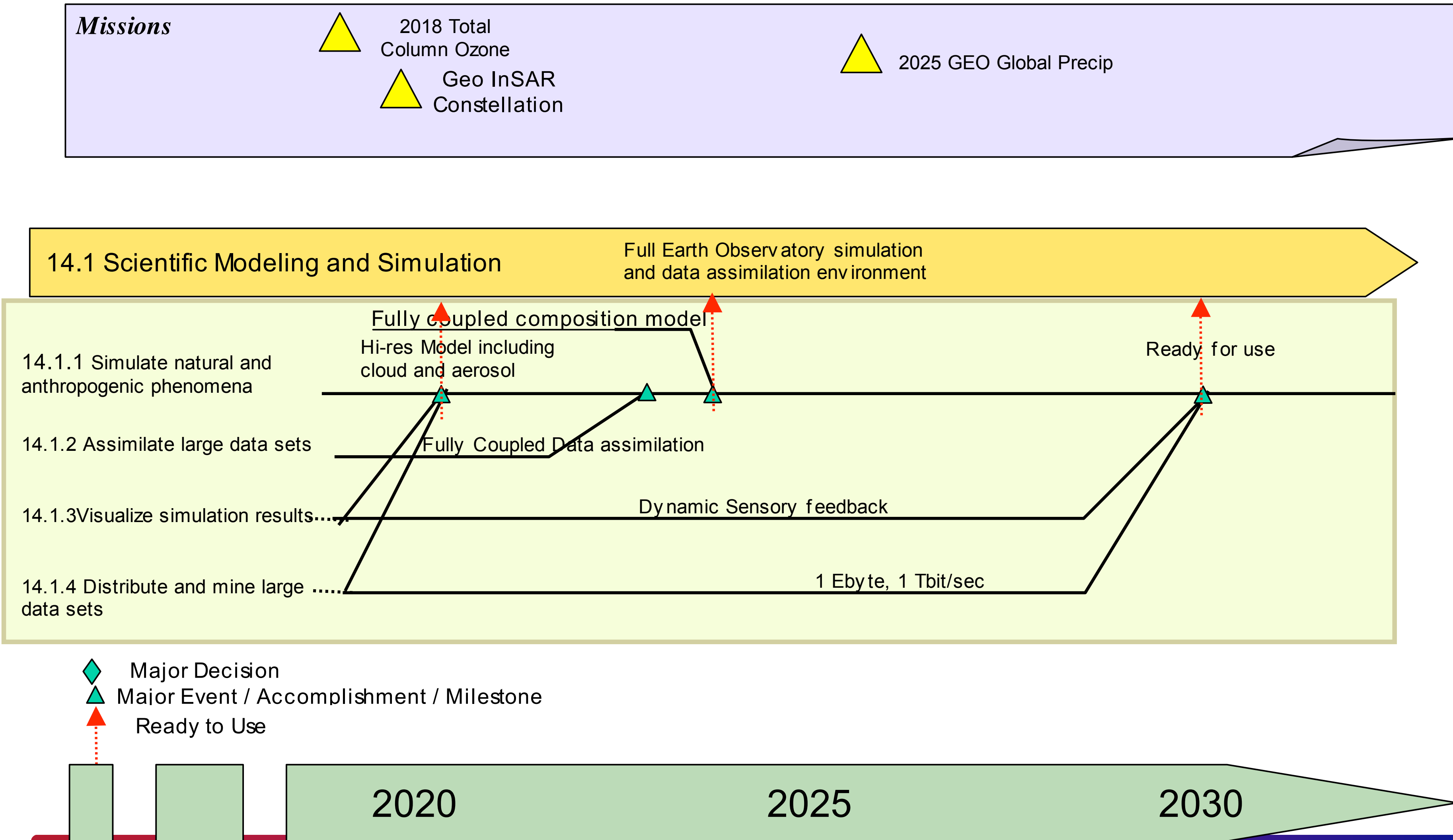
Capability 14.1: SM&S Space Weather Roadmap



Capability 14.1: SM&S Full Earth Observatory



Capability 14.1: SM&S Full Earth Observatory



Capability 14.1: SM&S Goals and Milestones (v1)

Science	Capability	By 2015	By 2020
• Coupled Air-Sea-Land model for weather and climate simulations • Crustal dynamics models for earthquakes and plate motion • Predictive coupled space environment model to simulate space storms and SEP events • Comprehensive planetary hazard models to support human exploration • Cosmological and galactic dynamics models • Disk magentosphere interactions, protostellar disk and planetary formation models	Simulations & Data assimilation	Routine simulations with 1B degrees of freedom	Routine simulations with 1B degrees of freedom
	Visualization	Capability to resolve HDTV quality in a streaming and interactive environment	Capability to resolve HDTV quality in a streaming and interactive environment with full sensory feedback
	Data volume	Capability to store and distribute 100 Pbyte of data from simulations or observations, and to provide streaming data at 100 Gbit/s	Capability to store and distribute 1 Exa-byte of data from simulations or observations, and to provide streaming data at 1 Tbit/s

Capability 14.1: SM&S Goals and Milestones (v2)

2010	2015	2020	2030
Validated, coupled Sun-to-Earth space environment model to simulate space storms and SEP events	**Validated, predictive Sun-to-Earth space environment model to provide 3 hours forecast of solar storms and SEP events**	**Validated, interactive predictive Sun-to-Earth space environment model to provide 24 hours forecast of solar storms and SEP events to support human activities on the Moon**	**Validated, interactive predictive Sun-heliosphere space environment model to provide 72 hours forecast of solar storms and SEP events to support human exploration of Mars and robotic exploration of the outer planets**
Comprehensive planetary hazard models to support human exploration	**Validated simulation of Martian atmospheric density, temperature and near surface winds.**	**Validated simulation of Martian aeolian dust transport and storms. Predictive capability for atmospheric or subsurface transport of biohazards and biogenic materials.**	**Weather forecasting for atmospheric density, near surface winds, and dust storms. Predictive models for ionizing radiation at the surface.**
Crustal dynamics models for earthquakes and plate motion	**Validated, predictive simulation of interacting active faults in a region the size of California at a scale of 1 km resolution, to provide 5 years forecast of earthquakes larger than 5.**	**Validated, predictive simulation of interacting active faults in a region the size of California at a scale of .1 km resolution, to provide 2 years forecast of earthquakes larger than 5, with capability of full data assimilation in real time using interferometric radar data.**	**Validated, predictive simulation of interacting active faults in a region the size of California at a scale of .01 km resolution, to provide 6 months forecast of earthquakes larger than 4, with capability of full data assimilation in real time, and real time, streaming, immersive visualization of simulation data merged with observed interferometric data.**
Coupled Air-Sea-Land model for weather and climate simulations	Validated model of probabilistic predictions of future climates and transitional climate change at several hundred kilometer resolution Full four-dimensional variational data assimilation of aerosol particles, trace gases and satellite properties. Routine , validated predictions of climate anomalies, such as El Nino, 6-12 months in advance.	Integrated earth system model with interactive hydrology, dynamic vegetation and biogeochemistry producing validated results as several hundred kilometer resolution.	Earth system modeling suite , validated through extensive and comprehensive data assimilation systems employing observations from space-based earth monitoring systems. This modeling system will produce probabilistic predictions of regional manifestations of global changes based on scenarios of human activity, including population changes, energy technology strategies and water use.
• **Cosmological and galactic dynamics models**			

Capability 14.1: SM&S Maturity Levels -- Technology

- **Leading technology candidates**
  - Grid computing
  - Leadership class computing system
  - Immersive and interactive visualization
  - Frameworks
  - Federated data bases
  - Web service architectures for distributed/coupled models
- **Key gaps between current state-of-the-art and required performance levels**
  - Distributed, grid based computing portal that enables to build, run and analyze integrated simulations
  - Collaboratories
  - Model infrastructure tools for high spatial, resolution, and temporal simulations

Capability 14.1: Scientific Modeling&Simulation Related Technologies and Dependencies

Capability 14.1: Priorities

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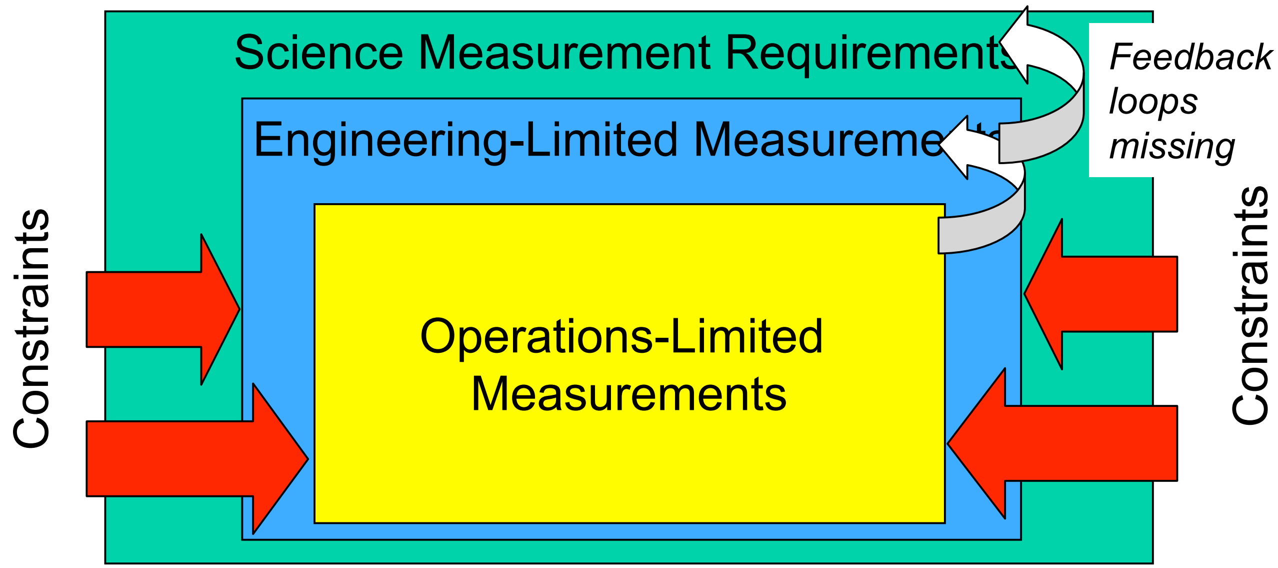
Capability 14.2 M&S for Operations

Speaker: Ron Fuchs, Lead
Erik Antonsson

Advanced Planning & Integration Office

Capability 14.2 Description: M&S for Operations

- **Simulation of all aspects of missions for the purpose of requirements development, training, mission rehearsal, anomaly resolution, validation of subsystems and systems, or developing human-system interfaces.**
  - **Includes interfaces to scientific and engineering M&S**
  - **Includes Human-in-the-loop simulations**



Capability 14.2 M&S for Operations - Motivation

- NASA missions are increasing in complexity and inter-dependency
  – Human exploration systems must evolve into tightly integrated partnerships between humans and machines.
  – Increasingly large quantities of data, upon which decisions are based, present needs for models, visualization, situational awareness and decision aids to support human operations in space.
  – Robotic exploration systems require modeling of instrument and spacecraft systems for scheduling, control, mission operations and anomaly resolution.
  – Operations models must be introduced early in the design cycle.
  – Operations modeling depends on the science and engineering models. Development of operations must be done in concert with the development of the science goals and engineering systems.
  – Communications and information management must be included.
  – Models of human biomechanics and human factors must be included.
- Complex missions lead to geometric increase in potential risks
  – Realtime simulations of operations are needed to meet safety targets for human spaceflight.
  – Future missions require training and scenario evaluation for ground controllers and in-space flight operations for both mission execution and anomaly resolution.
- Budget pressures will increasingly stress the ability to meet goals
  – Operations costs have dominated human spaceflight operations.
  – M&S Can reduce these costs by reducing amount of live testing

Benefits of Capability 14.2 M&S for Operations

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Reduced Risk* – *mistakes are made during development and training in the virtual world rather than the real world.

Sound system requirements* – *essential to the systems engineering process that has been shown to result in better cost effectiveness of programs.

Improved Performance* – *"Optimal" overall human-machine integration during all phases of a program.

Rapid understanding of anomalies* - *Simulations are the basis for reconstructing an understanding of systems during anomalous events

Preflight understanding of communication limitations* - *Impact of communication time-of-flight delays can be evaluated.

Capability 14.2: Requirements & Assumptions

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- What missions are driving the requirements?
  - All manned missions
    - CEV
    - Human Lunar
    - Human Mars
  - Missions requiring a system of systems approach
    - Lunar Robotic
    - Robotic Mars
    - Air Transportation System
- Additional Assumptions that the team used that drove the need for the capability
  - The increasing challenge of future NASA missions will dictate the need for more integrated system of systems approaches
  - Budget pressures will constrain live testing and experimentation to levels that will significantly increase mission risk without a robust M&S environment
  - Greater international participation will be the norm for ambitious programs, which implies needs ranging from new collaboration techniques to improved export control

Capability 14.2: Current State-of-the-Art

- Requirements Development
  - Simulators at the individual system level
  - Manual interfaces between many system simulated components
- Training
  - Purpose-built single task trainers
  - Limited integrated system training capability
- Mission Rehearsal
  - Good representation of today's relatively simple missions
- Human-System Interfaces
  - Trial and error approach
  - High cost development due to large numbers of labor intensive trials
- Anomaly Resolution
  - Good representation of portions of the systems
- Subsystem Validation
  - Purpose built testing environments that substitute for prohibitively expensive live testing of specific components
- General
  - Lack of integrated simulations makes development and analysis of systems of systems difficult

Capability 14.2: Maturity Level Assessment

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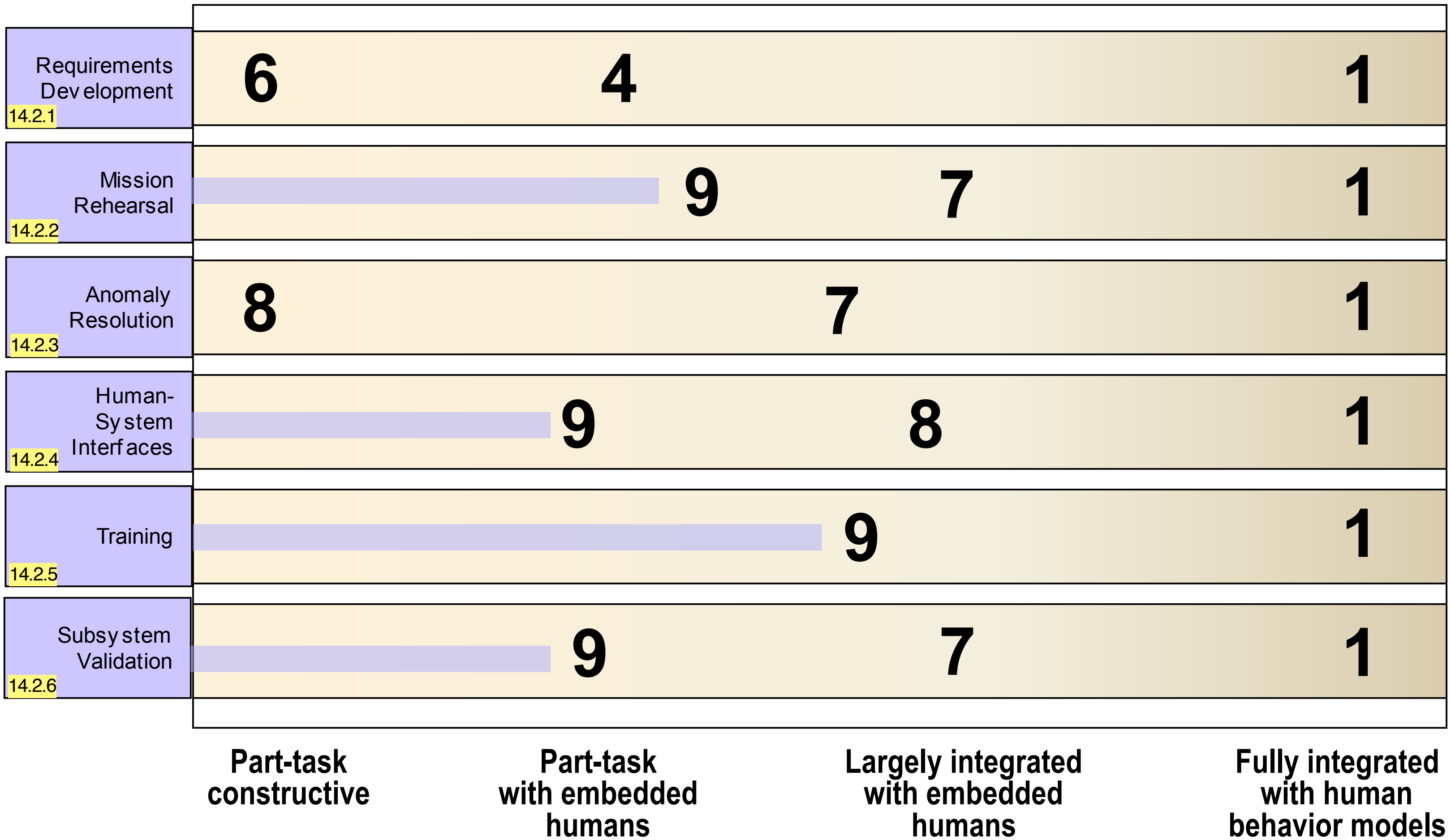
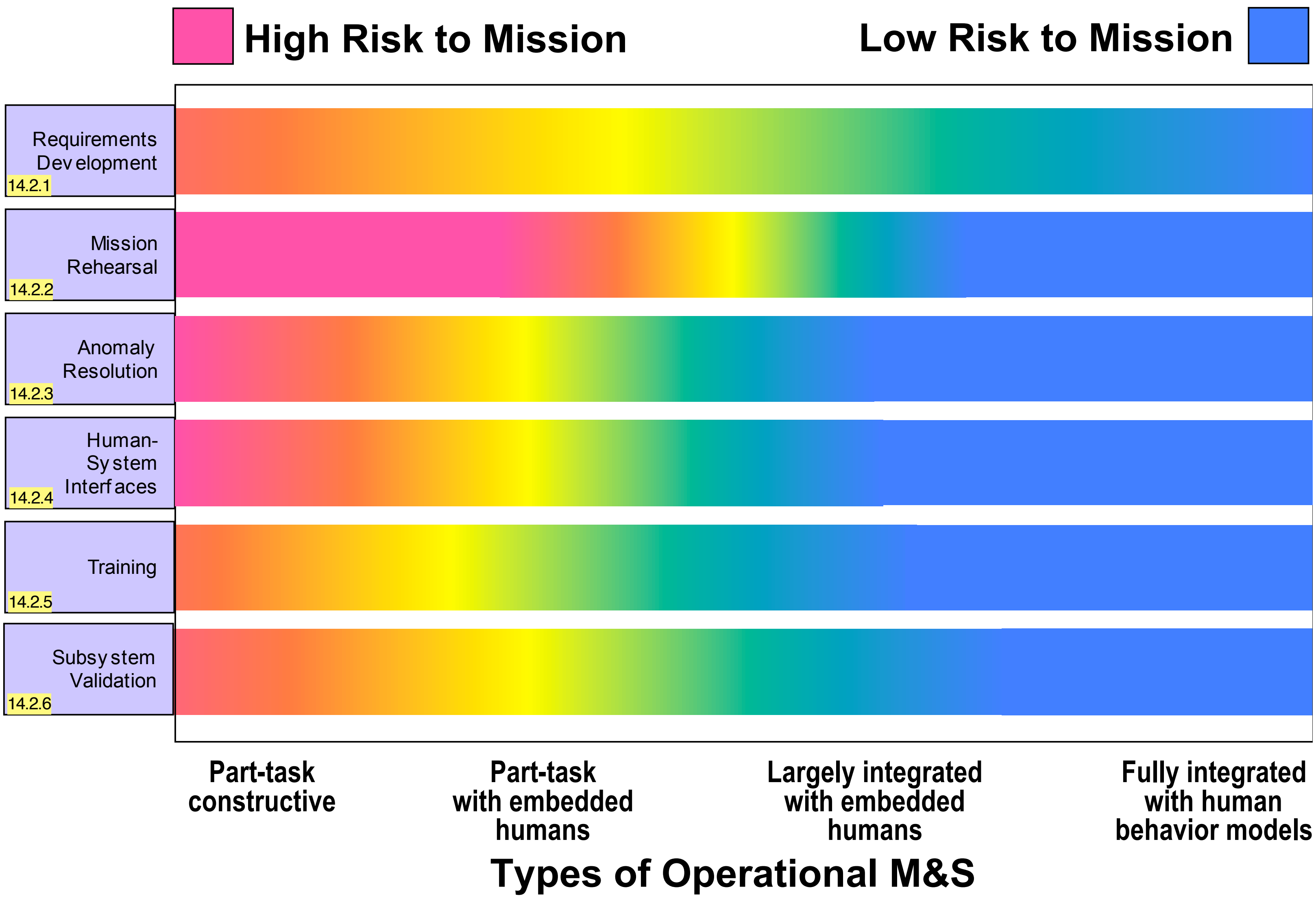
Numbers represent average current TRL for each area

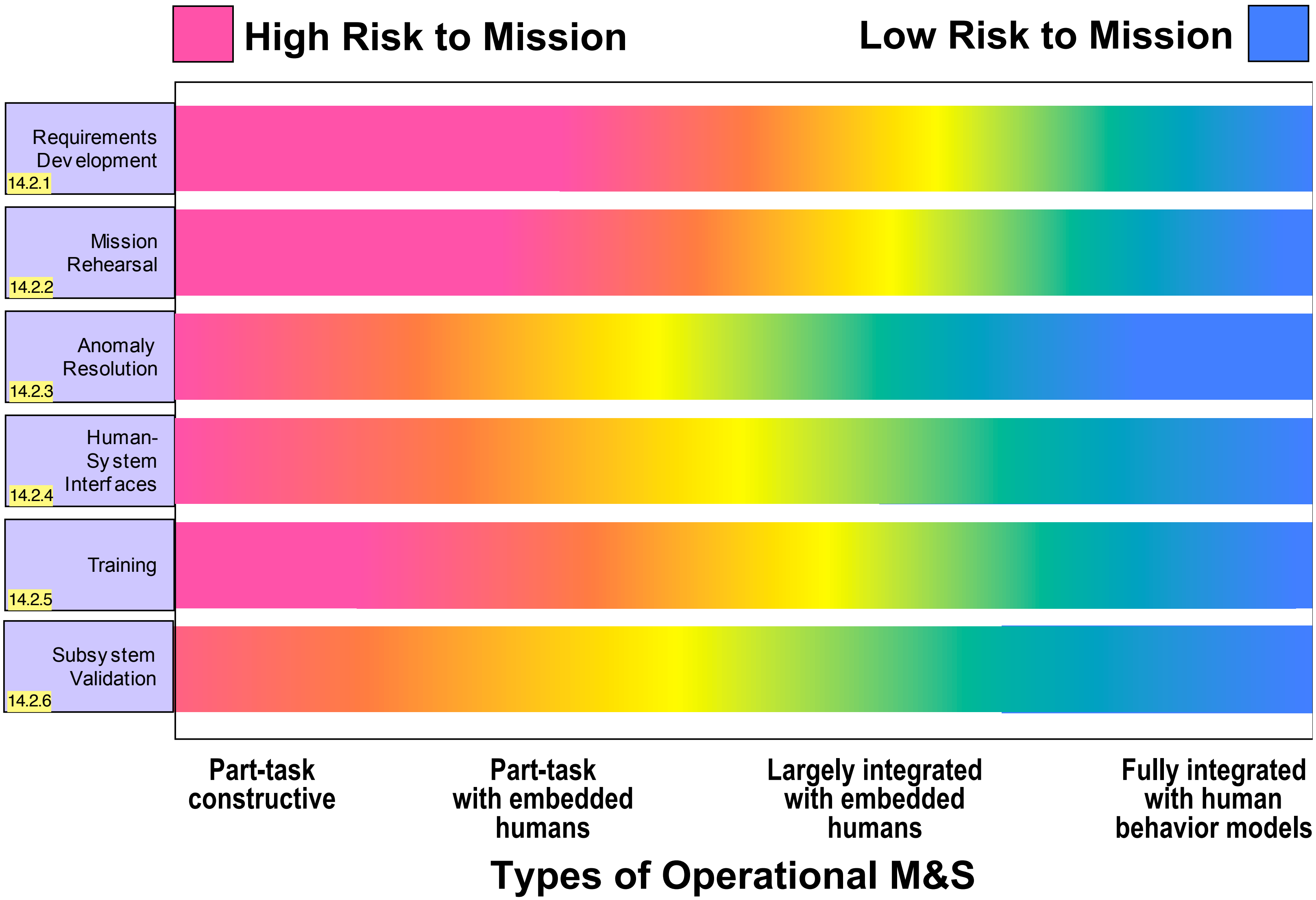


Types of Operational M&S

Capability 14.2: CEV Requirements



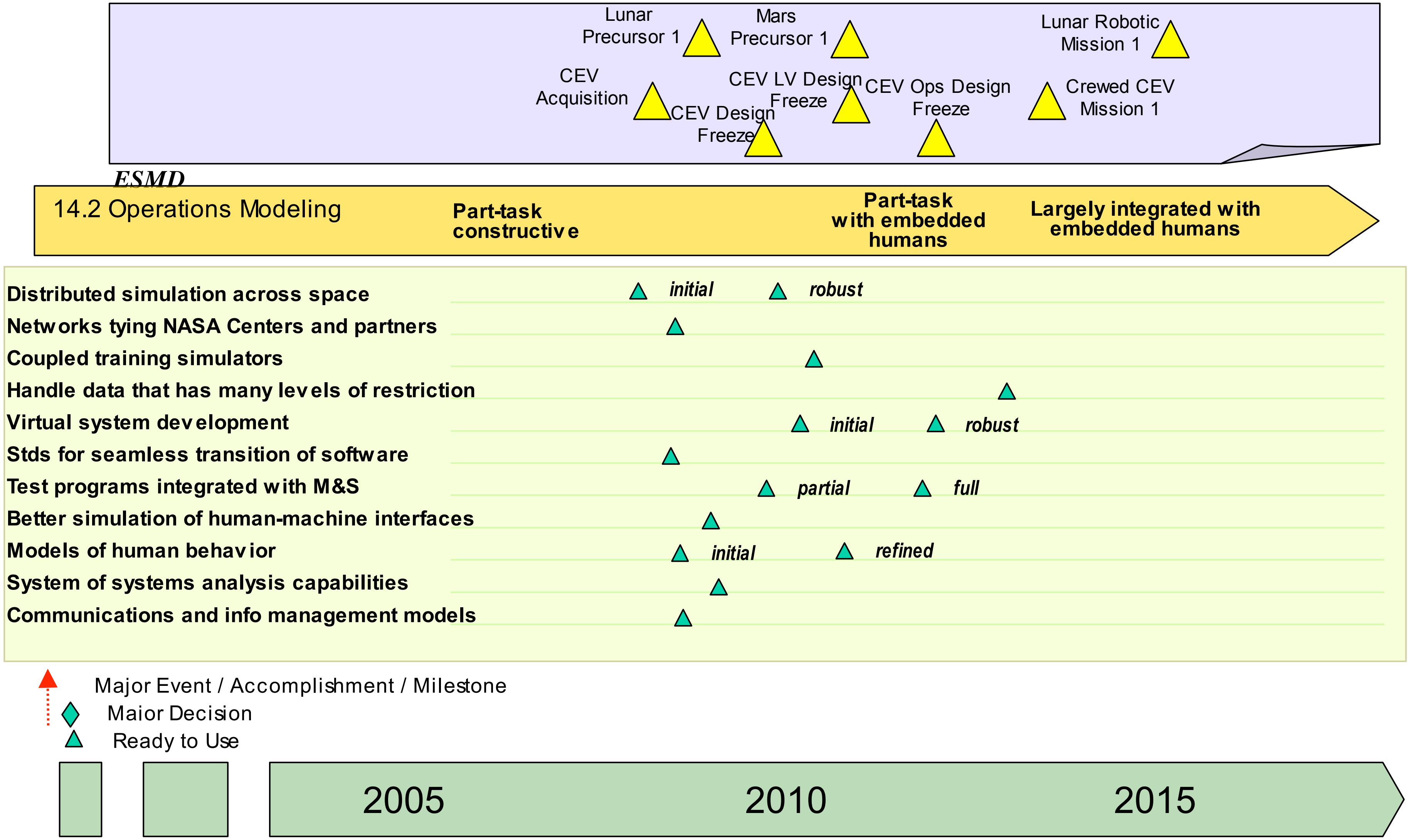
Capability 14.2: Mars Human Requirements



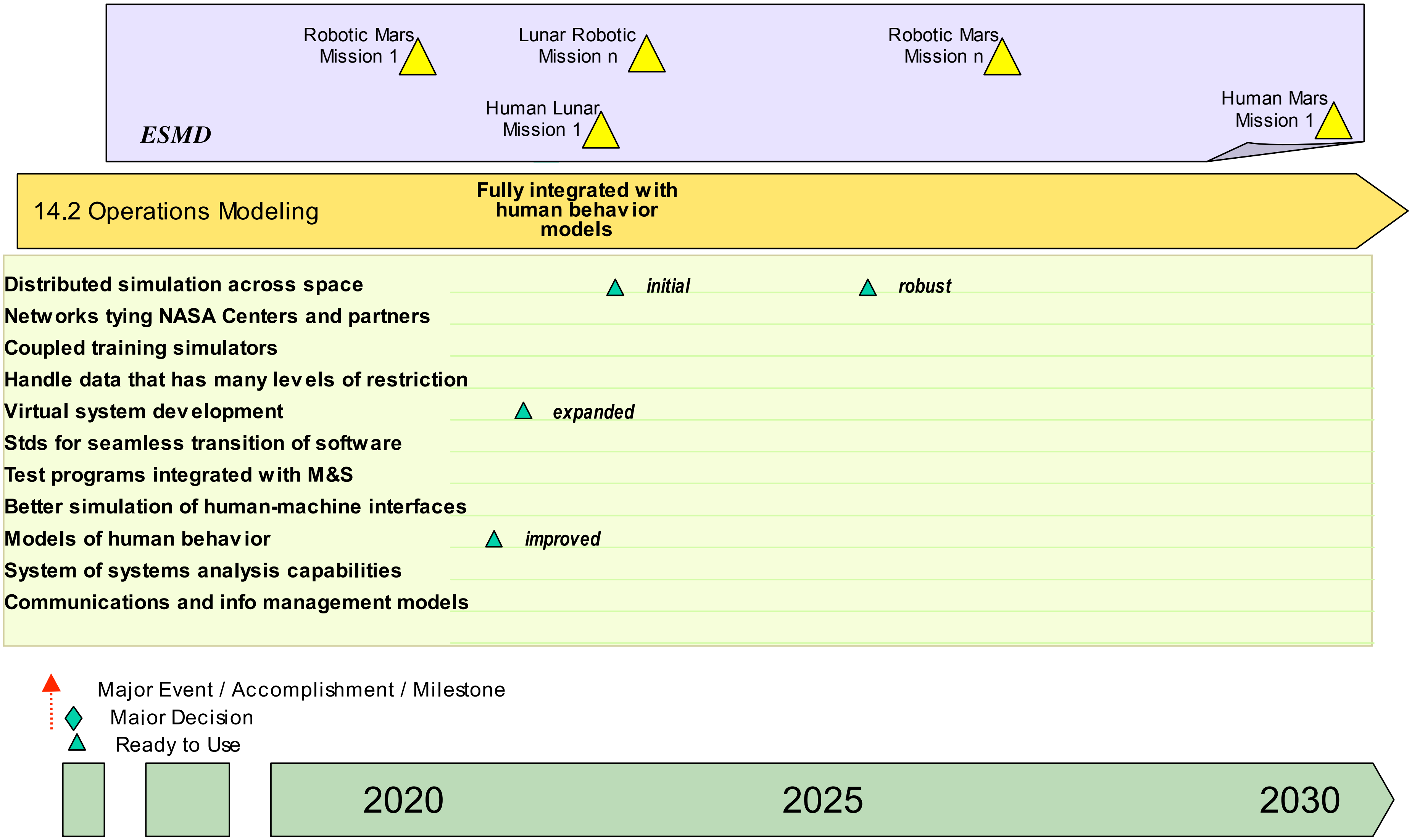
Capability 14.2: Capabilities Needed

- NASA needs an more integrated approach to M&S
  - Distributed simulation capabilities
    - Distributed simulation across long distances (space)
  - Networks tying NASA Centers, international, and industry partners
  - Coupled training simulators
  - Ability to handle data that has many levels of restriction (proprietary, classified, ITAR, …)
- NASA needs a virtual development/production/test/operation environment
  - Virtual system development to expand options and reduce costs
  - Standards for seamless transition of software from virtual to real environments without redevelopment
  - Test programs integrated with modeling and simulation approach
- NASA needs affordable human inclusion in M&S
  - Better simulation of human-machine interface systems
  - Models of human behavior
- NASA needs some new tools
  - System of systems analysis capabilities
  - Communications and information management system models

Capability 14.2: M&S for Operations Roadmap



Capability 14.2: M&S for Operations Roadmap



Capability 14.2: Metrics

Requirements Development	Time to evaluate a candidate architecture's cost, performance and risk
Mission Rehearsal	Effectiveness in creating a realistic environment as judged by participants
Anomaly Resolution	Time to ascertain root cause Time to develop corrective actions
Human-System Interface	% of time correct decisions are made Consistency of decisions across crew members
Training	Time to train to desired proficiency levels Length of time training effects are retained
Subsystem Validation	% of subsystems that can be fully tested Risk of subsystem failure due to lack of validation

Capability 14.2: OM&S
Related Technologies and Dependencies

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- Many of the Operations M&S areas overlap with the Systems Engineering needs, particularly in requirements derivation and testing. The technologies developed need to be coordinated across these areas.
- Operations M&S must be integrated with the engineering M&S processes and tools to make relevant trades during the entire system life cycle, but particularly during the design phase.

Capability 14.2: Priorities

1. NASA needs an more integrated approach to M&S
   - Distributed simulation capabilities
     - Distributed simulation across long distances (space)
   - Networks tying NASA Centers, international, and industry partners
   - Coupled training simulators
   - Ability to handle data that has many levels of restriction (proprietary, classified, ITAR, …)
2. NASA needs some new tools
   - System of systems analysis capabilities
   - Communications and information management system models
3. NASA needs a virtual development/production/test/operation environment
   - Virtual system development to expand options and reduce costs
   - Standards for seamless transition of software from virtual to real environments without redevelopment
   - Test programs integrated with modeling and simulation approach
4. NASA needs affordable human inclusion in M&S
   - Better simulation of human-machine interface systems
   - Models of human behavior

Capability 14.3 Engineering Modeling

Presenter: Mike Lieber
Thomas Zang
Charles Norton
Karen Fucik

Advances in Engineering Modeling and Simulation Enable Future Missions

- **In this section we propose advanced engineering modeling and simulation for adressing the following questions:**
  - **How could NASA reduce overall mission risk, maximize resources, and enhance overall system engineering processes for future missions?**
    - **By evolving current integrated models to a Large-Scale System Modeling architecture and using them early in the design process.**
  - **How do we better address unexpected and sometimes catastrophic events?**
    - **By development of Anomalous Behavior Models with expert system oversite.**
  - **Given the environmental difficulties and cost of system ground testing, how does NASA best insure future mission success?**
    - **By developing and validating Virtual System Test models.**
  - **How does NASA determine the quality and bounds on modeling predictions?**
    - **By developing Uncertainty Models from rigorous mathematics and firm understanding of relationship to performance models.**
  - **How can NASA best utilize robotics in space for assembly and servicing?**
    - **By developing interactive and dynamic machine-machine models to pre-assemble/ service in a virtual environment.**

The Challenge to Reduce Development Cost - Industry Experience

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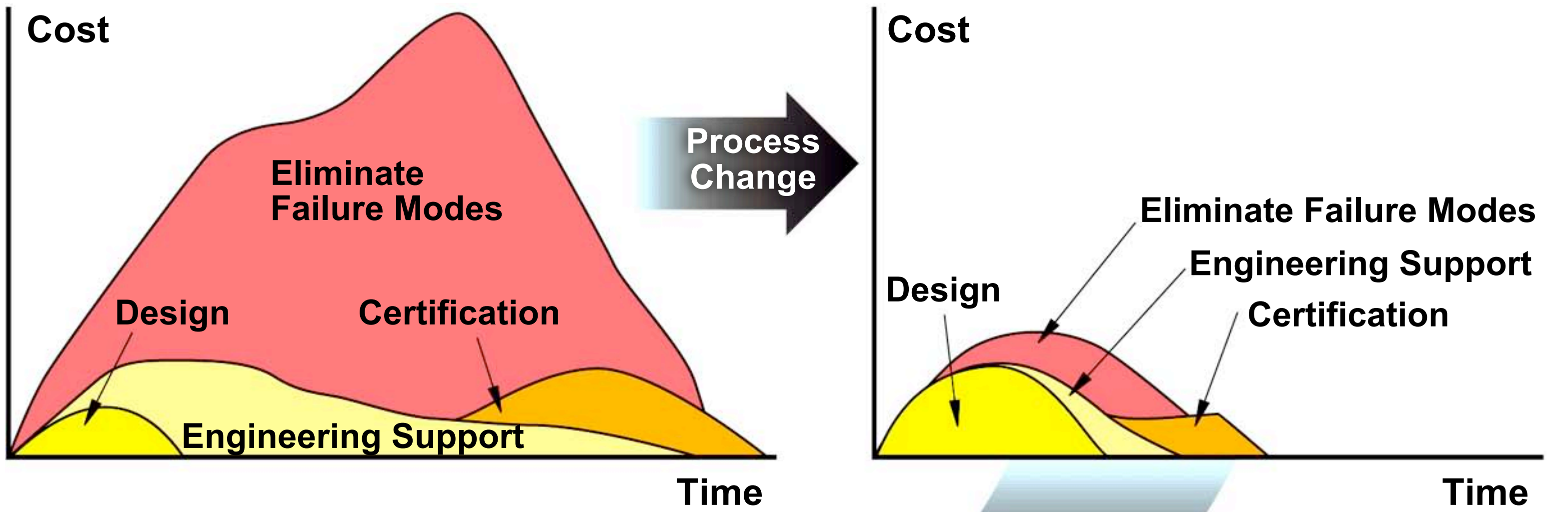
Traditional Design Process

Robust Design Process



Results

Test-Fail-Fix Cycle Representing 73% of Cost

REDUCE BY FACTOR OF 4

Similar experiences in auto and jet Engine industries

* Borrowed from Rocketdyne/ Boeing presentation

Description of Capability 14.3 Engineering Modeling(1/2)

- **14.3.1 Large-scale system modeling**
  - Rapid integrated model deployment, cradle-to-grave, evolutionary, hierarchical structure, discrete event, hybrid system modeling, advanced data structures.
  - Imbedded data management, design space exploration/ multiple optimization engines.
  - Distributed grid computing, distributed collaboration.
- **14.3.2 Anomalous Behavior Models**
  - Failure modes and effects, mitigation, real-time anomaly resolution, sabotage evaluation.
  - AI driven "agents of doom" for scenario generation.
  - High-fidelity predictions of performance under damaged/ abnormal conditions.

Description of Capability 14.3 Engineering Modeling(2/2)

- **14.3.3 Virtual System Testing**
  - Modeling the untestable, updates flight large-scale model, test definition (reverses paradigm)
  - Selective replacement testing with modeling, HIL emulation.
  - Robotic exploration and virtual world interactions.
- **14.3.4 Uncertainty Modeling**
  - Supports V&V with advanced modeling techniques for characterizing and propagating system uncertainty.
  - Characterizes modeling error bounds.
- **14.3.5 Robotics manufacturing and servicing**
  - Dynamically replicated virtual environment for assembly, servicing and repair in space.
- **14.3.6 Visualization**
  - Converting data into knowledge. Dynamic, multidimensional.

Benefits of Capability 14.3 - Engineering Modeling (1/2)

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- <u>14.3.1 Large-scale system modeling</u>
  - Rapid integrated model deployment, design tracebility throughout life cycle.
  - Increased design knowledge leads to better system decisions (enables system trades with respect to performance, risk, and costs).
  - Increased multidiscilinarian communication.
  - Decreased number of "test-fail-fix" cycles.
- <u>14.3.2 Anomalous behavior models</u>
  - Minimize failure modes and consequences in the design phase.
  - Anticipate and avert incipient failure during operations.
  - Real-time Identification of alternative failure recovery paths.

Benefits of Capability 14.3 - Engineering Modeling (2/2)

- <u>14.3.3 Virtual System Testing</u>
  - Modeling the untestable, the unobservables, enhanced visualization.
  - Cost/schedule benefit.
  - Robotic path planning in remote environments optimizes resource.
- <u>14.3.4Uncertainty Modeling</u>
  - Supports V&V, confidence builder for decision maker, design robustness, reflects true environments.
- <u>14.3.5 Robotics manufacturing and servicing models</u>
  - End-to-end evaluation of machine-machine dynamics for design feedback and system engineering optimization and failure predictions.
- <u>14.3.6 Visualization</u>
  - Enhanced communication tools.
  - Facilitates understanding of model and results.

Current State-of-the-Art for Capability 14.3 Engineering Modeling(1/2)

- <u>14.3.1 Large-scale system modeling</u>
  - Remaining heritage to bucket brigade approach and "test-fail-fix" approaches.
  - Integrated modeling, like JPL IMOS, picemeal developed in parallel with program resulting in many architectural gaps.
  - Tie in weak or missing to optimization engines, comprehensive data management, cost and risk linkage, rapid deployment, science and operations.
  - Cradle-to-grave system capability not part of mission cycle.
- <u>14.3.2 Anomalous behavior models</u>
  - Not typically part of engineering cycle except as part of parameter variability studies.
  - Modified versions of models for post-mortem or emergency response.
- <u>14.3.3 Virtual System Testing</u>
  - Capability very scale dependent.
  - Complete end-to-end virtual system not in place.

Current State-of-the-Art for Capability 14.3 Engineering Modeling(2/2)

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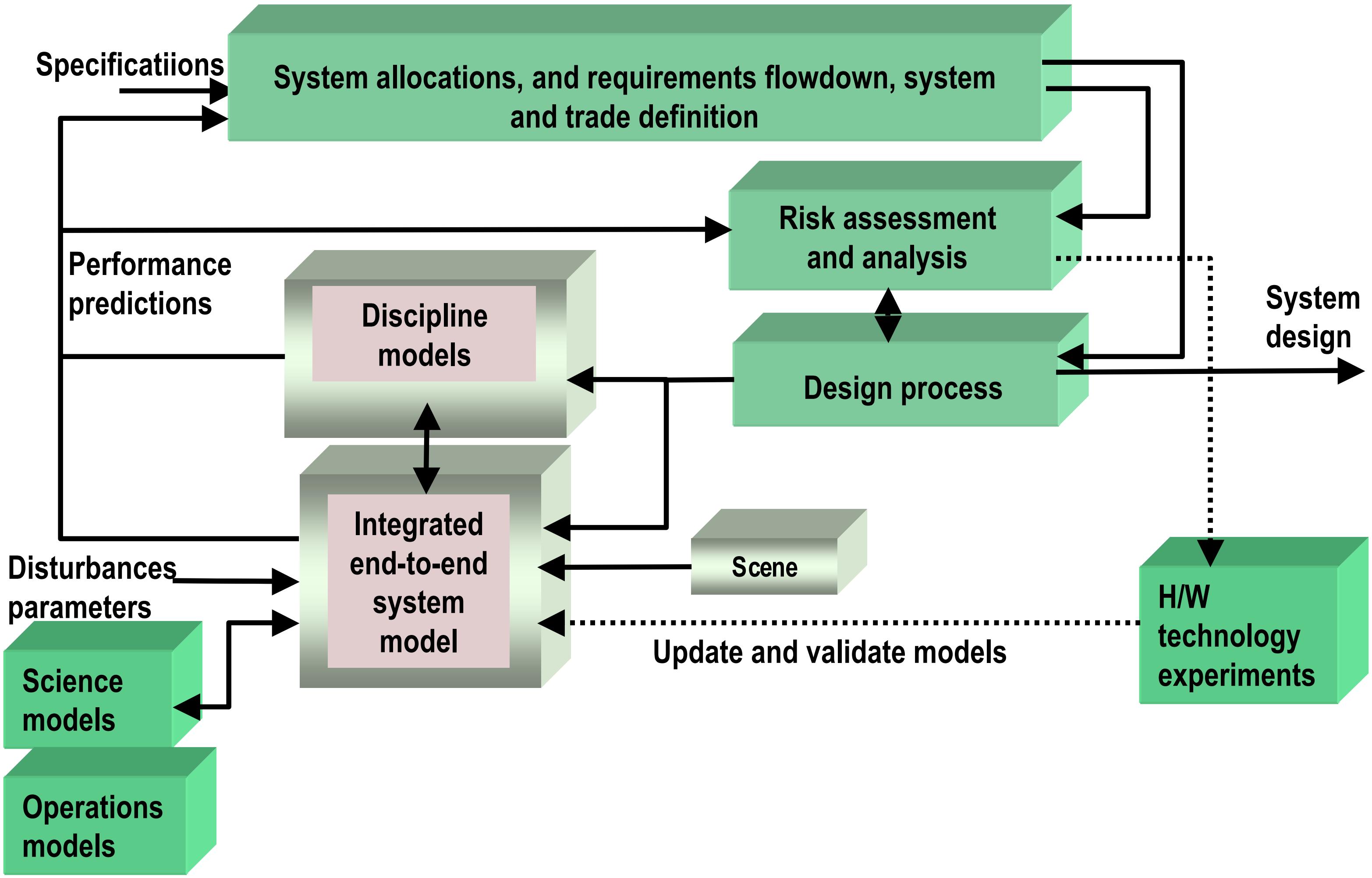
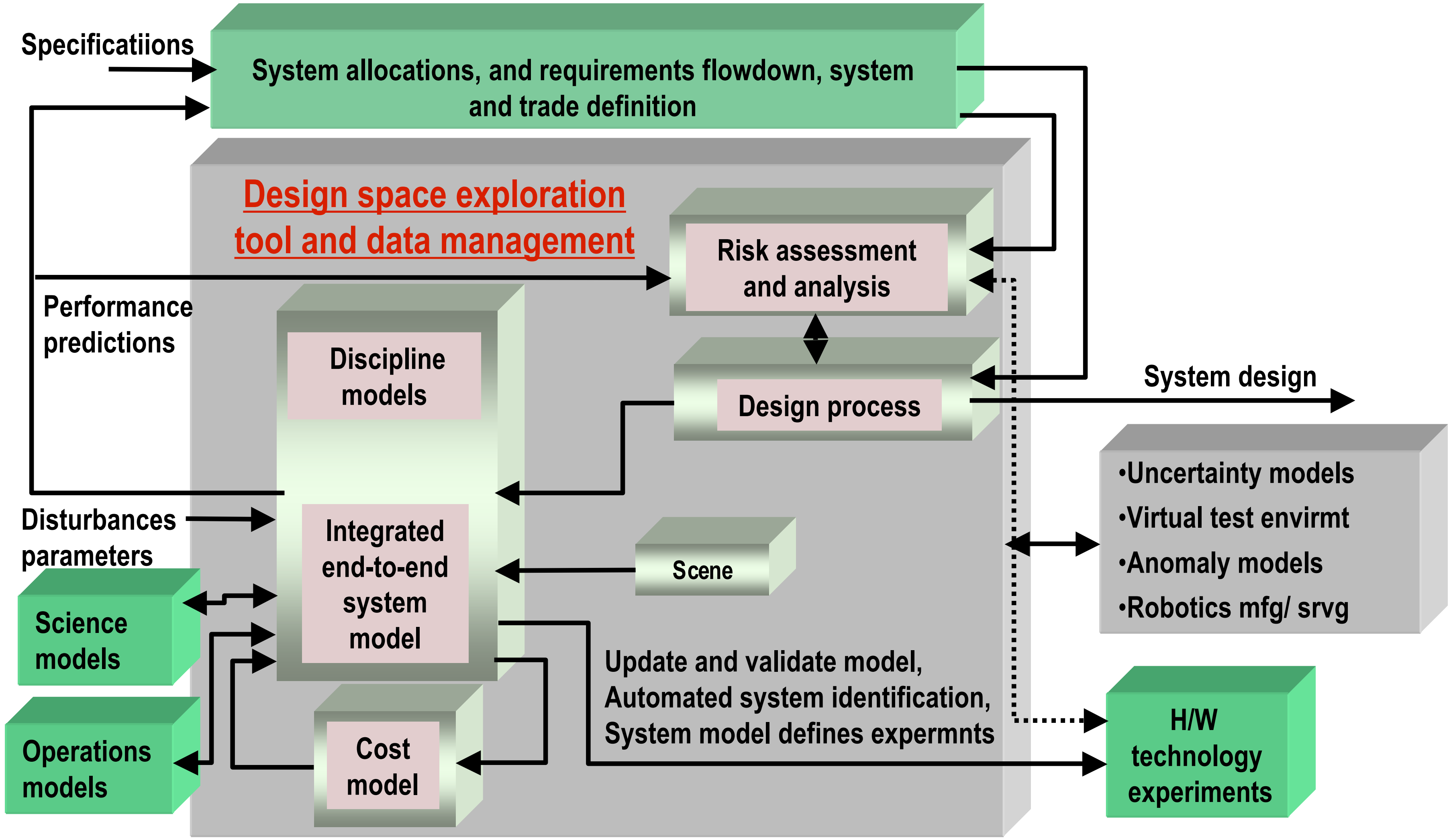
- 14.3.4 Uncertainty Modeling
  - Many COTS tools for propagation of probabilistic uncertainties.
  - Underlying parametric uncertainties poorly characterized.
  - Modeling of non-probabilistic uncertainties, e.g., model fidelity uncertainty, is very primitive and often mathematically unsound.
- 14.3.5 Robotics manufacturing and servicing models
  - Complete dynamics models exists for robotics systems but incomplete characterization for prediction of machine-machine processes.
  - Architecture advancements required for complete assembly/ servicing scenario.
- 14.3.6 Visualization
  - Embedded into commercial design modeling tools, exists as
    - separate packages and tool libraries,
    - high-end/experimental systems appropriate for large data sets on parallel computers for time-dependent 3D modeling.
  - Design space exploration visualization just starting to emerge.

14.3.1 Current Engineering – Discipline and Integrated System Modeling



14.3.1 Future Engineering modeling – Large-Scale System Modeling



14.3.1 Large-Scale System Modeling (LSSM) Environments Enables Future Missions

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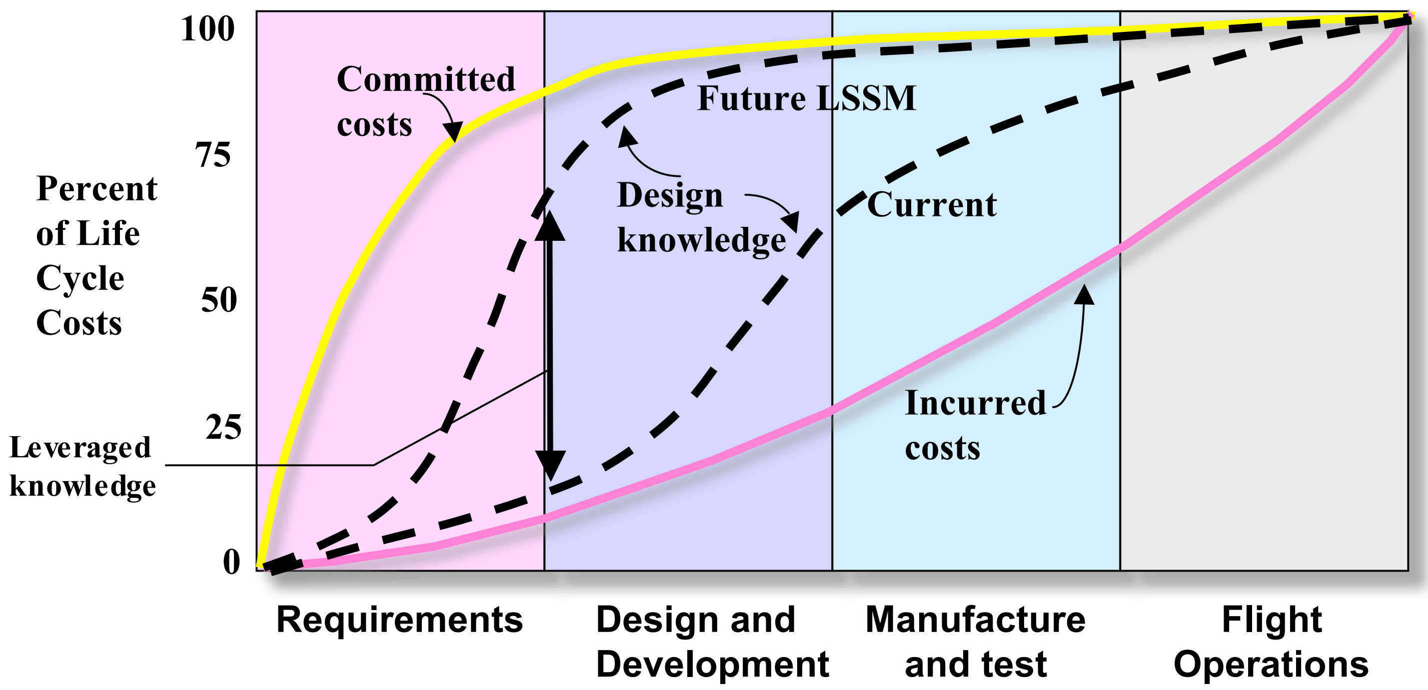
- Much of mission costs are committed within the first part of the development cycle.
- LSSM environments proposed for the future provide early in-the-process knowledge for reducing mission cost and risk.
  - Much of current modeling resources not used efficiently.

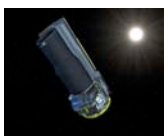


14.3.1 Current Modeling Support Over Mission Cycle

Current missions - Just-in-time modeling, serial modeling support

- Discipline/ developmental integrated models, Monte Carlo methods
- Local computing

Spitzer



Chandra

Science models

Concept performance

Bucket brigade or limited capability IM

Coarse predictions/ error budgets

Refined models

Bucket brigade or limited capability IM

Final predictions/ error budgets

Operations models

- Targeting/ manuevering
- Mid-course corrections
- Anomaly resolution
- Data processing

Science flowdown

Coarse cost

Subsystem flowdown

Ad hoc system ID, model update

Subsystem testing

Complete system testing

Requirements	Design and Development	Manufacture and test	Flight Operations

14.3.1 Future of Modeling - Cradle-to-Grave System Engineering Support

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Current missions

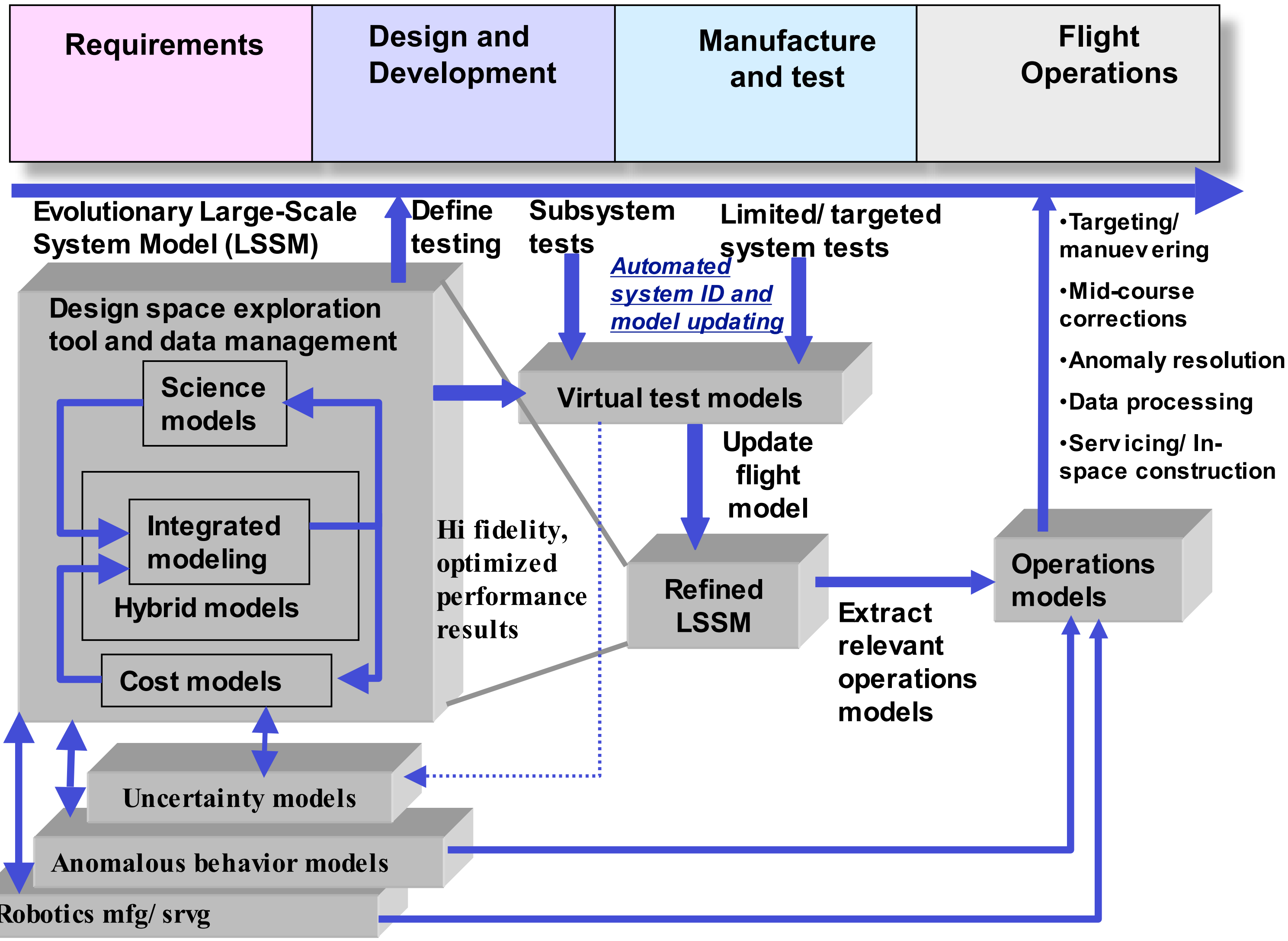
Complexity increasing, subsystem coupling, ground testing constraints (environmental, programatics)

Future missions -

Large-scale integration, cradle-to-grave, rapid prototyping, multple models, expert systems, uncertainty bounds, distributed computing, anomalous behavior models, model-driven testing.

LISA

TPF-I



Assumptions
for Capability 14.3 - Engineering Modeling

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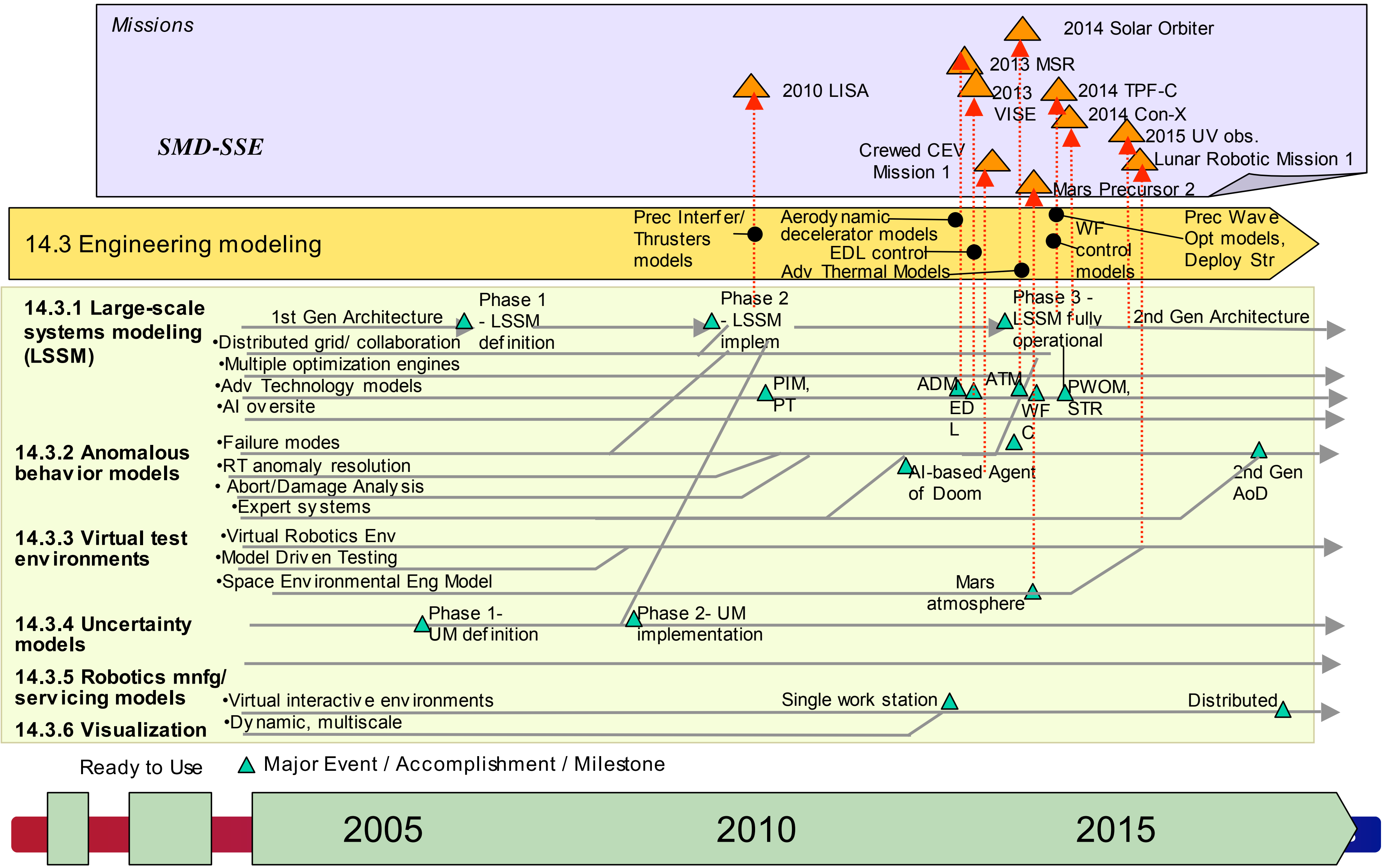
- Modeling is part of all programs at many levels and scales.
  - "State-of-the-art" is actually state-of-the-practice, ie, exceptions can be found.
- Detailed engineering technology/discipline models are discussed in other roadmaps. Detailed modeling needs align with technology needs.
- System engineering roadmap will cover cost and risk modeling whereas AMSA includes integrating these into large scale modeling architecture.
- Current COTS discipline tools will evolve to support general engineering analysis tools with a broad market, but not a NASA-driven market.
- Historical trends will continue in terms of engineering system and technology complexity increasing.
- Engineering CBS includes design-driven Operations models that are critical to engineering process, such as Anomalous Behavior and Robotics Assembly/ Servicing.
- Modeling of human-machine interaction is covered under other Operations CBS.
- Examples and terminology tailored to SMD missions, with an instrument focus, but have clear anologies for exploration and aeronautics.
- Technology identified on capability timeline charts is developed several years prior to program infusion.

Drivers for Capability 14.3 - Engineering Modeling

- *__Large scale system modeling__* driven by large, technically complex programs but useful to all missions:
  - LISA, TPF, Black Hole Imager, SAFIR, Planet Imager, Life Finder, Explorer Vision
- *__Virtual test environment__* drivers same as above with planetary exploration missions especially critical drivers.

Capability 14.3: Engineering Modeling



Capability 14.3: Engineering Modeling

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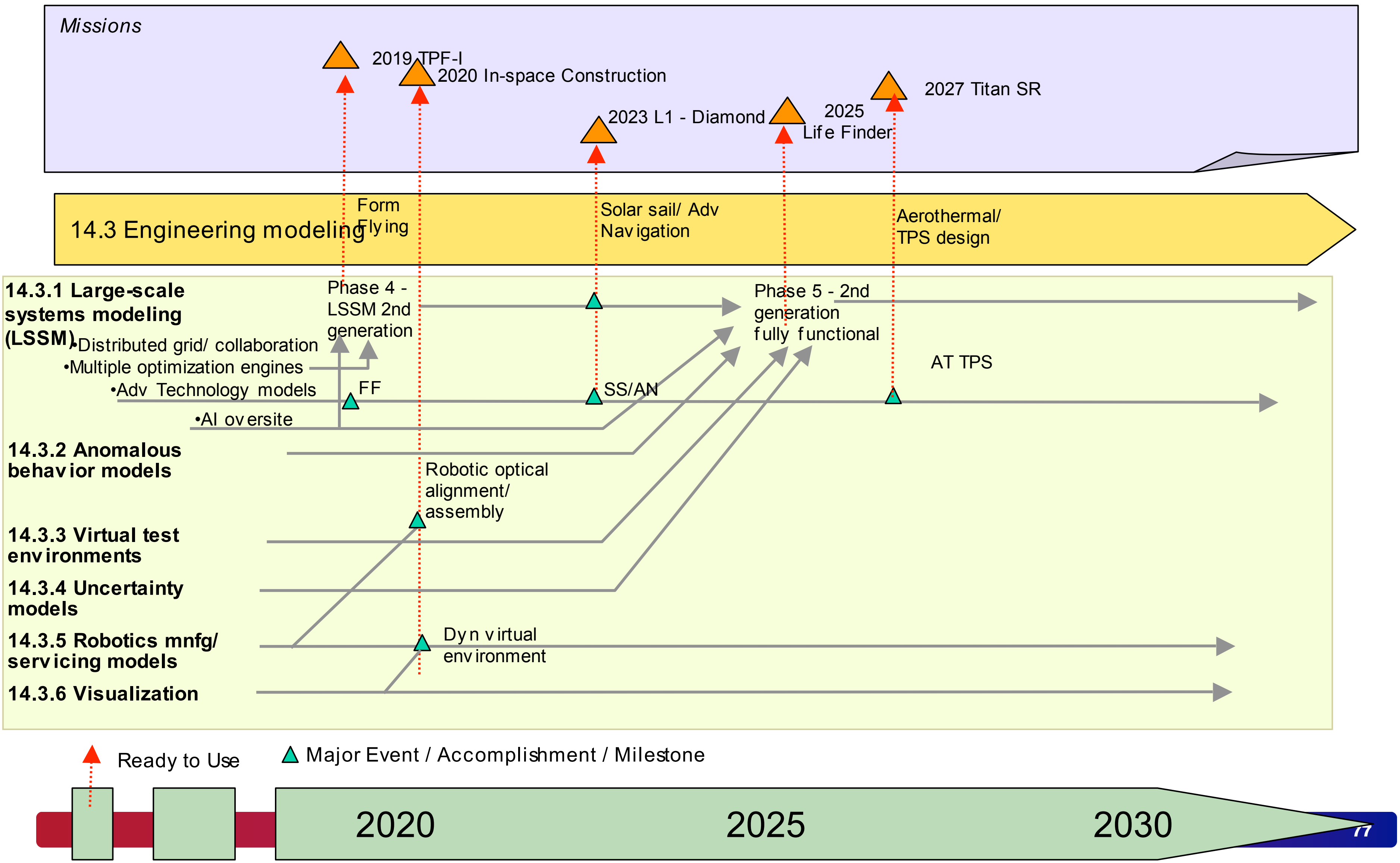

Capability 14.3 Engineering Modeling- Goals and Milestones

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Engineering	Today's Capability	2010-2015	2016-2020	2021-2035
Large-scale system modeling	Bucket-brigade Developing integrated system modeling, significant discipline modeling & optimization, approximate models	Cradle-to-grave models, rapid model deployment, imbedded data management, integrated cost models, selected advanced discipline models, MDO	Seamless model evolution through design phases, integrated risk models, design traceability, additional advanced discipline models, agent-based.	Distributed, MDO, environment for optimization, advanced data management, cost/ risk integrated, science and operations, cradle-to-grave models, rapid prototyping.
Virtual test environment	Widely varies, not baseline approach. Fit tool for manufacturing	Human exploration hazard models	Robotic assembly testing	Expansive HWIL, max modeling/ min testing, auto sys ID/ model update, order of magnitude reduction I&T.
Uncertainty models	Pprobabilistic uncertainty propagation tools. Some uncertainty characterization.	Non-probabilistic uncertainty tools. Expanded uncertainty characterization.	Tools for rigorous uncertainty bounds in the validation domain.	Tools for rigorous uncertainty bounds in the predictive domain. Input uncertainties fully characterized.
Anomalous behavior models	Typical using current models with some add-ons as mishap investigation.	Subsystem AI agent of doom. High-fidelity abort & damage analysis..	Full system AI agent of doom.	Explore full failure/ anomaly mode space during design. AI agent of doom. Real-time isolation and resolution.
Robotics mfg/ servicing (MS) models	Commercial mainly, minimal space-based modeling (servicing), Mars exploration.			Virtual toolset enabling dynamic assessment of designs for space/ planetary based MS.
Visualization technology	3D, small-scale dynamic visualization, single discipline analysis.	Multidiscipline analysis, design space exploration	Interactive design steering, design space exploration agents	Hologram, instant visualization of dynamic events at multiple scales.

Capability 14.3: Related technologies / dependencies

Capability 14.3: Priorities

Capability 14.4 Integration

Speaker: Walt Brooks, Lead

Ron Fuchs

Mark Gersh

Loren Lemmerman

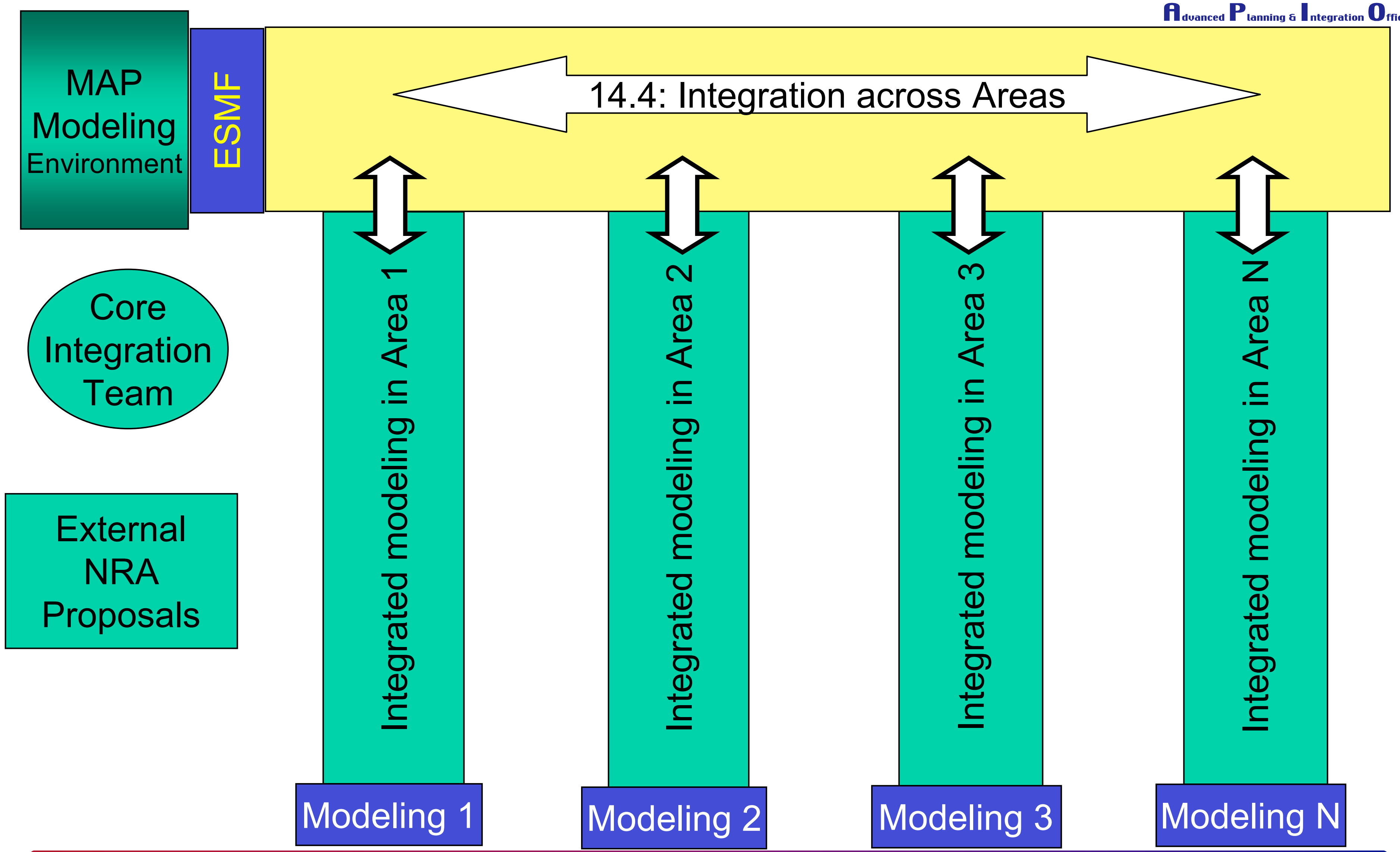
Capability 14.4 Description : Integration

Advanced Planning & Integration Office

Integration occurs recursively at all levels

- Definition: In this section we treat a level of integration of ops, eng and sci. that enables a full system simulation enabling mission optimization in engineering, ops and science
  - Assumes that progress is being made at the science, engineering and operations level, each of which has their own internal integration challenges
  - Customer: A primary customer of this is Systems engineering
  - uses this capability in a "mixed" initiative mode to stimulate engineering design trades
- Motivation: Goals of defining and supporting a focus on integration
  - -product/capability that will not emerge through normal science or engineering processes
  - decisions support in full system simulation
- Essential Eventual ability to assess risk and cost across the entire mission
- State of the art now is mixed mode
  - Deep analysis with heuristics simple models not yet characterized the holes in this process - have not characterized where we have sufficient fidelity
  - Huge high fidelity codes are "manually" integrated using Viper
  - Trusted legacy codes - keeping them vital moving to new platforms- V&V

Capability 14.4 Description : Integration



Capability 14.4: Benefits

Advanced Planning & Integration Office

- Mission design phase you gain more complete insight into feasibility creating better costs estimates and risk assessments
  - Model inputs that didn't exist before so that all major technical issues and subsystems are handled analytically and interact dynamically as opposed to using approximations and manual integration
  - Allows you to explore design optimization earlier, more realistically and to explore a larger design space
- During anamoly resolution allows rapid response with self consistent underlying assumptions
  - Integration insures rapid response and eliminates the labor intensive and sometimes insurmountable issues associated with linking complex models that have been developed in the absence of a framework
- Directly validated a fully integrated system
  - Individual validation of models ignores the linear and non linear interactions of the subsystems and systems of systems

Capability 14.4: Requirements /Assumptions

Advanced Planning & Integration Office

- Missions driving the requirements
  - Engineering
    - CEV
  - Complex operations
    - Moon Mars spirals -
  - Reference Science list
    - - “whole” earth Model
    - Large aperture telescopes-TPF,…

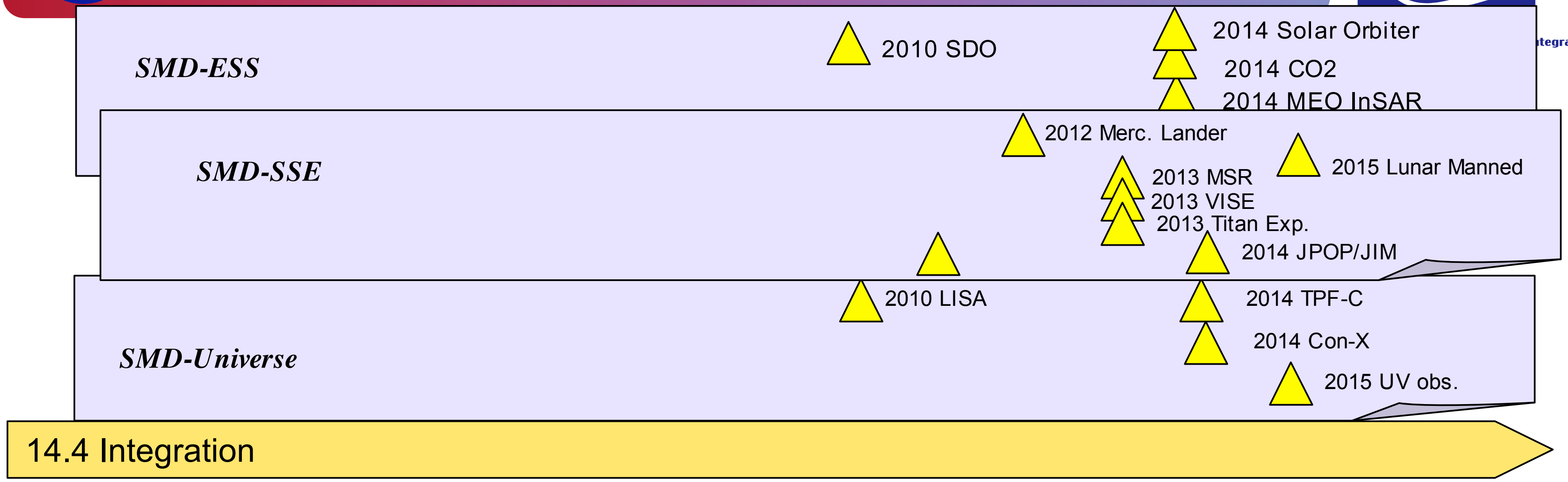
- Additional Assumptions that the team used that drove the need for the capability
  - Discipline model development wil continues and that integration at the component level
  - NASA cannot do this on its own we will partner with other agencies and industry and academia to develop the key components
    - There are some areas in which NASA is the world leader and these models must continue to be developed
  - Somebody has to be responsible
  - You don’t integrate in the absence of a problem/reqts
  - Infrastructure will exist and be supported within the agency to facilitate the process of developing this

Capability 14.4: Current State-of-the-Art

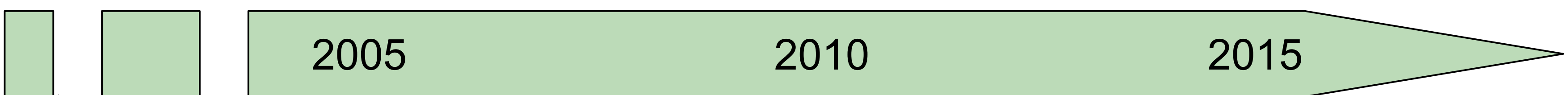
- Integration is occurring within science and engineering sub discipline disciplines-
  - a few selected examples of focused science and engineering integration
  - Specific Examples
    - IMOS
    - ESMF
    - SWMF
    - Mars EDL
- The Infrastructure tools required for science and engineering teams in compute, viz and networks are just adequate to handle this first tier of integration - full system integration will require several orders of magnitude increase in these capabilities
  - Computing -TFLOPS
  - Networks-Gbps
  - Viz-Tbyte data sets
- Archives, collaboration and integration tools are marginally integrated
- Standards and protocols are emerging within communities there is no focus on bringing these together at a system level

Capability 14.4: Need Statement / Gap analysis

Capability 14.4: Integration Roadmap



14.4.1 V&V "OSSE"
14.4.2 Standards and protocols
14.4.3 Infrastructure Model migration
14.4.4 Archive Data repository

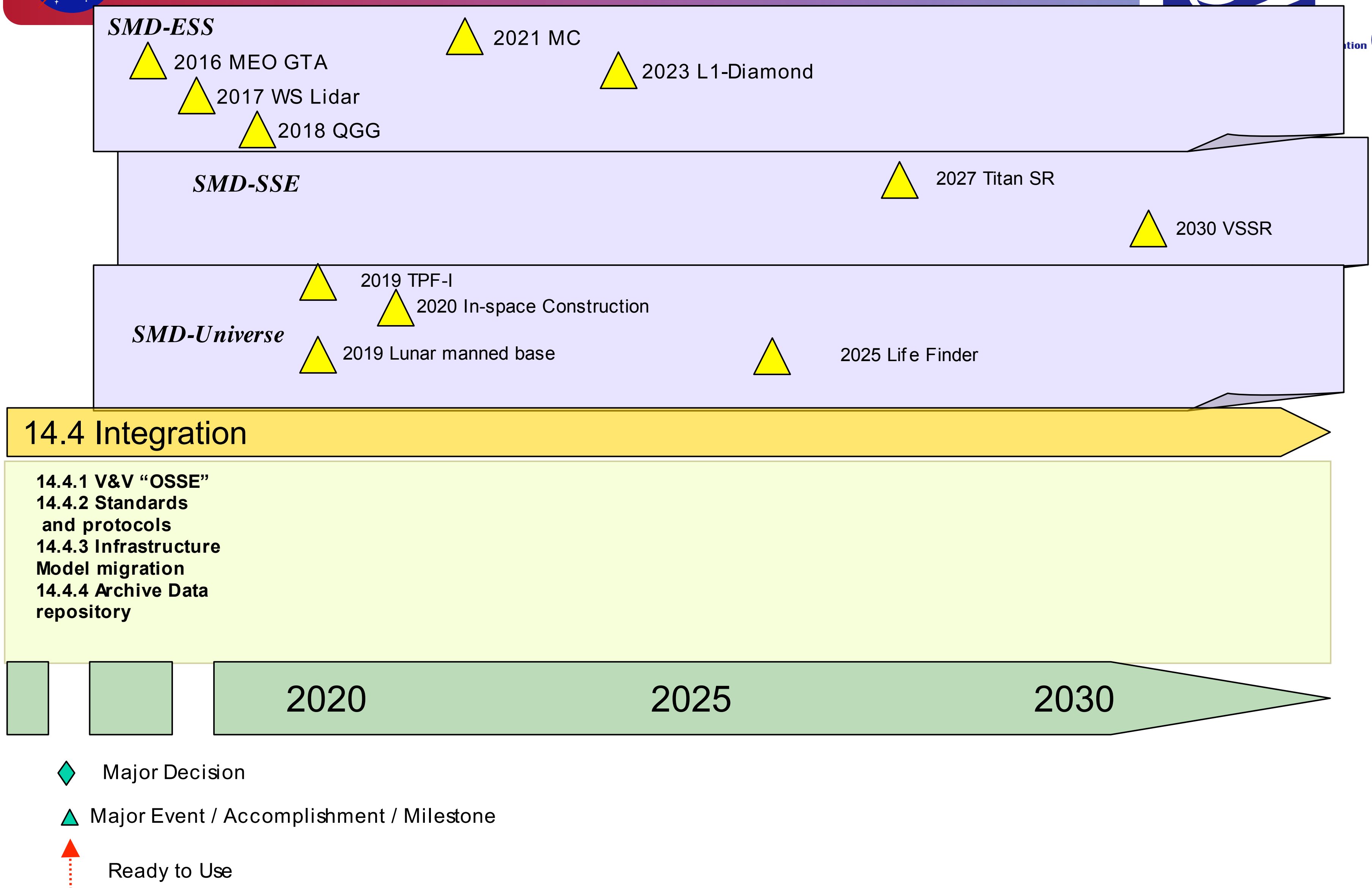


Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Capability 14.4: Integration Roadmap



Capability 14.4: Metrics

- Identify metrics (specify for technology or sub-capability)
  - Number of models integrated
  - Acceptance and use by broad system engineering community
  - Success in using initial integration to contribute to near term missions
  - Migration of the tools to next generation missions and spirals
  - Acceptance and eventual “commercialization”
  - Reduction in the number and disparity of models
    - -evolution of standard models that are V&V
- Figures of merit for the technology
  - Radical reduction in the cost of mission development and time to “market”/solution
  - Ability to have a complete view of the system and it’s sensitivities and interactions
  - Ability to query and to make broad system trades while maintaining the relevant “physics”

Capability 14.4: Maturity Level Assessment

Advanced Planning & Integration Office

- Assessment of current state-of-the-art of capability
  - Description of how key component technologies or sub-capabilities are integrated to provide the capability
  - Current Capability Readiness Level (CRL) (Note: In limited cases where CRLs do not apply, other appropriate methodologies may be used to assess capability readiness)
  - Capability development needed to achieve CRL required by a mission; level of performance and expected deliverables
  - Need date
  - (THIS CAN BE A TABLE)

Needed

Capability 14.4: Related technologies/ dependencies

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- Assessment of current state-of-the-art of key component technologies
  - Leading technology candidates
  - Current technology readiness levels (TRLs)
    - Define TRL for specific capabilities (Note: In limited cases where TRLs do not apply, other appropriate methodologies may be used to assess capability readiness)
    - What current/planned capabilities is this being applied to?
  - Key gaps between current state-of-the-art and required performance levels
  - Need date to reach required TRL f[illegible] (or text description of readiness level)

Needed

Capability 14.4: Priorities

Capability 14.5: M&S environments and infrastructure

Speaker: Mark Gersh, Lead

Dave Bader	Irene Qualters
Mark Gersh	Dan Reed
Tsengdar Lee	Ricky Rood
Steve Meacham	Quentin Stout
Charles Norton	Thomas Zang

Capability 14.5 Description: M&S environments and infrastructure

- Specifies processes, specialized infrastructure, and technology required to enable successful development and implementation of modeling and simulation constructs
  - Product model libraries and data repositories
    - Hierarchies of model components with static and dynamic behavior attributes
    - Geographically distributed but logically coherent
  - Verification, Validation & Accreditation new capabilities
    - Processes using modeling & simulation to test
    - Testing and calibrating models & simulations
  - Simulation tools and environments
    - Visualization tools
    - Data assimilation techniques
  - Modeling application tools, methods and environments
    - Modeling frameworks
    - Software engineering
    - Parallelization of codes
    - Legacy code integration
  - Model-based contracting
    - Going beyond digital text to facilitate procurement transactions between customer and supplier

Capability 14.5: Benefits

- Captures capabilities and technologies that “crosscut” and span the science, engineering, operations, and integration elements
  - Capabilities and technologies extend commercially available abilities
  - Raises visibility, focuses attention and insight
- Identifies issues that transcend individual elements
  - Every mission affected by each crosscutting theme
  - Cost- and time-to-solution considerations dictate that activities identified as cross-cutting be approached in a consistent manner
- Recommends resolution approaches that benefit the broad constituency
  - Provides vehicle for sustainable leverage from cross agency and industry collaborations

Capability 14.5: Underlying Assumptions

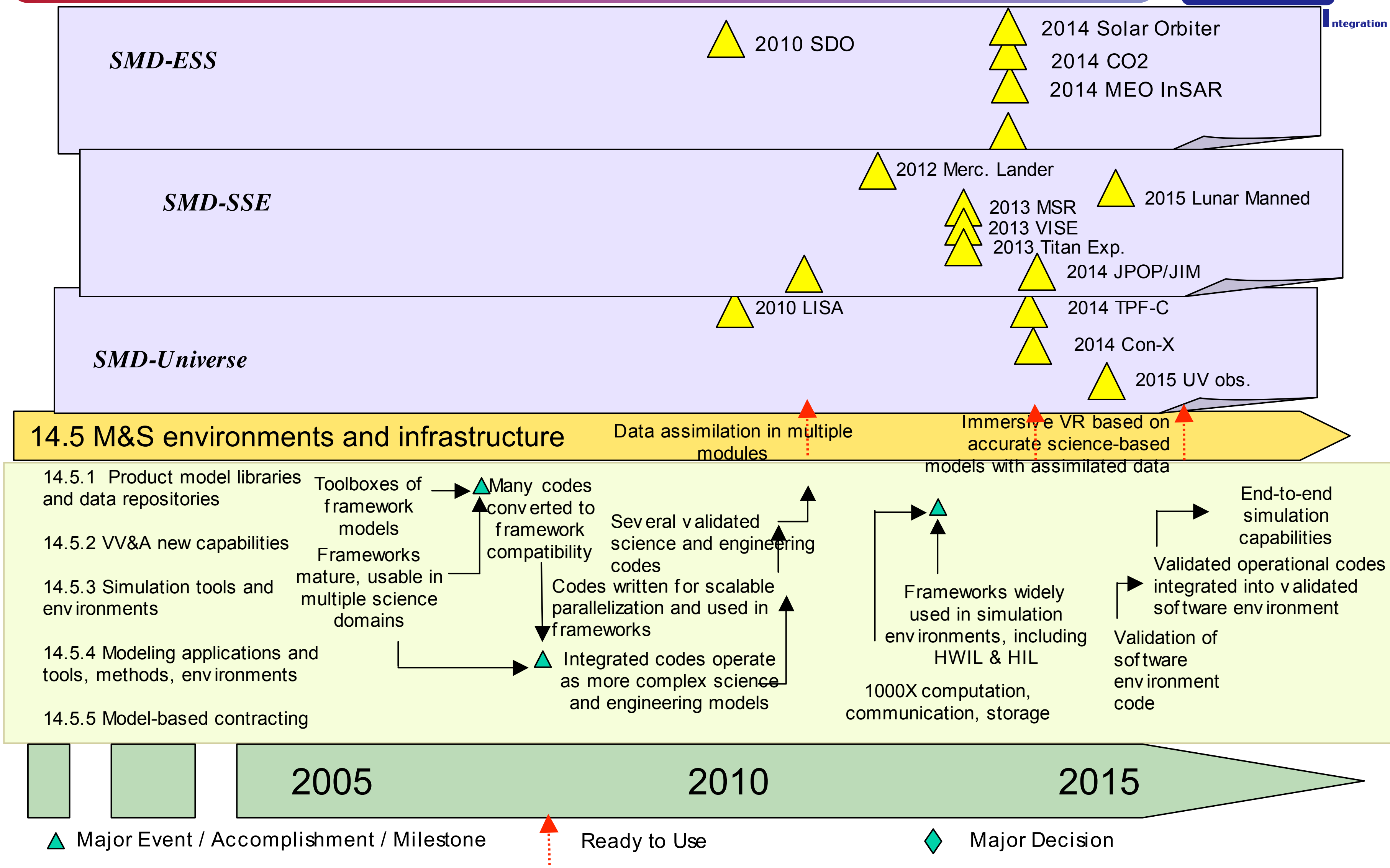
- **Recognize computational community and technology will continue to march forward and NASA cannot dictate pace**
- **Standards & Protocols:** will continue to evolve driven by standards bodies, professional societies, government intervention, and marketplace dynamics
- **Information Security and Access:** systematic vigilance, commercial and federal standards and best practices followed
- **Availability of infrastructure capabilities assumes progressive technology trends**
  - **Computing trends:** massively parallel systems, hybrid computing architectures
  - **Communication trends:** exponential growth in traffic, universal high bandwidth
  - **Data storage and management:** peta- to yotta- scale data storage, development of scalable management tools and methodology
  - **Integration technology and capability:** tools continually expand their range of applicability and scale

Capability 14.5: Current State-of-the-Art

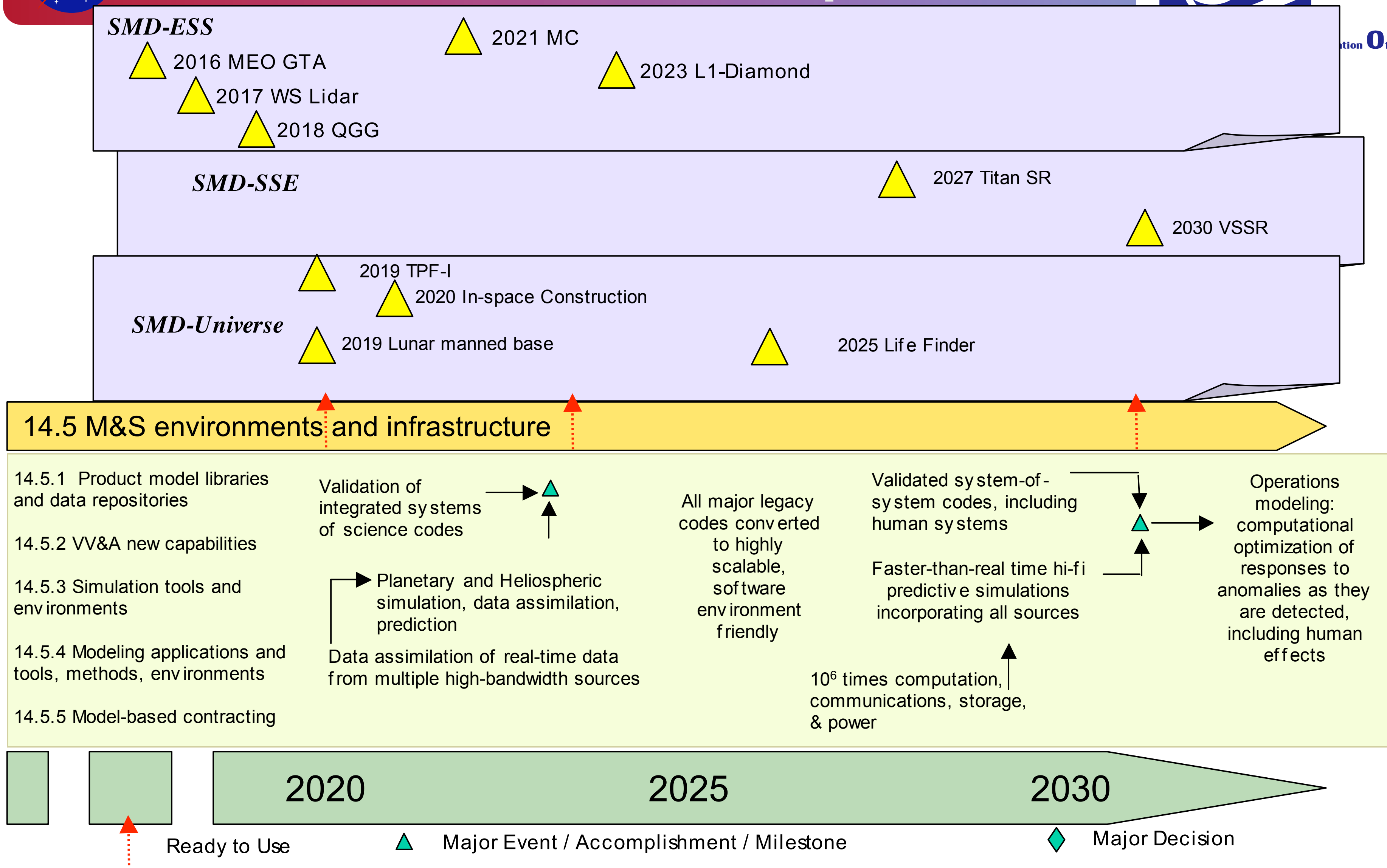
- Product model libraries and data repositories
  - Rudimentary, discipline-explicit libraries with little cross domain integration
  - Creation of some generic, tailor-able components
- Verification, Validation & Accreditation
  - Little methodology and directives for using M&S within VV&A processes
  - Limited use of M&S techniques in VV&A
- Simulation tools and environments
  - DoD High Level Architecture Run Time Environment supports military operational war fighting simulations
  - Highly limited to domain specific implementations
- Modeling applications and tools, methods, environments
  - Fragmented; difficult to integrate multidisciplinary models
  - Very few models are implemented in scalable parallel codes
  - Data management is more document driven than granulized to the object level
- Model-based contracting
  - Mostly research constructs and prototype demonstrations
  - No defined legal or organizational policies and procedures in place

Capability 14.5: Need statement / Gap Analysis

Capability 14.5: M&S environments and infrastructure Roadmap



Capability 14.5: M&S environments and infrastructure Roadmap



Capability 14.5: Maturity Level

Advanced Planning & Integration Office

Capability Element	2005	2010	2015	2020	2030
Product model libraries and data repositories	Individualized meta data models and model libraries Data repositories logically and physically distributed	Meta data Standards Model interfaces Logical Data Architecture	Full data life cycle	Full system life cycle implemented for selected model communities	Full system life cycle for all mission critical modeling communities
Verification, Validation & Accreditation new capabilities	No process No use of automation Ad hoc unit-level complexity	Uniform systematic Unit-level complexity	Uniform systematic Subsystem-level complexity	Uniform systematic System-level complexity	Uniform systematic Systems-of-systems-level of complexity
Simulation tools and environments	Virtual reality demo projects Data assimilation typically ad hoc manner.	VR quite common Data assimilation techniques expanded	High fidelity VR Mature science-based unit data assimilation for single data modes Simulations run in software frameworks	Use of hifi VR with systems-level data assimilation incorporating restricted data modes	Systematic use of hifi VR using system of system models with science-based assimilated multimodal real-time data
Modeling applications and tools, methods, environments	Demo frameworks, Parallel codes available for some components, most based on legacy codes.	Frameworks used by selected communities. Parallelization tools expand their range of usefulness.	All new codes are written for software environment with parallelization.	Major legacy codes replaced by scalable parallel ones which run in software environment.	Systematic use by all M&S developers for full lifecycle of NASA missions. Complete complex models run efficiently on highly parallel systems.
Model-based contracting					

Capability 14.5 Critical Supporting Considerations

Advanced Planning & Integration Office

- Intellectual Property/ITAR and Data Rights
  - Envision a marketplace of models interfacing within a bazaar of simulations
  - Sharing and integrating best of breed will rule the day
- Enabling Partnerships
  - NASA must leverage extensive DOD and DOE experience and efforts in “high-end” M&S policies, procedures, and infrastructure
  - NASA must exploit COTS software when available and fund needed functionality as an extension to commercial capability
  - NASA, along with other Agencies, must support university and industrial research to help achieve capabilities
- Human Resources Development
  - Success requires cultural change in Agency attitudes and available abilities catalyzed by focused training and education of civil servants and contractors
- Sustained software infrastructure maintenance
  - Incorporate funding mechanism to support full system life cycle including maintenance and evolution of M&S tools used throughout Agency
  - Create suitable career paths for people designing and maintaining software infrastructure

Capability 14.5: Priorities

AMSA Summary

Tamas Gombosi

Capability 14: AMSA Summary

Advanced Planning & Integration Office

- AMSA is about fundamentally changing the way NASA does technical business
  - To lower risk of future demanding missions
  - To enable classes of missions not doable with today's modeling technology
  - To improve decision-making throughout NASA by enabling end-to-end system simulations.
- Key capabilities are
  - Scientific modeling simulation
  - Operations modeling
  - Engineering modeling and simulation
  - Integration
  - M&S environments and infrastructure

Capability 14: Driving Missions

Advanced Planning & Integration Office

Full AMSA list		Driver for				
Mission	***Year***	***Science***	***Operations***	***Engineering***	***Integration***	***M&S Env.& infra.***
		√				
NPP	2009	√				
SDO	2010	√				
NPOESS	2010			√		
LISA	2010	√				
Global Trop Wind	2013			√		
MSR	2013			√		
VISE	2013			√		
Crewed CEV Mission 1	2013	√		√		
Solar Orbiter	2014	√				
JPOP/JIM	2014	√				
IHS	2014			√		
TPF-C	2014			√		
Con-X	2014	√		√		
Lunar Manned	2015			√		
UV Obs.	2015	√				
Global Trop Aerosols	2016	√				
Total Column Ozone	2018			√		
TPF-I	2019	√				
Lunar manned base	2019	√				
Geo InSAR Constellation	2020			√		
IN-space construction	2020	√				
L1-Diamond	2023	√				
GEO Global Precip	2025			√		
Life finder	2025			√		
Titan SR	2027	√				

Capability 14: Capability Technical Challenges for AMSA

Key technical challenges:

- Major challenges in meeting required technologies/capabilities

- Alternatives or offramps

AMSA relationship to other CRMs- Overview

Advanced Planning & Integration Office

	High Energy Power & Propulsion	In-space Transportation	Advanced telescopes & observatories	High-capacity telecom /information transfer	Robotic access to planetary surfaces	Human planetary landing systems	Human Health and support systems	Human exploration systems and mobility	Autonomous systems and robotics	Transformational Spaceport and Range	Scientific instruments/ sensors	Insitu resource utilization	Advanced modeling and simulation	Systems engineering cost/ risk analysis	Nanotechnology/ advanced concepts
High Energy Power & Propulsion															
In-space Transportation													???		
Advanced telescopes & observatories															
High-capacity telecom /information transfer															
Robotic access to planetary surfaces															
Human planetary landing systems													???		
Human Health and support systems															
Human exploration systems and mobility													???		
Autonomous systems and robotics															
Transformational Spaceport and Range															
Scientific instruments/ sensors															
Insitu resource utilization													???		
Advanced modeling and simulation															
Systems engineering cost/ risk analysis															
Nanotechnology/ advanced concepts															

Moderate Relationship

No Relationship

Critical Relationship

Relationship to other CRMs-Detail

Advanced Planning & Integration Office

Advanced Modeling, Simulation, Analysis capability	Capability Flow and Criticaltiy	Related Roadmap	Nature of Relationship
Scientific modeling and simulation engineering modeling and simulation All instrument/sensor types	→	**Scientific Instruments & Sensors**	*Enables Systems architecture studies *Provides applications for science discovery and analysis *Enables instrument design tradespaces *Allows end-to-end instrument design and performance assessment
Engineering modeling and simulation	→	**Systems engineering and cost/risk analysis**	*Provides advanced modeling techniques for all aspects of project *Provides frameworks for tying multiple models together
Operations modeling and simulation	→		Requirements determination, and expansion of the trade space
Engineering modeling and simulation	→	**Advanced telescopes and observatories**	Provides understanding of system trades and risks across implementation approach Enables system level assessment of size and stability (mechanical & thermal) properties from both passive and active approaches
Engineering modeling and simulation	→		Provides advanced mission system and subsystem level modeling, simulation and analysis tools to analyze and do design trades on future telescope and observatory architectures and systems.
Engineering modeling and simulation Operations modeling and simulation System Integration	↔		Provides advanced modeling, simulation and analysis software and hardware tools for highly integrated end to end modeling (structural, thermal, optical, control, …)
M&S Environments and Infrastructure	→		Provides infrastructure tools that enable efficiently managed data for future advanced telescopes and observatories
Engineering modeling and simulation	→	**Nanotechnology and advanced concepts**	Provides multi-scale modeling for materials, devices and systems
Engineering modeling and simulation	→	**Robotic access to planetary surfaces**	Provides EDL modeling (CFD) for entry systems
Engineering modeling and simulation	→		Prov ides EDL Control sys modeling for entry systems
Scientific Modeling and Simulation	→		Prov ides planetary atmospheres modeling for designing entry controls systems
Engineering modeling and simulation	→		Provides TPS modeling for TPS design

Relationship to other CRMs-Detail

Advanced Modeling, Simulation, Analysis capability	Capability Flow and Criticaltiy	Related Roadmap	Nature of Relationship
Engineering modeling and simulation	→ (blue)	**Space Communications**	Improved modeling and manufacturing process increases power efficiency for RF communications
Engineering modeling and simulation	→ (red)	**Autonomous Systems, Robotics, and Computing Systems**	High fidelity terrain modeling and analysis; Model-based detection for ISHM; Logistics: Modeling of failure mechanisms; ISHM: V&V methods for models;
M&S Environments and Infrastructure	→ (red)		Collaborative information analysis and sharing
Operations	→ (red)		Activity plan development and analysis; Autonomous Science Analysis, Predictive Modeling, and Optimization
Engineering modeling and simulation	→ (red)	**High Energy Power and Propulsion**	Autonomous Control (Nuc Power) Design/Model; Heat Rejection System design analysis and trades; Shield design analysis and trades.
Engineering modeling and simulation	→ (blue)	**Human Health & Support Systems**	Space Human Factors Models & simulations; Design tools & requirements; Maintain, improve risk assessment models/ Analyze proposed mission architectures; Risk analysis model for med events; Med simulation model (testbed); Biomedical models of human systems

AMSA Relationship to SRMs

Advanced Planning & Integration Office

AMSA Identified Need (orange)
SRM Identified Need (blue)

Broad Topics Captured / SRM Teams	Lunar: Human & Robotic	Mars: Human & Robotic	Solar System Exploration	Search for Earth-Like Planets	Exploration Transport System	International Space Station	Space Shuttle	Universe Exploration	Earth Science & Apps. From Space	Sun-Solar System Connection	Aeronautical Technologies	Education	Nuclear Systems
Large Deployable Lightweight Apertures				SRM			No Data Available	SRM	SRM			No Data Available	
System/Instrument Design and Performance		SRM	SRM	SRM				SRM	SRM	SRM			SRM
On-Board Processing		SRM							SRM				
Mission Planning, Impact, and Operations	SRM	AMSA	SRM	AMSA	SRM	SRM		AMSA	SRM	SRM			
Space Environment Effects	AMSA	SRM	SRM		SRM	SRM		AMSA	SRM	SRM			
Spacecraft Design and Broad Applicability		SRM			SRM	SRM				SRM	SRM		SRM
In Situ Exploration and/or Sample Return	AMSA	SRM	SRM										
Science Needs		SRM	SRM	SRM		SRM		SRM	SRM	SRM			
Engineering Analysis and Design Needs			SRM		SRM	SRM			AMSA	SRM	AMSA		SRM
Planetary Environment, Protection Habitability	AMSA	SRM	SRM		AMSA				SRM	SRM			
Data Synthesis, Analysis, and Visualization			SRM	AMSA					SRM	SRM			
Navigation and/or Formation Flying		SRM	SRM	SRM	SRM			SRM	SRM	SRM			SRM
Telecommunications (Deep Space)		SRM	SRM		SRM	SRM		AMSA		SRM			SRM
Materials Science and Durability		SRM		SRM	SRM								
Robotics, Surface Terrains, and Mobility	AMSA	SRM	SRM										
SRM Identification of AMSA Support	None	None	Partial	None	None	Some		None	Major	Major	None		Some

(blue) Areas where SRMs either mentioned modeling or the topic area need in general

(orange) Gaps, where SRMs did not mention modeling, nevertheless modeling should be applied

View of AMSA support indicates if an SRM explicitly identified how the AMSA CRMs would aid their goals

Identified topics are based only on data within SRM documents

AMSA Relationship to SRMs

Advanced Planning & Integration Office

AMSA Identified Need (orange) — shown as **AMSA**
SRM Identified Need (blue) — shown as **SRM**

Broad Topics Captured / SRM Teams	Lunar: Human & Robotic	Mars: Human & Robotic	Solar System Exploration	Search for Earth-Like Planets	Exploration Transport System	International Space Station	Space Shuttle	Universe Exploration	Earth Science & Apps. From Space	Sun-Solar System Connection	Aeronautical Technologies	Education	Nuclear Systems
Aero-assist, Aero-capture		SRM			SRM		No Data Available					No Data Available	
Human in-the-loop (EDL training, field experiments, virtual testbeds, flight tech.)	AMSA	SRM			SRM	SRM					AMSA		
Planetary Atmospheres and/or Interior			SRM	AMSA					SRM	SRM	AMSA		
In Space Propulsion and Transportation		SRM	SRM		SRM	SRM							SRM
Optical Systems			SRM	SRM				SRM					
Spacecraft /Aircraft System Validation	AMSA	AMSA		SRM					AMSA		SRM		
Automated Rendezvous and Docking	AMSA	SRM			SRM	SRM							
Safety										SRM	SRM		SRM
SRM Identification of AMSA Support	**None**	**None**	**Partial**	**None**	**None**	**Some**		**None**	**Major**	**Major**	**None**		**Some**

- (blue) Areas where SRMs either mentioned modeling or the topic area need in general
- (orange) Gaps, where SRMs did not mention modeling, nevertheless modeling should be applied

View of AMSA support indicates if an SRM explicitly identified how the AMSA CRMs would aid their goals

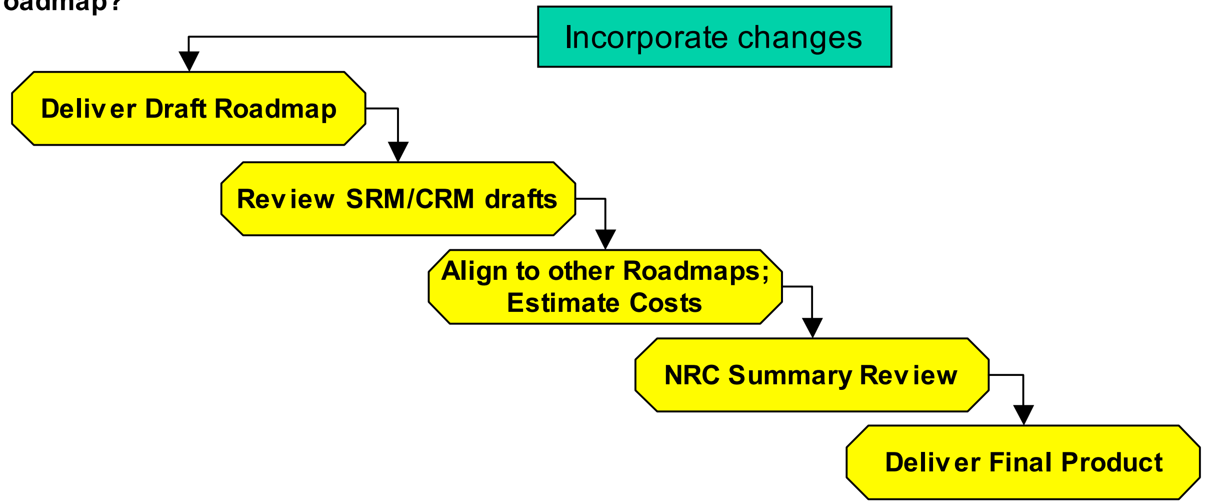
Identified topics are based only on data within SRM documents

Summary/ Forward Work

Advanced Planning & Integration Office

- Make changes to roadmaps based on verbal feedback from NRC review
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for AMSA capability
- Make changes to AMSA roadmaps to ensure consistency with Strategic Roadmaps requirements
- Develop rough order of magnitude cost estimates for the AMSA Capability Roadmap
- Prepare for 2nd NRC Review which will focus on 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Remaining



Acronyms

Advanced Planning & Integration Office

National Research Council Dialogue to Assess Progress on

NASA's Systems Engineering Cost/Risk Analysis Capability Roadmap Development

General Background and Introduction

Victoria Regenie

April 6, 2005

Agenda

Advanced Planning & Integration Office

- General Background and Introduction of Capability Roadmaps for Systems Engineering Cost/Risk Analysis
  - Agency Objectives
  - Strategic Planning Transformation
  - Review Capability Roadmaps and Schedule
  - Review Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

Advanced Planning & Integration Office

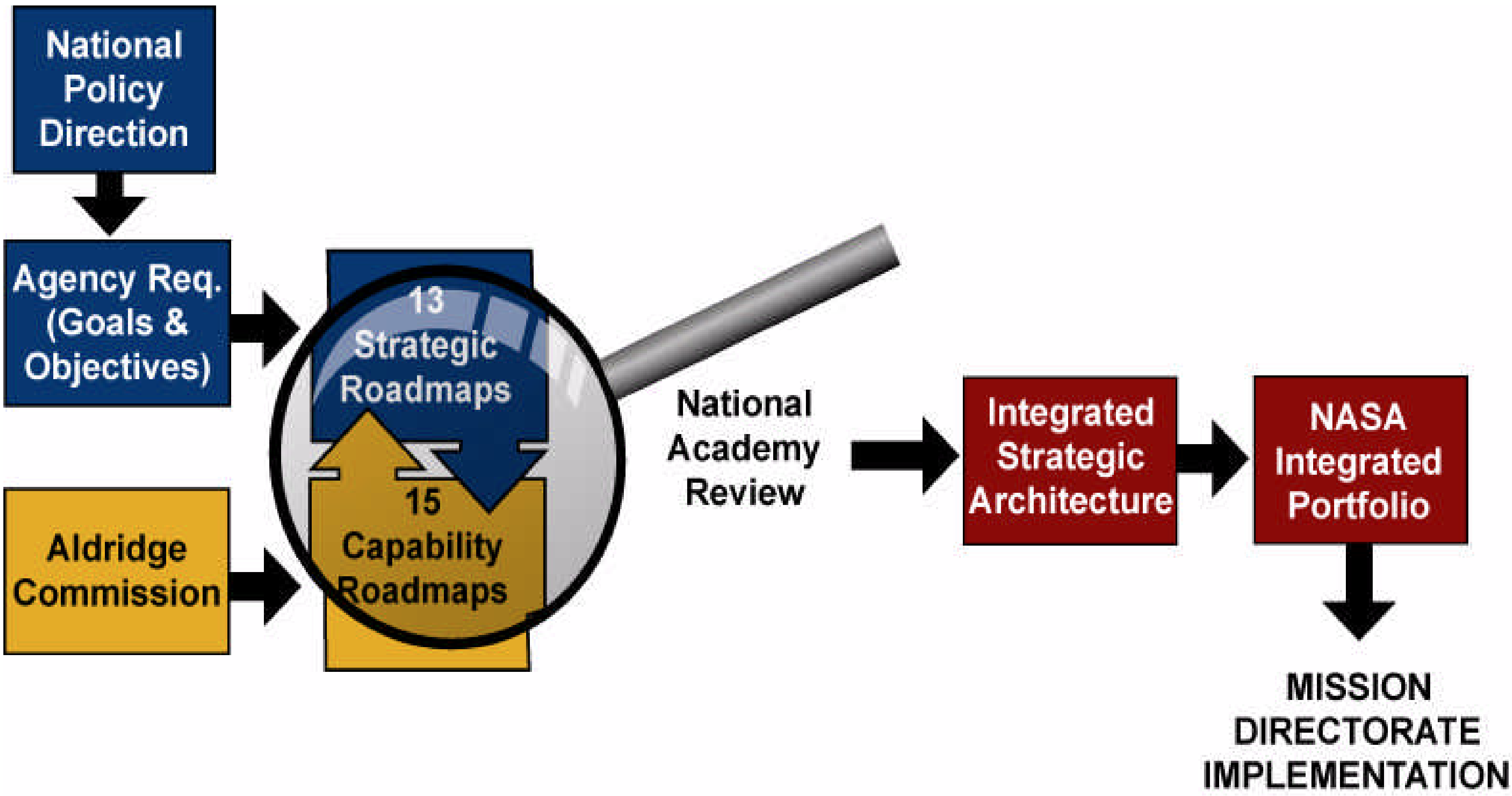
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	1. Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	2. Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	1. Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	6. Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	2. Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	7. Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	3. Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	8. Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	4. Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	9. Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	5. Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	10. Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

Agency Goals and Objectives

Advanced Planning & Integration Office

National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	3. Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration.	4. Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	5. Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	11. Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	14. Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems. (SRM 9)	17. Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)
	12. Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	15. Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)	18. Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)
	13. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	16. Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	

Strategic Planning Transformation - continued



Capability Roadmaps

Advanced Planning & Integration Office

- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

Advanced Planning & Integration Office

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June timeframe will include the integrated strategic and capability roadmap product

Capability Roadmaps - continued

Capability	NASA chair	External chair
High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators also with each team

◤ = DoD Participation

Capability Roadmaps - continued

Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

Advanced Planning & Integration Office

MILESTONE	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Begin Roadmap Teams Formation	▲										
Public Workshop in Washington	▲										
Working First Drafts of Roadmaps	▲	▬	▬	▬	▲						
Strategic Planning Council Preview				▲							
Engineering Academy (NRC) Dialogues					▲	▲					
Identify Potential Gaps for POP Input						▲	▬	▲			
Strategic Roadmap Drafts Complete						▲					
Align with Strategic Roadmaps						▲	▬	▲			
Phase 2 - Engineering Academy (NRC) Summary Review								▲	▬	▲	
Brief Strategic Planning Council									▲		
Finalize Roadmaps										▲	▲

Purpose of NRC Review

- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:
- Four NRC Questions:
  - Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?
  - Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)
  - Are proper metrics for measuring advancement of technical maturity included?
  - \- Do the Capability Roadmaps have connection points to each other when appropriate?

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Nanotechnology Presentation Agenda

Advanced Planning & Integration Office

7:30	Continental Breakfast	
8:00	Welcome and Review Process, Panel Chair & NRC Staff	
8:15	Introduction by APIO to NASA Capability Roadmapping	Julie Crooke
8:50	Nanotechnology Presentation Agenda	Murray Hirschbein, NASA
9:00	Background: Nanotechnology at NASA	Minoo Dastoor, NASA
9:45 - 10:15	– *Break* –	
10:15	Overview and Summaries of Roadmapping Activity	Minoo Dastoor, NASA
10:45	Nano-Structured Materials	Ilhan Aksay, Princeton (Mike Meador and Len Yowell, NASA)
11:15	Sensors and Devices	David Janes, Purdue (Harry Partridge, NASA)
11:45 - 12:45	– *Lunch* –	
12:45	Intelligent/Integrated Systems	Chih-Minh Ho, UCLA (Benny Toomarian, JPL)
1:15	Summary and Next Steps	Minoo Dastoor
1:30	Closure and Crosswalk (with other Roadmaps)	Murray Hirschbein
2:00	Open Discussion	
3:30	– *Break*/NRC Panel Closed Session –	
4:15	NRC Panel Discussion with NASA	
5:00	Adjourn	

Background: Nanotechnology at NASA

Advanced Planning & Integration Office

Background: Nanotechnology at NASA

Presentation to the National Research Council

March 8, 2005
Washington, D.C.

Co-Chairs:

M. Dastoor (NASA HQ) M. Hirschbein (NASA HQ) D. Lagoudas (Texas A&M)

Nanotechnology

- **Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 *nm* range, in order to understand, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure**

- **NNI definition encourages new contributions that were not possible before.**
  - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain
  - the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions
  - integration along length scales, and fields of application

Capability Roadmap: Nanotechnology

Interdisciplinary "horizontal" Knowledge Creation

with "vertical" transition from basic concepts to Grand Challenges and technology integration - Converging Technologies

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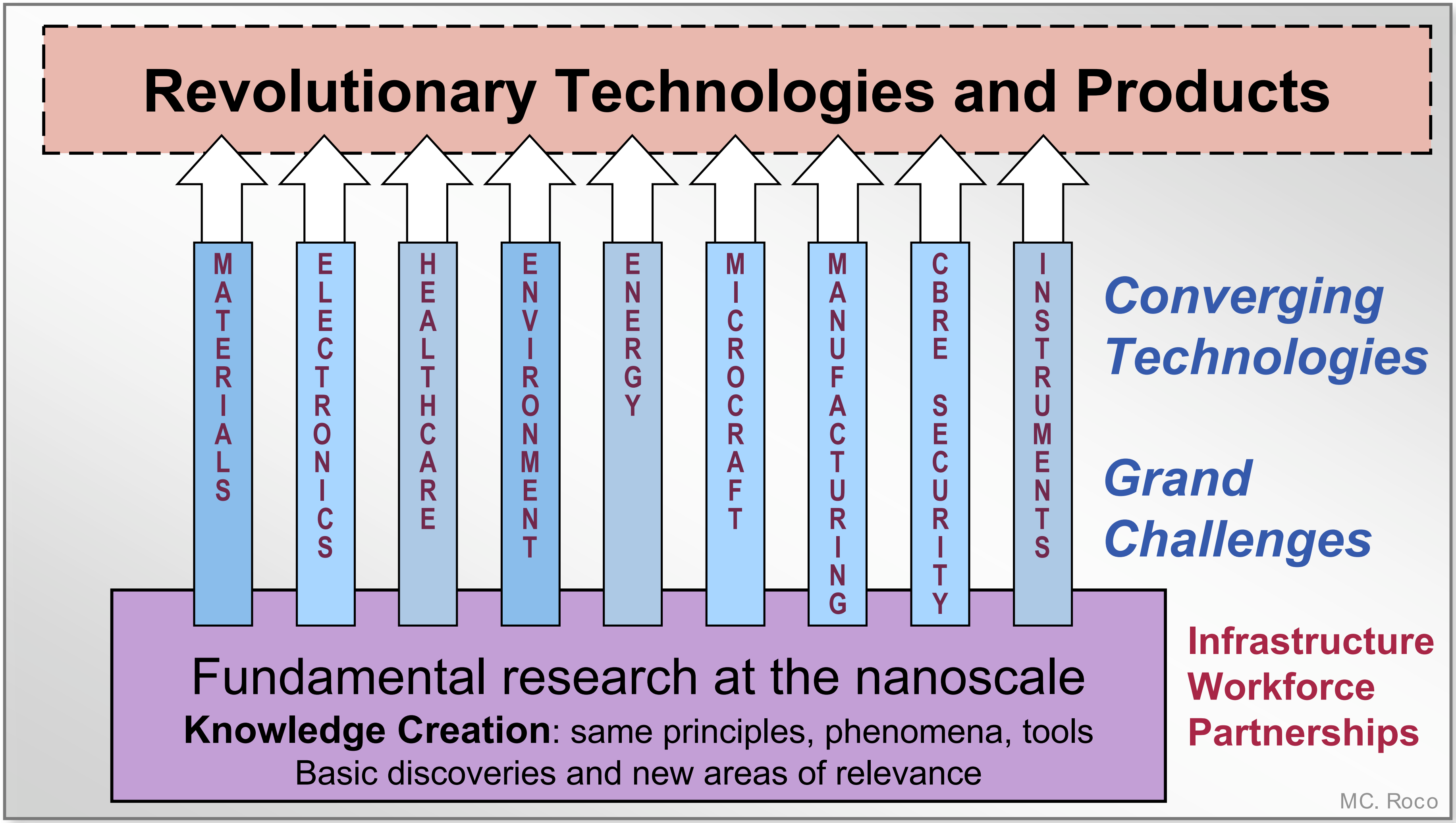
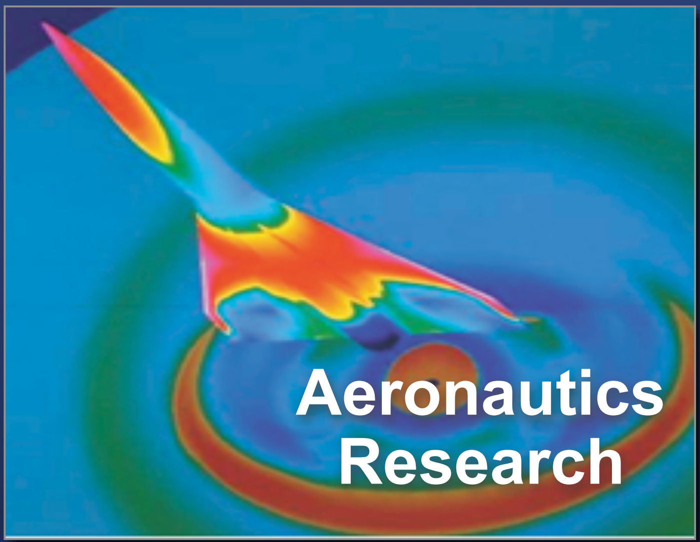
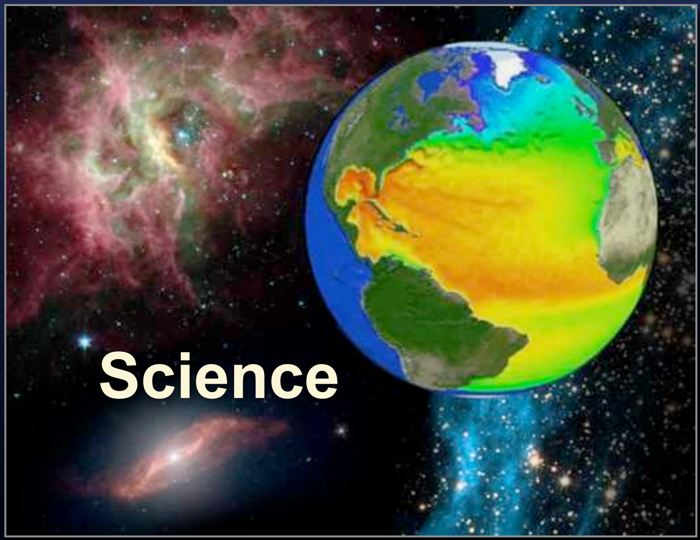


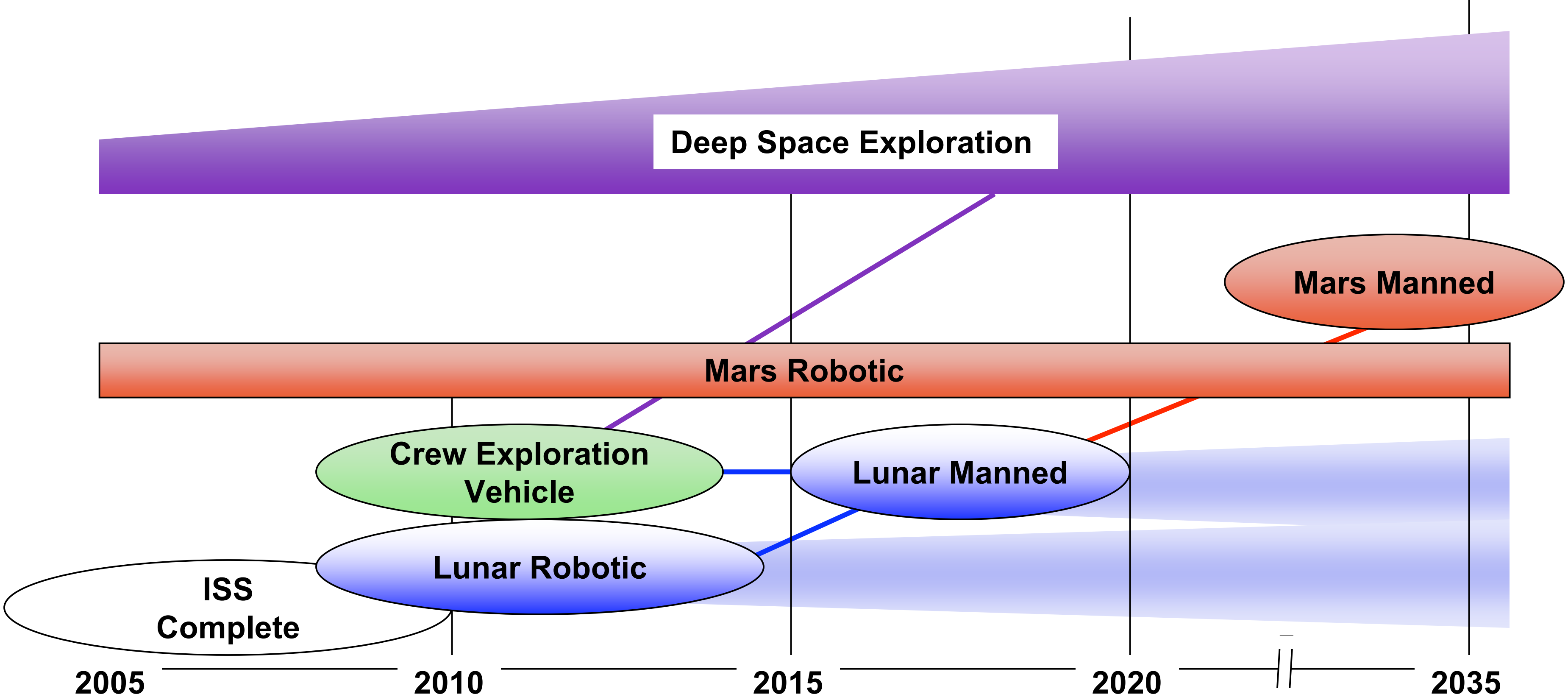
NASA's Strategic Enterprises





The Space Exploration Plan

- Enable human and robotic exploration



Capability Roadmap: Nanotechnology

Astronaut Health Management

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Personal Biomedical Monitoring

- Identification of molecular indicators for onset of conditions
- High sensitivity assays
- Short prep-time assays, no prep-time assays and in vivo monitoring
- Multiple simultaneous assays

Major Medical Operations

- Contrast agents to target specific sites for surgery
- Bio-mimetic or engineered compounds to help wound healing
- Miniaturized electron microscopes for biopsies

Personal Countermeasures

- Timed drug release
- Targeted drug therapy
- Triggered drug release
- Indicators for drugs effectiveness

Life Support

- High surface area materials for CO_2 removal
- Inorganic coatings that catalyze the revitalization of air and water
- Sensors to monitor harmful vapor and gases

Basic Biomedical Research

- The role that forces plays on cell mechanisms (gravitational forces)
- Molecular machines (ATPase, Kinesin, Microtubules, Polymerase, etc.)
- In vivo monitoring of ultra-low concentration proteins and biomolecules

Toxicology & Ethics

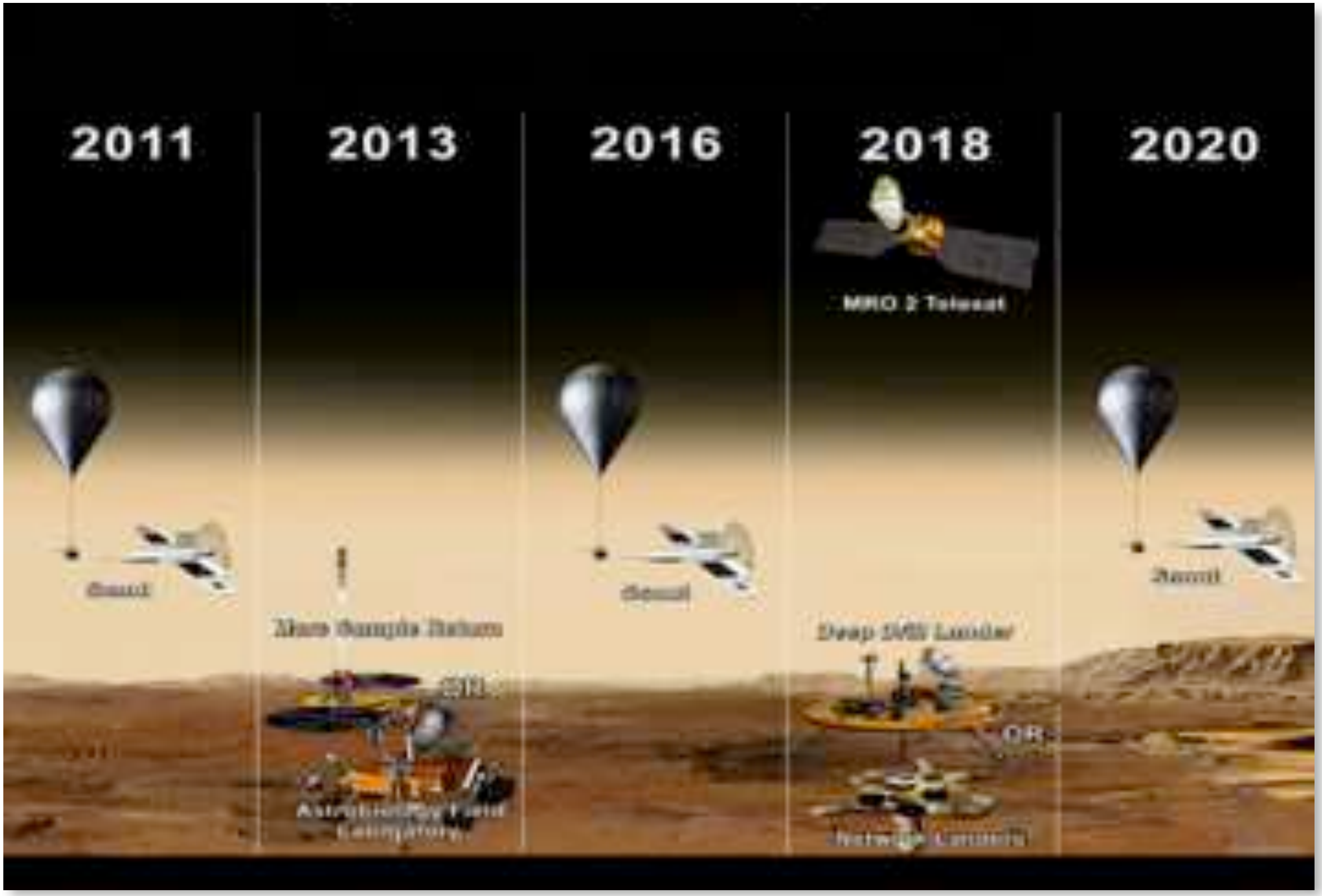
- Biodistribution of nanoparticles
- Toxicology of nanoparticles
- Ethical use of information from nanotech devices

Systems Integration

- Develop ‘common toolkit’ for bio-nano chemistry and assembly processes

Capability Roadmap: Nanotechnology

Mars Exploration Pathway - Next Decade



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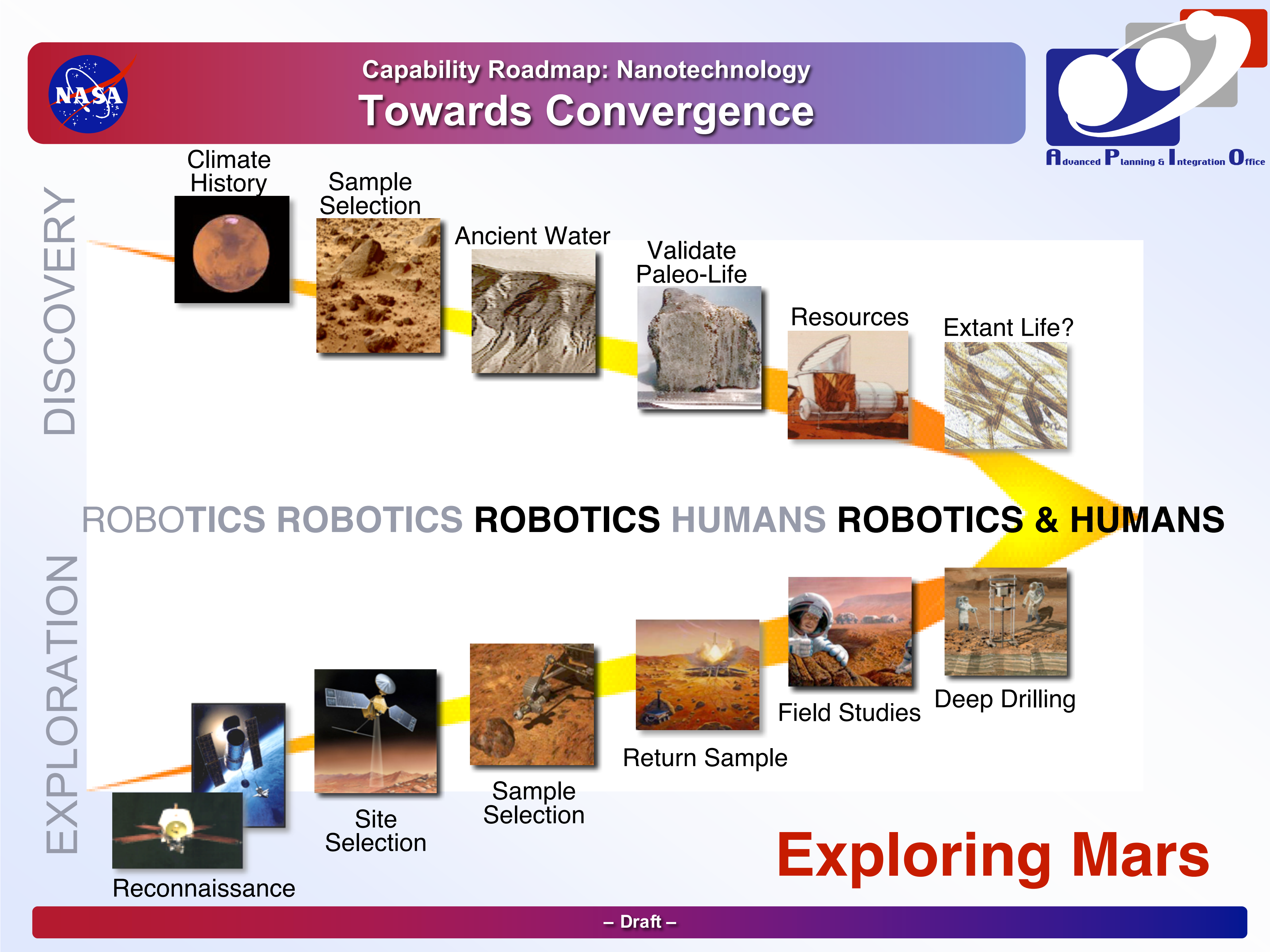
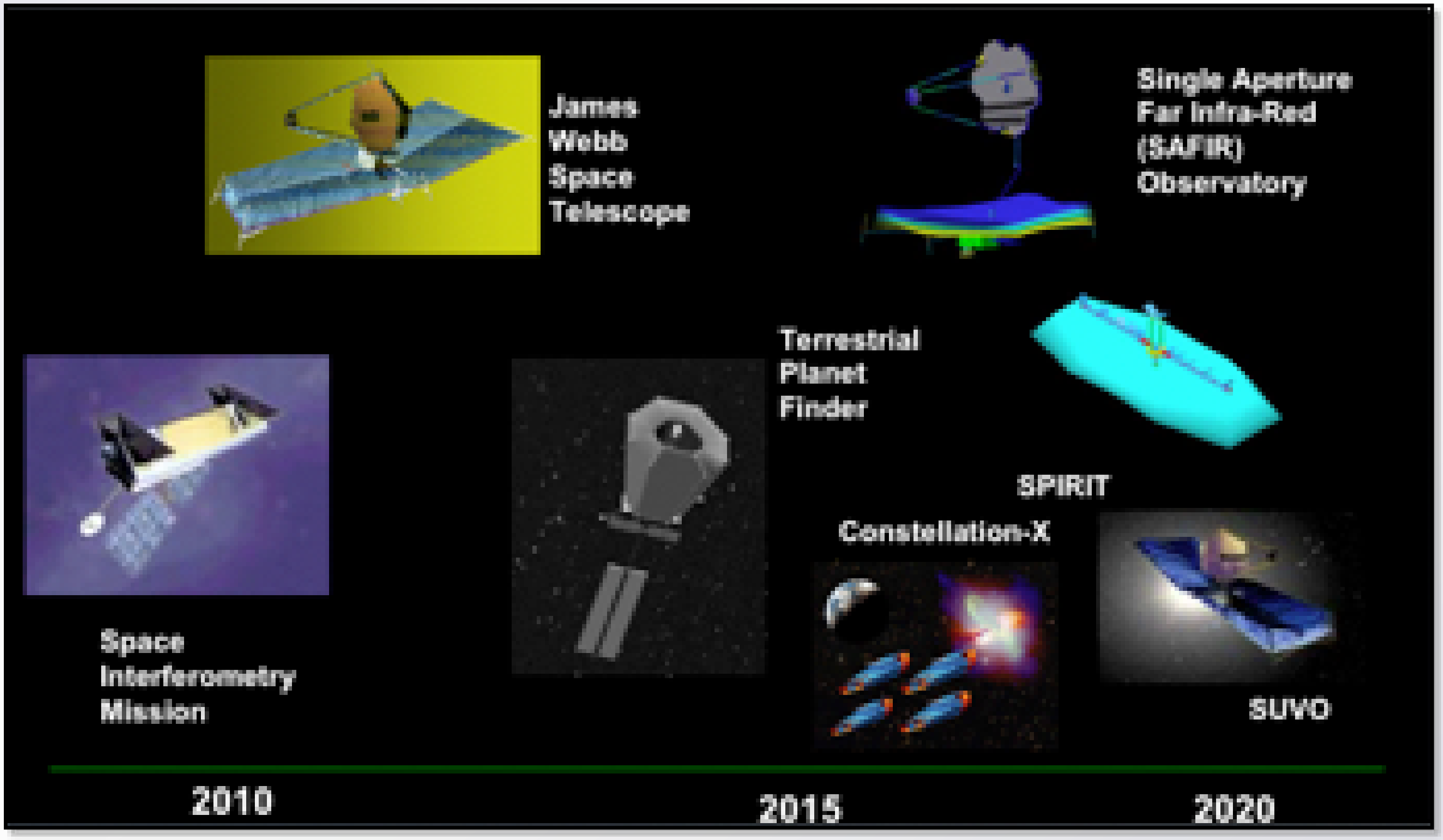

Capability Roadmap: Nanotechnology
Towards Convergence
Advanced Planning & Integration Office
DISCOVERY
Climate History
Sample Selection
Ancient Water
Validate Paleo-Life
Resources
Extant Life?
ROBOTICS ROBOTICS ROBOTICS HUMANS ROBOTICS & HUMANS
EXPLORATION
Reconnaissance
Site Selection
Sample Selection
Return Sample
Field Studies
Deep Drilling
Exploring Mars
– Draft –

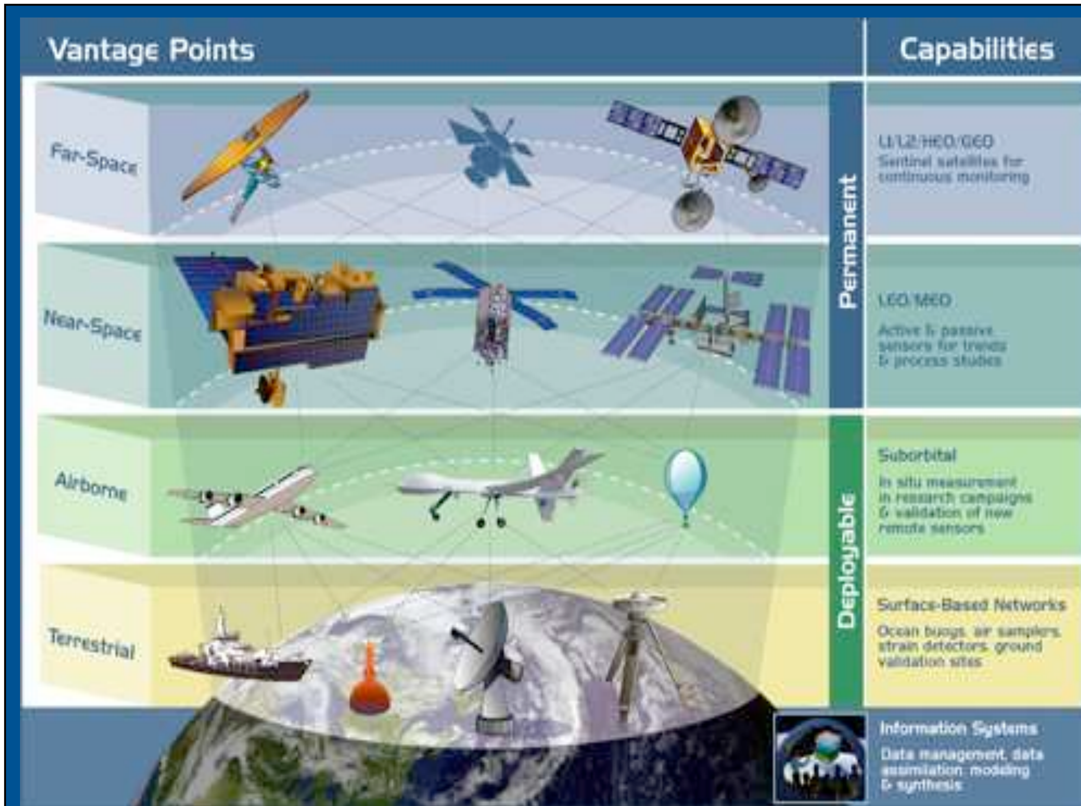
Capability Roadmap: Nanotechnology

Next Generation of Observatories



Capability Roadmap: Nanotechnology

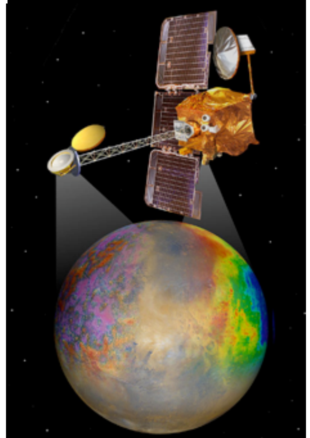
Observing Sensor Webs: *A System of Systems*

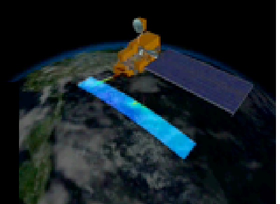


Space

Airborne/ Suborbital

Surface/ Subsurface



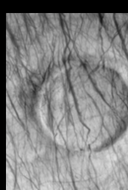


Dynamic Space and Earth Science Events

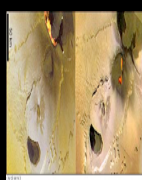
The Bigger Picture…

CME

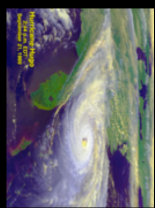
Gamma Ray Burst



Mars Dust Devils



Io Lava flow



Hurricane

Volcanic Ash Plume

Aeronautics Challenges

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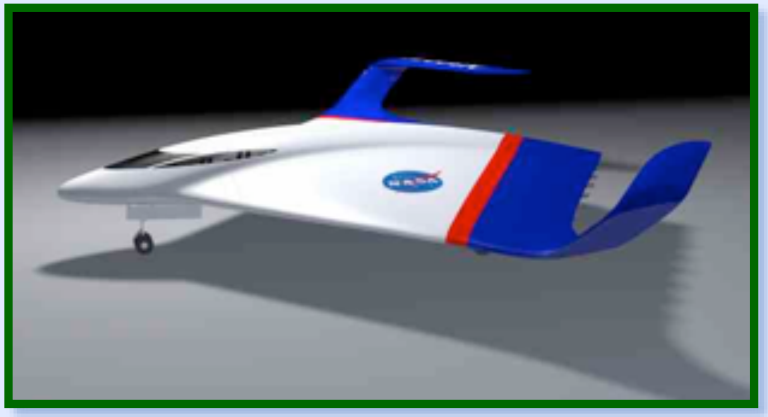
Hydrogen fuel, electric propulsion – zero environmental impact



Clean and Quiet Aircraft

- Light Weight
- High Strength
- High Reliability
- High Efficiency

High Altitude and Long Endurance (HALE) for….

Science and….

"Perpetual Flight"

Exploration ….

About the Earth and Other Planets

Overarching Needs

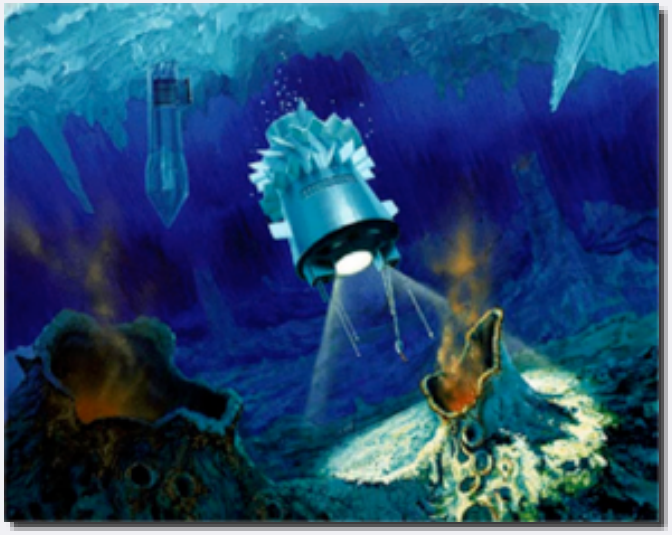
- Performance in Extreme Environments (Radiation, Temperature, Zero Gravity, Vacuum)
- Light Weight
- Frugal Power Availability (for Space Systems)
- High Degree of Autonomy and Reliability
- Human “Agents” and “Amplifiers”

Impact of Nanotechnology on NASA Missions

- New and Powerful computing technologies
  - Onboard computing systems for future autonomous intelligent vehicles; powerful, compact, low power consumption, radiation hard
  - High performance computing (Tera- and Peta-flops)
    - processing satellite data
    - integrated space vehicle design tools
    - climate modeling

- Smart, compact devices and sensors
  - Ultimate sensitivity to analytes
  - Discrimination against varying and unknown backgrounds
  - Ultrasmall probes for harsh environments
  - Advanced miniaturization of all systems

- Microspacecraft/Micro-Nanorovers
  - "Thinking" Spacecraft with nanoelectronics/nanosensors
  - Size reduction through multifunctional, smart nanomaterials



High Impact Application Areas for Nanotechnology: Exploration Missions

- **Advanced Materials**
  - High strength-to-weight composites for vehicle primary structures and habitats
  - Hydrogen resistant nanostructured materials for cryotanks
  - High thermal conductivity materials for heat sinks, heat pipes, and radiators
  - High temperature materials for propulsion systems and thermal protection systems
  - High electrical conductivity materials for wiring
  - Self-healing materials for repairing impact damage and wire insulation
  - Space-durable materials resistant to ultraviolet and particle radiation
  - Self-assembling materials for in-space fabrication
- **Power**
  - High energy density batteries and fuel cells
  - High efficiency photovoltaic cells
- **Sensing**
  - Bio-chemical sensors for monitoring environmental contaminants in crew habitats
  - Bio-chemical sensors for detecting the signatures of life on other planets
  - Chemical systems for identifying, processing, and utilizing planetary resources
- **Integral Health Management**
  - Systems that incorporate integral sensors and processors for fault detection and diagnosis
- **High Performance Computing**
  - Fault-tolerant reconfigurable processors, micro-controllers, and storage devices
- **Extreme Environment Electronics**
  - Microelectronic devices that can operate reliably in extreme temperature and radiation environments

Capability Roadmap: Nanotechnology
High Impact Application Areas for Nanotechnology: Science Missions

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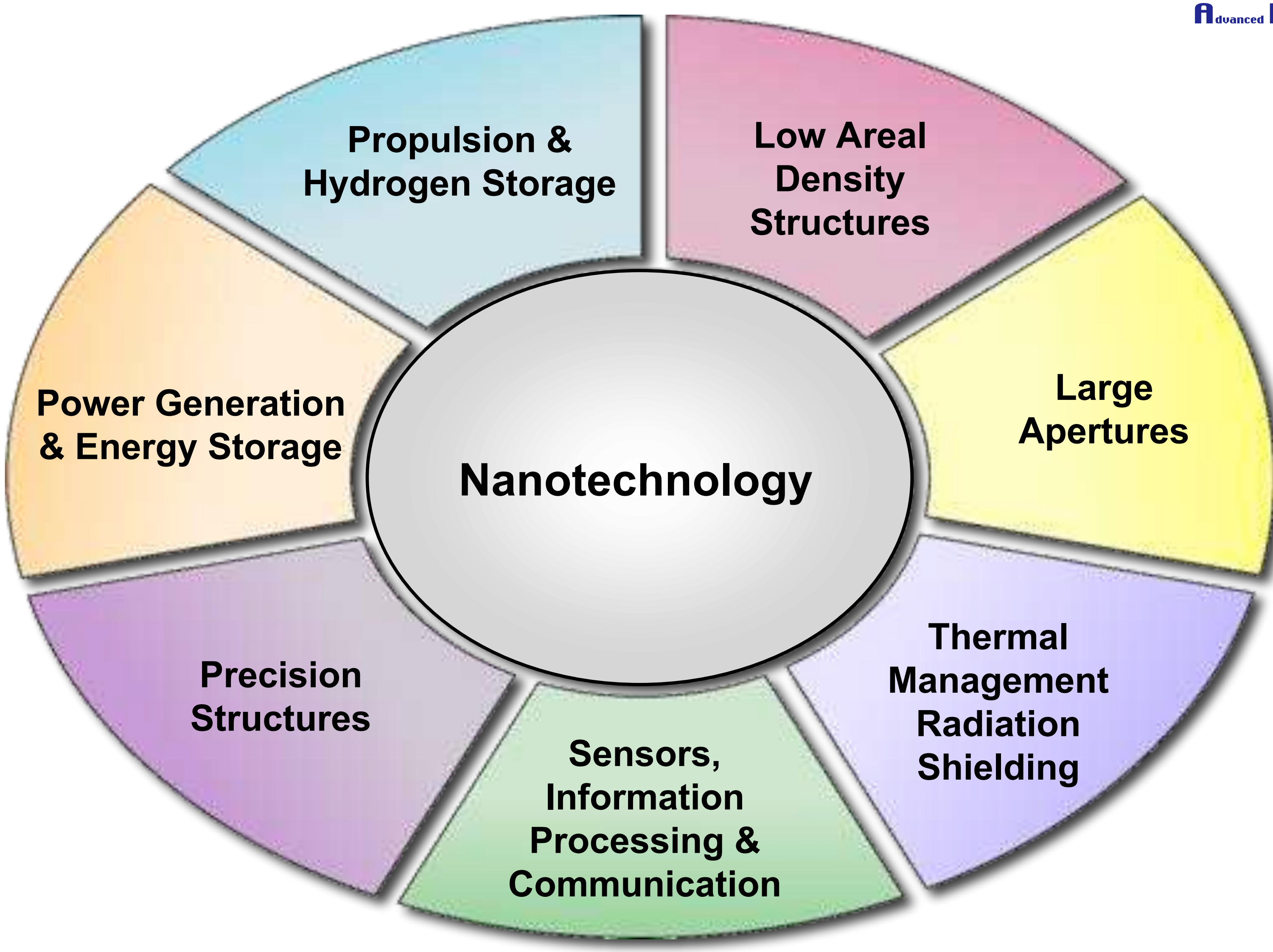

Capability Roadmap: Nanotechnology

Focus of NASA Investment

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- **Nanostructured Materials**
  - High strength/mass, smart materials for aerospace vehicles and large space structures
  - Materials with programmable optical/thermal/mechanical/other properties
  - Materials for high-efficiency energy conversion and for low temperature coolers
  - Materials with embedded sensing/compensating systems for reliability and safety
- **Nano Electronics and Computing**
  - Devices for ultra high-capability, low-power computing & communication systems
  - Space qualified data storage
  - Novel IT architecture for fault and radiation tolerance
  - Bio-inspired adaptable, self-healing systems for extended missions
- **Sensors and Microspacecraft Components**
  - Low-power, integrable nano devices for miniature space systems
  - Quantum devices and systems for ultrasensitive detection, analysis and communication
  - NEMS flight system @ 1μW
  - Bio-geo-chem lab-on-a-chip for in situ science and life detection
- **University Research Engineering and Technology Institutes**
  - Bio-nano-information technology fusion (UCLA)
  - Bio-nanotechnology materials and structures (Princeton)
  - Bio-nanotechnology materials and structures (Texas A&M)
  - Nanoelectronics computing (Purdue)

URETIs

Bio-Inspired Design and Processing of Multi-Functional Nano-Composites (BIMat)

- Design and modeling of hierarchically structured materials capable of bio-sensing catalysis and self-healing

- **Princeton**
- UCSB
- Northwestern
- U of NC
- Nat'l Inst. Aerospace

Institute for Nanoelectronics and Computing (INAC)

- Develop fundamental knowledge and enabling technologies in: ultradense memory, ultraperformance devices, integrated sensors, and adaptive systems

- **Purdue**
- Yale
- Northwestern
- U of Fl
- Cornell
- UCSD
- Texas A&M

Institute for Intelligent Bio-Nano Materials and Structures for Aerospace Vehicles (TiiMS)

- Basic and applied research in: the integration of sensing, computing, actuation and communication in smart materials

- **Texas A&M**
- Rice
- Texas Southern
- Prairie View A&M
- U of T-A
- U of Houston

Center for Cell Mimetic Space Exploration (CMISE)

- Bio-informatics for the development of new, scalable nano-technologies in sensors, actuators and energy sources

- **UCLA**
- CIT
- Ariz. St
- UCI

Capability Roadmap: Nanotechnology

Electron Sources - Application Regimes

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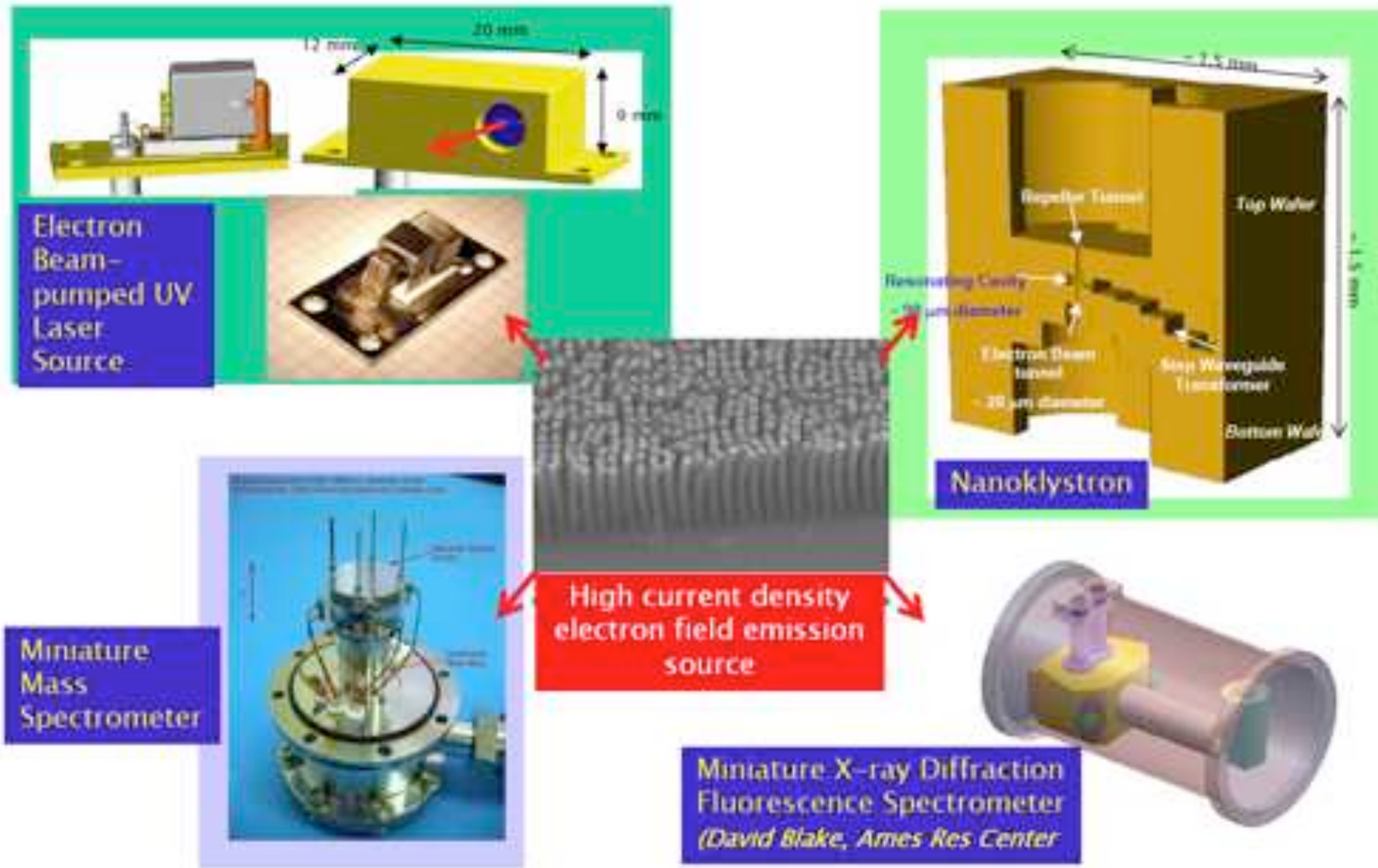

Future Research Directions

NOVEL PHENOMENA

Present Phase

- Production of Nanomaterials
- Characterization at Atomic/Bulk Scale
- Nanoscale Modeling and Simulation

Next Phase

- Integration of “Nanoworld” with the “Macroworld”
- Integration of Wet World with Dry World
- Emergence of Intelligence from Complexity
- Multi-scale Modeling and Simulation Hierarchy

NOVEL PHYSICS (NANOSCALE)

Barriers and Challenges for Nanotechnology

- **Science at the nanoscale**
  - The Physics of the behavior of molecules/atoms at the mesoscale is poorly understood. The full potential of nanotechnology will be realized when such "new" laws are established.
- **Production of nanomaterials**
  - Quantity, quality, control of properties & production in specified forms
- **Characterization at both atomic and bulk scale**
  - Fundamental mechanical, electrical and optical properties
- **Modeling & Simulation**
  - Prediction of physical/chemical properties and behavior from nanoscale to macroscale as well as models for material production

Backup

Capability Roadmap: Nanotechnology

Europa Lander: Radiation Dose

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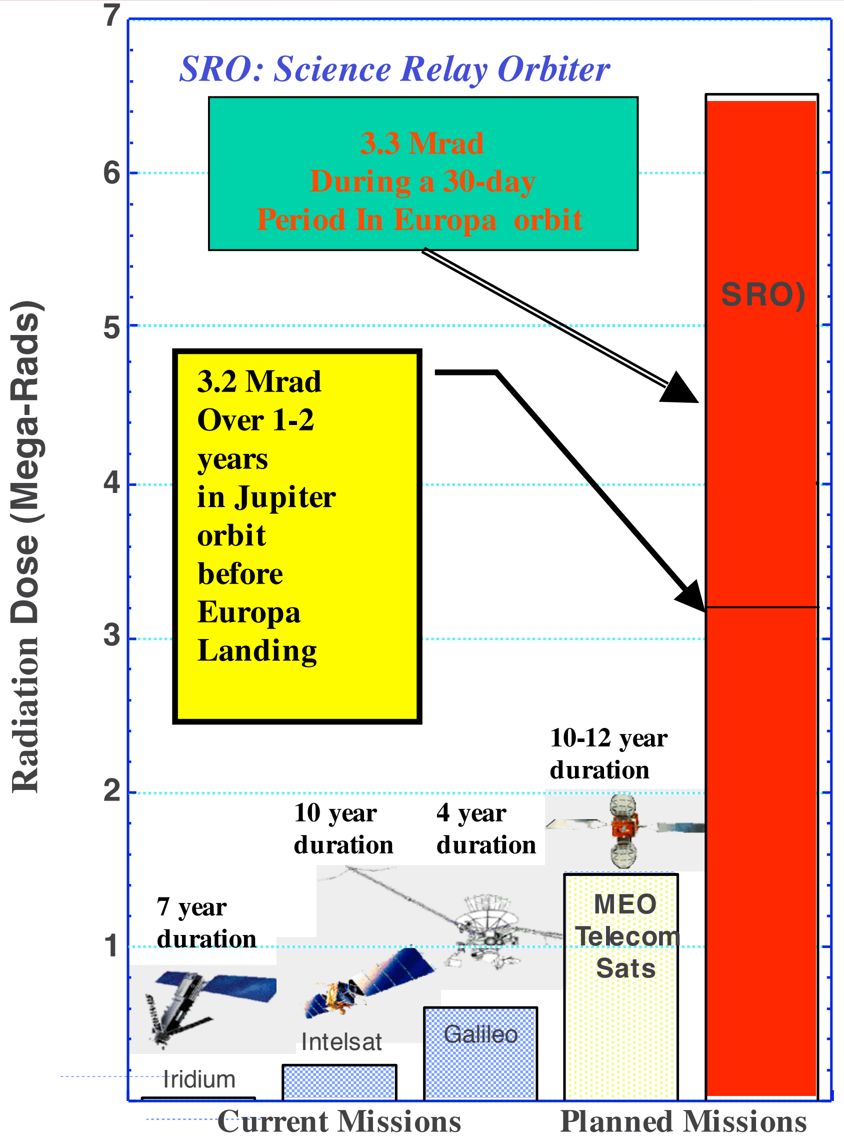

Capability Roadmap: Nanotechnology

X-Aerogels Have Potential as Structural Materials

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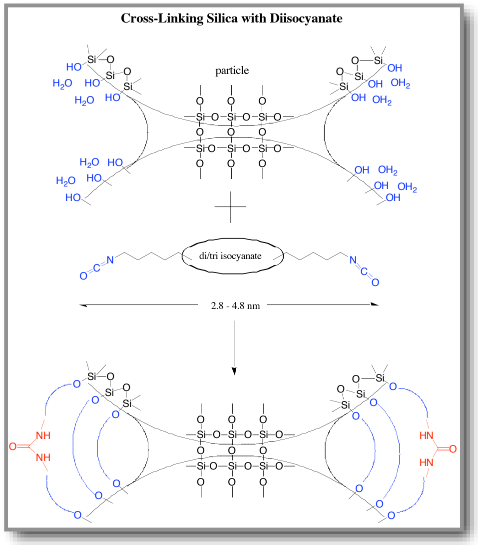
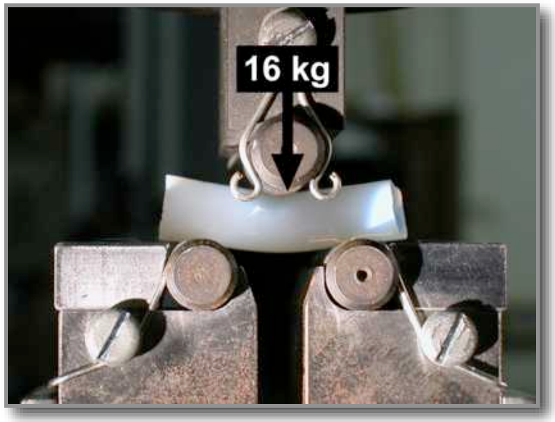
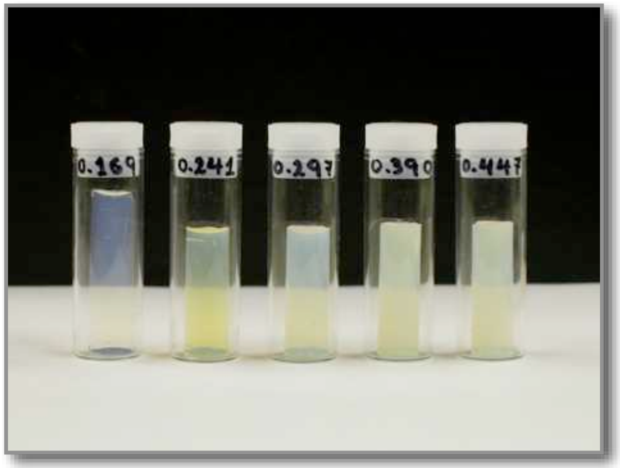
Versatile Cross-linking Chemistry



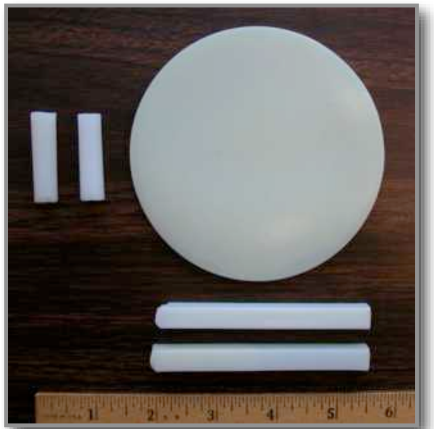
<u>400 Fold Increase in Strength</u>



Tailorable Properties



Simplified (Ambient Pressure) Processing, Improved Machinability

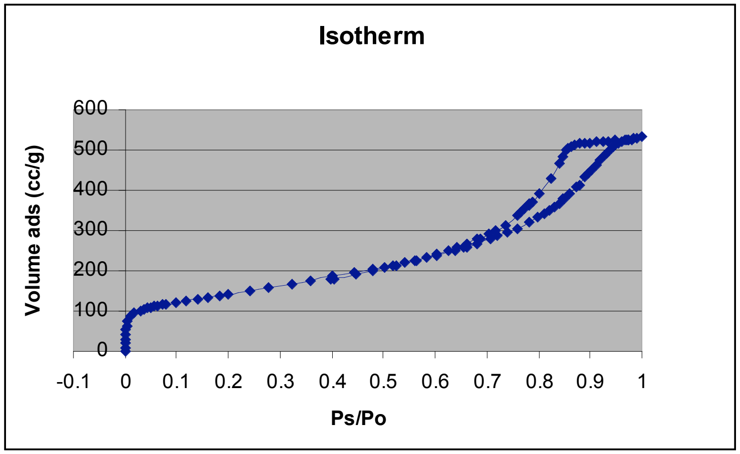


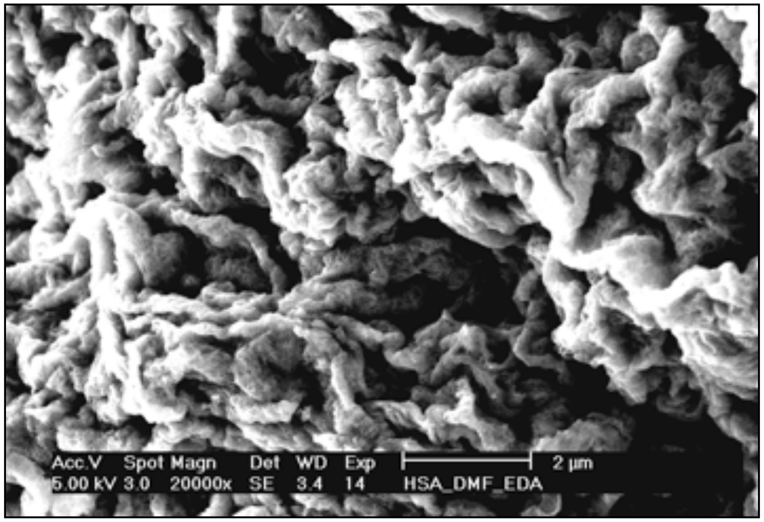
Air Revitalization: Regenerable CO_2 Removal

- Modified Ames process for high/engineered surface area
- Characterization of SWCNT material:
  - BET – Quantitative surface area + pore size
  - SEM – Qualitative surface area characteristics
- **Initial Performance Test:**
  - Solid amine coating: University of Connecticut
  - **Thermogravimetric Equilibrium Experiment**
    - **Pressure Swing**
    - **Temperature Swing**

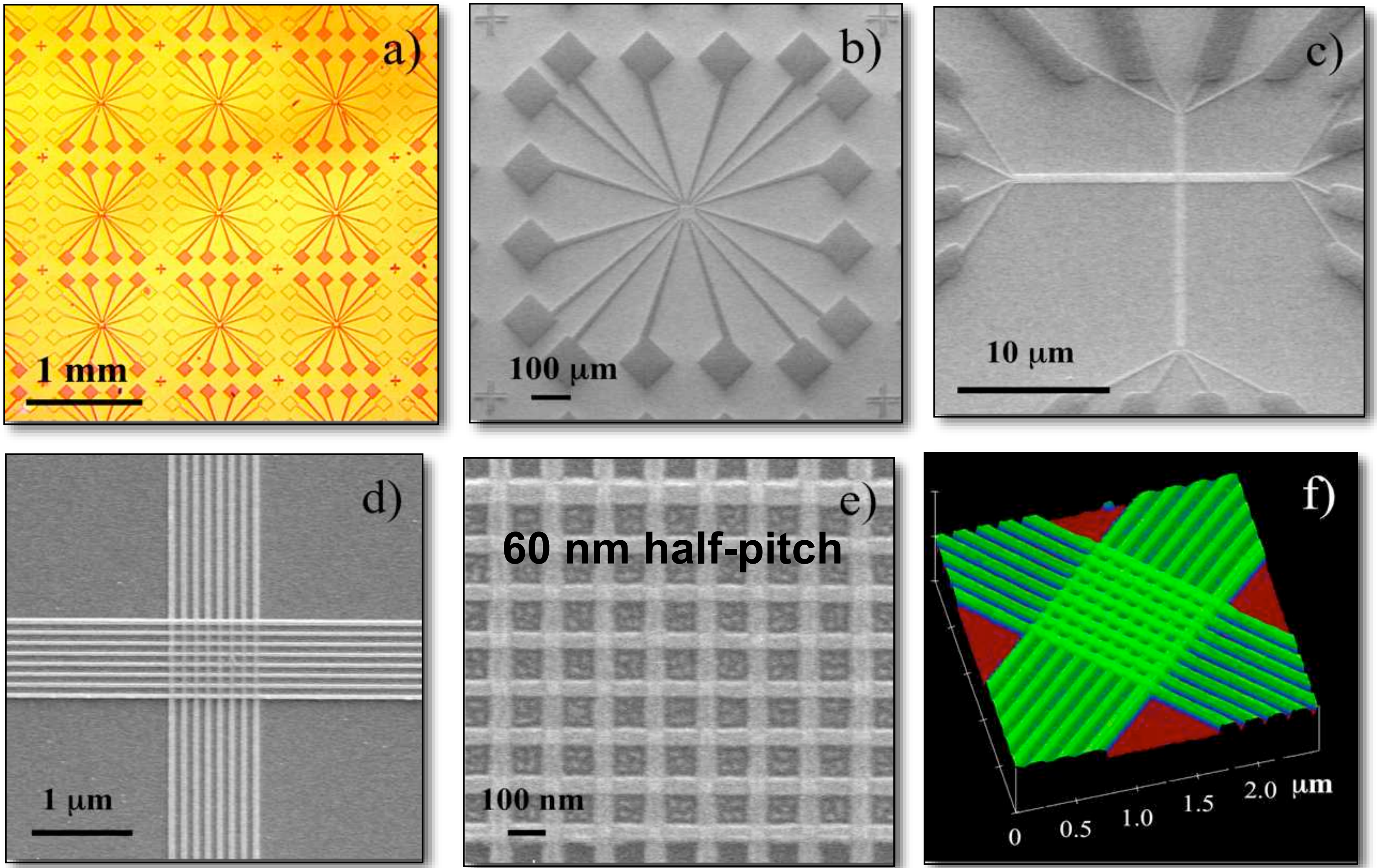
- **Reduce system volume**
- **Increase efficiency**
- **DoE Smokestack application**

BET Surface area 510 m^2/g





Nano-imprinted Crossbar Arrays



Courtesy of Stan Williams, Hewlett-Packard

NASA Grand Challenge Workshop

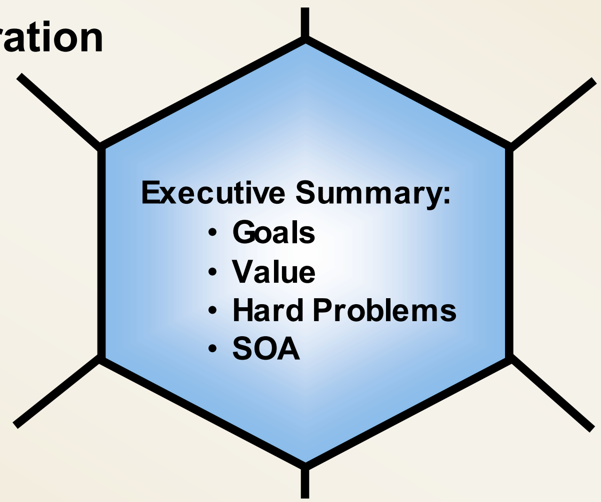
- **September 2004 Workshop on Micro-Spacecraft and Robotics**
  - NASA-led National Nanotechnology Initiative Grand Challenge area
  - Expanded scope covered elements of President's Exploration Vision
    - Nano-materials
    - Nano-Sensors and Instruments
    - Nano-Robotics
    - Nano-Micro-Macro Integration
    - Microcraft
    - Astronaut Health Management

Charge To Workshop Breakout Sessions

Microcraft
Deep Space Probes
Orbiters
Planetary Entry / Surface Probes
Micro/Nano/Pico-craft

Nano-Micro-Macro Integration
Electronics
Sensors / Instrumentation
Actuators
New algorithms
Communications

Nanomaterials
Structural
Power / Energy Storage
Thermal Management
Shielding
Multifunctionality



Nanorobotics
Actuation and Control
Molecular Actuation
Micromachines

Nanosensors and Instrumentation
Biological
Chemical
Radiological
System / Vehicle Health
In-situ Analysis

Astronaut Health Management
Personal Biomedical Monitoring
Personal Countermeasures
Basic Biomedical Research
Major Medical Operations
Life Support

Microcraft & Constellations Summary

Goals

- Reduce mass of microcraft by factor of ~100 in 10 years and ~1000 in 20 years, while maintaining full functional capability at no increase in cost/kg
- Fly "Constellations" of 100s-1000s microcraft and enable them to managed by a few (maybe only one) human operators

Hard Problems

- Systems-level design and integration of nanotechnology into single microcraft and constellations for ≥ 10X performance over SOA: power, propulsion, communications, computing, sensing, thermal control, guidance/navigation, etc.
- Assuring durability and endurance, especially in harsh environments
- Increase on-board computational performance by ~100X for self-directed, intelligent operations

Value to Space Systems

- Much greater capability at much lower cost
- Distributed robust monitoring and inspection for safer operations
- Simultaneous dense sampling of phenomena for exploration and accurate modeling of Earth, planetary, and space environments

State of the Art

- Commercial satellites (e.g. Orbcom) @ 40Kg
- Sojourner Mars Rover @ 11.5 kg
- "Picosats" (some MEMS) 0.27 to 1 Kg flown on expendable and STS vehicles
- Variety of lab prototype vehicles at 10-100 g, all with sensing, computation, communications, and actuation

Capability Roadmap: Nanotechnology

Astronaut Health Management Summary

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Goals

- To provide medical care (prevent, diagnose, and treat) during long-term transportation and extended presence in Moon and Mars
- The rapid development in the field of nanotechnology and biotechnology will provide significant solutions in the Astronaut Health Management arena during the long-term manned mission to Moon and Mars

Hard Problems

- Biocompatibility, especially toxicity of the nano-derived systems with the humans
- Management of the large volume of data and timely analysis of the data for medical assessment and subsequent treatment
- Integration of different disciplines from product development to clinical maturation
- Requirement for instrumentation autonomy while maintaining reliability

Value to Space Systems

- Screening for Personnel for minimal risk (radiation susceptibility, genetically high risk)
- Monitoring and countermeasure (radiation, bone loss, immune, muscle…)
- Autonomous Medical Care (Non-invasive Diagnostics, non-invasive imaging and Therapeutics, blood replacement therapy)
- Atmosphere monitoring and control (Environmental parameters, contaminants)
- Human Factors (Early assessment of performance quality)
- Antimicrobial coatings, High capacity regenerative adsorbants, Food packaging

State of the Art

In Shuttle and ISS

- Hearing test – EarQ
- Monitoring Heart Rate and Oxygen Consumption during exercise work load.
- Assess neurocognitive function (short term memory, verbal memory, math skills)
- Portable Clinical Blood Gas Analyzer – iStat (measures pH, blood gas, glucose…)
- Intra-vehicle radiation monitor to track crew exposure
- Ultrasound for research purposes only

Advanced Planning & Integration Office

Overview and Summaries of Roadmapping Activity

Overview:
Nanotechnology Capability Roadmap

Presentation to the National Research Council

March 8, 2005
Washington, D.C.

Co-Chairs:

M. Dastoor (NASA HQ) M. Hirschbein (NASA HQ) D. Lagoudas (Texas A&M)

Content

- Capability Roadmap Team
- Capability Breakdown Structure
- Roadmap Approach
- Top Level Assumptions
- Top Level Mission Sets
- Roadmap Schedule
- Capability Presentations by Leads under Roadmap (Repeated for each capability under roadmap)
  - Capability Description, Benefits, Current State-of-the-Art
  - Capability Requirements and Assumptions
  - Roadmap for Capability
  - Maturity Level - Technologies
  - Metrics
- Summaries of Top Level Capabilities

Capability Roadmap Team

Co-Chairs

NASA: Murray Hirschbein (Headquarters)
NASA: Minoo Dastoor, (Headquarters)
External: Dimitris Lagoudas, (Texas A&M, URETI Director*)

Government (NASA/JPL)

Mike Meador (Glenn Research Center)

Harry Partridge (Ames Research Center)

Mia Siochi/Mike Smith (Langley Research Center)

Benny Toomarian (Jet Propulsion Laboratory)

Len Yowell (Johnson Space Center)

Industry

Dan Herr, (SRC)

John Starkovich, (Northrop-Grumman)

Stan Williams (Hewlitt-Packard)

Academia

Wade Adams (Rice, Center for Nanoscale S&T)

Ilhan Aksay (Princeton, URETI* Director)

Supriyo Datta/David Janes (Purdue, URETI* Director)

Chih-Ming Ho (UCLA, URETI* Director)

Coordinators

Directorate: Harley Thronson (Science)
APIO: Julie Crooke (GSFC)

• **University Research Engineering and Technology Institute**

Capability Breakdown Structure

NASA Co-Chair: Minoo Dastoor

16.0 Nanotechnology

NASA Co-Chair: Murray Hirschbein

External Co-Chair: Dimitris Lagoudas

16.1 Nano-structured Materials

External Lead: Ilhan Askay
NASA Lead: Mike Meador
Len Yowell

- 16.1.1 Structural Efficiency
- 16.1.2 Efficient Power and Energy
- 16.1.3 Thermal Protection and Management
- 16.1.4 Radiation and EM Protection
- 16.1.5 Life Support/Health Management
- 16.1.6 Sensing and Actuating

16.2 Sensors and Devices

External Lead: David Janes
NASA Lead: Harry Partridge

- 16.2.1 Sensing
- 16.2.2 Electronics
- 16.2.3 Mechanisms/Actuators
- 16.2.4 Modeling and Simulation

16.3 Intelligent Integrated Systems

External Lead: Chih-Ming Ho
NASA Lead: Benny Toomerian

- 16.3.1 Multi-Scale Modeling
- 16.3.2 Multi-Scale Manufacturing
- 16.3.3 Interconnectivity
- 16.3.4 Utilization of Nano-Scale Properties
- 16.3.5 Information Representation

Roadmap Approach

- **Build on 5+ years of similar activity including prior roadmaps and involvement in the National Nanotechnology Initiative (NNI)**
  - Recent planning for the second 5 years of NNI
  - NASA NNI workshop Microcraft and Robotics
  - Recent workshop among the four NASA University, Research, Engineering and Technology Institutes in nanotechnology (URETI)
  - Utilize existing informal NASA team, including URETIs, that has evolved over the past several years
- **The scope will include both aeronautics and space**
  - Both near and mid-term opportunities and long-term vision
  - Tie development of capability to enabling higher level applications
  - Key demonstrations and quantifiable milestones to guage progress
- **<u>Focus on fundamental underlying technological capability</u>, such as**
  - Theory and analysis from the nano-scale to the macro-scale to predict properties and behavior
  - Materials processing for desired properties and behavior
  - Design and development of devices and systems based on nano-scale technology
  - Integration of nano-scale devices and systems into micro- to macro- systems
  - Training and Education

Roadmap Approach

(Continued)

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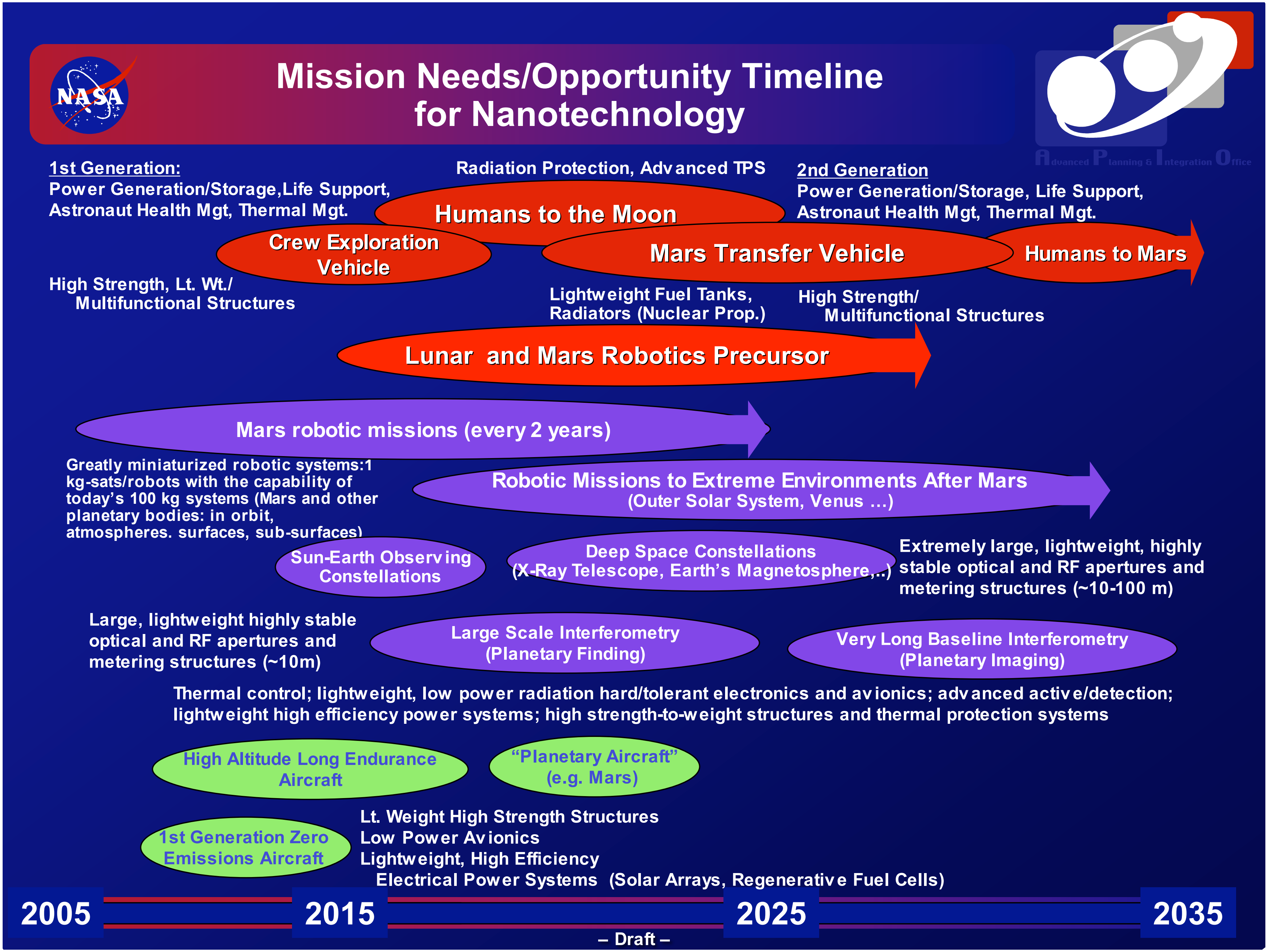
- Continue active participation in the National Nanotechnology Initiative to enhance broad government coordination and cooperation
- NASA will work closely with….
  - NIH in matters of astronaut health
  - DOD across broad common interests in aeronautics and space
  - DOE in materials, especially energy related
  - NIST on fabrication and manufacturing (NASA fabricates, but does not manufacture)
  - Semiconductor industry (ITRS) for electronics and system integration

Top Level Assumptions

- Nanotechnology is a “push” technology driven by breakthroughs and opportunities
  - No mission currently “requires” nano-scale technology
  - All planned and future missions can significantly benefit from advances in nano-scale technology
- The most significant breakthroughs in nano-scale technology likely have not yet occurred – predictions beyond a few years are very speculative
- Most advances benefiting NASA will come from external sources
- The target level for the nanotechnology roadmap is about Technology Readiness Level 4 (fully demonstrate/validate functionality)
- Leveraging Commercial/Academia developments is essential
- NASA will have unique needs and requirements not met by external sources
- A strong internal emphasis and highly competent internal talent is essential to benefit from external sources and satisfy unique needs and requirements


Mission Needs/Opportunity Timeline
for Nanotechnology
Advanced Planning & Integration Office
1st Generation:
Power Generation/Storage,Life Support,
Astronaut Health Mgt, Thermal Mgt.
Radiation Protection, Advanced TPS
2nd Generation
Power Generation/Storage, Life Support,
Astronaut Health Mgt, Thermal Mgt.
Humans to the Moon
Crew Exploration Vehicle
Mars Transfer Vehicle
Humans to Mars
High Strength, Lt. Wt./ Multifunctional Structures
Lightweight Fuel Tanks, Radiators (Nuclear Prop.)
High Strength/ Multifunctional Structures
Lunar and Mars Robotics Precursor
Mars robotic missions (every 2 years)
Greatly miniaturized robotic systems:1 kg-sats/robots with the capability of today's 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres. surfaces, sub-surfaces)
Robotic Missions to Extreme Environments After Mars
(Outer Solar System, Venus …)
Sun-Earth Observing Constellations
Deep Space Constellations
(X-Ray Telescope, Earth's Magnetosphere,..)
Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)
Large, lightweight highly stable optical and RF apertures and metering structures (~10m)
Large Scale Interferometry
(Planetary Finding)
Very Long Baseline Interferometry
(Planetary Imaging)
Thermal control; lightweight, low power radiation hard/tolerant electronics and avionics; advanced active/detection; lightweight high efficiency power systems; high strength-to-weight structures and thermal protection systems
High Altitude Long Endurance Aircraft
"Planetary Aircraft" (e.g. Mars)
1st Generation Zero Emissions Aircraft
Lt. Weight High Strength Structures
Low Power Avionics
Lightweight, High Efficiency
Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)
2005
2015
2025
2035
– Draft –

Roadmap Schedule

- Team established in November

- First team meeting December 14-15, 2004
  - External perspectives
  - Organized sub-teams
  - Focused on what should NASA do in nanotechnology and why

- Second team meeting February 1-2, 2005
  - Developed final capability breakdown structure
  - Focused on how and when NASA could achieve Agency needs/benefits in nanotechnology
  - Initial draft of roadmaps including state-of-the-art, metrics and timelines

Roadmap Schedule (continued)

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- NRC review March 8, 2005
  - Integral part of nanotechnology roadmapping plan
  - “Mid-term” assessment of assumptions, scope, direction and overall technical content
  - Early enough in the process to affect final product

- Third meeting in March
  - Incorporate NRC feedback
  - Finalize content

Nano-Structured Materials

Capability 16.1 Nanostructured Materials

Presenter/Team Lead:

Ilhan Aksay

Co-Leads:

Mike Meador-GRC

Leonard Yowell – JSC

Team Members:

Wade Adams – Rice University

Mike Smith - LaRC

John Starkovich – Northrop Grumman

Capability 16.1 Nanostructured Materials

- Nanotechnology is producing materials with properties, processing and durability far exceeding that of conventional materials. These materials will have a significant, pervasive impact on all NASA missions:
  - Reduced mass, improved structural efficiency
  - Extreme environmental performance
  - Efficient power (frugal consumption, efficient generation, storage and management)
  - High reliability
  - Human safety

Requirements /Assumptions for Capability 16.1 Nanostructured Materials

- Critical drivers for all NASA Missions:
  - Weight
  - Performance
  - Power and Energy
  - Safety
- Benefits and improvements identified by theoretical and laboratory based experimental results are achievable at scales required for NASA missions
- TRL 4 includes scale-up to appropriate size/quantity
- Resources will be available to develop technologies to TRL4
- Nanotechnology Roadmap assumes that technology will be developed to TRL4, other CBS and WBS Roadmaps will :
  - Identify opportunities for insertion of nanotechnology
  - Develop roadmaps for insertion and maturation to higher TRLs

Benefits of 16.1 Nanostructured Materials

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Why Nanotechnology

Mechanical	
Strength	nano length scales below Griffith criteria
Toughness	distributed deformation at nanolength scales
Damping	efficient energy dissipation at nano-interfaces, nanomorphology, increased viscoelasticity with nanoparticle addition
Hardness	supermodulus effect - nanoscale inclusions
Modulus/Stiffness	enhanced molecular alignment- more perfect structures - achieve theoretical limits
Recoverable strain	quantum level nanoeffects,
Compressive	toughened interfaces through nanoscale particles, nanovoids
Impact /Dynamic Loading	nanomorphology effects on energy dissipation
Friction and Wear	tailored nanostructures to fit asperities
Thermal	
Conductivity/Insulation	geometry and size effects at a wide range of temperatures (cryo to reentry)
CTE	nanoscale morphology (voids) effects, phonon coupling, enables tailorable CTE
Emissivity	enhanced surface area/roughness,possible quantum effect

Benefits of 16.1 Nanostructured Materials

Advanced Planning & Integration Office

Why Nanotechnology

Electrical	
DC Conductivity	nanoscale design/defects, enables ballistic conductivity
Semiconductive	nanoscale tailoring of bandgaps
Dielectric Constant	nanopores
Current Density	enables ultra-high current densities, eliminates/controls defects, size effects, gating of nanowires
Percolation Threshold	high aspect ratios
Field emission	high aspect ratio
Thermoelectric	larger density of states, more phonon scattering
Optical	
Transparency	size effects (clearly)
Color/Absorption	size effects
Photonic Band Gap	tailored bandgaps through nanostructures, size effects (lambda/10)
Left-Handed	size effects
Surface Area	size, radius of curvature and geometry effects, tailorability
Porosity	heirarchical distribution, functionalization

Benefits of 16.1 Nanostructured Materials

Advanced Planning & Integration Office

Why Nanotechnology

Mass Transport/Permeability	nanoscale morphology (voids) effects,length scale effects on diffusion mechanisms
Density	nanomorphology (inclusion of nanopores)
Environmental	
Radiation	electronics (smaller cross-section, redundancy,spintronics), human (size effects on energy dissipation??, design flexibility)
Temperature Stability/Performance	nanoscale morphology (new interfaces), inhibits degradation (diffusion)
Corrosion	surface area, interface tailoring
Magnetic	size effect
Piezoelectric	size effect
Chemical Reactivity	surface area, interface tailoring
Materials Interactions	surface area and tailoring, interface tailoring

Future Exploration Missions Requirements Cannot Be Met with Conventional Materials

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Satellites and rovers

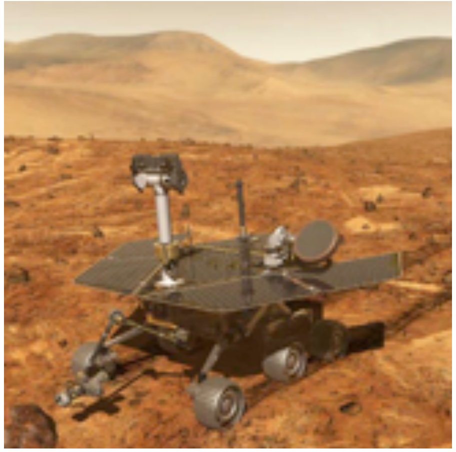
- Reduced mass and volume
- Reduced power requirements
- Increased capability, multifunctionality

Vehicles and habitats

- Reduced mass
- High strength
- Thermal and radiation protection
- Self-healing, self-diagnostic
- Multifunctionality
- Improved durability
- Environmental resistance (dust, atmosphere, radiation)

EVA Suits

- Reduced mass
- Increased functionality and mobility
- Thermal and radiation protection
- Environmental resistance



Nanostructured Materials Can Impact Science Missions and Exploration

NanoTechnology

NORTHROP GRUMMAN
Space Technology

The Vision & The Challenges

- N+2 generation civil space missions require spacecraft and payload instruments with Order-of-Magnitude greater scale, resolution, and precision than present systems afford
- Revolutionary designs and breakthrough technologies will enable development of such systems
- NanoTechnology, particularly NanoEngineered materials may be key to realizing this vision

Very Large Membrane Reflectors · Orbital Transfer Vehicles · Large Deployable Structures · Relocatable Power Beam Stations · Dynamically Stable Platforms / Instruments · Space Based Radar & Comsats

Nanostructured Materials are Critical for Future Aeronautics Demonstrators

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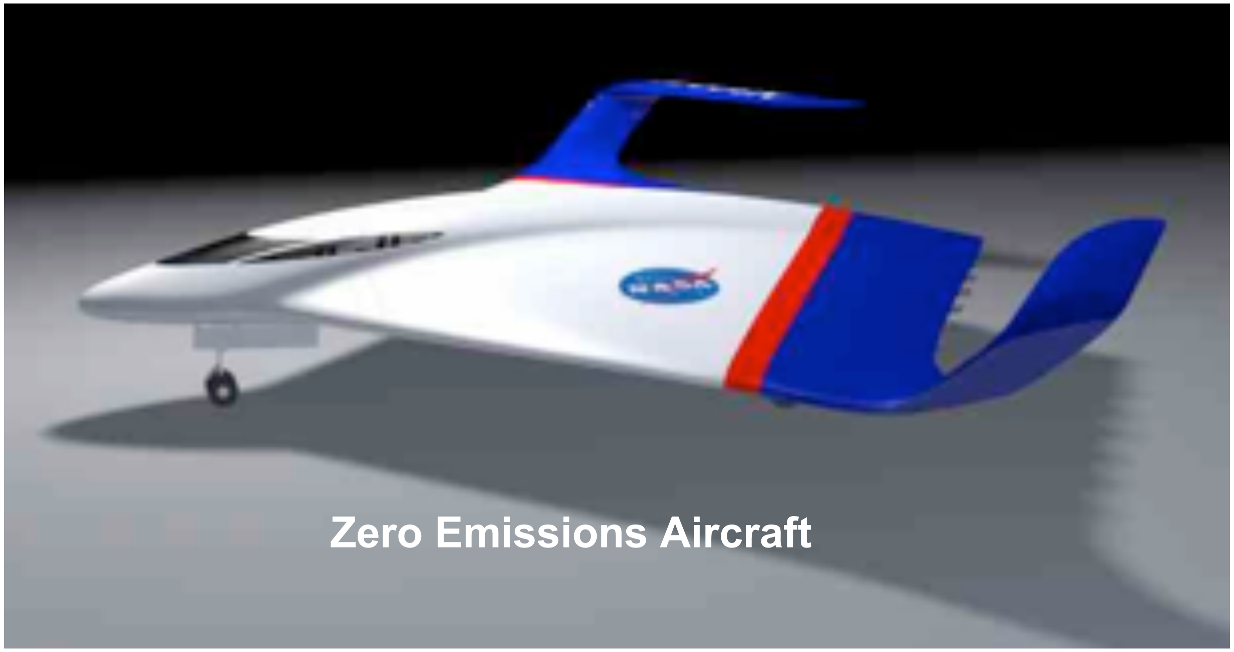

Zero Emissions Aircraft

- Airframe – ultralightweight, high strength, multifunctional nanocomposites
- Cryopropellant Tanks – low density, durable aerogel insulation & ultralow permeability nanocomposites
- Fuel Cell Power – nanostructured electrode materials
- Electric Motors – high conductivity, lightweight nanocomposites, nanolubricants

Key Assumptions: Potential NASA Applications

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Structural Efficiency
- In-Space or In-Field Repair Methods
- Composite Cryotanks
- 20% Lighter Airframe and Propulsion Structures
- Propulsion/Airframe Strutures with 10X Life
- 50% Lighter Composite Structures

Efficient Power and Energy
- EVA Suit and Rover Power
- Power for UAVs
- Exploration Systems Power Distribution, All-Electric Aircraft

Thermal Protection and Management
- Cryotank insulation
- Insulation for EVA suits and rovers

Radiation and EM Protection
- Spacecraft Charging and Dust Mitigation
- Multifunctional Materials for Vehicles, Habitats, Suits

Life Support/ Health Mgt.
- Water Purification for Vehicles and Habitats
- Astronaut Health Monitoring/Diagnostics
- Air Revitailization for Vehicles, Habitats, EVA suits

2005 2010 2015

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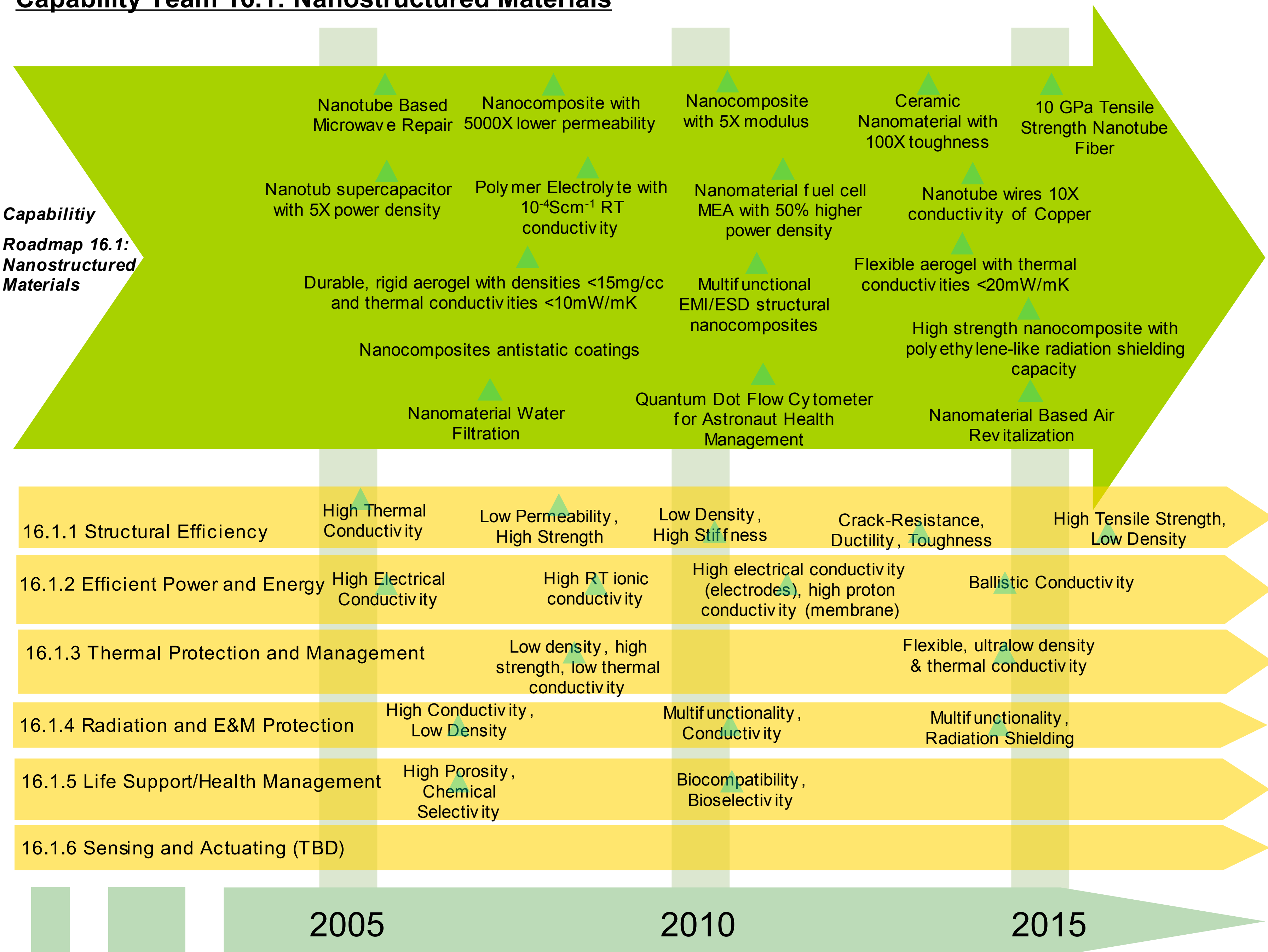
Capability Team 16.1: Nanostructured Materials



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Key Assumption: Potential NASA Applications

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Structural Efficiency
- 50% component weight savings
- High temperature components with 100X longer life
- Enables ultralightweight tethers

Efficient Power and Energy
- Lightweight Batteries for EVA Suits and Rovers
- 50% Efficiency, Durable, Deployable PV Arrays

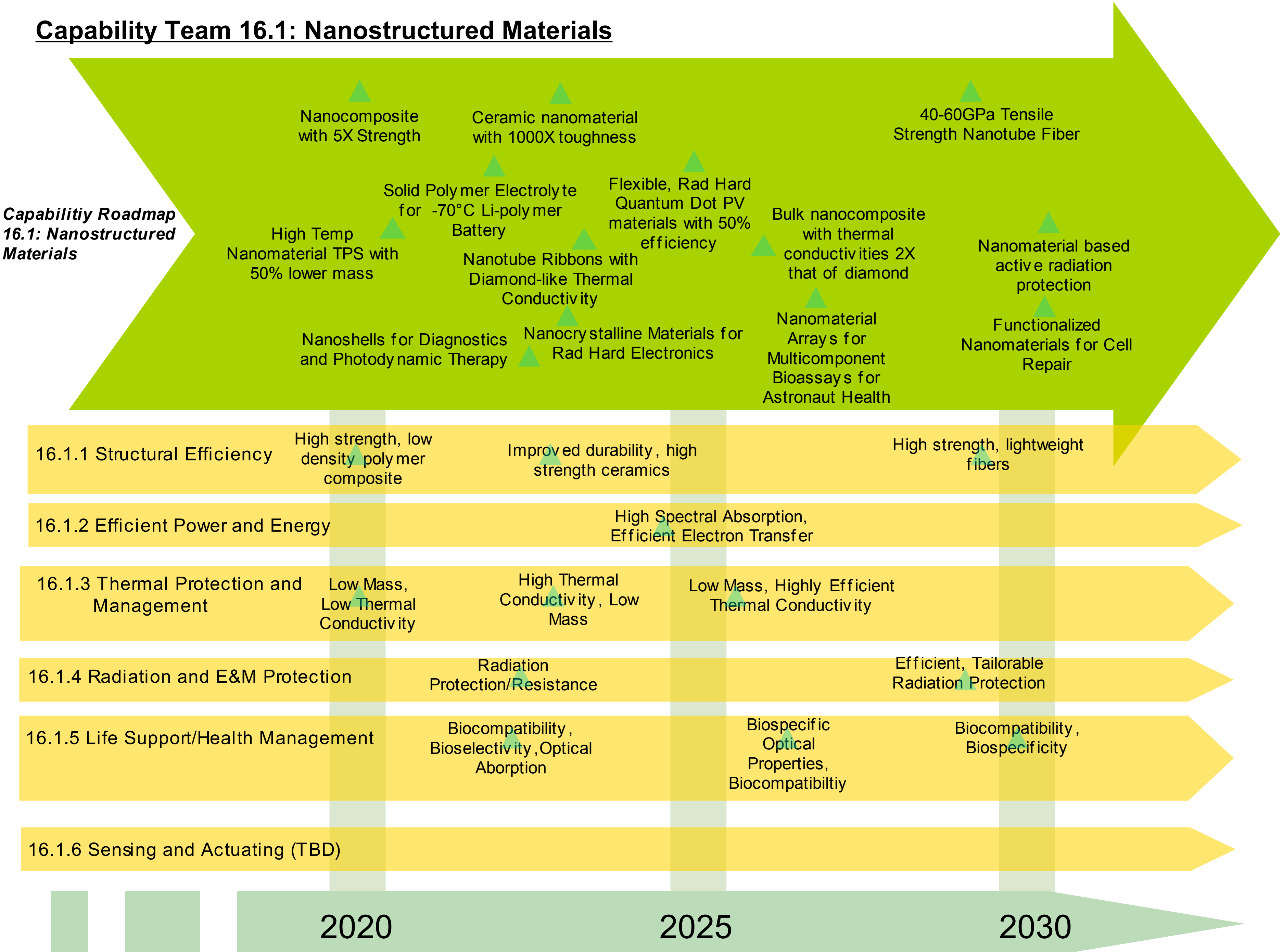
Thermal Protection and Management
- 50% Mass for TPS, Insulation
- Reduced Mass, Efficient, Passive Thermal Control

Radiation and EM Protection
- Radiation Hard Electronics, Sensors
- Advanced Radiation Shielding for Vehicles, Rovers, Habitats

Life Support/ Health Mgt.
- Astronaut Health Monitoring/Coutnermeasures
- Real-time, Multicomponent Astronaut Health Monitoring
- Astronaut Health Care/Countermeasures

2020 2025 2030

Capability Team 16.1: Nanostructured Materials



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Remaining Work

- Review milestones and metrics for comprehensiveness
  - Fill in gaps – have we left out important needs?
  - Looking for expertise within and outside the Agency for validation of existing roadmaps and help with Sensing and Actuating Subcapability

- Coordinate Roadmaps with other CRM teams:
  - High Energy Power and Propulsion
  - Advanced Telescopes and Observatories,
  - Science Instruments and Sensors
  - Advanced Modeling, Simulation and Analysis

Detailed Challenges and Roadmaps

NASA NNI Grand Challenge Workshop (2004) Reliable Production of Nanomaterials

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Grand Challenge: Develop the ability to reliably and consistently control functional material synthesis and assembly from nano to macro scales

Barriers/Needs:

– Integration of physical and chemical forces with external fields to get desired properties during processing and use (> 10 years)
– Inexpensive production (terrestrial and other planets) of highest quality nanomaterials (>10 years)
– Control of processes over all length scales (>10 years)
– Adaptable synthesis, processing and characterization methods to efficiently utilize resources on other planets (>10 years)
– Lack of fundamental understanding of synthesis, growth, nano-macro structure development mechanisms (5-10 years)
– Lack of real-time methods to characterize structural development during processing and/or synthesis (5-10 years)
– Lack of predictive models/simulations to guide materials and processing design (<5 years)
– Control of interfacial properties and processes (<5 years)
– Lack of approaches that draw upon previous experiences from other disciplines (bio, electrical engineering) (<5 years)
– Failure detection and prediction tools (<5 years)
– Lack of high throughput experimentation and characterization techniques (<5 years)

Grand Challenge: Demonstrate that materials, devices and systems based on nanotechnologies can reliably execute prolonged (DECADE +) Human and Robotic Exploration Missions .

- Radiation (space environment & propulsion radiation sources)
- Chemical/reactive environments
- Thermal swings (-120 C to 600 C)
- Fatigue
- MMOD Impact
- Mechanical and launch/entry loads
- Electrostatic charging
- Abrasion
- Synergistic effects.

Barriers/Needs:

- Accelerated life testing for issues listed above
- End-to-end test capability
- Lack of fundamental understanding of materials and interactions with radiation
- Simulation effects from Nano-micro-meso scale is imperative
- In Space repair and regeneration
- Integrated system health management
- Self-repair

16.1.1 Structural Efficiency

- Includes:
  - Low Density
  - Strength
  - Stiffness
  - Toughness
  - Vibration/Acoustic Damping
  - Permeability
  - Dimensional and Dynamic Stability
  - Environmental Durability
  - Impact Resistance
  - Self-Healing
- SOA:
  - Polymer/clay nanocomposites with 100X lower permeability than base resin
  - Nanocomposites with strength equivalent to conventional carbon fiber
  - Ceramic nanocomposites have toughness 10X that of best ceramic
  - Vibration damping - ?
  - Impact Resistance
  - Self-healing ionomers demonstrated that can heal 1 cm diameter cut, not space compatible

16.1.1 Structural Efficiency

- Metrics:
  - Nanocomposites with 5000X lower H2 permeability
  - Composite materials with 5-fold increase in specific strength and stiffness over conventional composites
  - Ceramic nanocomposites with 100 to 1000x better tougness
  - Vibration damping – (Will get information from Starkovich)
  - Impact resistance- Nanocomposite bumbers and self-healing foam support to improve performance 10-100X
  - Nanotube based microwave active repair materials
- Barriers:
  - Lack of fundamental understanding of synthesis, growth, nano-macro structure development mechanisms
  - Reliable and affordable scale-up methods
  - Interface design, functionalization, control and characterization
  - Predictable structural control (dispersion and alignment) over all length scales
  - Lack of robust modeling tools across all length scales
  - In-situ characterization and diagnostic techniques are limited

Capability 16.1 Nanostructured Materials Roadmap

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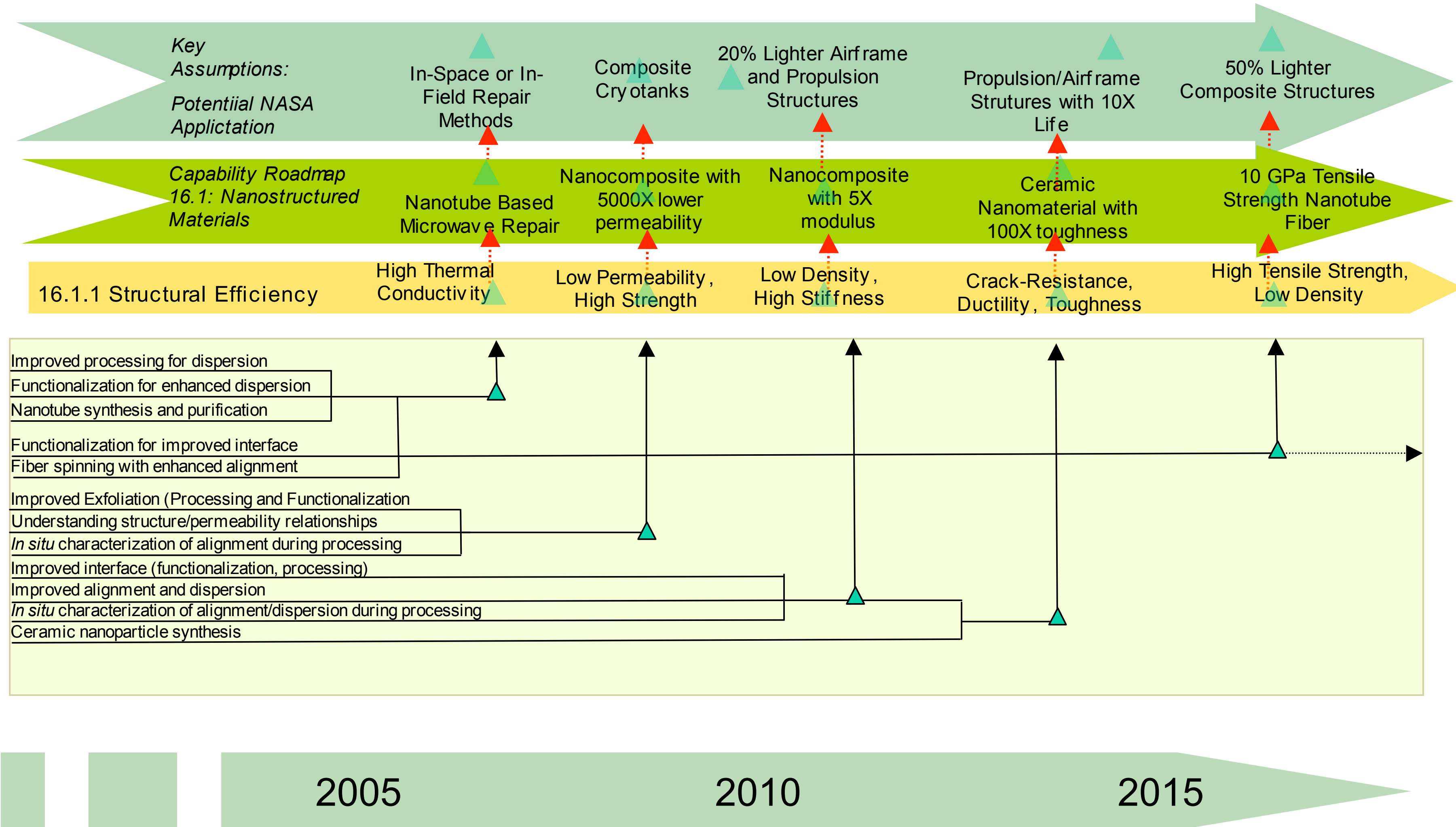
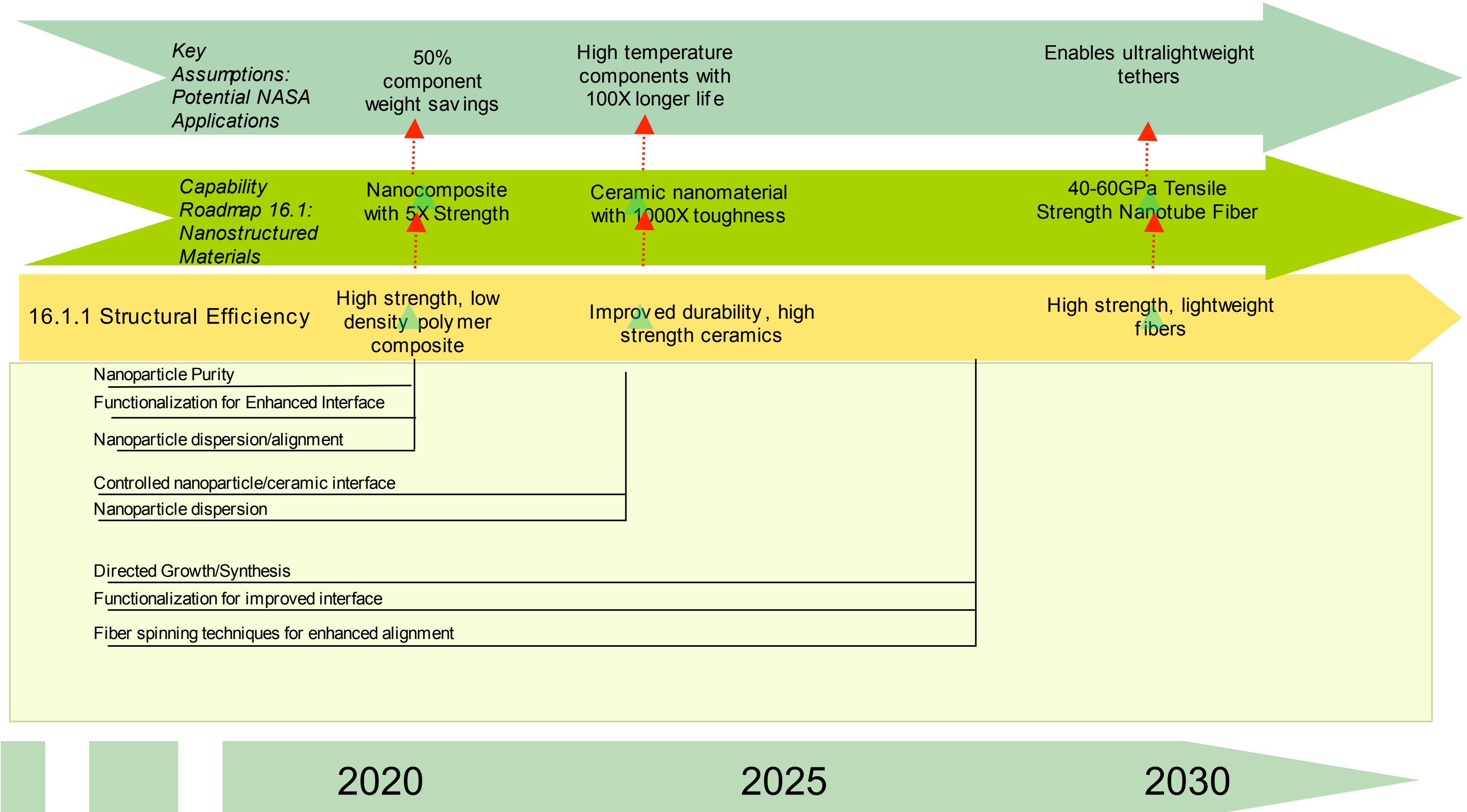


Capability 16.1 Nanostructured Materials Roadmap

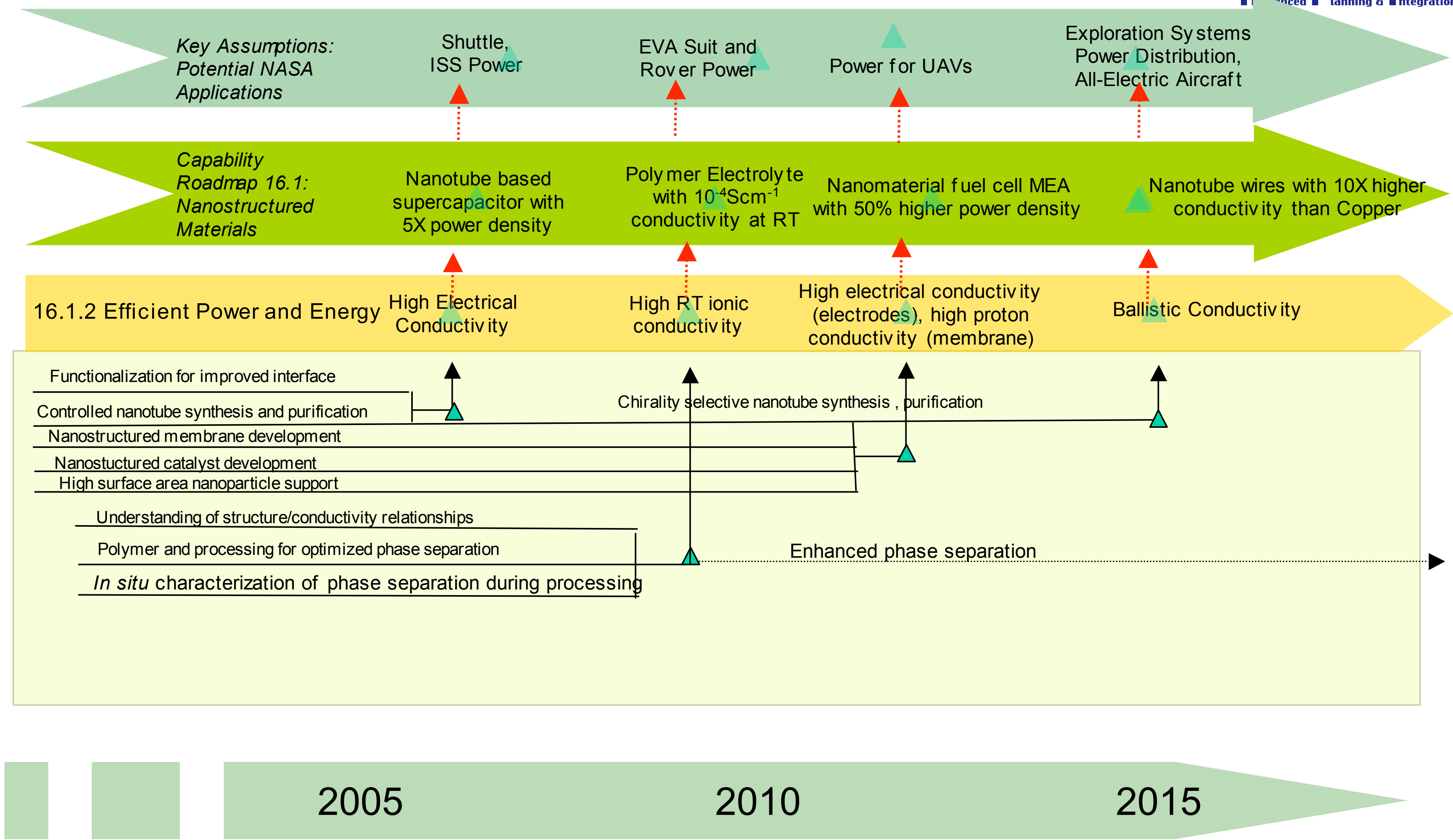
Advanced Planning & Integration Office



16.1.2 – Power and Energy Density

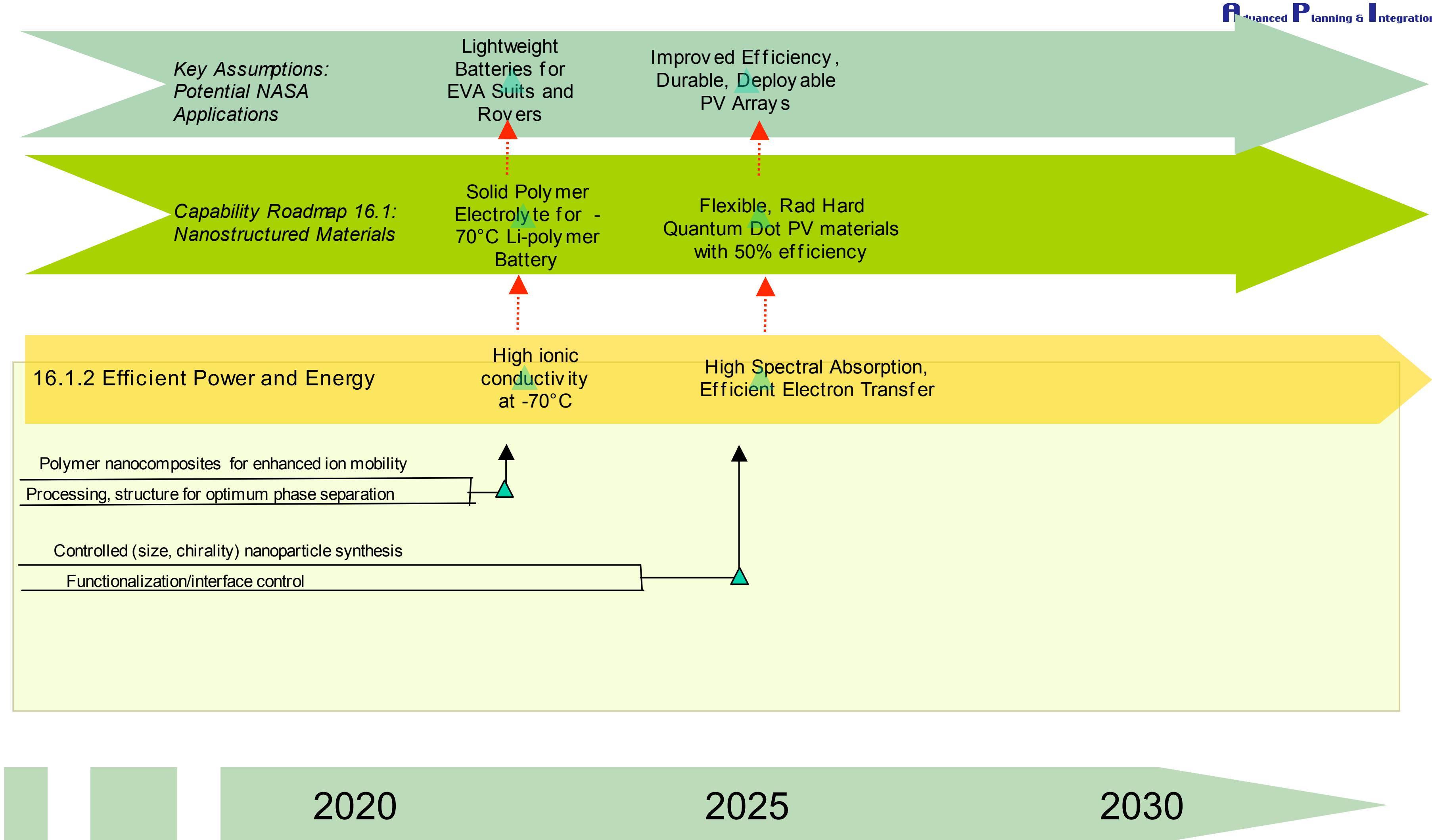
- Includes:
  - High Specific Power
  - High Specific Energy
  - Low Loss Power and Energy Distribution
- SOA:
  - Quantum dot/nanotube based photovoltaics with XX% efficiency
  - Nanotube double layer supercapitor with 5x power and 30x specific power of conventional supercapitors
  - Self-assembled polymer electrolyte with 10X ionic conductivity of conventional electrolyte at room temperature
  - Aerogel based membrane with Nafion-like conductivity but at 200°C and no need for external humidification
  - Wires??
- Metrics:
  - Material system capable of power generation, storage and self-actuation total aerial weight of 0.8Kg/m2 and capable of 1.0 kw/kg power generation
  - Solid polymer electrolytes with ionic conductivities >10-4 scm-1 at -70°C and structural capabilities
  - Multifunctional electrode materials for reversible fuel cells
  - Flexible, photovoltaic materials with 50% PV efficiency
  - Membranes?
  - Arm chair nanotube-based wires with 10X conductivity of copper at 1/6th the weight

Capability 16.1 Nanostructured Materials Roadmap



Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office



Ready to Use ▲ Major Decision ◆ Major Event / Accomplishment / Milestone

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16.1.3 – Thermal Protection & Management

- Includes:
  - Thermal Conductivity
  - Insulation
  - Emissivity
- SOA:
  - Flexible silica aerogel insulation with thermal conductivities below 20mW/mK
  - Zirconia/carbon nanotube TBC insulation with 50% lower thermal conductivity
  - Magnetically aligned nanotube ribbon conductors with metal-like thermal conductivities (200W/mK)
  - Emissivity
- Metrics:
  - Durable, aerogel insulation with densities below 15mg/cc and thermal conductivities below 10mW/mK
  - Nanotube ribbons with diamond-like thermal conductivities (1000-2000W/mK)
  - Emissivity?

Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office

Key Assumptions: Potential NASA Applications

Cryotank insulation

Insulation for EVA suits and rovers

Capability Roadmap 16.1: Nanostructured Materials

Durable, rigid aerogel with densities <15mg/cc and thermal conductivities <10mW/mK

Flexible aerogel with thermal conductivities below 20mW/mK

16.1.3 Thermal Protection and Management

Low density, high strength, low thermal conductivity

Flexible, ultralow density & thermal conductivity

Nanotemplated coating development

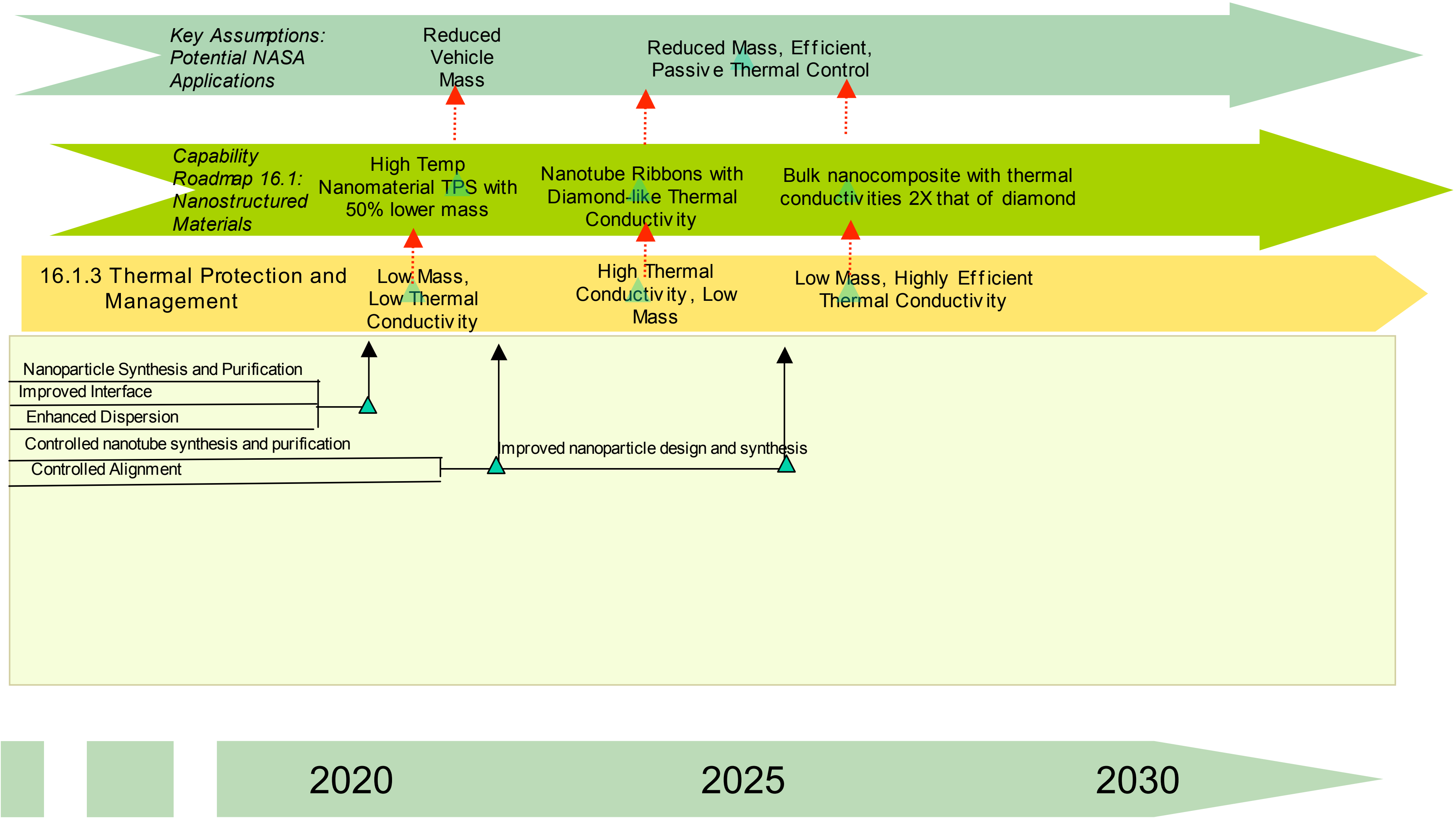
Controlled nanoporous morphology

Aerogel & Nanocoating optimization

2005 2010 2015

Capability 16.1 Nanostructured Materials Roadmap

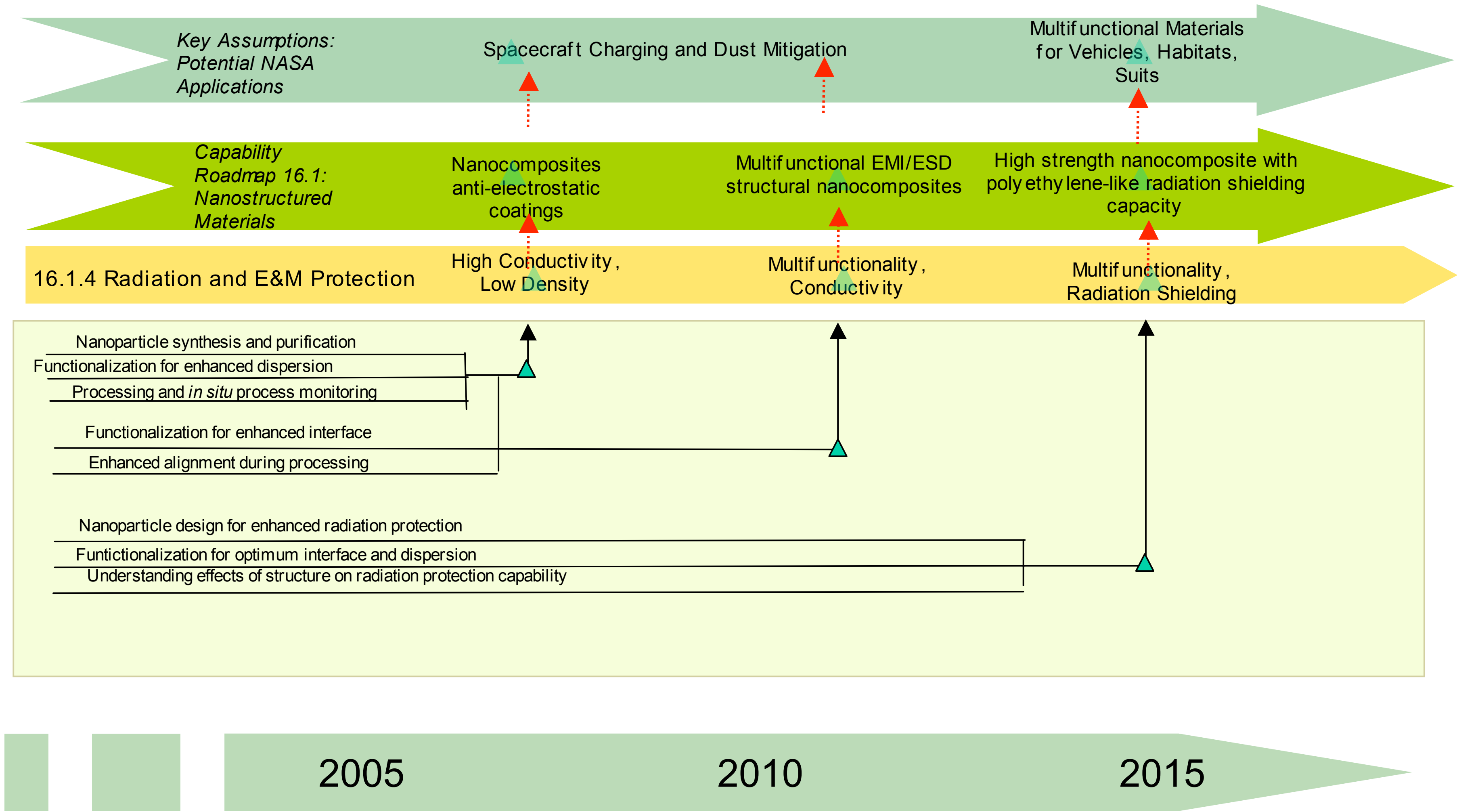
Advanced Planning & Integration Office



16.1.4 – Radiation Protection and E&M

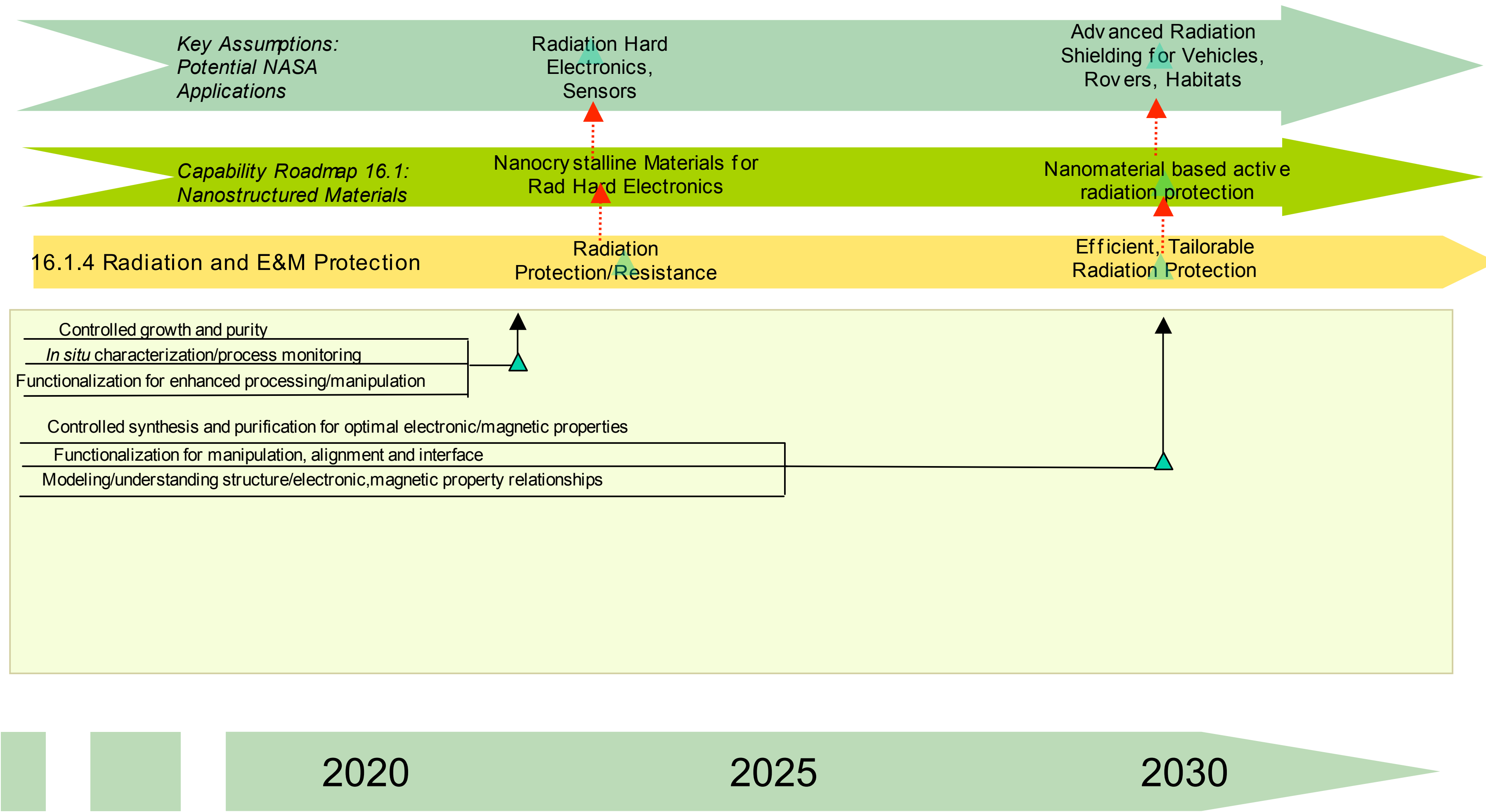
- Includes:
  - Radiation Protection
  - EMI Shielding
  - Electrostatic Control
  - Active (Magnetic) Shielding
- SOA:
  - Nanotube based anti-static coatings
  - Polyethylene (non-nano) shielding
- Metrics:
  - Nanostructured materials with polyethylene-like radiation protection and structural capability

Capability 16.1 Nanostructured Materials Roadmap



Capability 16.1 Nanostructured Materials Roadmap

Advanced Planning & Integration Office



16.1.5 – Life Support – Health Management

- Biocompatability
- Selectivity (Separation and Filtration)
- Monitoring
- Counter-measures

• SOA:
  - Quantum dot bioassays for medical diagnostics/health monitoring
  - Functionalized nanotube membranes for water and air revitalization
  - Surface modified C60 anitioxidants
  - Silica/metal nanoshells for diagnostics and photodynamic therapy and tissue welding

• Metrics:

Capability 16.1 Nanostructured Materials Roadmap

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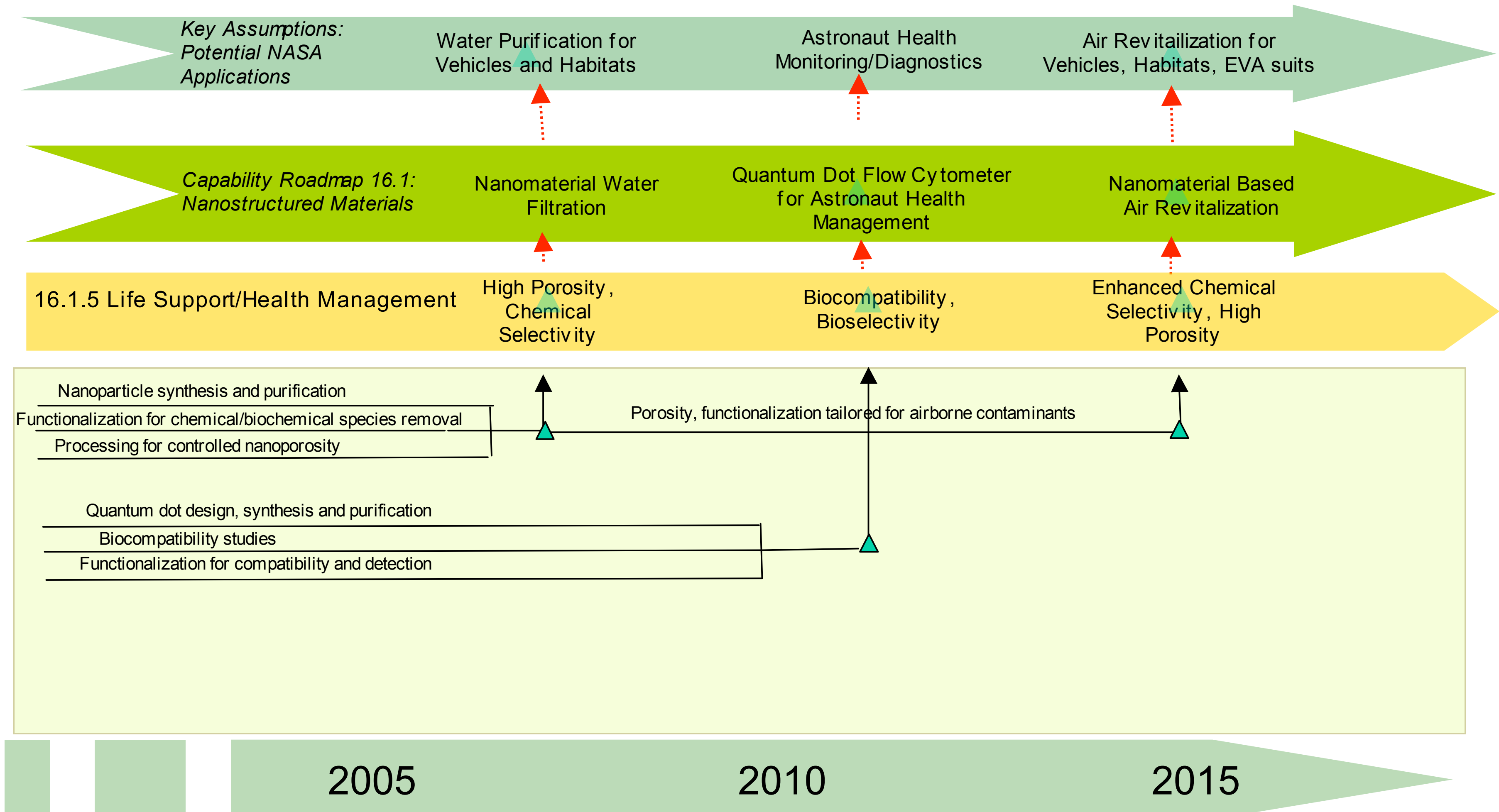

Capability 16.1 Nanostructured Materials Roadmap

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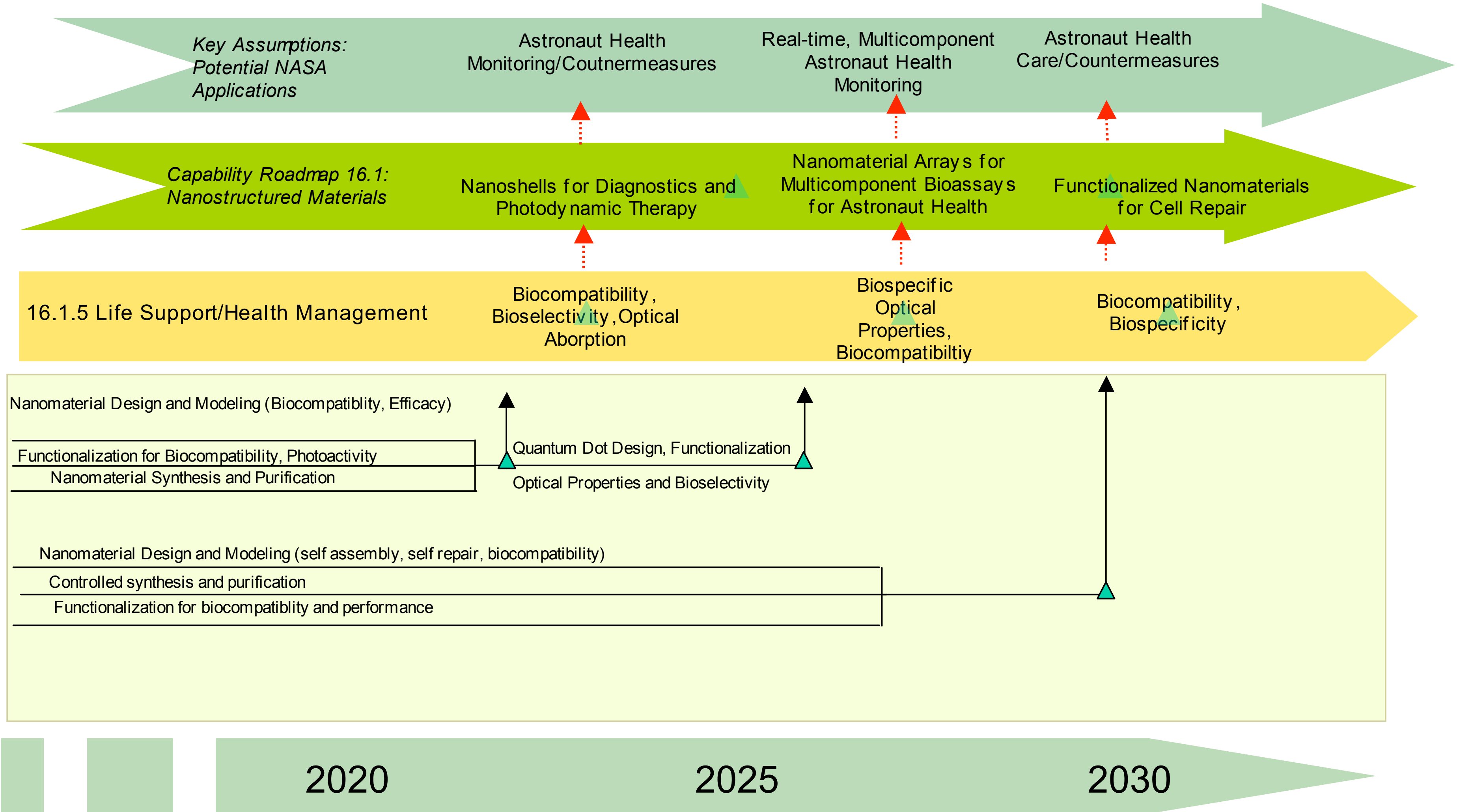

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Capability 16: Nanotechnolgy

Capability 16.2 Sensing and Devices

Presenter/Team Lead:
David Janes
NASA Co-Leads:
Harry Partridge

- # Scope of Sensing and Devices

  Provide the ability to detect, process data, communicate and interpret information, as well as manipulate or control this environment on a common platform by combining capabilities of nano/micro scale sensors and computing

- # Why Nano Sensing and Devices?
  - Unparalleled sensitivity, selectivity, multi-functionality and integration
  - Devices suitable for highly integrated systems
  - Considerable reduction in power consumption
  - Enabling multi-point monitoring and enhanced functionality from multi-node system (eg health management and microcraft)
  - Redundancy for fault-tolerance and elimination of false positives
  - Potential performance improvement in extreme environments (radiation, temperature (min/max & swings, pressure, zero gravity, etc.)
  - Bottom-up engineering of materials for device properties through independent control of physical parameters at nano-scale are becoming feasible.

- Why NASA?

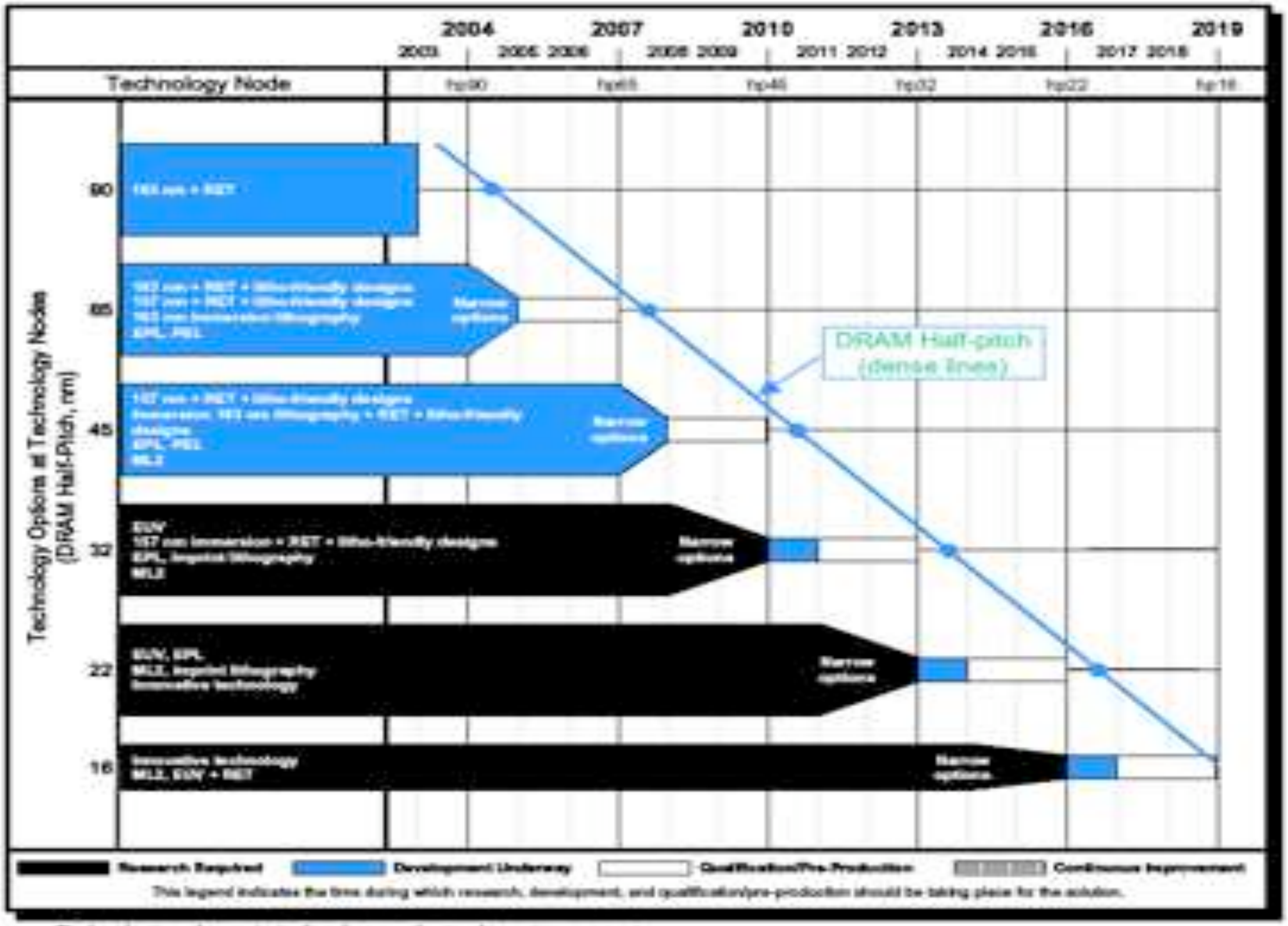
  - Unique environment in space
    - **radiation, temperature, micro-gravity, low power, resource limited**
  - Operation/Vehicle Safety
    - **environmental management, systems status and health monitoring**
  - Astronaut health and environment monitoring and countermeasures
    - **on-board and highly autonomous medical diagnosis and response capabilities with minimal resource requirement**
  - Unique measurements
    - **Low photon counts, long wavelength, extreme temperatures and pressures, harsh chemical environment, detect biomarkers in remote environments**
  - Isolation from Earth
    - **Need for low power, and high redundancy for increased autonomy because of communication delay**
    - **unique shelf life and reliability** requirements for decades in radiation fields.
    - **Materials with low outgas and devices with closely matched thermal expansion for thermal swings**
  - Intelligent, extremely small robotics systems for monitoring and science
    (NASA is the NNI lead agency for microcraft)
  - Highly specialized and low volume manufacturing requirements not met by commercial development

Capability 16.2 CBS Sensing and Devices

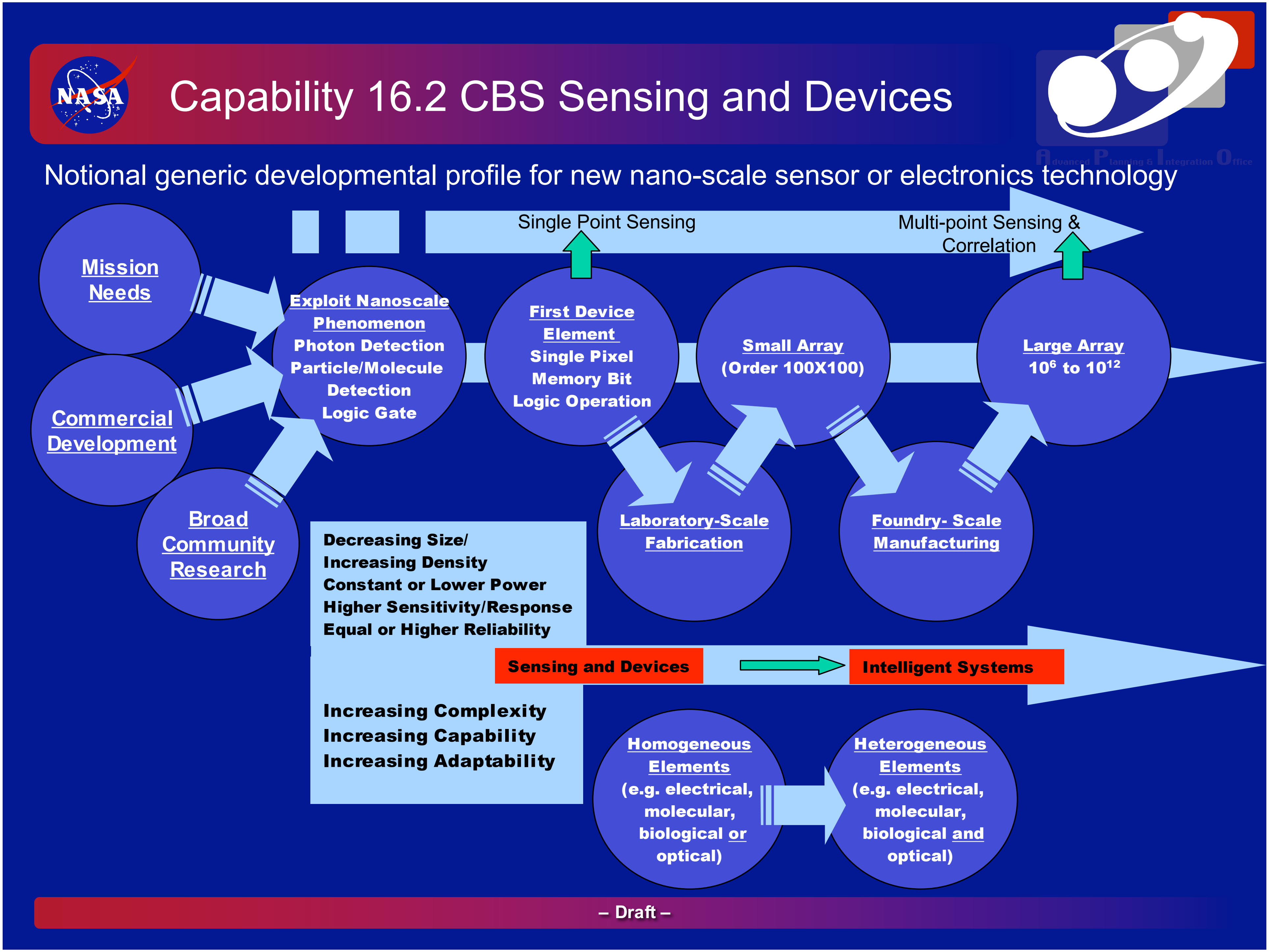
Key Assumptions:

- Developments under National Nanotechnology Initiative, and other funded nanotechnology research, will continue to advance state of the art
- Sensor community is very dynamic and will continue to develop new nano-scale technologies
- Path available to transition from TRL 4 to mission insertion
- Predictions of the state of nano-scale technology beyond about 2010 are highly speculative
- Wireless technology available for integration of sensors and devices
- Electronic device downscaling as per International Technology Roadmap for Semiconductors (ITRS).

International Technology Roadmap for Semiconductors (ITRS): Opportunity



Technologies shown in italics have only single region support.
RET—resolution enhancement technology EUV—extreme ultraviolet EPL—electron projection lithography
ML2—maskless lithography PEL—proximity electron lithography



Capability 16.2 CBS Sensing and Devices
Notional generic developmental profile for new nano-scale sensor or electronics technology
Single Point Sensing
Multi-point Sensing & Correlation
Mission Needs
Commercial Development
Broad Community Research
Exploit Nanoscale Phenomenon
Photon Detection
Particle/Molecule Detection
Logic Gate
First Device Element
Single Pixel
Memory Bit
Logic Operation
Small Array
(Order 100X100)
Large Array
10^6 to 10^{12}
Laboratory-Scale Fabrication
Foundry- Scale Manufacturing
Decreasing Size/
Increasing Density
Constant or Lower Power
Higher Sensitivity/Response
Equal or Higher Reliability
Sensing and Devices
Intelligent Systems
Increasing Complexity
Increasing Capability
Increasing Adaptability
Homogeneous Elements
(e.g. electrical, molecular, biological or optical)
Heterogeneous Elements
(e.g. electrical, molecular, biological and optical)
– Draft –

Capability 16.2 CBS Sensing and Devices

Key Relationships:

- Nanomaterials (16.1):
  Material developments will enable device improvements
- Nano Systems (16.3):
  Sensors/Devices will support development of Systems

- Sensors and Instrumentation (Capability 12):
  - Sensor component developments for In-Situ Sensing (12.6) and Direct Sensing of -- Fields, Waves and Particles (12.5)
  - Improved optical sources/detectors – for Multi-Spectral Imaging / Spectroscopy (12.2) and LASER/LIDAR Remote Sensing (12.4)
  - Principle source of relevant sensor priorities and metrics

- Autonomous Systems & Robotics (Capability 10)
- Human health and Support Systems (Capability 8
- Robotic Access to Planetary Surfaces (Capability 6)
- Advanced Modeling, Simulation and Analysis (Capability 14)

Capability Breakdown Structure

Advanced Planning & Integration Office

12.0 Science Instruments and Sensors

Chair: Richard Barney NASA/GSFC
Co-Chair: Maria Zuber
Deputy: Juan Rivera NASA/GSFC

12.1 Active and Passive Microwave Remote Sensing

Chair: Soren Madsen /JPL
Co-Chair: Chris Ruf/UM

- 12.1.1 Radar Altimetry
- 12.1.2 Real Aperture Radar
- 12.1.3 Synthetic Aperture Radar
- 12.1.4 Interferometric SAR
- 12.1.5 Radar Subsurface Sounding
- 12.1.6 Passive Microwave Real Aperture Imager
- 12.1.7 Passive Microwave Synthetic Aperture Imagers
- 12.1.8 Passive Microwave Sounder
- 12.1.9 GPS – Radio time-of-flight triangulation
- 12.1.10 Other Technology

12.2 Multi-Spectral Imaging/Spectroscopy (vis-IR-FIR)

Chair: Craig McCreight/ARC
Co-Chair: Ron Polidan/NGST

- 12.2.1 Visible Imagers, Photometers, Radiometers, Sounders
- 12.2.2 Visible Spectrometers / Interferometers
- 12.2.3 Visible Spectral (& hyperspectral) Images
- 12.2.4 IR/FIR Imagers, Photometers, Radiometers, Sounders
- 12.2.5 IR/FIR Spectrometers / Interferometers
- 12.2.6 IR/FIR Spectral (& hyperspectral) Images

12.3 Multi-Spectral Imaging/Spectroscopy (UV-Gamma)

Chair: Brian Ramsey/MSFC
Co-Chair: David Chenette/LM

- 12.3.1 UV Imaging and Spectrometry
- 12.3.2 X-Ray Timing and Polarimetry
- 12.3.3 X-Ray Interferometry
- 12.3.4 Gamma Ray Imaging and Spectrometry

12.4 Laser/LIDAR Remote Sensing

Chair: Maria Zuber/MIT
Co-Chair: Richard Barney/GSFC

- 12.4.1 Altimeters
- 12.4.2 Transponders
- 12.4.3 Atmospheric LIDARS
- 12.4.4 Spectrometers
- 12.4.5 Interferometers

12.5 Direct Sensing of Fields, Waves, and Particles

Chair: Dick McEntire/APL
Co-Chair: Carl Stahl/GSFC

- 12.5.1 Energetic Particle and Plasma Imagers and Spectrometers
- 12.5.2 High Energy Particle Detector Systems
- 12.5.3 Magnetometers
- 12.5.4 Electric Fields and Waves Instruments
- 12.5.5 Gravitational Waves and Fields Instruments

12.6 In Situ

Chair: Tim Krabach/JPL
Co-Chair: Rich Dissly/BATC

- 12.6.1 Imaging/Microscopy
- 12.6.2 Mineralogical/Elemental Analysis
- 12.6.3 Chemical Detection & Identification
- 12.6.4 Isotope Analysis/Age Dating
- 12.6.5 Biological Detection and Identification
- 12.6.6 Geophysical Measurements
- 12.6.7 In Situ Instrument Engineering
- 12.6.8 Fundamental Technologies and Components

Draft – 02/05

Specific Potential Connectivity to Sensors and Instruments CRM

Advanced Planning & Integration Office

Microwave Instruments and Sensors

- Massively parallel digital correlators - nanoelectronics

Active and Passive Microwave Remote Sensing

- Radiation hardened processors - nanoelectronics

Note: Radiation hardened electronics is a critical cross-cutting technology area for science instruments and sensors

Multi-spectral, VIS-IR-FIR

- Single photon counting sensing in FIR - sensors
- Readout electronics (ex: single electron transistor) - nanoelectronics
- Example: InSb nanowire hyperspectral IR detector, superior to today's technololgy in terms of quantum efficiency, higher operating temperature and sensitivity further into the IR.

Specific Potential Connectivity to Sensors and Instruments CRM

Multi-spectral, UV-Gamma

- Mega-channel, radiation hard analog electronics - nanoelectronics

Laser/LIDAR

- Higher power lasers which have lifetimes of 5 years - sensors/devices

Direct Sensing of Particles, Fields, and Waves

- Low power, radiation hard, fault tolerant nanoelectronics: emphasis on operation in more radiation harsh, and small satellite constellations
- Miniaturized and sensitive magnetometers - sensors
- High power laser (up to 300 W!) to operate for 5 years - sensors/devices

In-Situ

- Biomarker detection - sensors
- Chemical identification at high spatial resolution - sensors

Capability 16.2 CBS Sensing and Devices

Advanced Planning & Integration Office

Electronic Devices

- Micro/Nano Electronics

    CMOS-Based device technologies (TRL 4-8, various ITRS nodes)

- Energy Conversion

    Example: Thermoelectrics (Devices: TRL 1; Materials: TRL 2-3)

- Sources (x-ray, optical)

    Example: Miniaturized X-Ray Source (TRL 5)

- Memory

    Example: CNT based memory (TRL 2-4)

    Nanowire based memory (TRL 2-3)

    Representative Examples in Appendix

Nano-electronics: Opportunities and Challenges

Advanced Planning & Integration Office

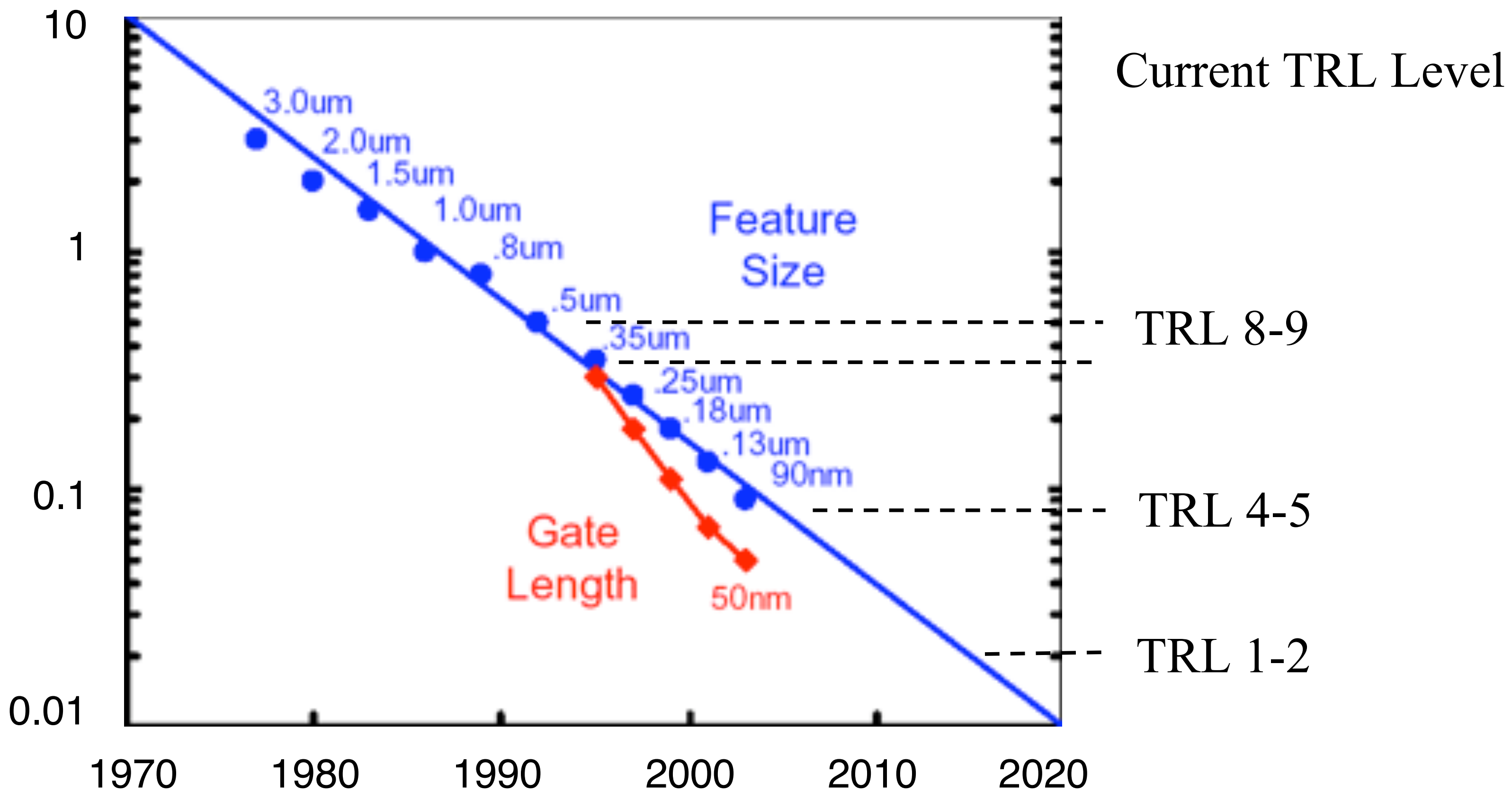
Challenges:

- Stay on the ITRS Roadmap
- Assuring space durability
- Develop of reliable designs and fabrication methods for nano-scale devices suitable for heterogeneous integration
- NASA space-qualified electronics ~3 generations behind ITRS roadmap

Opportunities:

- Semiconductor industry is initiating new partnerships with government and academia (including National Research Initiative)
- Partnership with industry can advance technologies for both commercial, NASA needs
- Participation by NASA can ensure that NASA-specific needs are addressed in technology development

Micro-electronics is becoming Nano-electronics



www.intel.com/research/silicon/90nm_press_briefing-technical.htm

Capability 16.2 CBS Sensing and Devices

Advanced Planning & Integration Office

Sensing Devices

- Devices for Chem/Bio sensors (TRL 2-3)

  Example: Conductance-based devices (e.g.nanowires)

- Bioassay/virus/other bioparticles (TRL 1-3)

  Example: Mass/Resonance based (e.g. cantilever)

- Devices/materials for in-situ, optical-based spectroscopy (TRL 2)

  Example: Surface Enhanced Raman (SERS) using nanoparticles)

- LASERs and Photonic/Optoelectronic devices for remote sensing/imaging (TRL 2-3)

  Example: Devices employing quantum dots for multi-wavelength detectors, imagers

Representative Examples in Appendix

Nano-sensors: Opportunities and Challenges

Advanced Planning & Integration Office

Challenges:

- Sensor industry not as centralized as microelectronics industry
- Many potential species/quantities to sense
- Many emerging approaches to sensing and electronics: “winners” still TBD

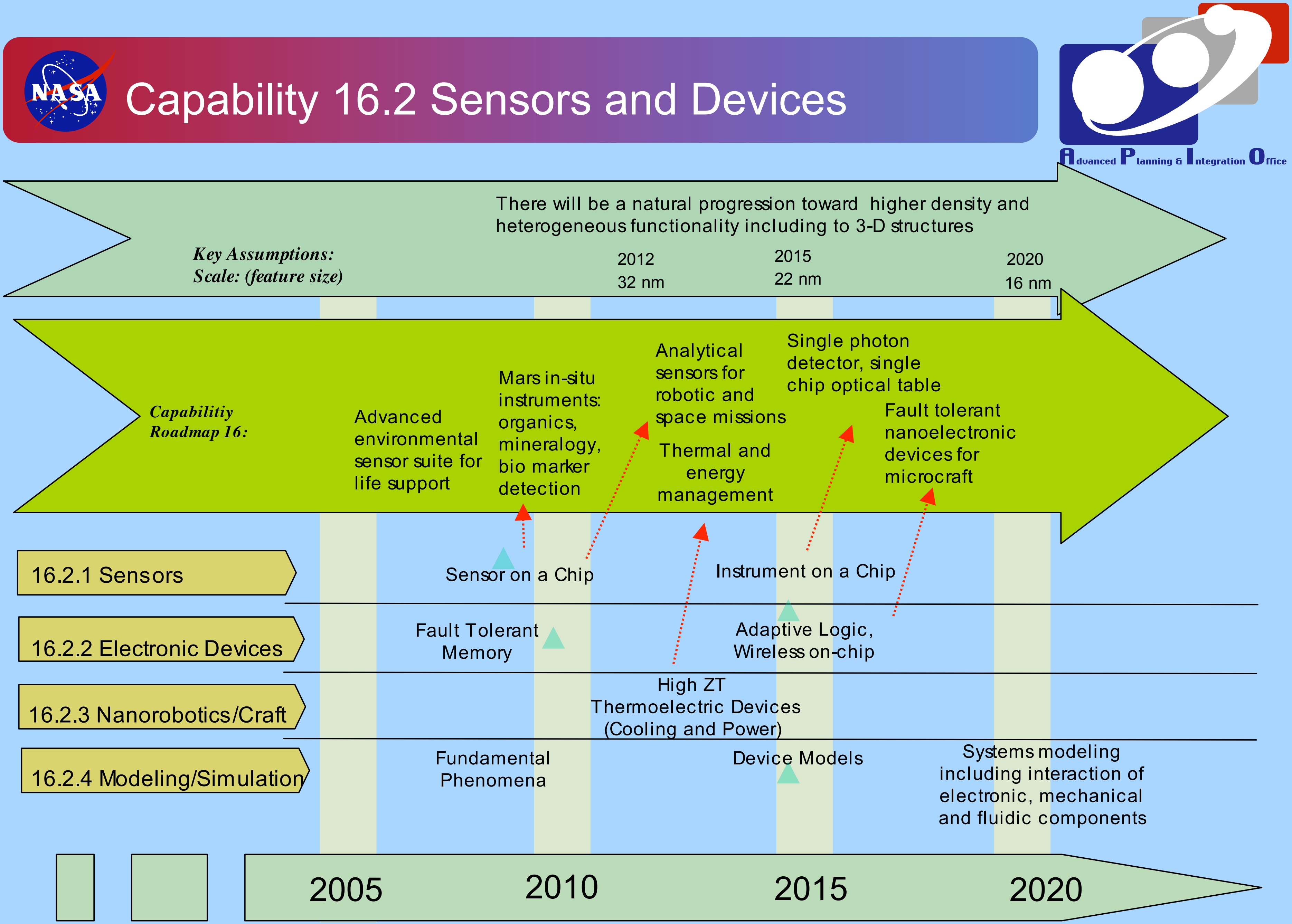
Opportunities:

- Strategic investment will be leveraged with dual-use developments
- Nanosensors will enable miniature instruments for rovers, microcraft, spacecraft

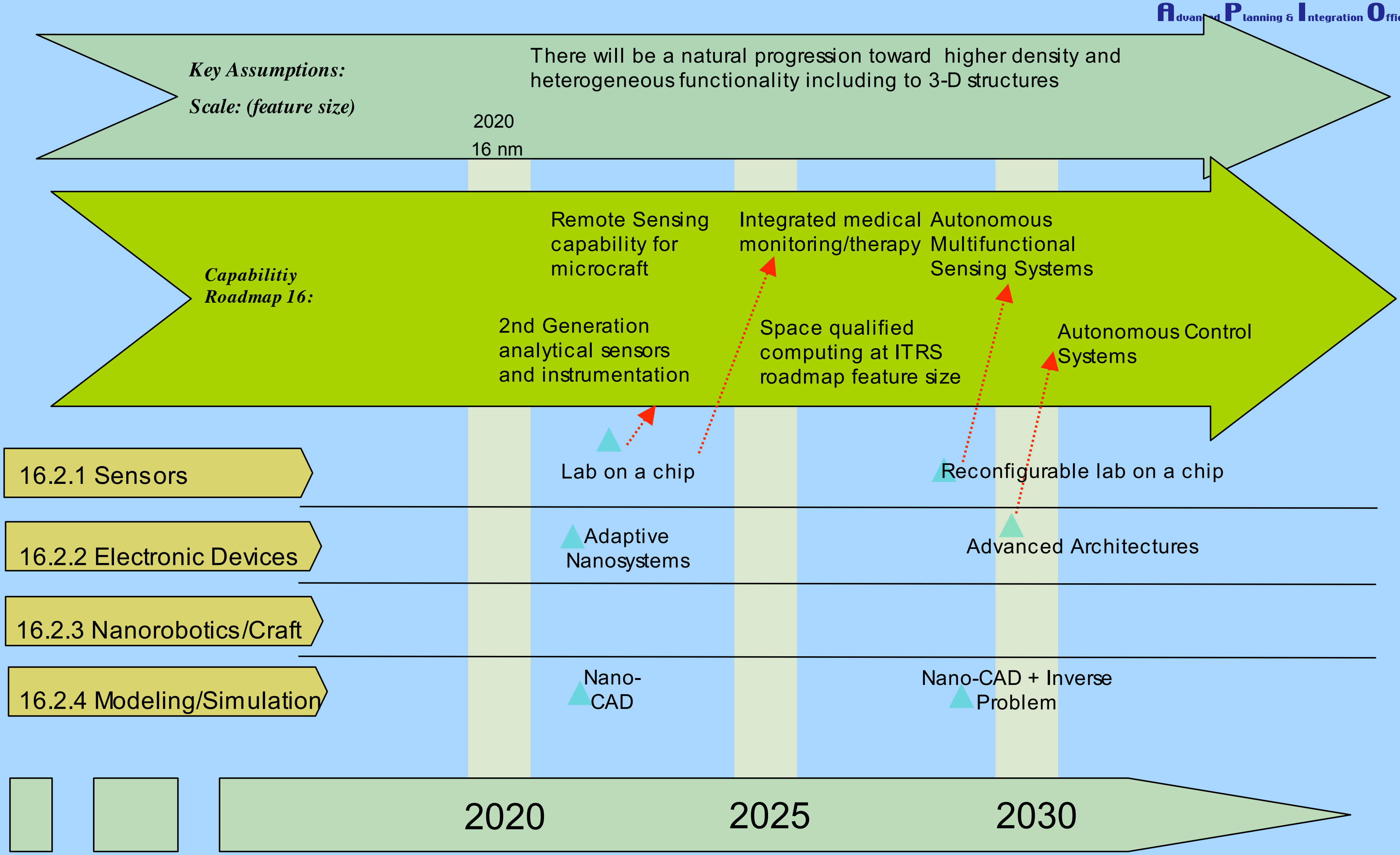
Draft: Roadmaps

- Roadmaps are currently draft only
- Represent first cut at organizing needed technological capability and timelines when it may be available
- Will be modified as more definitive priorities and roadmaps are produced by other capability road mapping teams

Capability 16.2 Sensors and Devices



Capability 16.2 Sensors and Devices



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Detailed Roadmaps

Capability 16.2 Nanotechnology Roadmap

Advanced Planning & Integration Office

Key Assumptions:
ITRS roadmap
NNI roadmap

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

2012 32 nm | 2015 22 nm | 2020 16 nm

Capability Roadmap 16:

Advanced environmental sensor suite for life support

Advanced sensor suite for Earth science

Sensor Constellations, multipoint environmental

Vehicle health monitoring

Sensor Constellations, multipoint environmental

Advanced sensor suite life detection

16.2.1 Sensing — Sensor on a chip — Instrument on a chip — Lab on a chip

Chem Bio:	Multiplex sensing components		Single chip sensing, bioassays	Health monitoring suite
Photon:	Discrete sources/detectors		Single photon detector, single chip optical table	Network of optical sensor chips
State Variables/ Particles:		Imbedded sensors for structural integrity	Imbedded sensors for structural integrity and performance	
Sensor Systems:			Wireless comm for distributed sensors	Distributed sensors with Integrated communication
Extreme environment operation:	High Temperature 150-400K		High Radiation, temp and pressure	Venus conditions

2005 | 2010 | 2015 | 2020

Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
ITRS roadmap
NNI roadmap

2020
16 nm

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

Capability Roadmap 16:

Multifunctional Microcraft/ Microrovers

Advanced Life Support System

16.2.1 Sensing

Lab on a chip — Reconfigurable lab on a chip

	2020	2030
Chem Bio:	Health monitoring suite	Automatic health monitor/ response, Integrated Trigger
Photon:	Network of optical sensor chips	
State Variables/		
Particles: Sensor Systems:	Distributed sensors Integrated communication	Large-scale wireless sensor systems
Extreme environment operation:	Venus conditions	Near-Sun conditions

2020 2025 2030

Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
ITRS roadmap
NNI roadmap

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

2012 32 nm

2015 22 nm

2020 16 nm

Capability Roadmap 16:

On-chip interfaces and controls for advanced instruments

Highly reliable non-volatile on-board memory

On-board computing near ITRS performance levels

16.2.2 Electronics	Fault Tolerant Memory		Adaptive Logic	Adaptive Nanosystems
General Computation:	Low power, fault tolerant memory architecture; demos of nanoelectronics in extreme environments		Low power, adaptive logic; NASA electronics near ITRS performance	Self-adaptive/ configurable NASA electronics at ITRS performance
Sense and control:		On-chip interfaces and controls	Ultra-low noise electronics for sensors	Integrated sense/ computing
Special purpose:			On-chip photovoltaics Flexible electronics	THz Local Oscillator

2005 2010 2015 2020

– Draft –

Capability 16.2 Nanotechnology Roadmap

Advanced Planning & Integration Office

Key Assumptions:
ITRS roadmap
NNI roadmap

2020
16 nm

There will be a natural progression toward higher density and heterogeneous functionality including to 3-D structures

Capability Roadmap 16:

Rad-hard, fault tolerant electronics
Pico probes

16.2.2 Electronics

Adaptive Nanosystems

Advanced Architectures

General Computation:

Self-adaptive/ configurable

NASA electronics at ITRS performance

Spintronics

Quantum computing

Integrated sense/control:

Integrated sense/ electronics

Special purpose:

THz Local Oscillator

Ultra-sensitive atomic interferometric gyroscope

2020 | 2025 | 2030

Capability 16.2 Nanotechnology Roadmap

Key Assumptions:
ITRS roadmap
NNI roadmap

2012	2015	2020
32 nm	22 nm	16 nm

Capability Roadmap 16: Thermal and Energy Management

16.2.3 Nanorobotics TBD TBD TBD TBD

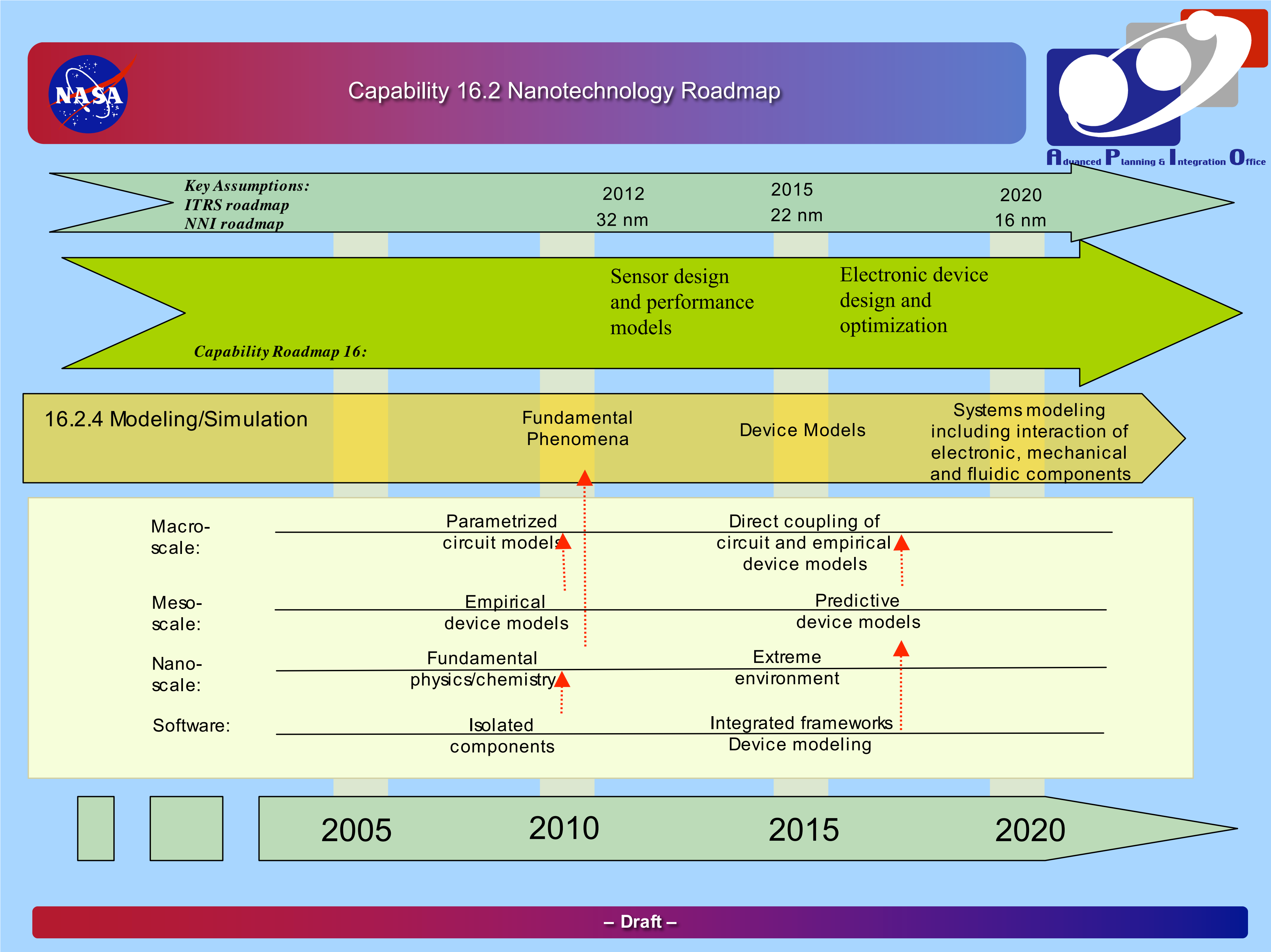
Incomplete

NEMS Devices

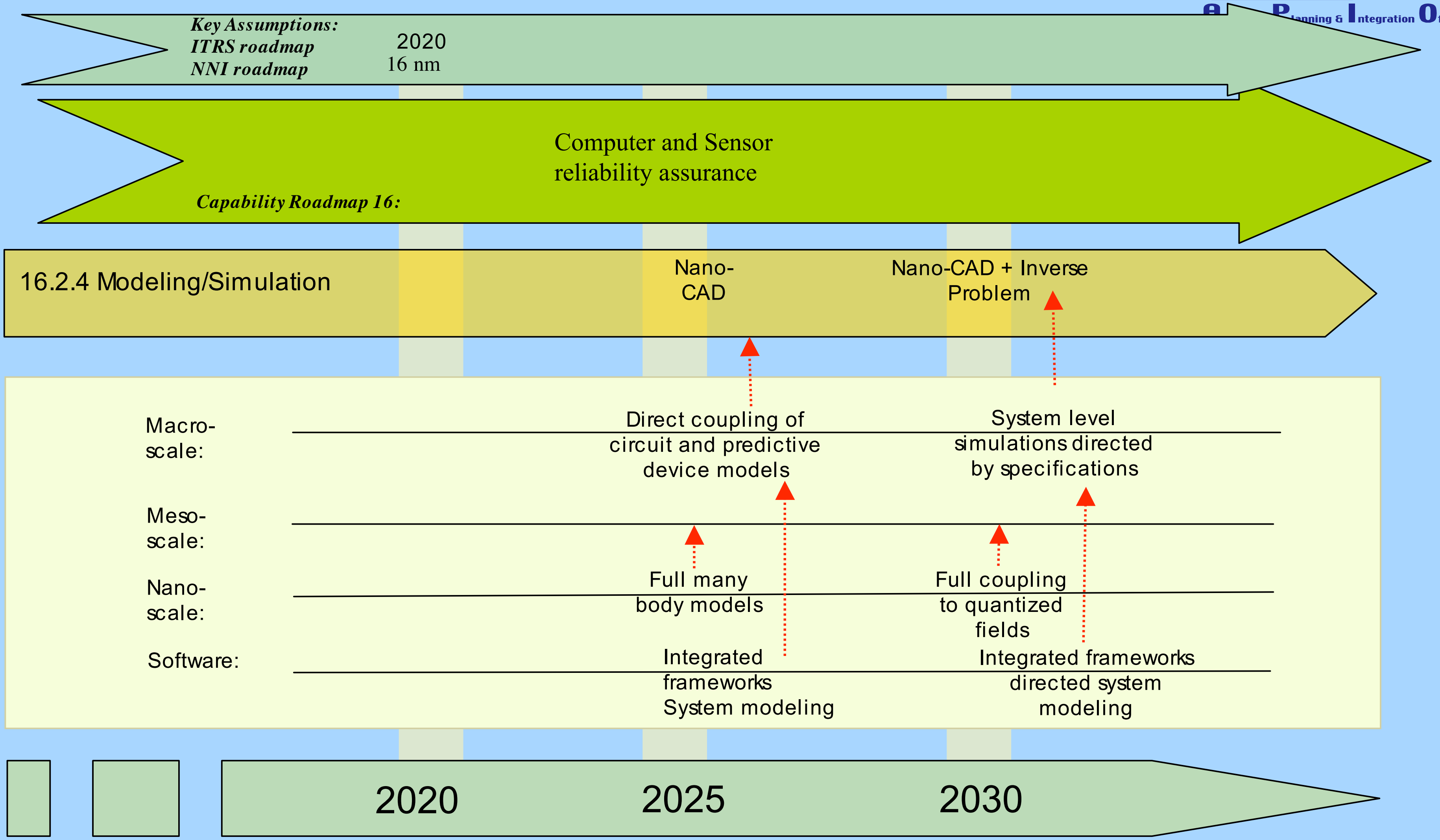
Thermal Management: High ZT Thermoelectric Devices (Cooling and Power)

Computing

2005 2010 2015 2025 2030


Capability 16.2 Nanotechnology Roadmap
Advanced Planning & Integration Office
Key Assumptions:
ITRS roadmap
NNI roadmap
2012
32 nm
2015
22 nm
2020
16 nm
Sensor design and performance models
Electronic device design and optimization
Capability Roadmap 16:
16.2.4 Modeling/Simulation
Fundamental Phenomena
Device Models
Systems modeling including interaction of electronic, mechanical and fluidic components
Macro-scale:
Parametrized circuit models
Direct coupling of circuit and empirical device models
Meso-scale:
Empirical device models
Predictive device models
Nano-scale:
Fundamental physics/chemistry
Extreme environment
Software:
Isolated components
Integrated frameworks Device modeling
2005
2010
2015
2020
– Draft –

Capability 16.2 Nanotechnology Roadmap



– Draft –

Appendix I – Representative Examples of Nano Devices/Sensors

(used in evaluating connectivity to other CRM areas and TRL levels)

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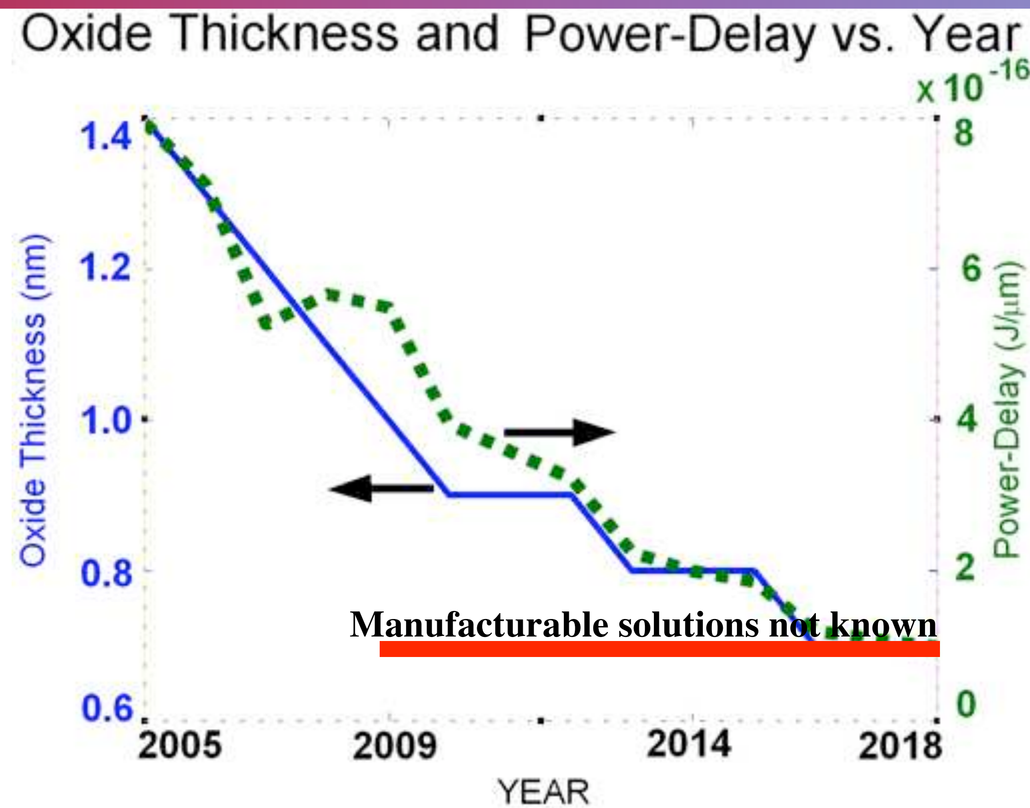
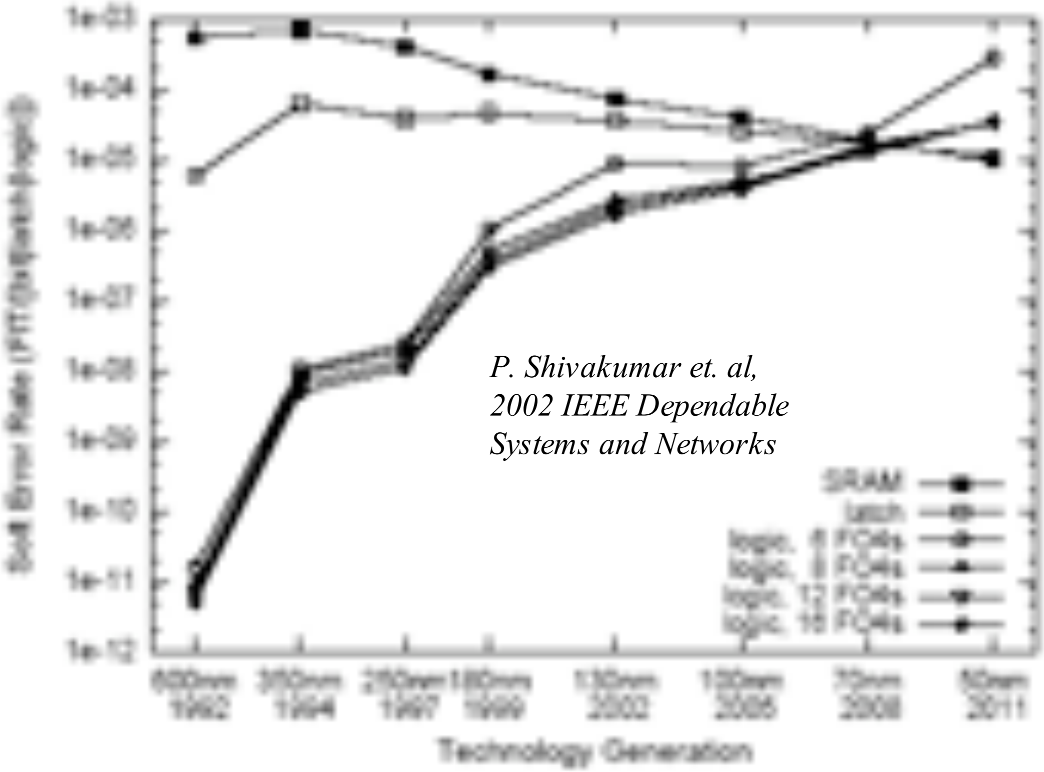


- Manufacturable solutions do not exist
  - Oxide thickness scaling, gate capacitance
  - Source-drain resistance
  - Reliable interconnects
- Power delay product is large making chips hot

Downscaling of electronics has major bottlenecks

Soft Error Rate (SER)



- SER of a single SRAM decreases with technology generation
- SER of logic increases → Decrease in critical charge involved in latchup

Fabrication and design to avoid latchup become increasingly important

Thermoelectric Energy Conversion

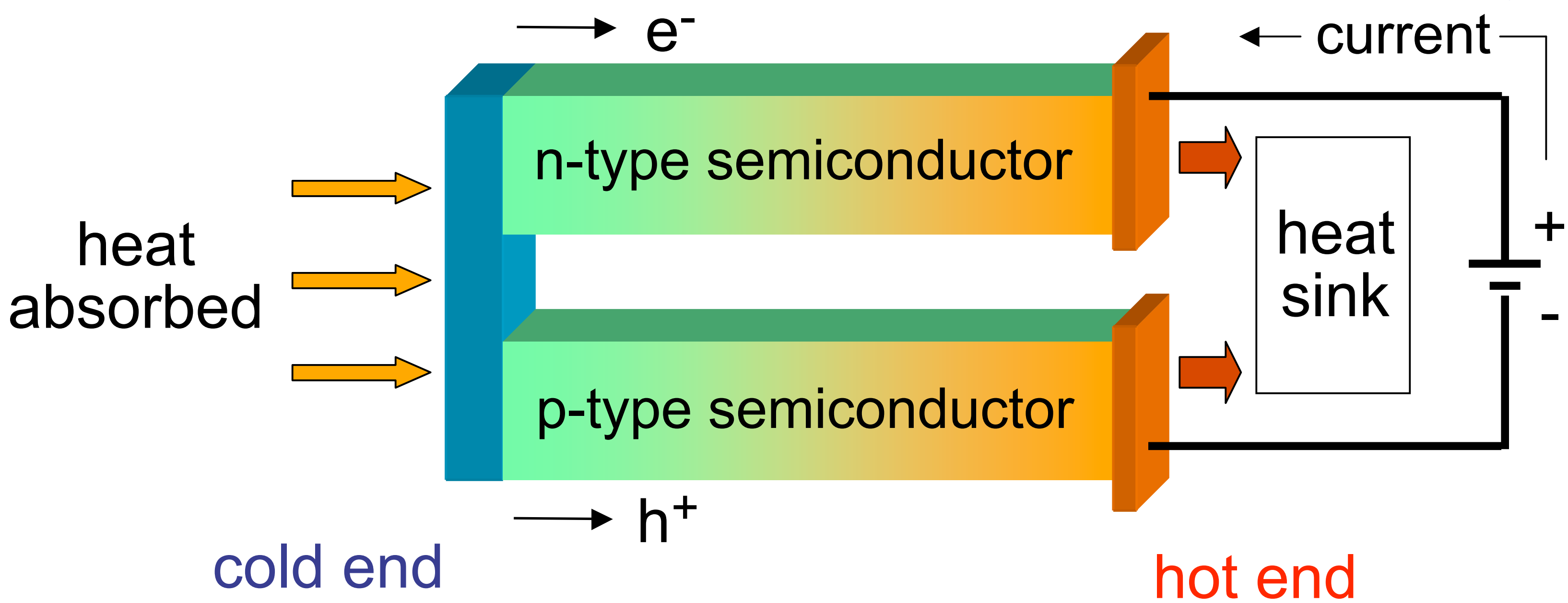


Figure of Merit:

$$ZT = \frac{S^2\sigma}{\kappa} T$$

Large Seebeck Coefficient (S)
Small Thermal Conductivity (κ)
Large electrical conductivity (σ)

In bulk materials, maximum ZT ~ 1

Little progress in 20 years.

Need ZT ~ 4 to displace with other technologies

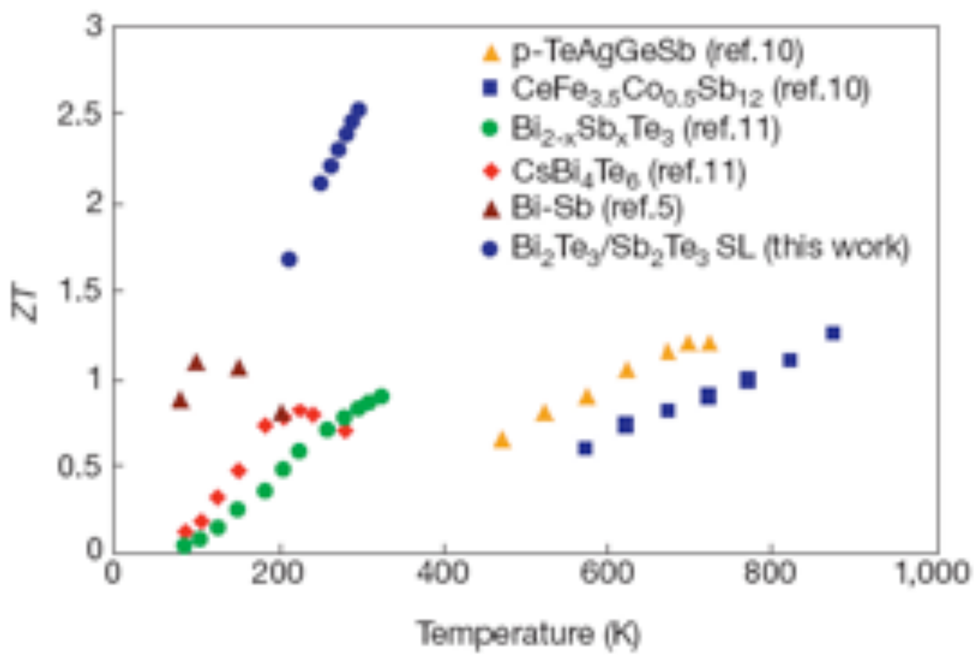
Thermoelectric Energy Conversion

Advanced Planning & Integration Office

Nanostructuring materials to improve ZT

Two Dimensional Superlattices

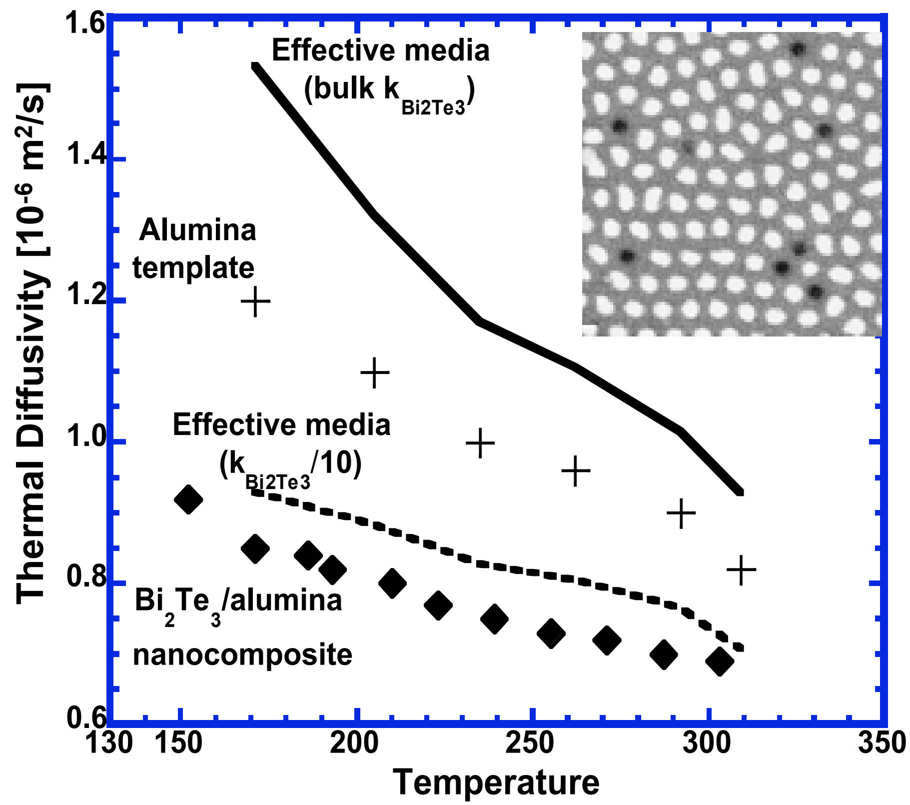
Bi_2Te_3/Sb_2Te_3



Venkatasubramanian, et al. (GTRI), Nature **413** p. 597 (2001)

Arrays of One-Dimensional Wires

(50 nm Bi_2Te_3 wires in nanoporous alumina)

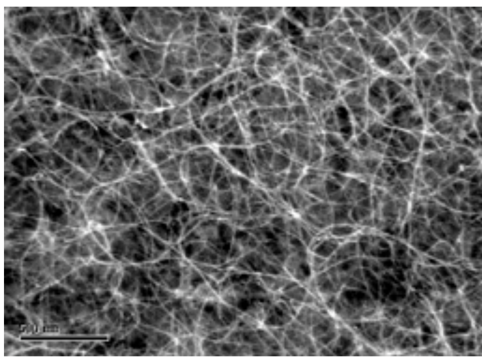


Source: Tim Sands, Purdue

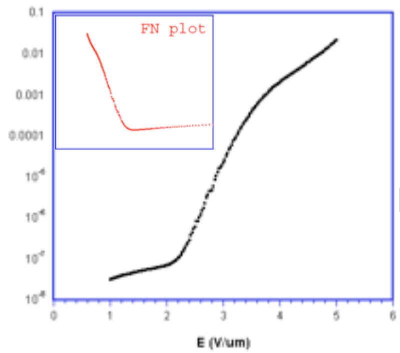
Carbon Nanotube Field Emission

Carbon-Nanotubes: Sharp local tips provide efficient field emission
Miniature X-Ray tube: slated for 2009 NASA mission

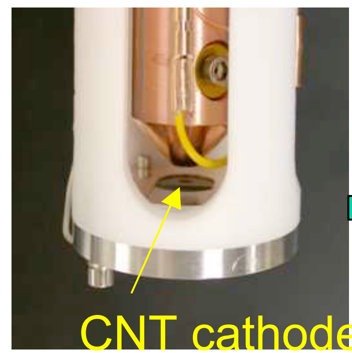
Ames Research Center



CNT emitter fabrication
NASA Ames



Field emission characterization
NASA Ames



Integration in miniature X-ray tube
(Oxford XTG Inc.)

- SWNT - MWNT - nanofibers
- Silicon and metal substrates
- Film, arrays

➢ Optimum type of CNT?

➢ Optimum CNT/substrate attachment?

➢ Optimum site density?

Surface Enhanced Raman Scattering (SERS) enhancement Using Nanostructured Surface

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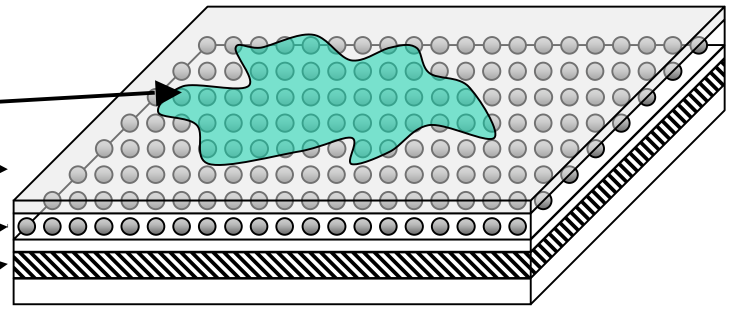
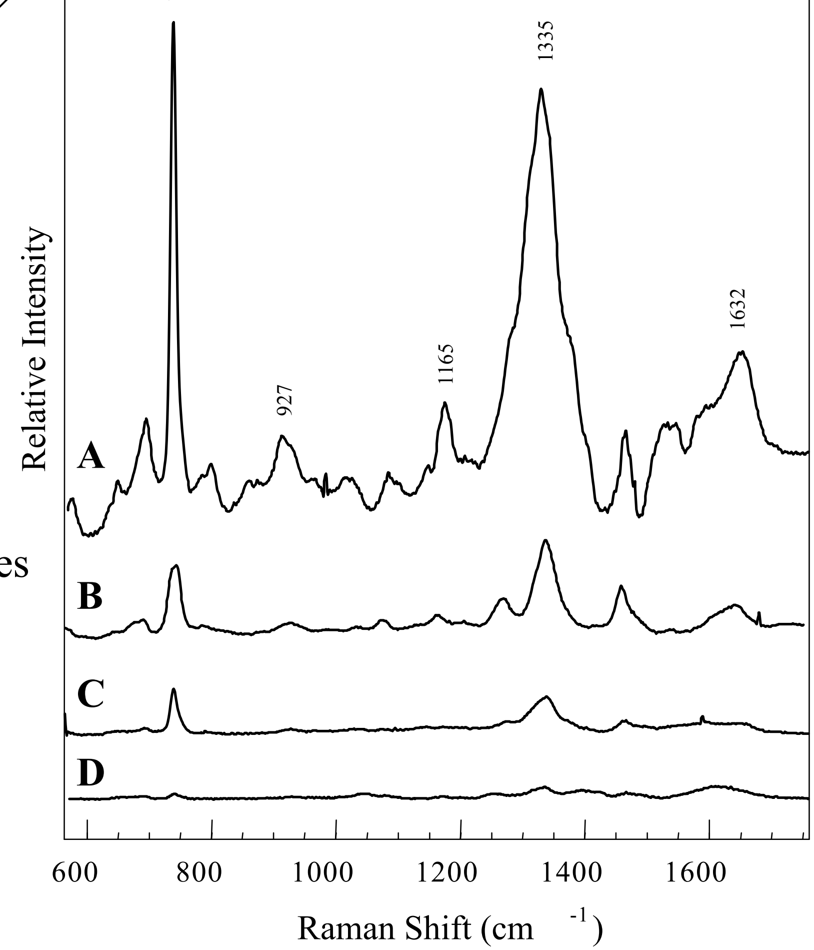


Nanoparticle based structure is produced by self assembly of particles that create a substrate for use in Surface Enhanced Raman Spectroscopy (SERS).

(A) on plasmon resonant substrate with metal nanoparticles (460 nm plasmon maximum), (B) on electrochemically roughened Ag electrode, (C) on laser ablated Ag films (old), and (D) on laser ablated film (new).

Raman signal enhancement for adenosine base subunit of DNA:

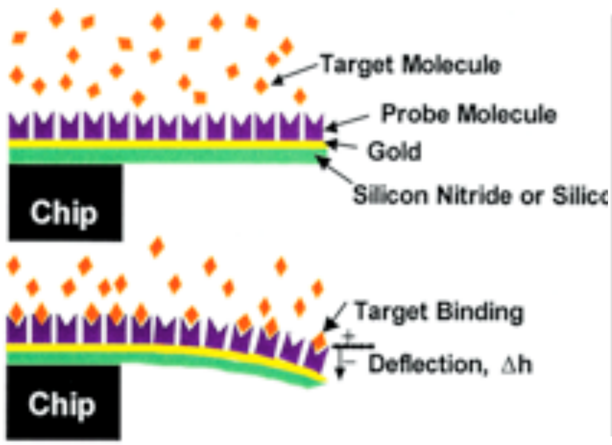


Source: Viktor Stolc, NASA Ames Research Center

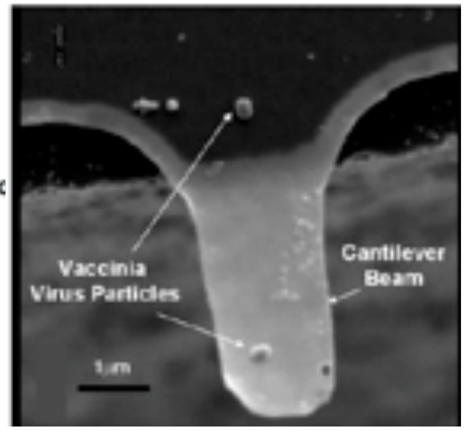
Ames Research Center

Biosensor

- Optical, Electrical, Mechanical methods for detection



Cantilever based sensor
Wu, PNAS (2001)



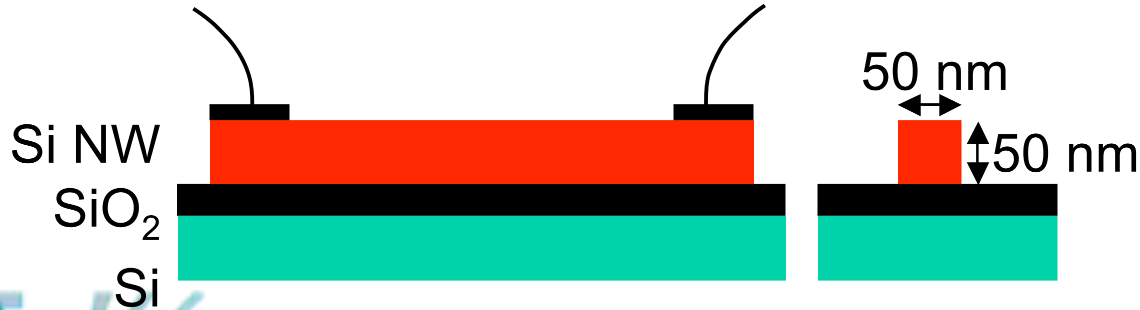
Mass sensing of single virus,
Gupta et. al, APL (2004)

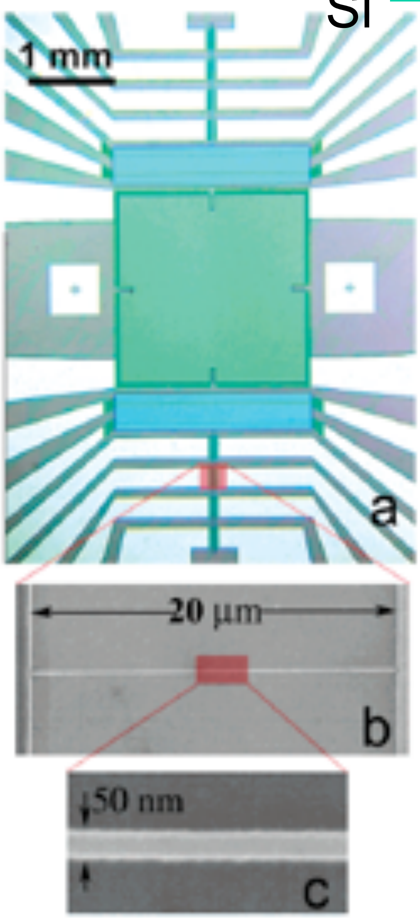
Silicon Nanowire (20 nm) based
DNA sensor, Hahm, Nanolett (2004)

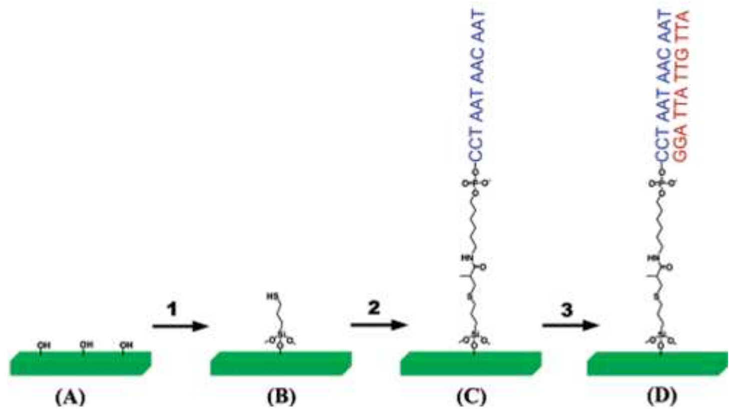
100 fM DNA solution

- Label free detection of biomolecules in real time
- Cantilever Bending: Probe is attached to top surface. Hybridization causes bending
- Nanowire: Charge of biomolecule affects electrical current in nanowire / nanotube
- Detection of mutation causing cystic fibrosis is demonstrated
- Ultra low detection limits, single particle detection in some cases

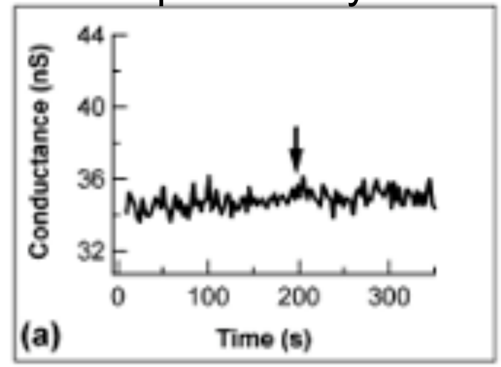
Electron-beam fabricated SOI DNA sensor



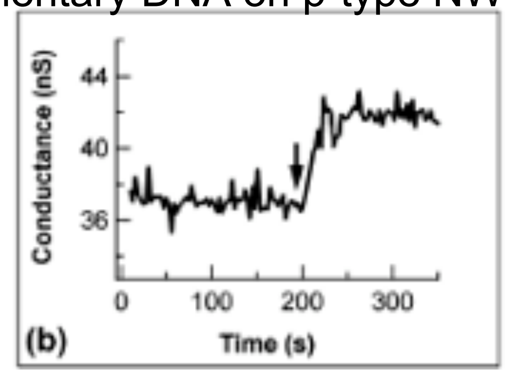




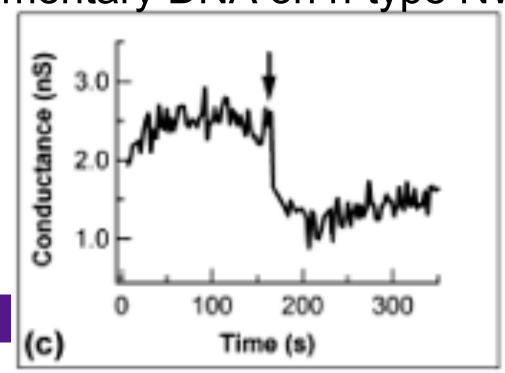
Noncomplementary DNA



Complementary DNA on p-type NW



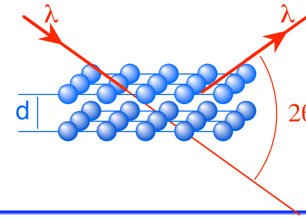
Complementary DNA on n-type NW

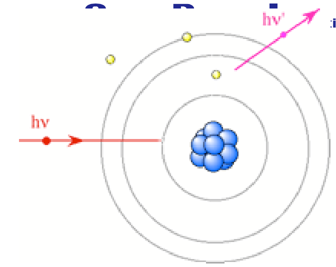


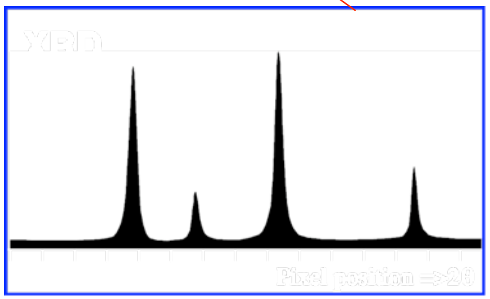
"Sequence-Specific Label-Free DNA Sensors Based on Silicon Nanowires," Z. Li, Y. Chen, X. Li, T. I. Kamins, K. Nauka, and R. S. Williams, Nano Letters **4**, 245-247 (2004).

Chemistry & Mineralogy

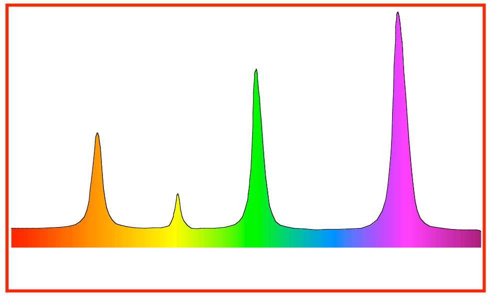
- DETECTOR
- SIMULTANEOUS ANALYSES
- NO MOVING PARTS



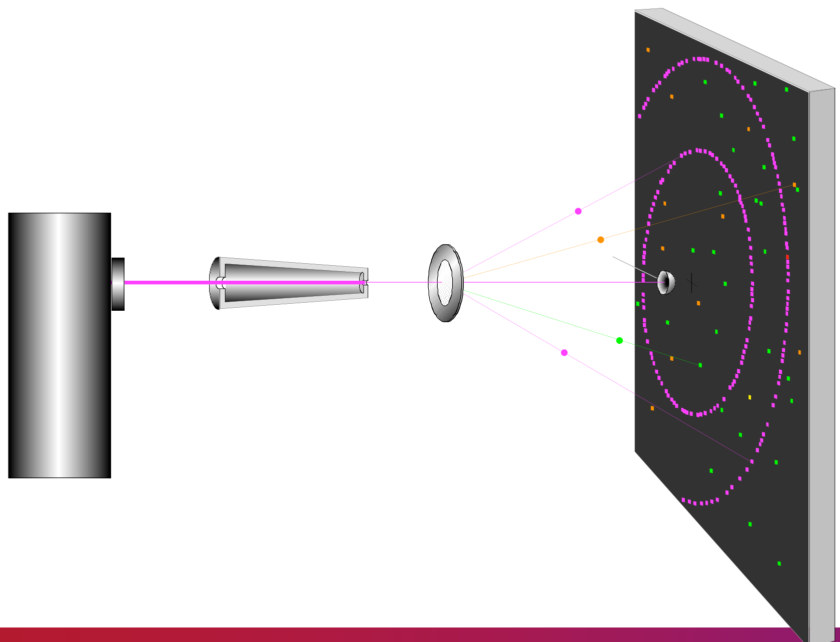




X-ray diffraction



X-ray fluorescence



- Carbon nanotube field emitters
- Low threshold for emission
- Volume < 10 liter (1 liter)
- Mass < 5 kilogram (1 kg)
- Power < 15 Watts (5 W)

Appendix III – Representative Example of potential (and actual) applications in Missions:

In-Situ Science Instruments for Mars

Mars Science in-situ Instruments

Office

Astrobiology Field Lab

Life Bio-markers
Detection and Identification

Mars Science Laboratory

Organic Detection & Mineralogy

Phoenix

Chemical Analysis & Microscopy

Capability

Time

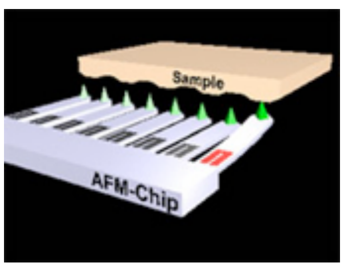
– Draft –

Selected In-situ Instruments for Future Mars Missions

Mars 2007 = Phoenix

Chemical analysis& Microscopy

- Thermal and Evolved Gas Analyzer (TEGA)
- Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)



The atomic force microscope will provide morphology images down to 10 nanometers--the smallest scale ever examined on Mars.

Mars 2009 = Mars Science Laboratory

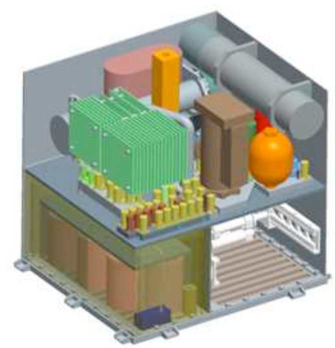
Organic Detection & Mineralogy

Sample Analysis at Mars (SAM)

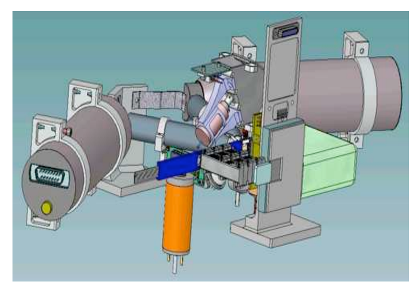
- Gas Chromatograph
- Mass Spectrometer
- Tunable Laser Spectrometer
  - Detection sensitivity of **ppm-ppb**

CheMin

- X-Ray Diffraction/X-Ray Fluorescence Instrument
  - (grain size 150 micron)



3D model of SAM Instrument

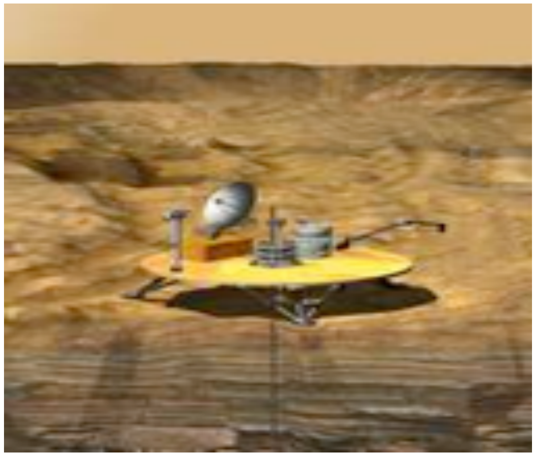


3D model of the CheMin instrument

Detection and identification of life bio-markers

- **Meso-Micro Scale Imaging**
- **Microscopy**
- **Mineralogical/Elemental Analysis**
- **Isotope Analysis/Age Dating**
- **Bio-Sensors**
- **Geophysical & Geochemical Measurements**

Astrobiology Field Lab



Deep Drill Lander

- Compact multi-hyper spectral imagers
  - E-beam fabrication of analog-relief diffractive optics
- Miniaturized Scanning electron microscopy,
  - Sub nm resolution imaging
- Light and tip enhanced AFM,
  - Sub nm resolution imaging
- Fluorescent nano-particulate tagging
- Nano structures based sources (UV, X-Ray, IR)
- Micro-nano electrodes,
- Micro-nano manipulators,
- Array of Ion channel sensors
- Array of nano sensors
- Micro-nano fluidics

- Measure pH, temperature, conductivity, and concentrations of major ions and redox sensitive aqueous compounds, including O_2, H_2, HCO_3^-, NO_3^-, Fe^{2+}, SO_4^{2-}, H_2S, NH_4^+ *(e.g., microelectrodes, micromanipulators).*
- Determine presence (if possible, concentrations) of DOC and aqueous organic monomers, including carboxylic acids, amino acids, sugars, hydrocarbons and/or corresponding functional groups *(e.g., liquid and gas chromatography, IR).*
- Determine presence (if possible, sequence or composition) of aqueous and particulate organic polymers, including proteins, lipids, nucleic acids, saccharides.
- Attempt to visualize and enumerate variably stained microbial cells in suspension or on particulate matter *(e.g., light or scanning electron microscopy, microspectroscopy, fluorescent nanoparticulate tagging)*.
- Consider culturing on 1-3 samples using ~10-100 pre-designed growth media at several different temperatures *(microfluidics, microculturing, "lab-on-a-chip")*.

Appendix IV – Excerpts from NNI Grand Challenges Workshop on

NATIONAL NANOTECHNOLOGY INITIATIVE

Advanced Planning & Integration Office

Biotechnology

Nanotechnology

NNI
“Research Directions II”
Workshop

September 8-10, 2004
Washington, D.C.

Grand Challenge: Microcraft & Robotics

Information Technology

Summary Quad Charts for: Nano-Sensor and Instrumentation Nanorobotics

– Draft –

Nano-sensors and Instrumentation

Goals

Enable missions with nano-sensors:

- Remote sensing
  - Viewing there
- Vehicle health and performance
  - Getting there
- Geochemical and astrobiological research
  - Being there
- Manned space flight
  - Living there

Hard Problems

- Band-gap engineered materials
- Control Atomic layers of substrates
- Template pattern controls
- Dark current reductions
- Readout electronics
- Assembly of large arrays
- Modeling, simulation and testing
- Upward integration into macro-systems

Value to Space Systems

- 10X to 100X smaller, lower power & cost
- Tailorable for very high quantum efficiency
- Tailorable for space durability in harsh environments
- Improved capabilities at comparable or reduced cost
- Mission enabling technology

State of the Art (all ground based)

- Designer bio/chemical sensors
  - Characteristic Properties of Molecules
  - Functionalized structures (CNTs, etc.)
- Assembly of nano-structures
  - Template development
  - Electro-static control
  - Nano-fluidics/separation tools

Nanorobotics

Goals

- Millimeter and sub-millimeter size robots
- 3D nanoassembly and nanomanufacturing
- Self-reconfigurable miniature robots
- Controlling biosystems
- Hybrid (biotic/abiotic) robots
- Cooperative networks of micro-robots
- Atomic and molecular scale manufacturing
- Design and simulation tools for nano-robots

Hard Problems

- **Mobility**: Surface climbing, walking, hopping, flying, swimming; Smart nanomaterials for adhesion, multi-functionality, …
- **Power**: Harvesting; Novel miniature power systems (e.g. chemical energy); Wireless
- **Actuation**: CNT, polymer, electrostatic, thermal, SMA, and piezo actuators
- **Complexity**: New programming methods for controlling massive numbers of robots

Value to Space Systems

- In-space (CEV, space station, Hubble telescope, & satellites) and planetary inspection, maintenance, and repair
- Searching for life on planets (retrieving and analyzing samples)
- Astronaut health monitoring
- Assembly and construction
- Manufacturing on-demand
- Microcraft

State of the Art

- **Miniature Micro/Nano-Robots:** Centimeter scale autonomous robots; Chemically powered bio-motor actuation; Endoscopic micro-capsules; MEMS solar cells powered micro-robots; Reconfigurable mini-robots
- **Micro/Nano-Manipulation:** Scanning Probe Microscope based nanomanipulation; 3D micro-assembly; Optical tweezers and dielectrophoretic bio-manipulation; Virtual Reality human-machine user interfaces

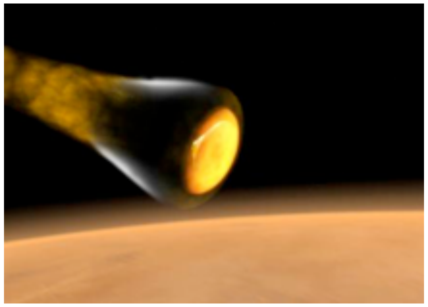
Advanced Planning & Integration Office

Intelligent / Integrated Systems

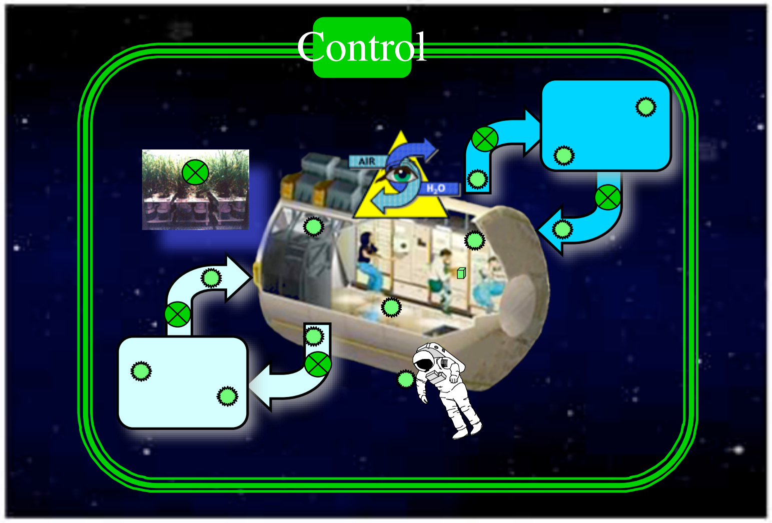
Capability 16.3 Intelligent Systems

Presenter/Team Lead:
Chih Ming Ho, UCLA
chihming@ucla.edu
Co-Lead:
Benny Toomarian - JPL
Team Members:
Minoo Dastoor – NASA HQ
Jose Fortes - Univ. of Florida,
Dan Herr - SRC,
Dimitris Lagoudas - Texas A&M Univ.
Stan Williams - HP Labs

- Principles, frameworks, and nano-components for the design, fabrication, integration of mission-appropriate intelligent systems capable of continua of awareness.



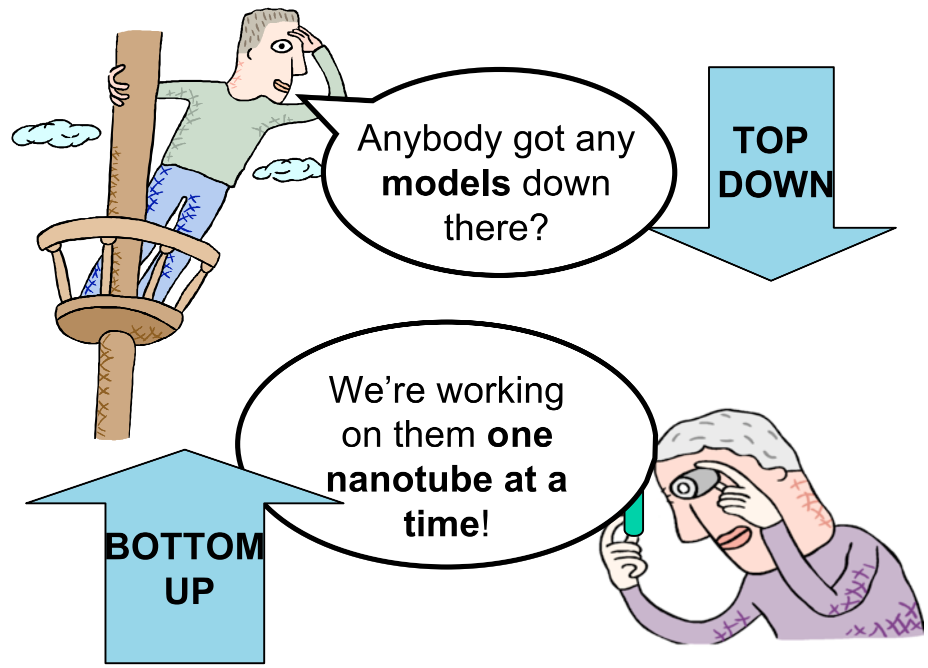
Guided entry for energy dissipation or precision / pinpoint landing



Monitoring & Controlling the environment

Key technical challenges:

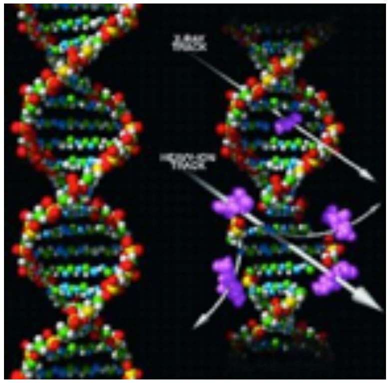
- Multiscale hierarchical models **for analysis and prediction /design /synthesis of intelligent systems.**
- Multiscale manufacturing processes **(that can encompass the nano, micro and the macro scales).**
- Interconnectivity **for signal and material transports**
- Preservation and utilization of nano-properties **at the device and system levels.**
- Information representation **and processing models and architectures from the nano scale to the macro scale that are well suited to emergent**



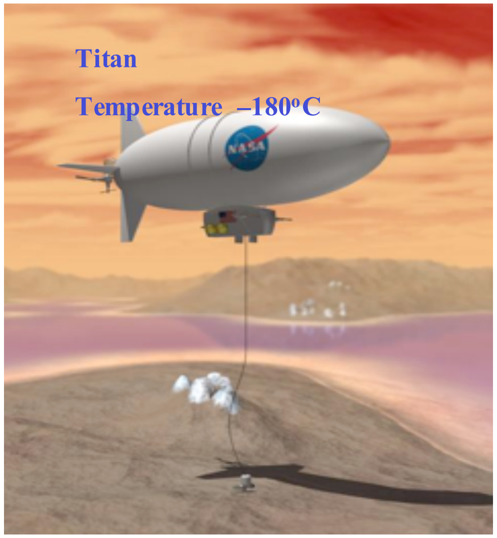
Benefits of the 16.3 Intelligent Systems

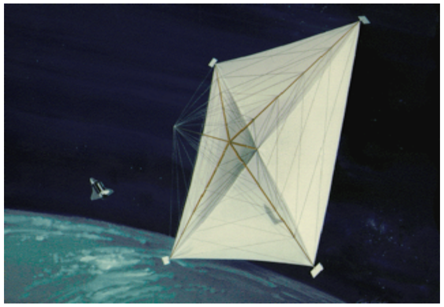
Intelligent systems will benefit:

- Crew health monitoring and drug delivery
  - Cell imaging and penetration
- Crew environment monitoring and control
  - Air and Water purification
- Miniaturized planetary probes, e,g,;
  - Titan probe
  - Mars astrobiology field laboratory
    - Integrated array of nano-sensors with nano fluidics
- Thermal protection system
  - Smart skin
- Large aperture systems
  - Smart skin,



High-energy cosmic radiation can cause damage to DNA and make cells behave erratically



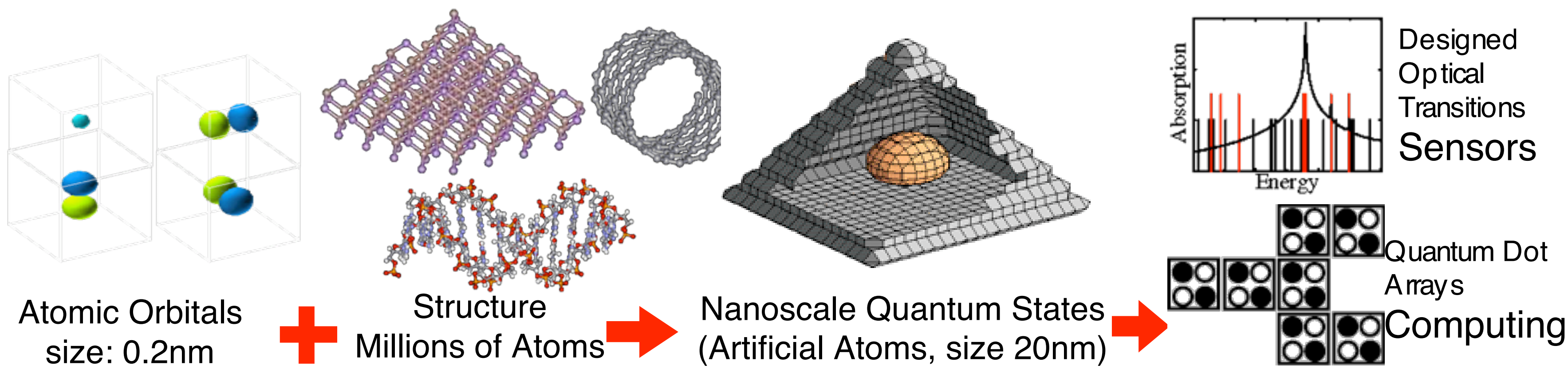


Interplanetary solar sail

Current State-of-the-Art for Capability 16.3 Intelligent Systems

Multi-scale Hierarchical Modeling. TRL=1-2

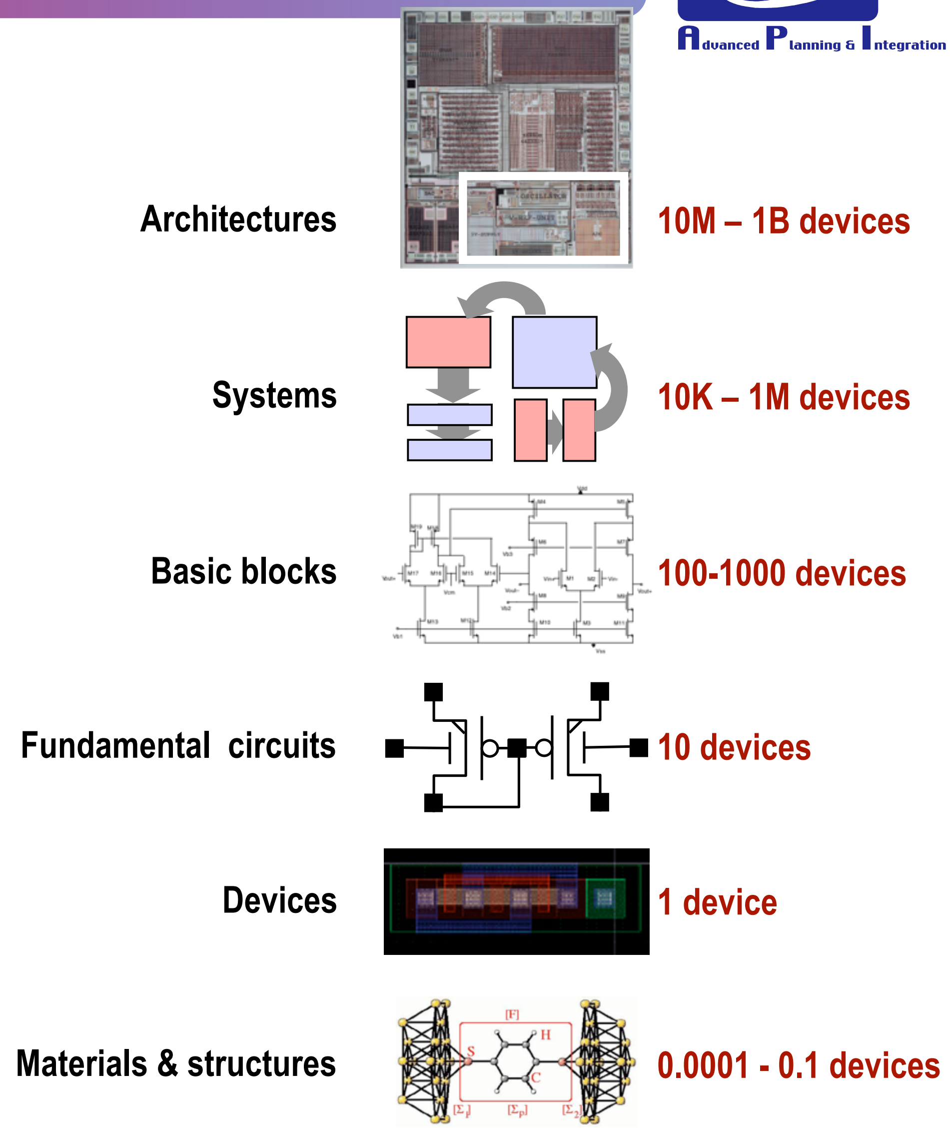
- **Robust multi-scale modeling exists from micro to macro for well-understood systems (excluding, for example, transport-based systems).**
- **Quantum-to-Nano-to-Micro modeling is at a primitive state.**



Current State-of-the-Art for Capability 16.3 Intelligent Systems

Multi-scale Manufacturing Processes.
TRL = 1-3

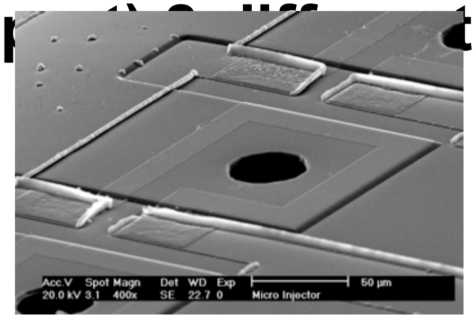
- **Top-down processes (lithography-based) are highly mature; state of the art at 90 nm half-pitch; limits (ITRS) at 32 nm**
- **Commercial sensors: biological bio-nano sensors (e.g., dna-based and protein-based) are very mature; limited capability to build integrated sensor systems (exceptional cases exist).**
- **Design of nanomaterials and upscale to nanocomposites still at infancy (some approaching commercialization).**
- **Nanoimprinting and related technologies are emerging primarily for research purposes (some commercially available).**
- **Directed self-assembly still immature.**

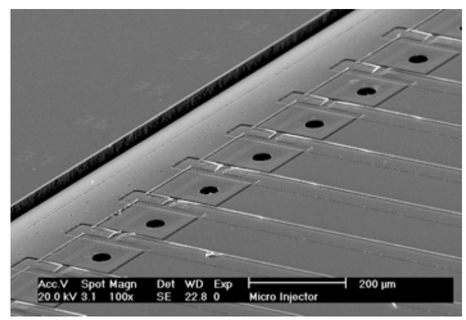


Current State-of-the-Art for Capability 16.3 Intelligent Systems

Interconnectivity. TRL = 2 - 4

- **Electronic-based signaling through multi-level metal wires (as in most ICs) is very mature … but reaching limits (ITRS) 90 nm at top level, ~ 8 levels**
- **Ink-jet printing (as an example of material transport) 3 different fluids and pico-liter drops**





Array of ink-jet nozzles for less than pico-liter fluid delivery
(Tseng et al, JMEMS 2002)

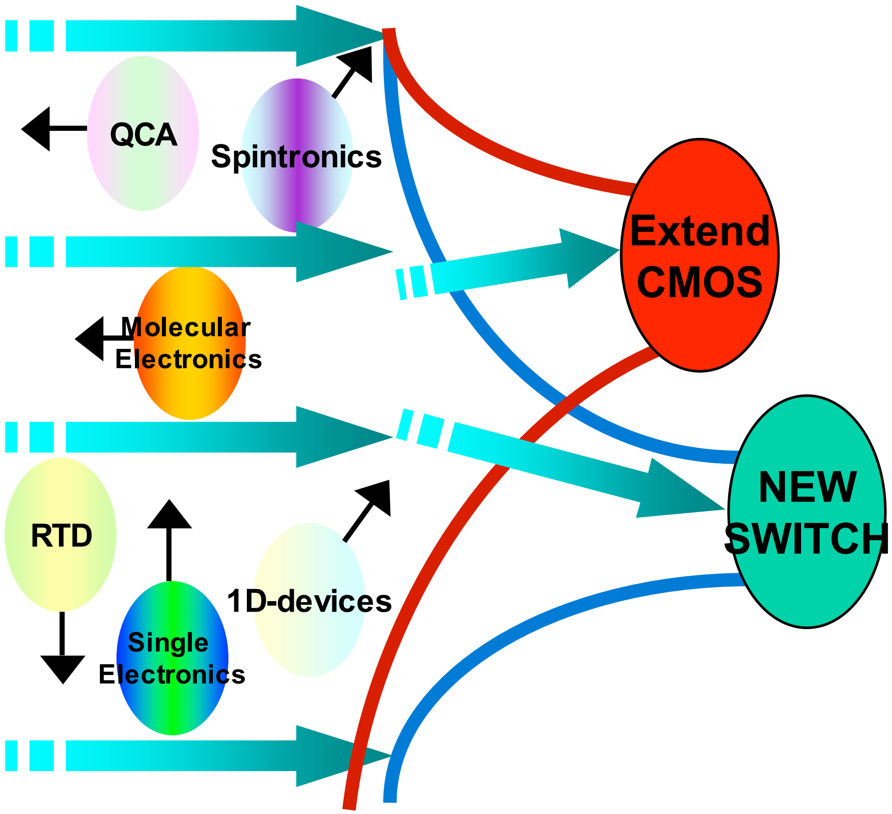
- Utilization of nano-properties. TRL = 1 to 4
  - **Quantum-well structures, giant magneto resistance (GMR) disk reading heads). SOA controlling phenomena in one dimension**
  - **Commercially available pharmaceuticals exploit designed molecule properties.**
  - **Quantum-dot based structures for research purposes (for tags)**

Current State-of-the-Art for Capability 16.3 Intelligent Systems

Advanced Planning & Integration Office

Information Representation TRL = 1 to 5

- **Von-Neumann models/computing is pervasive, dominated by major microprocessor architectures**
- **Programmable structures (a la FPGA) emerging as alternatives to lithographically-defined designs**
- **Neural networks/models and genetic algorithmics offer alternatives to programmed von Neumann systems by learning**
- **Bioinspired/Biomimetic/neuromorphic at research stage**
- **Emergent untried computing models (QCA, quantum**



Requirements /Assumptions for Capability 16.3 Intelligent Systems

Advanced Planning & Integration Office

- NASA will have a focused effort in nanotechnology
- Substantial progress in nanotechnology will continue based on support from other government and industry participants, which NASA can exploit (e.g. NNI roadmap)
- NASA will actively collaborate with academia and Industry in developments
- Modeling will utilize trend that computing power goes up 100 times every 10 years
- Level of development to TRL 4 in roadmap;
- Other "capabilities" are our principal customers

Capability 16.3 Intelligent Systems Roadmap

Advanced Planning & Integration Office

	2005	2010	2015
16.3 Intelligent Systems (capabilities)	Nanostructures based sources and detectors	Nanomaterial based air & water purification system	Arrayed Lab-on-a-chip
16.3.1 Multi-scale Modeling	Forward Nanoscale Modeling of Nanoscale Component nano-composites		Forward and Inverse Modeling of Nanoscale Component nano-photonic crystals
16.3.2 Multi-scale Manufacturing	Integrated regular top-down and undirected bottom-up DNA micro-sensor		Integrated irregular top-down and undirected bottom-up Sub-lithographical irregular arrays
16.3.3 Interconnectivity		Nanowire Interconnects Crossbar based memory	Material Transport Multiplexing arrayed lab-on-a-chip
16.3.4 Utilization of Nano Properties	Deep submicron-accurate uniform nanostructures Nanostructures based devices		Nanometer-accurate uniform nanostructures nano-composites & supramolecules
16.3.5 Information Representation		Nanoscale logic gates	Reliable reconfigurable nano-computing

Capability 16.3 Intelligent Systems Roadmap

Advanced Planning & Integration Office

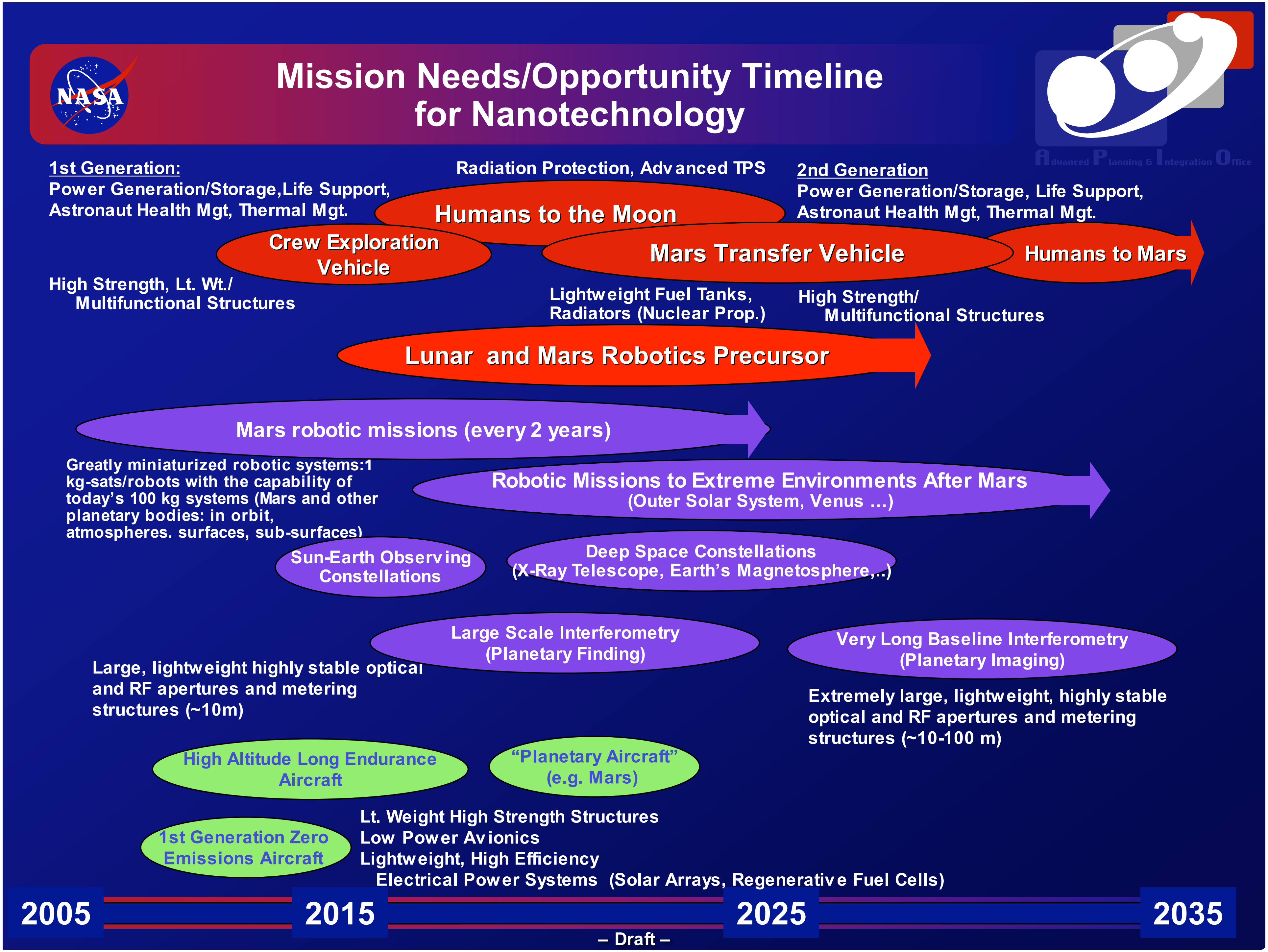
16.3 Intelligent Systems (capabilities)	"Artificial Muscle" / Lab in a Tea Cup	Self-Healing Materials / "Artificial Skin"	"Artificial Retina"
16.3.1 Multi-scale ` Modeling	Nano-micro interface models DNA-protein interactions; supra-molecular structures (20 nm3)	Nanoscale module models circuits/systems, nano-Spice	Nano CAD
16.3.2 Multi-scale Manufacturing	Directed bottom-up Artificial muscle	Fully integrated general bottom-up Self-healing materials	Large array systems Artificial skin
16.3.3 Interconnectivity	Nanowire routing (irregular layouts) Post-charge signal transfer	Programmable interconnect for material transport 3D lab-on-a-chip	Biotic/abiotic interconnections Electrochemical signaling Artificial retina Bio-silicon signaling
16.3.4 Utilization of Nano Properties	Atomically uniform nanostructures Quantum sensors	Integrated system level reliable nanostructure arrays Metrology and structure self aligning to optical tolerances of 200 picometers	
16.3.5 Information Representation	Distributed reconfigurable systems	Real Time Diagnosis and Prognosis.	
	2020	2025	2030

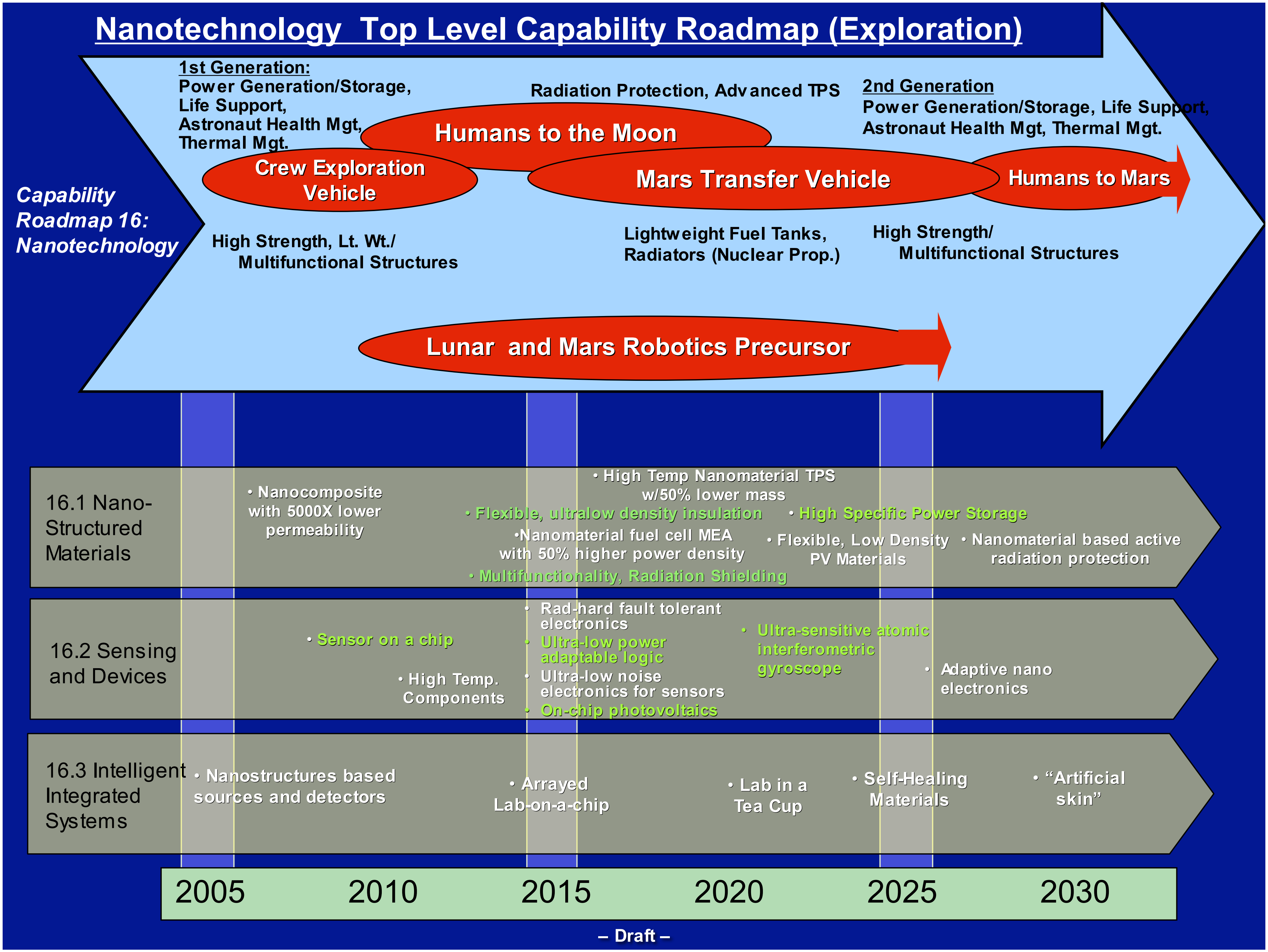
– Draft –

Crosswalk

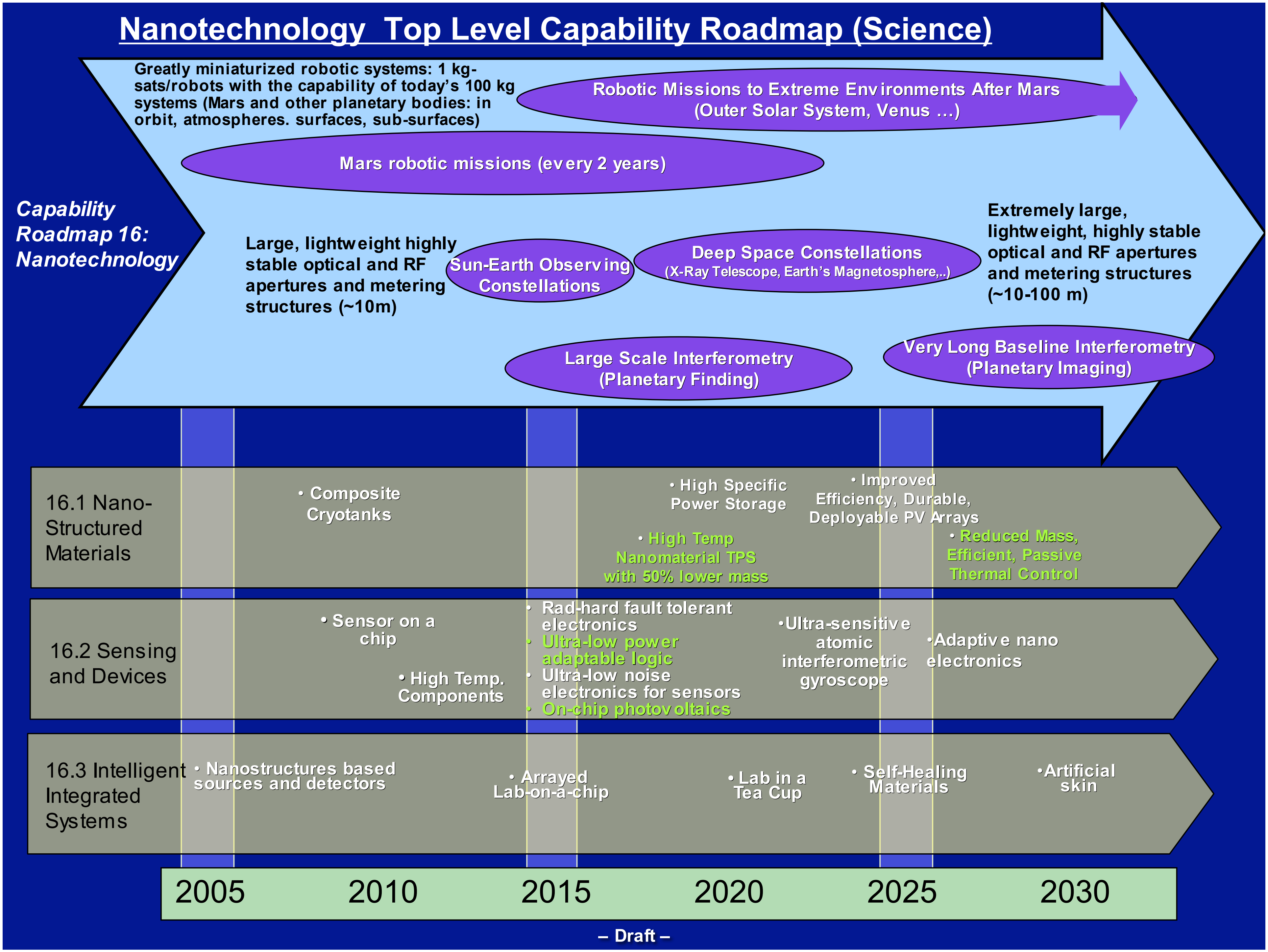
Sample Requirements	1: Multi-scale Models	2: Multi-scale Manufacturing	3: Inter-connectivity	4: Utilization of Nano-Properties	5: Information Reps. of Emerg. Props.
Robotic Access to Planetary Surface Autonomous Systems and Robotics	Self-reconfigurable miniature robots	3D Nano-assembly and Nano-Manufacturing	Programmable interconnect	Controlled Mechanical, Chemical, Thermal properties	Distributed Reconfigurable Systems for a single or network of nano-robots
Scientific Instruments and Sensors	Reliable nanoscale module	Large array systems (artificial skin)	Biotic – abiotic interconnection (artificial retina)	Integrated system level reliable nano-structure arrays	Biologically inspired high-distributed intelligent systems
Human Health and Support Systems	Reliable nano-micro interface models (DNA-Protein	Fully integrated general bottom up (self-healing materials)	Bio-electronic signaling for integrated non-invasive	Diagnosis and utilization of appropriate	Real Time Diagnosis and Prognosis

Summary and Next Steps


Mission Needs/Opportunity Timeline
for Nanotechnology
NASA
Advanced Planning & Integration Office
1st Generation:
Power Generation/Storage,Life Support,
Astronaut Health Mgt, Thermal Mgt.
Radiation Protection, Advanced TPS
2nd Generation
Power Generation/Storage, Life Support,
Astronaut Health Mgt, Thermal Mgt.
Humans to the Moon
Crew Exploration Vehicle
Mars Transfer Vehicle
Humans to Mars
High Strength, Lt. Wt./
Multifunctional Structures
Lightweight Fuel Tanks,
Radiators (Nuclear Prop.)
High Strength/
Multifunctional Structures
Lunar and Mars Robotics Precursor
Mars robotic missions (every 2 years)
Greatly miniaturized robotic systems:1 kg-sats/robots with the capability of today's 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres. surfaces, sub-surfaces)
Robotic Missions to Extreme Environments After Mars
(Outer Solar System, Venus …)
Sun-Earth Observing Constellations
Deep Space Constellations
(X-Ray Telescope, Earth's Magnetosphere,..)
Large Scale Interferometry
(Planetary Finding)
Very Long Baseline Interferometry
(Planetary Imaging)
Large, lightweight highly stable optical and RF apertures and metering structures (~10m)
Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)
High Altitude Long Endurance Aircraft
"Planetary Aircraft"
(e.g. Mars)
1st Generation Zero Emissions Aircraft
Lt. Weight High Strength Structures
Low Power Avionics
Lightweight, High Efficiency
Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)
2005
2015
2025
2035
– Draft –



Nanotechnology Top Level Capability Roadmap (Exploration)
Capability Roadmap 16: Nanotechnology
1st Generation:
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
Radiation Protection, Advanced TPS
2nd Generation
Power Generation/Storage, Life Support, Astronaut Health Mgt, Thermal Mgt.
Humans to the Moon
Crew Exploration Vehicle
Mars Transfer Vehicle
Humans to Mars
High Strength, Lt. Wt./ Multifunctional Structures
Lightweight Fuel Tanks, Radiators (Nuclear Prop.)
High Strength/ Multifunctional Structures
Lunar and Mars Robotics Precursor
16.1 Nano-Structured Materials
• Nanocomposite with 5000X lower permeability
• High Temp Nanomaterial TPS w/50% lower mass
• Flexible, ultralow density insulation
• High Specific Power Storage
•Nanomaterial fuel cell MEA with 50% higher power density
• Flexible, Low Density PV Materials
• Nanomaterial based active radiation protection
• Multifunctionality, Radiation Shielding
16.2 Sensing and Devices
• Sensor on a chip
• High Temp. Components
• Rad-hard fault tolerant electronics
• Ultra-low power adaptable logic
• Ultra-low noise electronics for sensors
• On-chip photovoltaics
• Ultra-sensitive atomic interferometric gyroscope
• Adaptive nano electronics
16.3 Intelligent Integrated Systems
• Nanostructures based sources and detectors
• Arrayed Lab-on-a-chip
• Lab in a Tea Cup
• Self-Healing Materials
• "Artificial skin"
2005
2010
2015
2020
2025
2030
– Draft –



Nanotechnology Top Level Capability Roadmap (Science)
Capability Roadmap 16: Nanotechnology
Greatly miniaturized robotic systems: 1 kg-sats/robots with the capability of today's 100 kg systems (Mars and other planetary bodies: in orbit, atmospheres. surfaces, sub-surfaces)
Robotic Missions to Extreme Environments After Mars (Outer Solar System, Venus …)
Mars robotic missions (every 2 years)
Large, lightweight highly stable optical and RF apertures and metering structures (~10m)
Sun-Earth Observing Constellations
Deep Space Constellations (X-Ray Telescope, Earth's Magnetosphere,..)
Extremely large, lightweight, highly stable optical and RF apertures and metering structures (~10-100 m)
Large Scale Interferometry (Planetary Finding)
Very Long Baseline Interferometry (Planetary Imaging)
16.1 Nano-Structured Materials
• Composite Cryotanks
• High Specific Power Storage
• Improved Efficiency, Durable, Deployable PV Arrays
• High Temp Nanomaterial TPS with 50% lower mass
• Reduced Mass, Efficient, Passive Thermal Control
16.2 Sensing and Devices
• Sensor on a chip
• High Temp. Components
• Rad-hard fault tolerant electronics
• Ultra-low power adaptable logic
• Ultra-low noise electronics for sensors
• On-chip photovoltaics
•Ultra-sensitive atomic interferometric gyroscope
•Adaptive nano electronics
16.3 Intelligent Integrated Systems
• Nanostructures based sources and detectors
• Arrayed Lab-on-a-chip
• Lab in a Tea Cup
• Self-Healing Materials
•Artificial skin
2005
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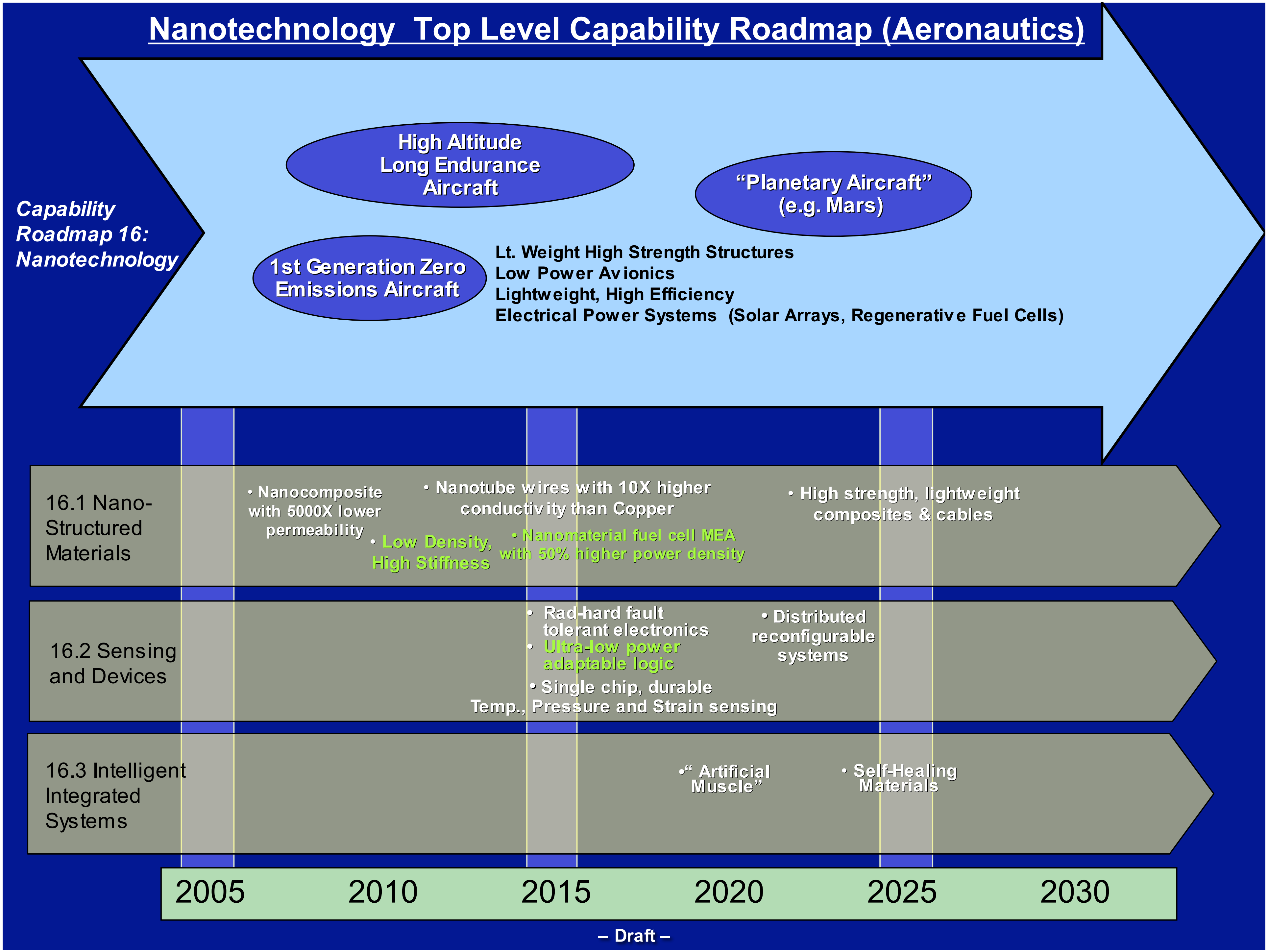

Nanotechnology Top Level Capability Roadmap (Aeronautics)
Capability Roadmap 16: Nanotechnology
High Altitude Long Endurance Aircraft
"Planetary Aircraft" (e.g. Mars)
1st Generation Zero Emissions Aircraft
Lt. Weight High Strength Structures
Low Power Avionics
Lightweight, High Efficiency
Electrical Power Systems (Solar Arrays, Regenerative Fuel Cells)
16.1 Nano-Structured Materials
• Nanocomposite with 5000X lower permeability
• Nanotube wires with 10X higher conductivity than Copper
• High strength, lightweight composites & cables
• Low Density, High Stiffness
• Nanomaterial fuel cell MEA with 50% higher power density
16.2 Sensing and Devices
• Rad-hard fault tolerant electronics
• Ultra-low power adaptable logic
• Distributed reconfigurable systems
• Single chip, durable Temp., Pressure and Strain sensing
16.3 Intelligent Integrated Systems
• "Artificial Muscle"
• Self-Healing Materials
2005
2010
2015
2020
2025
2030
– Draft –

Next Steps

- Make changes to roadmaps based on verbal feedback from NRC review
- Receive the draft Strategic Roadmaps
- Review and Assess all applicable Strategic Roadmaps and their requirements for Nanotechnology capability
- Make changes to Nanotechnology roadmaps to ensure consistency with Strategic Roadmaps requirements and other Capability Roadmaps
- Develop rough order of magnitude cost estimates for the Nanotechnology Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Closure and Crosswalk
(with other Roadmaps)

“Closure”

Co-Chairs:

M. Dastoor (NASA HQ) M. Hirschbein (NASA HQ) D. Lagoudas (Texas A&M)

Nanotechnology Closure

- Challenges
- Crosswalk
- Status
- Forward Work

Challenges

Technical

- Production of nanomaterials
- Characterization at both atomic and bulk scale
- Modeling & Simulation
- Applications Development
- System Integration

Managing Expectations (Most Difficult)

- Strongly advocate potential benefit
- Be responsive to needs of future technology users
- Avoid hype at all cost

Institutional

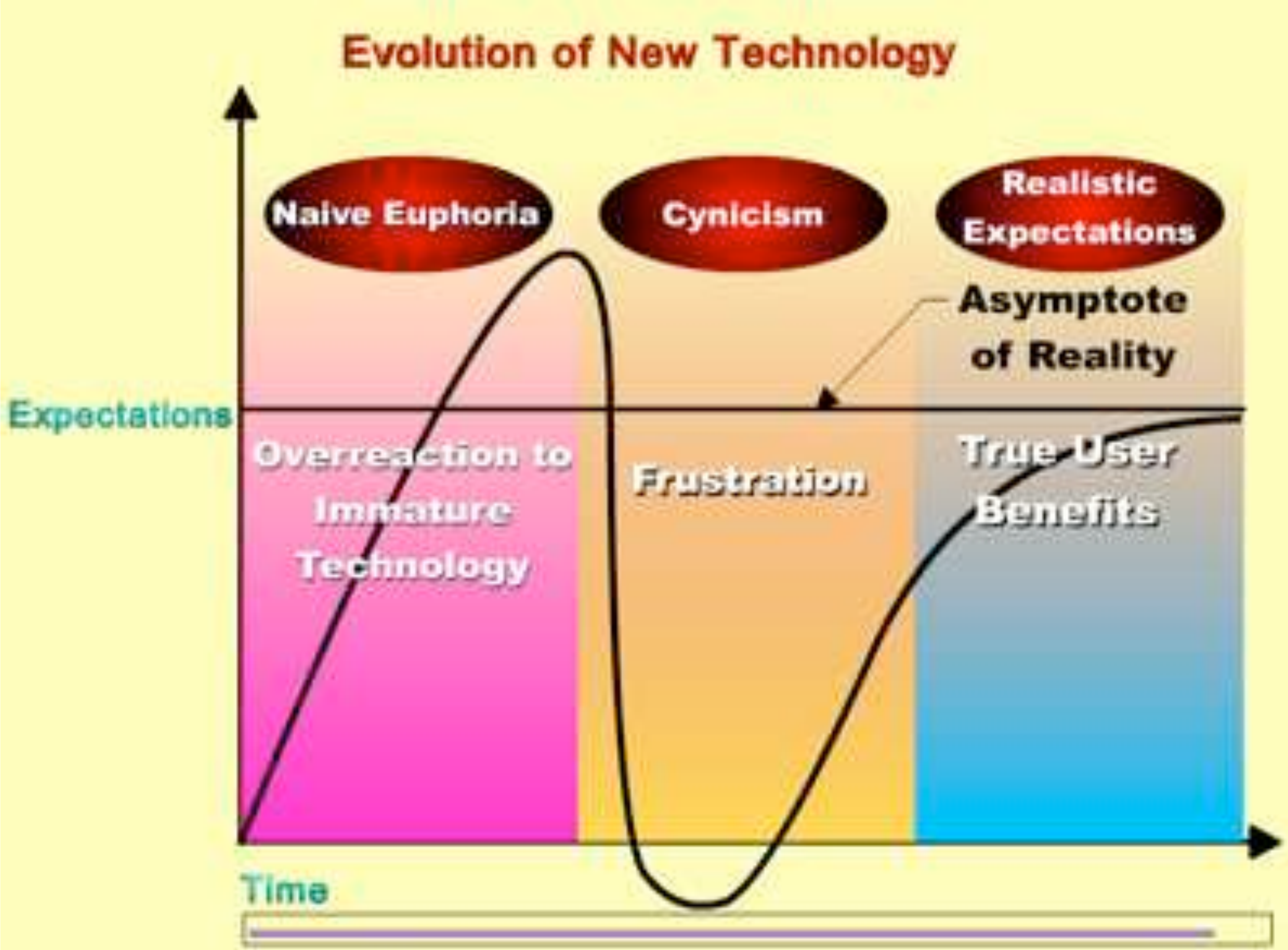
- Coordination/Cooperation among NASA/Industry/Academia/OGA
- Long-term Stability

"Roadmapping"

- Organization
- Condensation
- Connection

Technical Challenges

- **Production of nanomaterials**
  - Quantity, quality, control of properties & production in specified forms
- **Characterization at both atomic and bulk scale**
  - Fundamental mechanical, electrical and optical properties
- **Modeling & Simulation**
  - Prediction of physical/chemical properties and behavior from nanoscale to macroscale as well as models for material production
- **Applications Development**
  - Tools and techniques for applications of nanotechnology
  - Verification of predicted behavior/performance in actual environments
  - Systems Analysis to guide technology development
- **System Integration**
  - Macro-scale assembly and fabrication
  - Validation testing


Evolution of New Technology
Naive Euphoria
Cynicism
Realistic Expectations
Asymptote of Reality
Expectations
Overreaction to Immature Technology
Frustration
True User Benefits
Time

Major “Roadmapping” Challenge

- **Organization, Condensation and Connection**
  - Nanotechnology is extremely broad and deep
  - Multiple ways to present scope and content of nanotechnology
  - Being concise without loosing content -- nanotechnology affects many aspects of all other capability areas
  - Clearly show projection in to other capability areas

Major Institutional Challenges

- **Coordination/Cooperation among NASA/industry/academia/OGA**
  - Many common interests but different missions and priorities
  - All too often the attitude is, ‘why do we need to invest in nanotechnology too?’
  - Need to incentivize major industry: partnerships, long-range planning, investment, ….
- **Long-term stability**
  - Budget, education
  - Infusion of nanotechnology products into plans and missions (“crossing the valley of death between proof-of-concept and prototype”)

Impact: Highest Next Highest

Nanotechnology Crosswalk (Space)

High Energy Power and Propulsion	Very high efficiency PV, electrodes for advanced batteries, materials for high power fly wheels, supercapacitors, advanced thermoelectric materials, fuel cell membranes, light weight radiators and H2 tanks…
In-Space Transportation	Advanced high strength, lightweight structural materials
Advanced Telescopes and Observatories	Lightweight, high stiffness, low CTE materials for optics and large structures, thermal coatings….
Robotic Access to Planetary Surfaces Human Planetary Landing Systems	Lightweight thermal protection
Human Health and Support Systems	Health monitoring, diagnosis; membranes for life support processes (e.g. air purification, catalysis), radiation protection…
Human Exploration Systems and Mobility	Sensors, electronics, materials (light weight, high strength; high thermal conductivity; radiation protection; self-healing,…)
Autonomous Systems & Robotics	Low power computing and electronics; systems for sub-kg rovers
Scientific Instruments and Sensors	Ultra-sensitive, environmentally robust detectors; compact active sources (laser, X-ray, sub-mm); high temperature IR detectors…
In-Situ Resource Utilization	Process monitoring sensing, catalysis and filtration
Communications and Navigation	Advanced low power electronic and photonic devices and systems
Transformational Spaceport/Range	Sensing for environmental monitoring
Advanced Modeling Simulation & Analysis	Multi-scale modeling for materials, devices and systems
Systems Engineering Cost/Risk Analysis	TBD

– Draft –

Impact: Highest / Next Highest

Nanotechnology Crosswalk (Aero)

High Energy Power and Propulsion	Very high efficiency PV, electrodes for advanced batteries, actuators, motors, fuel cell membranes and lightweight tanks
Airframe (Transportation)	Advanced high strength/stiffness, lightweight structural materials
Autonomous Systems	Low power computing and electronics
Advanced Modeling Simulation & Analysis	Multi-scale modeling for materials, devices and systems
Systems Engineering Cost/Risk Analysis	TBD

A high degree of commonality between aeronautics and space applications

Status

- **Current roadmapping waypoint, about mid-way to two-thirds**
  - Work-in-progress
  - Significant work left to do
- **In a "forward-looking" mode**
  - Strategic roadmaps under development
  - Other capability roadmaps under parallel development with nanotechnology
  - Current nanotechnology roadmap based on "experience and knowledge"
- **After NRC reviews (end of March) other 14 capability roadmaps will be available**
  - Hold 3rd team workshop
  - Review and revise nanotechnology
  - Address institutional issues
- **Further convergence after strategic roadmaps developed**

Forward Work

– Make changes to roadmaps based on verbal feedback from NRC review

– Receive the draft Strategic Roadmaps

– Review and Assess all applicable Strategic Roadmaps and their requirements for Nanotechnology capability

– Make changes to Nanotechnology roadmaps to ensure consistency with Strategic Roadmaps requirements and other Capability Roadmaps

– Develop rough order of magnitude cost estimates for the Nanotechnology Capability Roadmap

– Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

Mature, Proven but Bounded Technology

New, Unproven but "Unboubded" Technology

"Old-Guard" Technology

Technology Limits

"New Era" Technology

Mission Needs

Oops! Maybe We Should Work Together.

Systems Engineering Cost/Risk Analysis Capability Roadmap Progress Review

Stephen Cavanaugh, NASA Chair
Dr. Alan Wilhite, External Chair
April 6, 2005

Agenda

Time	*Topic*	*Speaker*
7:30	Continental Breakfast	
8:00	Welcome and Review Process, Panel Chair & NRC Staff	
8:15	NASA Capability Roadmap Activity	Vicki Regenie, NASA
8:30	15.0 Systems Engineering Cost/Risk Analysis Overview	Stephen Cavanaugh, NASA
	-Sub-Team Presentations-	
9:00	15.1 Systems Engineering	Dr. Alan Wilhite, Georgia Tech
	- Break -	
11:15	15.2 Life Cycle Costing	Dr. David Bearden, Aerospace Corporation
12:00	***– Lunch –***	
12:45	15.3 Risk Management	Theodore Hammer, NASA
1:30	15.4 Safety and Reliability Analysis	Dr. Homayoon Dezfuli, NASA
2:15	Concluding Summary	Stephen Cavanaugh, NASA
	- Break -	
3:00	Open Discussion	NRC Panel

SE Capability Roadmap Team

Co-Chairs
NASA: Stephen Cavanaugh, LaRC
External: Dr. Alan Wilhite, Georgia Tech

Team Members

Government	Industry	Academia
Dr. Michael Gilbert, LaRC	Dr. David Bearden, Aerospace	Dr. Alan Wilhite, Georgia Tech
Theodore Hammer, HQ	Dr. Leonard Brownlow, Aerospace	
Dr. Homayoon Dezfuli, HQ	Gaspare Maggio, SAIC	
Stephen Creech, MSFC	Steven Froncillo, SAIC	
Phil Napala, HQ		
CAPT Daven Madsen, Navy/NSSO		
Dr. Steve Meier, NRO		
Richard Westermeyer, Navy/NSSO		

Consultants
Stephen Kapurch, HQ
David Graham, HQ
Dale Thomas, MSFC
Stephen Prusha, JPL
Chuck Wiesbin, JPL
Ron Moyer, HQ

Coordinators
Directorate: Vicky Hwa, HQ Technical
Doug Craig, HQ Integration
Betsy Park, HQ Integration
APIO: Victoria Regenie, DFRC

Capability Definitions

- ***Systems engineering*** **is a robust approach to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule, and risk.**

- ***Life-Cycle Cost*** **is an integrated, process-centered, and disciplined approach to life cycle management of projects providing real and tangible benefits to all project stakeholders.**

- ***Risk Management*** **identifies potential problem areas early enough to allow development and implementation of mitigation strategies to control cost, schedule and mission success.**

- ***Safety and Reliability Analysis*** **maximizes Mission Success while managing safety risk and affordably meeting mission objectives.**

Capability Roadmap Breakdown Structure

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- **SE, Cost & Risk Analysis** 15.0
  - NASA Chair: Steve Cavanaugh (LaRC)
  - External Chair: Dr. Alan Wilhite (Georgia Tech)
  - **Systems Engineering** 15.1 — Lead: Dr. **Alan Wilhite/GT**
    - Engineering 15.1.1
    - Support 15.1.2
    - Process Management 15.1.3
    - Project Management 15.1.4
  - **Life Cycle Costing** 15.2 — Lead: Dr. **Dave Bearden /Aerospace**
    - Tools 15.2.1
    - Skills 15.2.2
    - Process 15.2.3
  - **Risk Management** 15.3 — Lead: **Ted Hammer/HQ**
    - Prepare for Risk Management 15.3.1
    - Identify & Analyze Risks 15.3.2
    - Mitigate Risks 15.3.3
  - **Safety & Reliability Analysis** 15.4 — Lead: **Dr. Homayoon Dezfuli/HQ**
    - System Safety 15.4.1
    - System Reliability 15.4.2
    - Safety Management 15.4.3

This Capability Roadmap scope does not include performing the integration of all fifteen Capability Roadmaps. Roadmap coordinators (MD, Center, & APIO) comprise the Integration Team and facilitate the integration process by capturing Roadmap data and dependencies and documenting in relational database tool.

Need for Systems Engineering

- The President has challenged NASA to undertake exploration of the solar system
- In the face of tight budgets and mission risks, it is critical that these missions be executed flawlessly
  - Requires sound approach to Systems Engineering
    - Tools, methods, processes
      - Continuous improvement
    - Best of industry and government
    - Standard processes
      - All centers
      - All missions
      - All programs/projects
- System Engineering must be a “value added proposition” not an overhead burden
  - Consistent with the spirit of CAIB Recommendation

NASA’s new vision requires, more than ever, excellence in an integrated systems engineering cost/risk analysis capability

Four Systems Engineering Essentials

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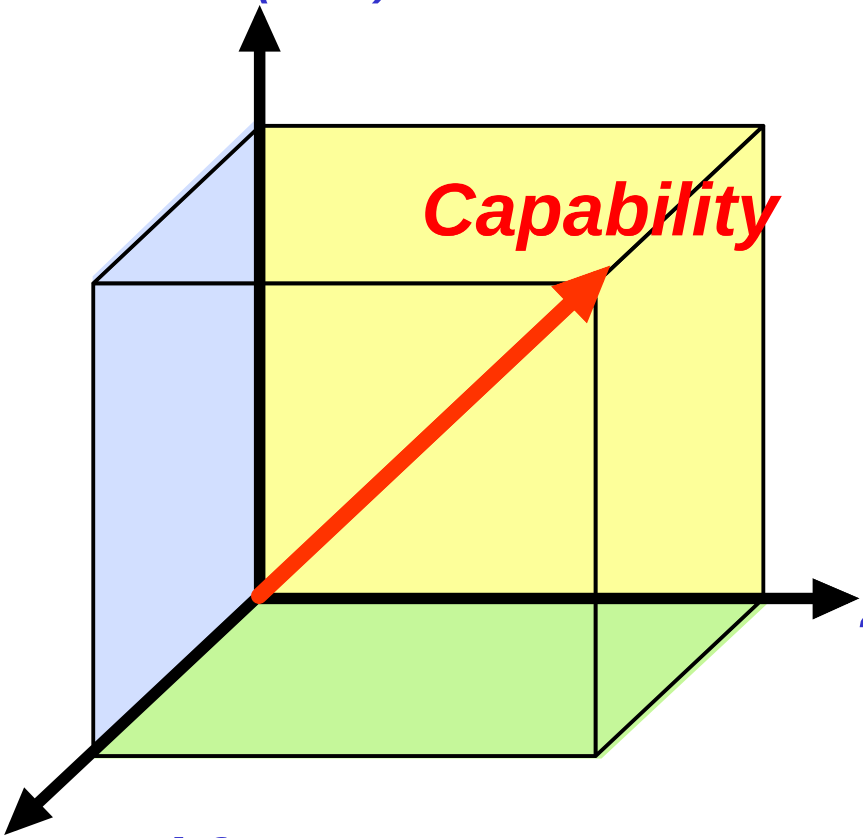
1st – Processes & Concepts

(What)



4th – How well organization implements and supports the framework with:

- **Policies & Procedures**
- **Process Improvement**
- **Human Resources**
- **Training**
- **Milestone & Decision Gate Review Criteria**
- **Management of Quality**

2nd - Performance Aids

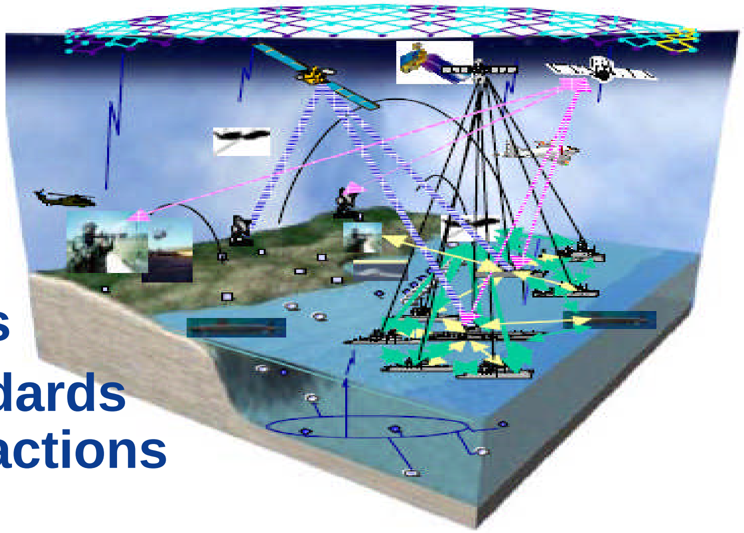
(How)

3rd - Workforce

(Who)

Complexity is a Major Issue

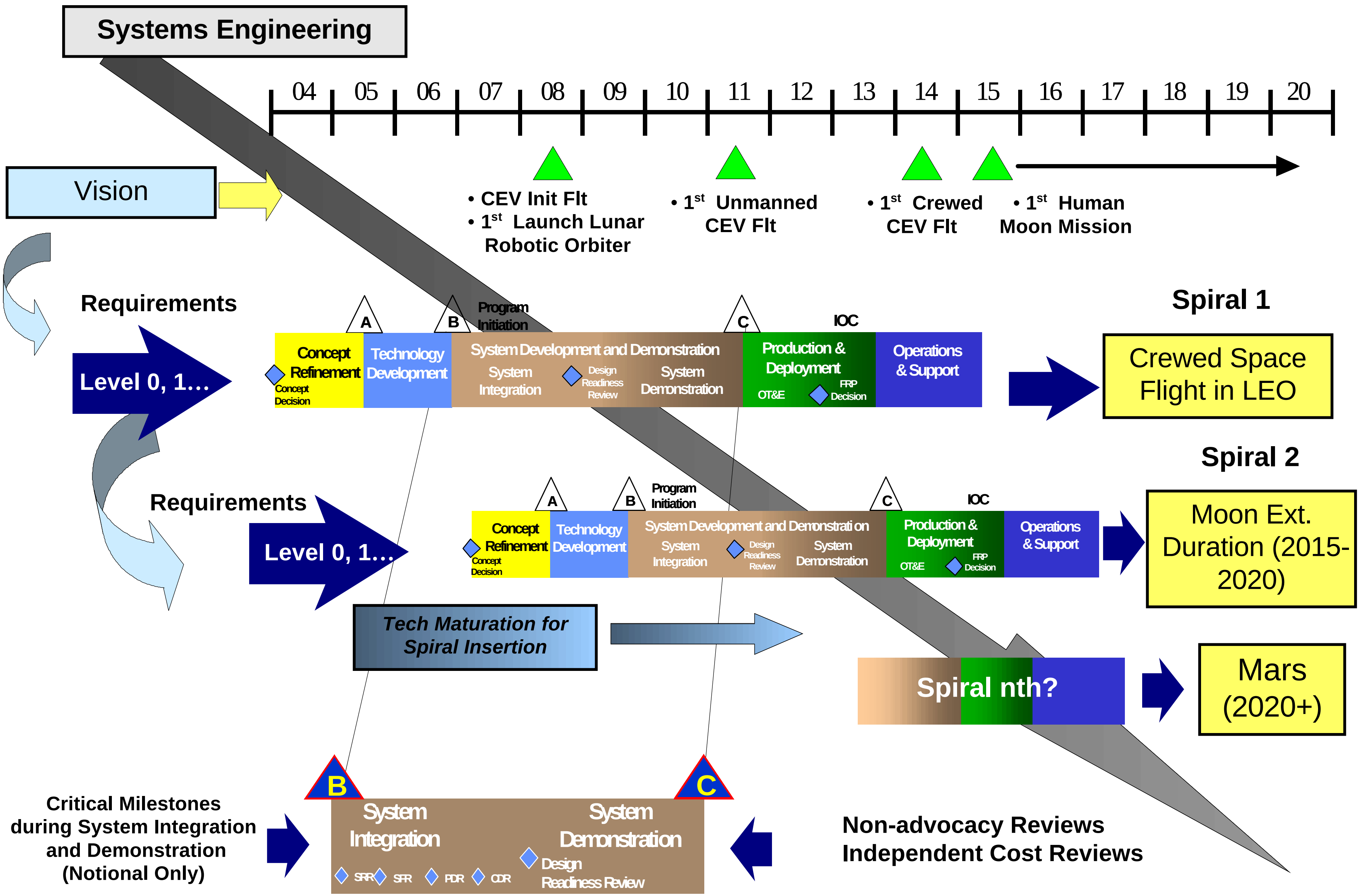
- Systems-of-Systems are Complex
  - As More Systems Are Added, the Interfaces Grow in a Non-Linear Fashion
  - Many of the Existing Systems Are Old and Not Built for These Interfaces
  - Conflicting or Missing Interface Standards Make It Hard to Define Interface Interactions



- Systems Engineering Must Deal With This Complexity
  - End-to-End Systems Engineering Is Needed, Including "Reengineering" Of Old Systems
  - Robust M&S, Verification And Validation Testing Are A Must
  - Need To Upgrade Modeling And Simulation Tools For Both Concept Definition And Verification And Validation Phases

Reference: 23 Feb. 2005 - James R van Gaasbeek
Northrop Grumman Integrated Systems

Project Constellation Timeline



Why is this Capability important?

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September 21, 2004 Letter from the National Academies

Dear RADM Steidle:

At your request, the National Research Council recently established the Committee on Systems Integration for Project Constellation.

The following quotes were taken from the report:

"Strengthening the state of systems engineering is also critical to the long-term success of Project Constellation. A competent systems engineering capability must be resident within the government and industry".

"NASA's human spaceflight systems engineering capability has eroded significantly as a result of declining engineering and development work, which has been replaced by operational responsibilities".

"The demand for experienced systems engineers, who can function credibly in a system-of-systems environment, is particularly acute".

"*Plans should be developed for maintaining a satisfactory base of systems engineering throughout the duration of this program".*

NASA SE&I Strategy Team

Preliminary Findings & Analysis

- "Systems Integration" Will Take Place At Multiple Tiers
  - Tiers structured around functional responsibilities
  - Must be prepared to support with maximum efficiency, minimum bureaucracy
  - Need to support Directorate and Technology Themes, as well as Constellation
  - SE&I authority should reside at lowest possible level
- System-of-Systems Integration Demands Creative Solution
  - No single model evaluated by NRC offers complete solution
  - Complete expertise and competence is not available in any one sector
  - Certain functions can only be executed by government personnel
  - "Hybrid model" using government, FFRDC, and industry is attractive
- ESMD SE&I Capability Will Be Phased-In Over Time
  - Government will perform SE&I work needed to complete Spiral 1 SRR
  - Near-term solution may evolve to different Long-term solution

Capability Roadmapping Process & Approach

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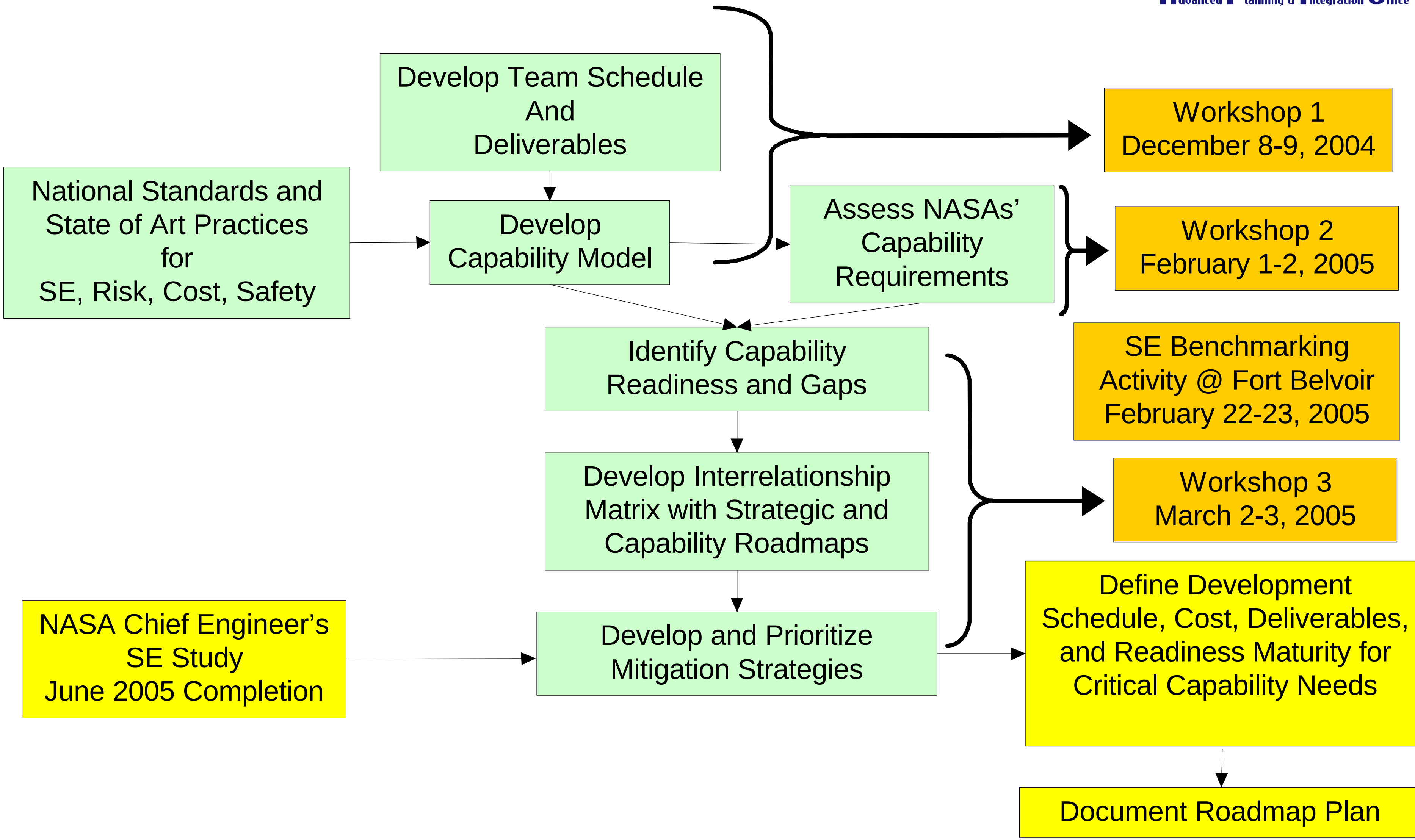

Basis for Assessment

- Quality Function Deployment (QFD)
  - A quality system that implements elements of Systems Thinking (viewing the development process as a system) and Psychology (understanding customer needs

- Benchmarking – Chief Engineers Fort Belvoir Workshop on February 22-23, 2005
  - Learning from the experience of others in Industry, DoD, and Other Agencies

- Literature Search – mostly Internet

- Limitations of Assessment
  - Budget limitations keep team small and limited in scope
  - QFD assessment limited to team size – small sample of NASA
  - Assessment more Qualitative vs. Quantitative

Capability Readiness Rating for process, tools, and skills

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Team Gap Assessment

- Minor or No Gap
- Significant Gap
- Critical Gap

APIO Capability Readiness Levels

7. Capability Operational Readiness
6. Integrated Capability Demonstrated in an Operational Environment
5. Integrated Capability Demonstrated in a Relevant Environment
4. Integrated Capability Demonstrated in a Laboratory Environment
3. Sub-Capabilities* Demonstrated in a Relevant Environment
2. Sub-Capabilities* Demonstrated in a Laboratory Environment
1. Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified

Capability readiness rating assignments are intended for future exploration missions and as such they should not be interpreted as capability ratings to perform the current missions.

Capability Team 15: Systems Engineering Top Level Capability Roadmap

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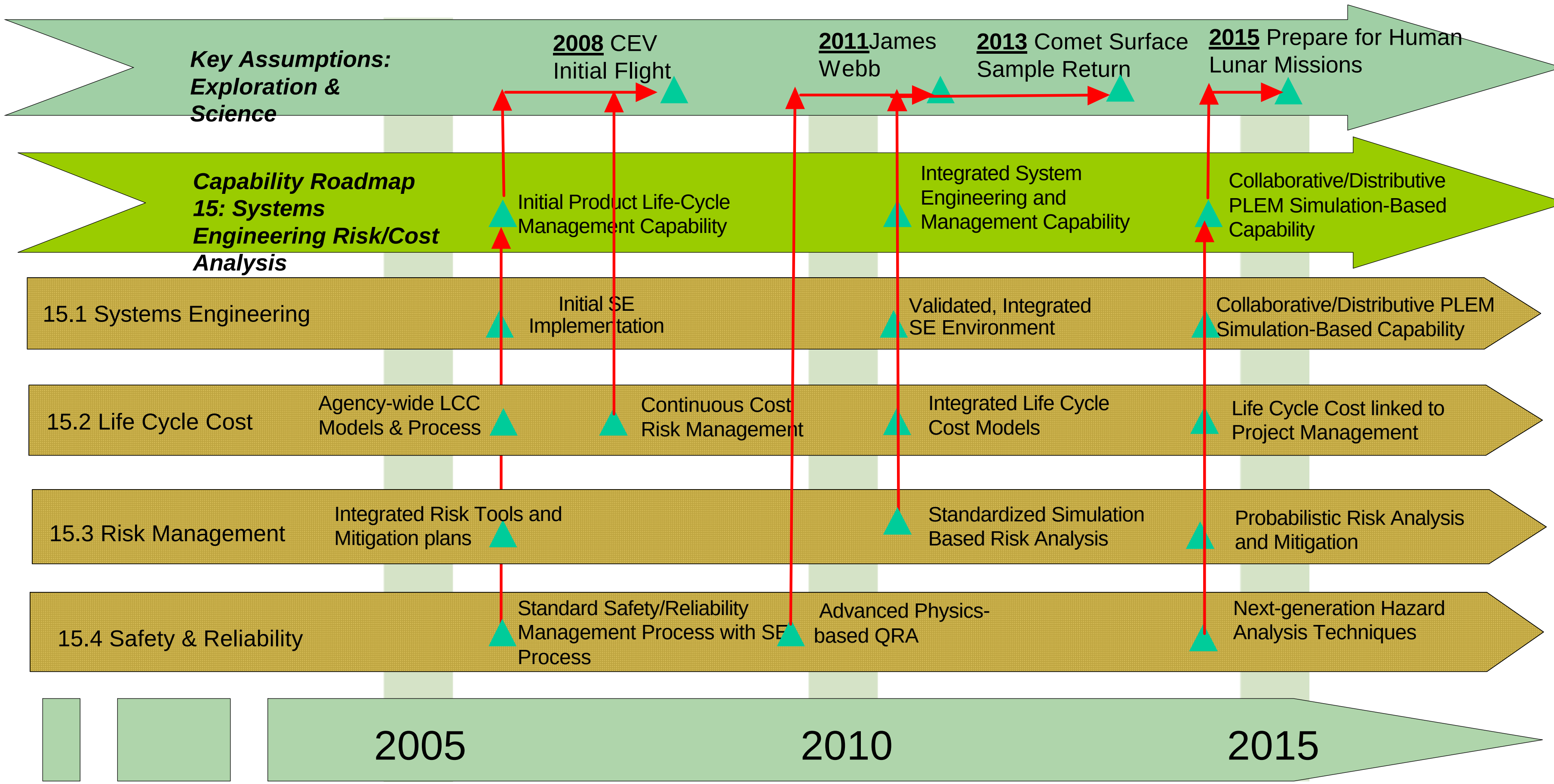


Major Decision

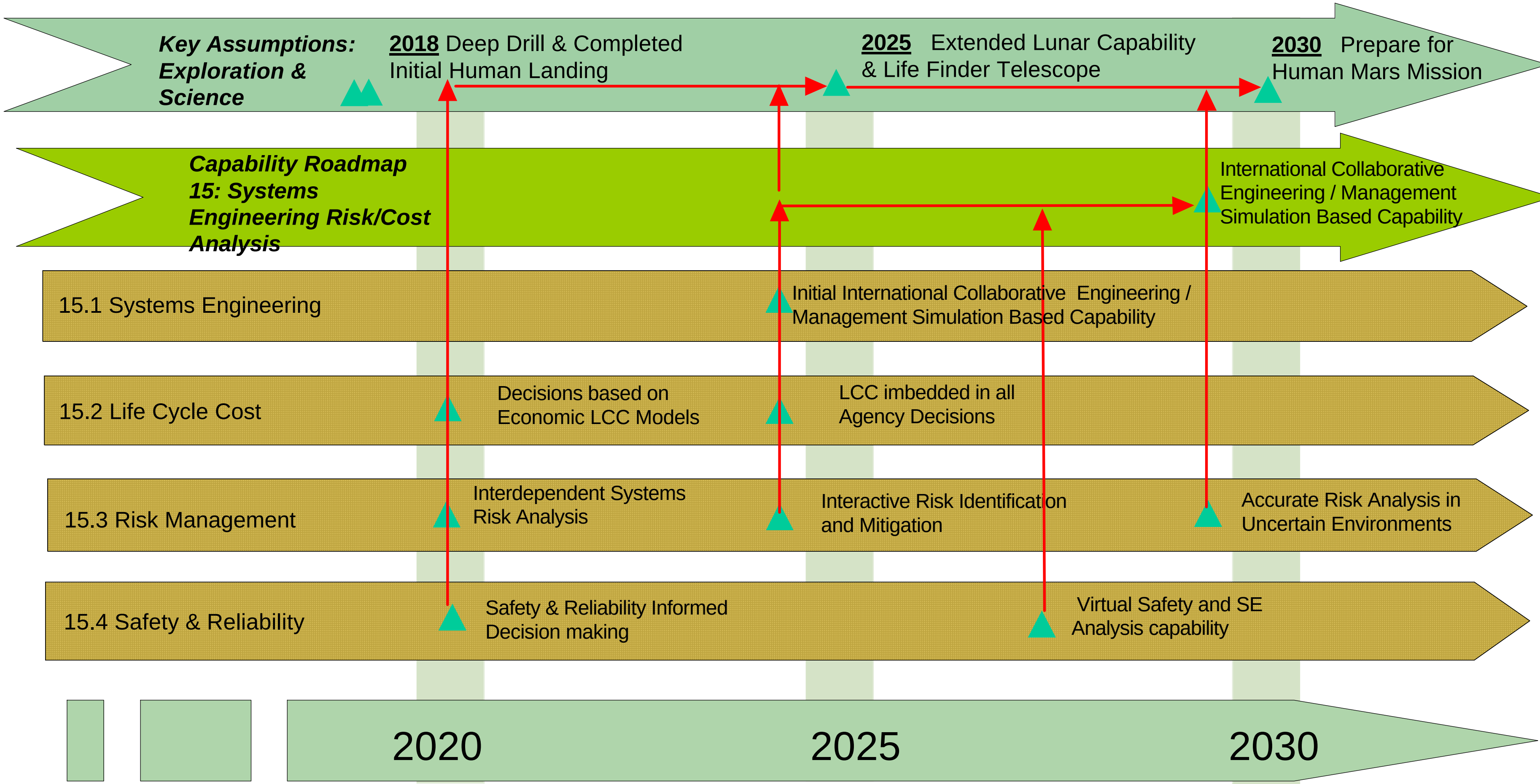
Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Capability Team 15: Systems Engineering Top Level Capability Roadmap



Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Future State Required to Meet NASA Exploration Vision

- **Process (What) – Need a common process for Systems Engineering, Cost, Risk and Safety. NASA Policy Requirements, guidelines and handbooks for this Capability need to be developed along with a need for an audible process.**
- **Tools (How) – Need a standardized approach for Systems Analysis. This includes a framework for advanced tools.**
- **People (Who) – Need qualified personnel. Training & Education programs including certification tied to job criteria and performance standards.**

"An immediate transformation imperative for all programs is to focus more attention on the application of Systems Engineering principles and practices throughout the system life cycle"

USAF Chief of Acquisition Memo, "Incentivizing Contractors for Better Systems Engineering, 9 Apr 03

Capability 15.1 Systems Engineering

Presenter:

Dr. Alan Wilhite

Benefits of Systems Engineering

- Requirements driven – build the right system
- Process driven – build the system right
- Integrated engineering and management for informed decisions
- Less cost / Less duration

Systems Engineering and Integration

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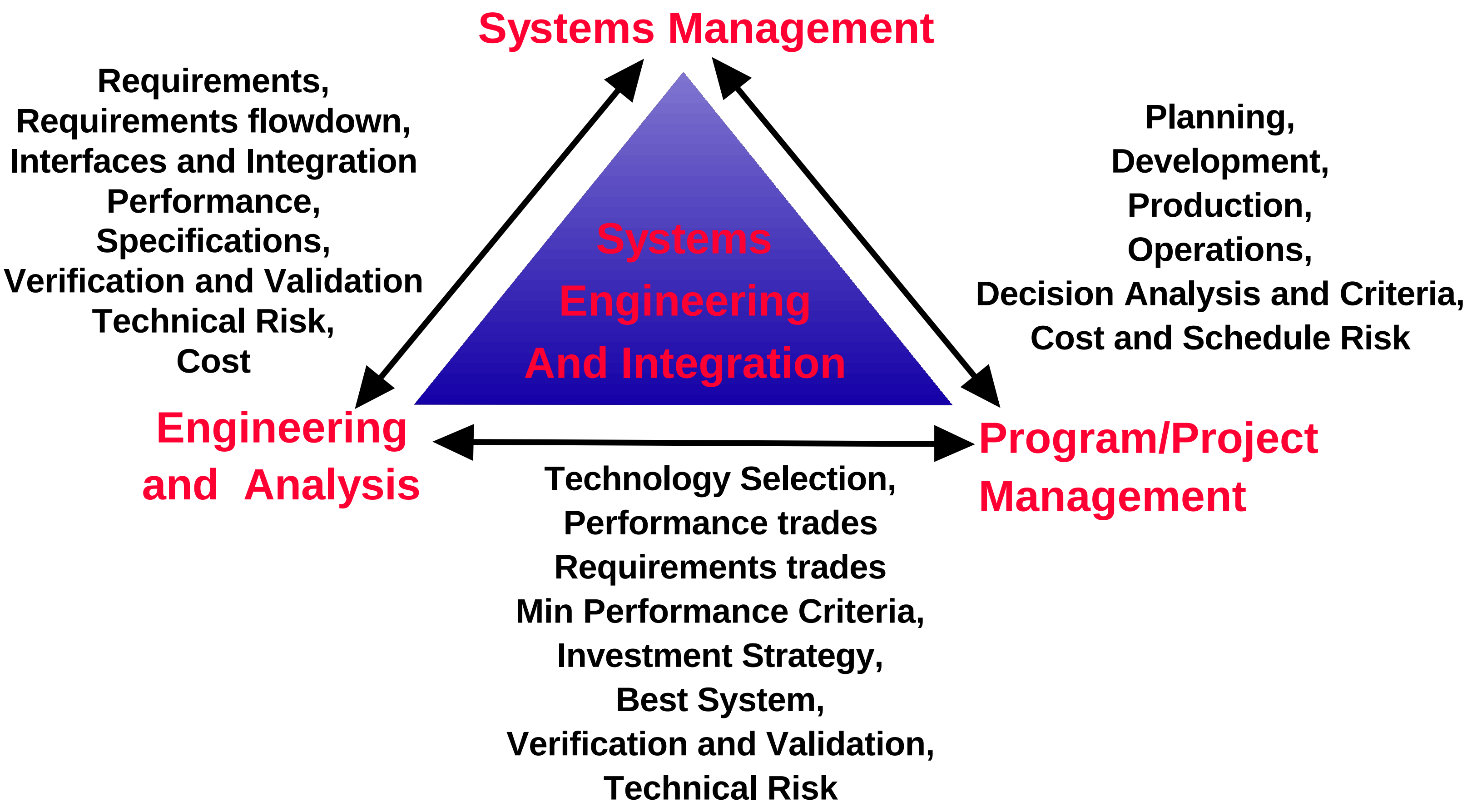

Ref. GaTech AE 6322

The Systems Engineering Process
(Ref. Mil STD 499B)

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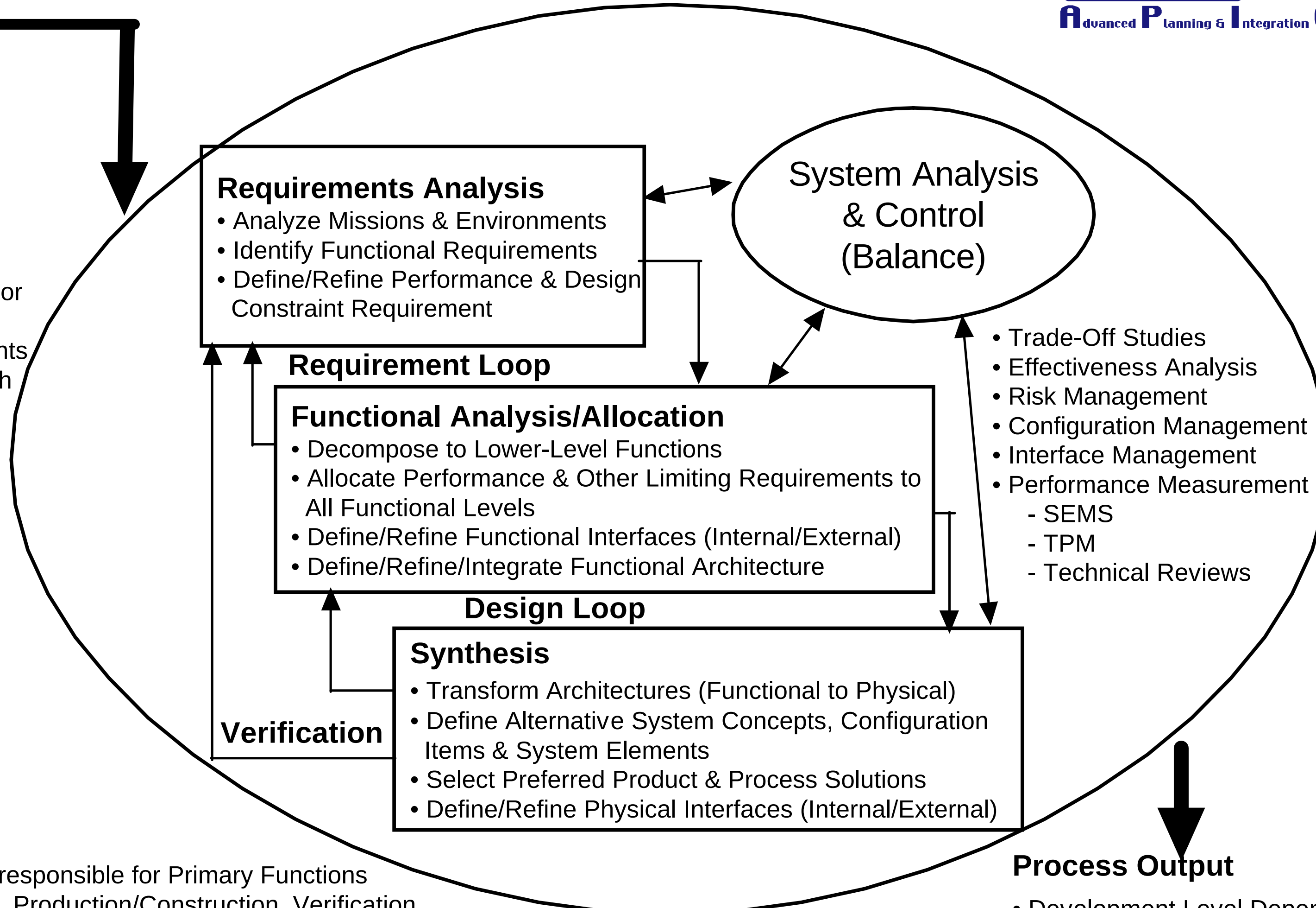
Process Input

- Customer Needs/Objectives/ Requirements
  - Missions
  - Measures of Effectiveness
  - Environments
  - Constraints
- Technology Base
- Output Requirements from Prior Development Effort
- Program Decision Requirements
- Requirements Applied Through Specifications and Standards



Related Terms:

Customer = Organization responsible for Primary Functions

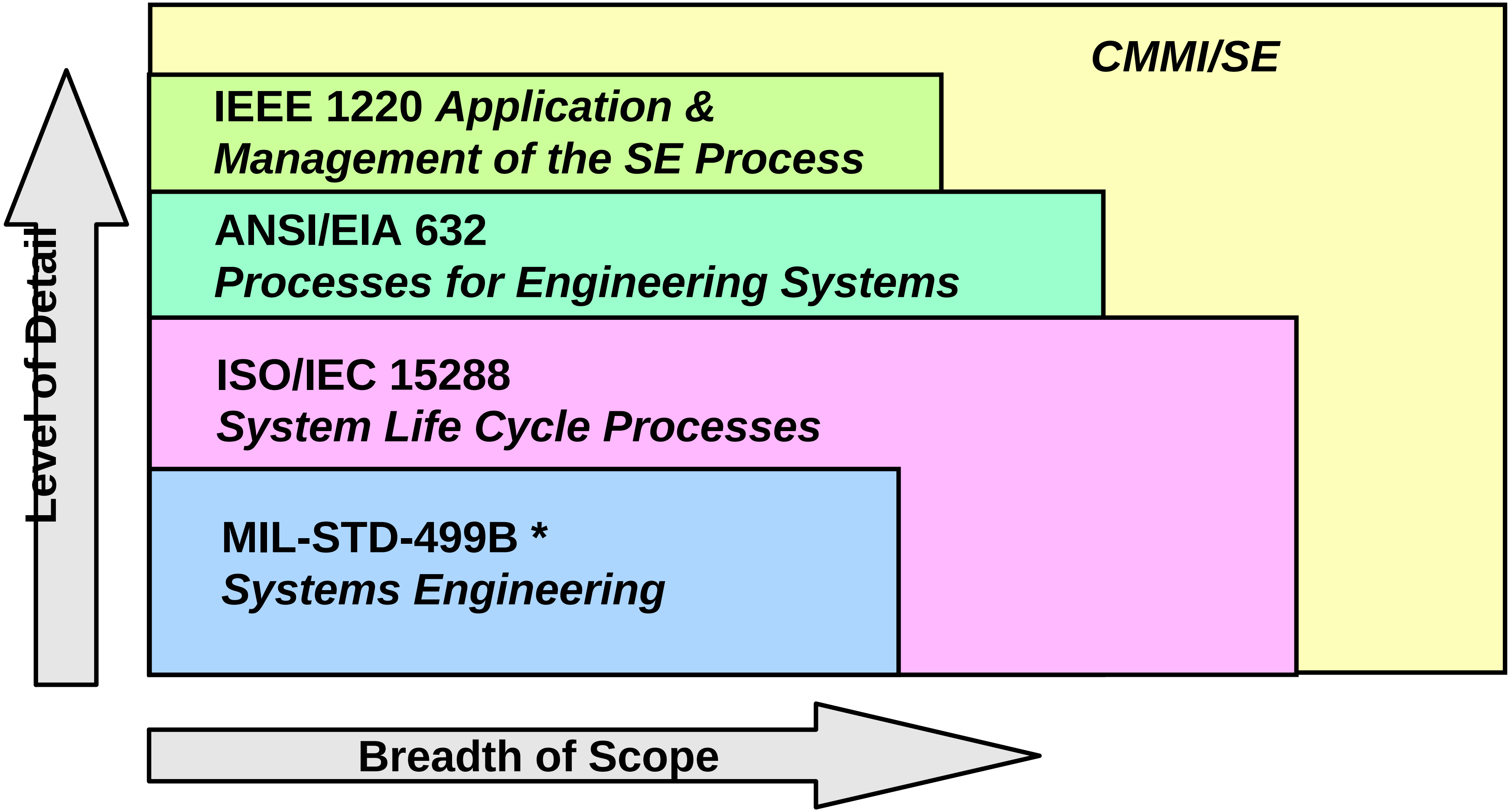
Primary Functions = Development, Production/Construction, Verification, Deployment, Operations, Support Training, Disposal

Systems Elements = Hardware, Software, Personnel, Facilities, Data, Material, Services, Techniques

Process Output

- Development Level Dependant
  - Decision Data Base
  - System/Configuration Item Architecture
  - Specification & Baseline

Scope of SE Standards



* Mil-Std-499C has more detail (similar to 15288) than Mil-Std 499B and has more breadth (similar to IEEE 1220)

Capability Maturity Model Integration

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CMMI – DoD developed integrated model for systems engineering, software engineering, integrated product process development, and supplier sourcing

CMMI

Process Management

- Organizational Process Focus
- Organizational Process Definition
- Organizational Training
- Organizational Process Performance
- Organizational Innovation and Deployment

Project Management

- Project Planning
- Project Monitoring and Control
- Supplier Agreement Mgmt.
- Integrated Project Mgmt.
- Integrated Supplier Management
- Risk Management
- Quantitative Project Mgmt.
- Integrated Teaming

Engineering

- Requirements Management
- Requirements Development
- Technical Solution
- Product Integration
- Verification
- Validation

Support

- Configuration Mgmt.
- Process and Product Quality Assurance
- Measurement & Analysis
- Decision Analysis and Resolution
- Causal Analysis and Resolution
- Organizational Environment for Integration

CMMI used as initial basis for strategic planning

Overview of the "State"

- The Standish Group (which exists solely to track IT successes and failures) surveyed 13,522 projects in 2003 and showed the following:
  - 34% of projects succeed (these projects are defined as those which deliver the contracted capabilities on time and on budget).
  - 15% of projects are out and out failures (these projects are defined as those abandoned midstream)
  - The rest (51%) are "challenged", meaning over budget, and/or over schedule, and/or deliver less capability / functionality than agreed upon and contracted for.
- According to a Lake & Sheard paper
  - Systems Engineering is practiced in a quagmire of SE Standards
    - MARC Proceedings 1999
- According to the AF Center for Systems Engineering:
  - "Systems Engineering is not broken."
    - GEIA-G47 meeting January 2005

Ref: Lake Briefing at February 2005 Ft Belvoir NASA Chief Engineer Workshop

Systems Engineering is not broken but needs significant advancement to improve NASA's program success rate

System Engineering Processes

SE Capability Team Assessment

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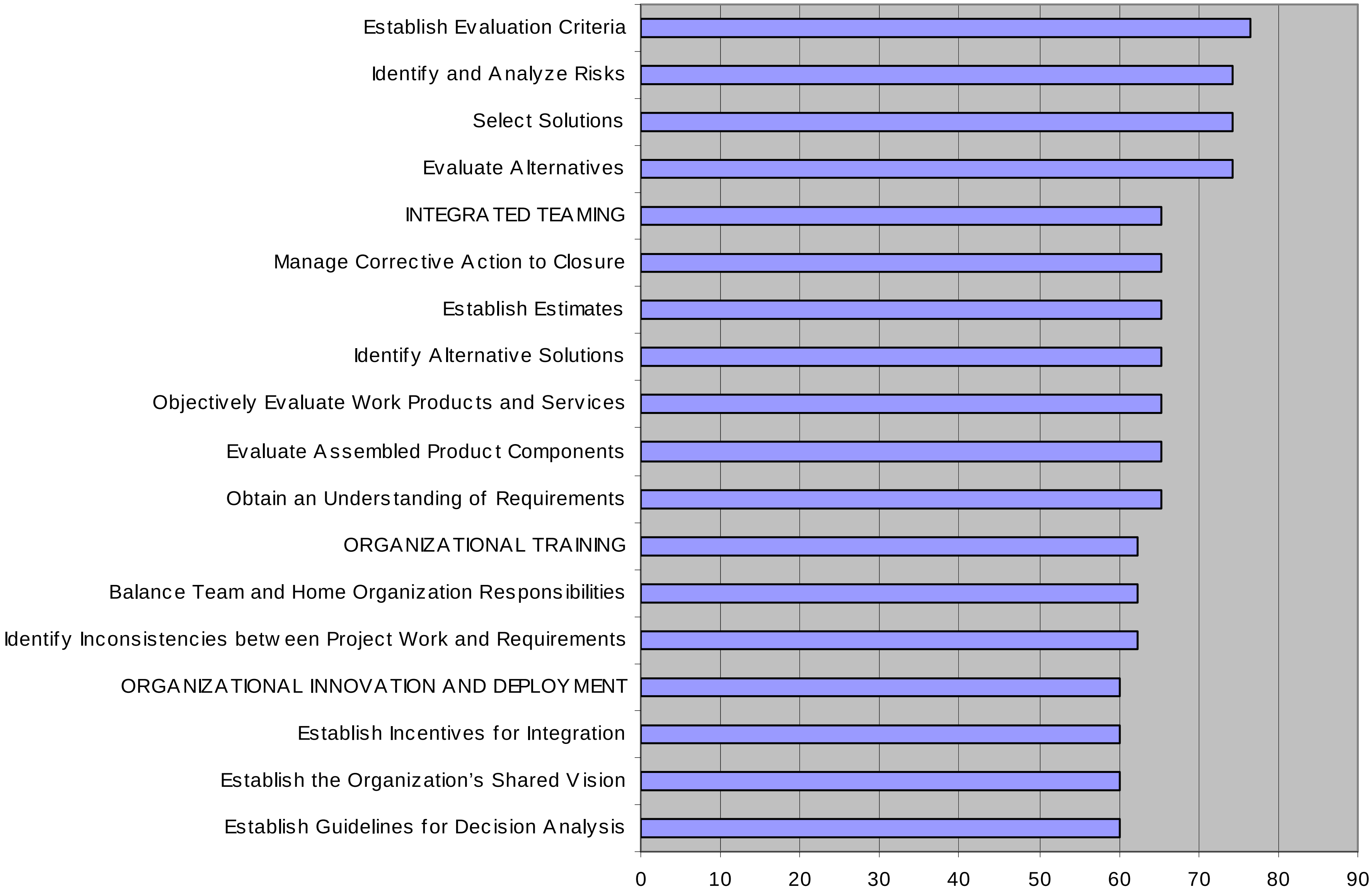
SE-CMMI		Team Assessment
ENGINEERING		
	REQUIREMENTS DEVELOPMENT	Red
	REQUIREMENTS MANAGEMENT	Red
	TECHNICAL SOLUTION	Yellow
	PRODUCT INTEGRATION	Yellow
	VERIFICATION	Yellow
	VALIDATION	Yellow
PROJECT MANAGEMENT		
	PROJECT PLANNING	Red
	PROJECT MONITORING AND CONTROL	Red
	SUPPLIER AGREEMENT MANAGEMENT	Yellow
	INTEGRATED PROJECT MANAGEMENT FOR IPPD	Red
	RISK MANAGEMENT	Red
	INTEGRATED TEAMING	Red
	INTEGRATED SUPPLIER MANAGEMENT	Yellow
	QUANTITATIVE PROJECT MANAGEMENT	Yellow
SUPPORT		
	CONFIGURATION MANAGEMENT	Green
	PROCESS AND PRODUCT QUALITY ASSURANCE	Green
	MEASUREMENT AND ANALYSIS	Green
	DECISION ANALYSIS AND RESOLUTION	Red
	ORGANIZATIONAL ENVIRONMENT FOR INTEGRATION	Green
	CAUSAL ANALYSIS AND RESOLUTION	Green
PROCESS MANAGEMENT		
	ORGANIZATIONAL PROCESS FOCUS	Green
	ORGANIZATIONAL PROCESS DEFINITION	Green
	ORGANIZATIONAL TRAINING	Green
	ORGANIZATIONAL PROCESS PERFORMANCE	Green
	ORGANIZATIONAL INNOVATION AND DEPLOYMENT	Green

Integrated rollup of Importance and Present Capability

Critical Gap	Red
Significant Gap	Yellow
No or Minor Gap	Green

Detail of Capability Assessment
(Top 10% out of 187 processes)



Other Identified SE Capability Gaps

Systems of Systems Integration	Red
Experienced SE Personnel	Red
Standard Process/Process Improvement	Yellow
Facilitate Advanced Technology	Yellow
Estimate and Manage Costs	Yellow
Acquisition Strategy	Yellow
Advanced Collaborative Environment	Yellow

Refs.

- NRC SE&I Study, 2004
- NASA SE Workshop, 2005

Critical Gap	Red
Significant Gap	Yellow
No or Minor Gap	Green

Quagmire of SE Standards

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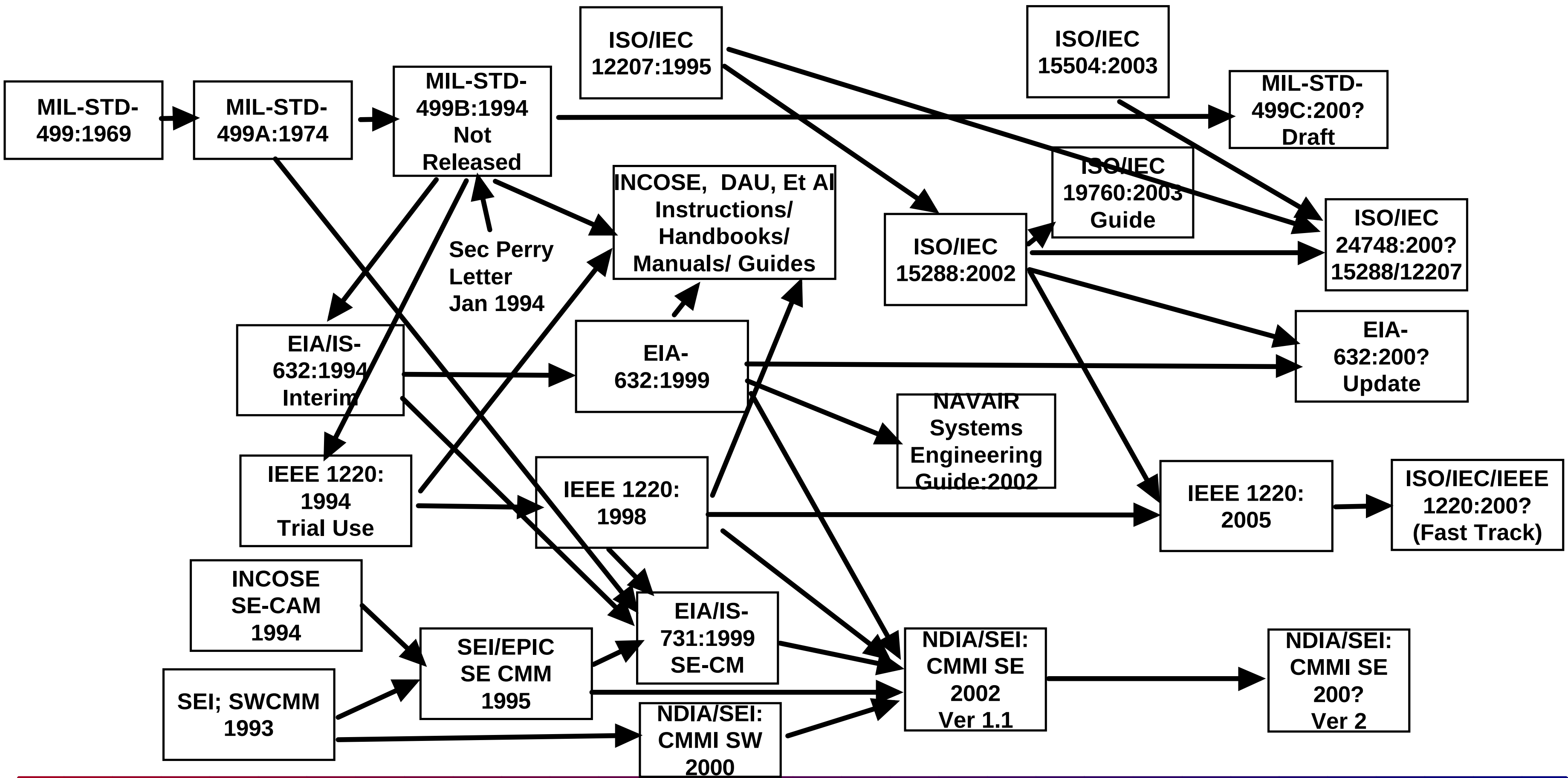
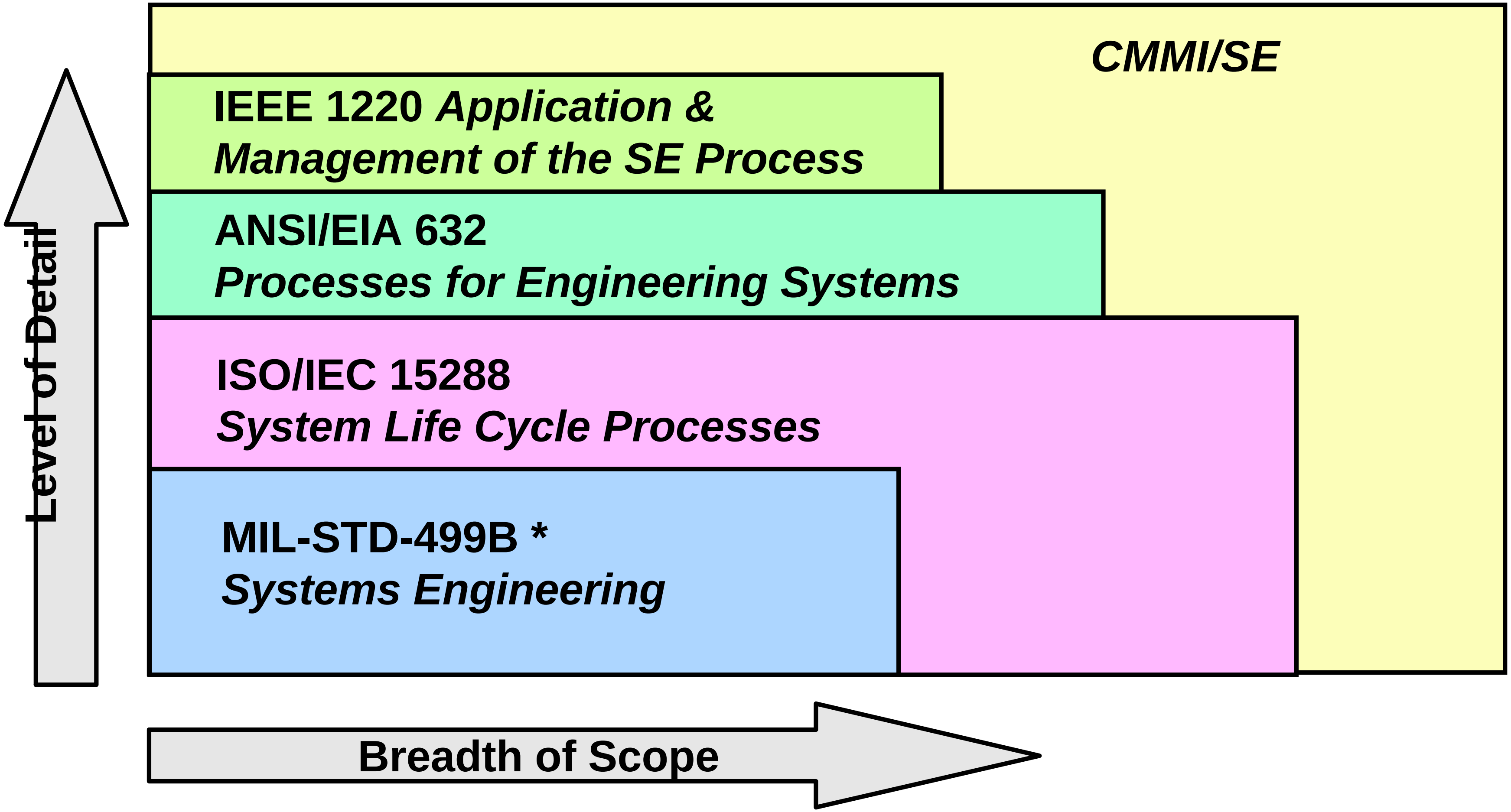
- But SE standard writers can't agree on what should be in a standard – Hence a quagmire!



Scope of SE Standards



* Mil-Std-499C has more detail (similar to 15288) than Mil-Std 499B and has more breadth (similar to IEEE 1220)

Ref: Lake **Briefing at February 2005 Ft Belvoir NASA Chief Engineer Workshop**

CMMI Recommended Maturation Path

	ML	CL1	CL2	CL3	CL4	CL5	Team Assessment
REQUIREMENTS MANAGEMENT	2	Maturity Level 2					
MEASUREMENT AND ANALYSIS	2						
PROJECT MONITORING AND CONTROL	2						
PROJECT PLANNING	2						
PROCESS AND PRODUCT QUALITY ASSURANCE	2						
SUPPLIER AGREEMENT MANAGEMENT	2						
CONFIGURATION MANAGEMENT	2						
DECISION ANALYSIS AND RESOLUTION	3	Maturity Level 3					
PRODUCT INTEGRATION	3						
REQUIREMENTS DEVELOPMENT	3						
TECHNICAL SOLUTION	3						
VALIDATION	3						
VERIFICATION	3						
ORGANIZATIONAL PROCESS DEFINITION	3						
ORGANIZATIONAL PROCESS FOCUS	3						
INTEGRATED PROJECT MANAGEMENT FOR IPPD	3						
RISK MANAGEMENT	3						
INTEGRATED SUPPLIER MANAGEMENT	3						
ORGANIZATIONAL TRAINING	3						
INTEGRATED TEAMING	3						
ORGANIZATIONAL ENVIRONMENT FOR INTEGRATION	3						
ORGANIZATIONAL PROCESS PERFORMANCE	4	Maturity Level 4					
QUANTITATIVE PROJECT MANAGEMENT	4						
ORGANIZATIONAL INNOVATION AND DEPLOYMENT	5	Maturity Level 5					
CAUSAL ANALYSIS AND RESOLUTION	5						

SE Gap Assessment indicates that CMMI Maturity Levels 2 and 3 should be developed in parallel for NASA

Systems Engineering Support to Program Management

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Program Management

- Planning
- Organizing
- Directing
- Monitoring
  - Maintaining insight or assessing
- Control

Common Areas

- Risk Mgt
- Config Mgt
- Performance
- Evaluation
- Mission Assurance

Systems Engineering

- Requirements & Functional Analysis and Allocation
- Design Synthesis
- Systems Analysis & Control (Balance)
- Integration &
- Verification

SE Gap Assessment also agrees with CMMI that Systems Engineering and Program Management must be integrated for NASA

Enterprise Systems versus Program Systems Engineering

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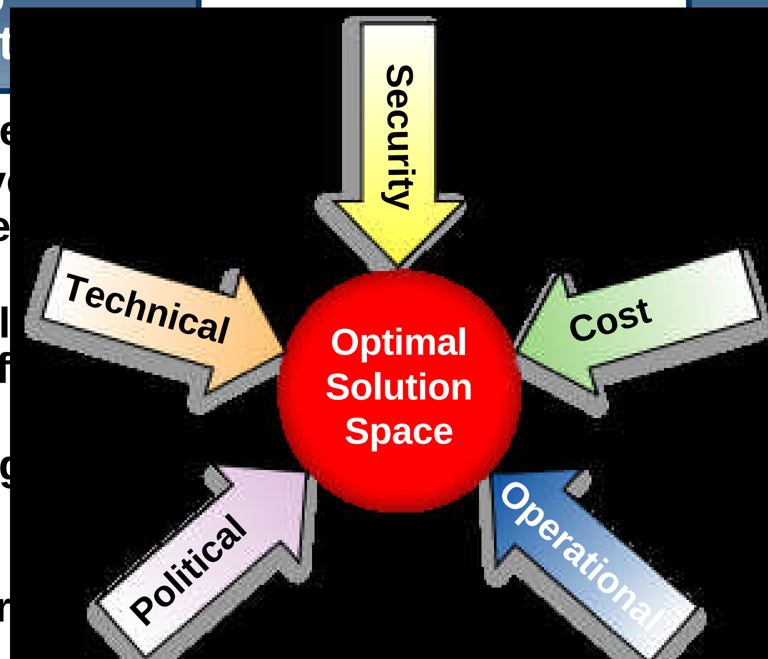
Single Systems Engineering (Stand Alone Syst

- End state well define
- Engineered and deve within a fixed budge and cost
- Well known schedul technical, and benef baseline
- Often replaces a "leg System
- Priority often
  - Technical/Secur
  - Operational
  - Cost
  - Political



Enterprise Systems Engineering System-of-Systems)

Dynamic end state

Systems-of-Systems evolves over time

Subject to annual budget revisions

Facilitates Senior Decision Makers

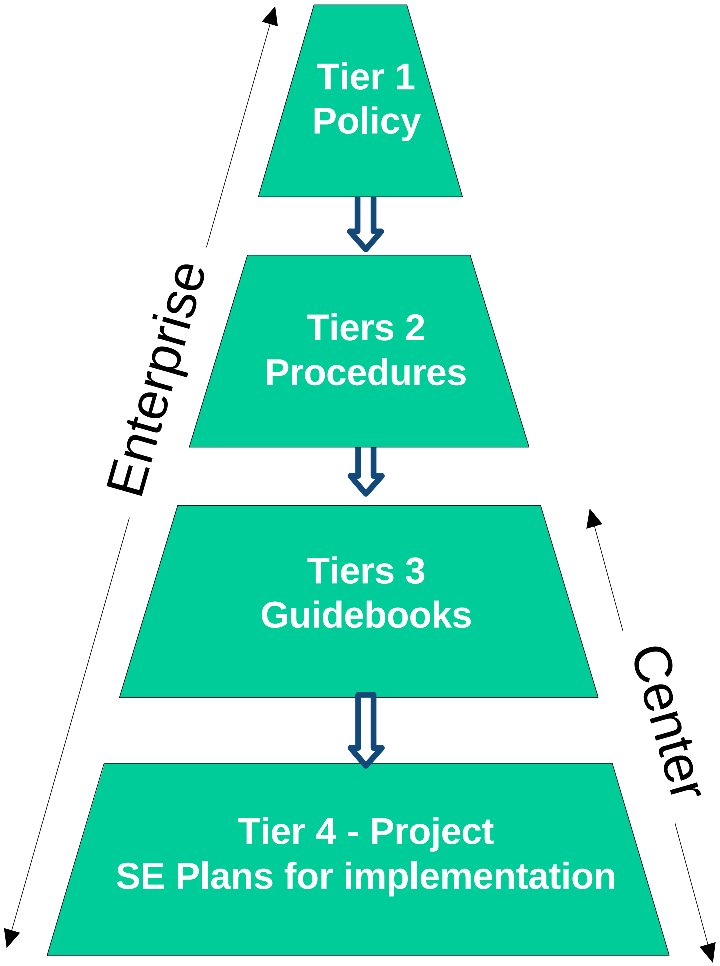
Priority often
- Political
- Cost
- Operational
- Security
- Technical

Competing Forces Addressed by Systems Engineering

Recommended NASA SE Process Development

- Tier 1: SE Agency Policy and Process Improvement Processes
  - **Process application policy**
  - **Architecture, Base and General Processes**
  - **Knowledge Management and Continuous Process Improvement**
- Tier 2: Process Area Procedures
  - **Specific standards and references identified**
  - **Process interfaces (HQ-Center, HQ-Contractor, Center-Contractor)**
  - **System of Systems integration**
  - **Can be tailored to specific directorate**
- Tier 3: Detailed Guidebooks

  Best practices of how to implement SE
  General tools and methods
- Tier 4: System Engineering Management Plans
  - **Technical program**
  - **Specific plans on SE implementation**
  - **Engineering specialty integration**
  - **Specific tools and methods selected**
  - **Organizational and contract interfaces defined**



System Engineering Processes Assessment and Vision

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Typical Today	5-Year Vision	10-year Vision	15-Year Vision
• national standard processes exist but in a quagmire of interfaces • NASA has a SE guideline (NASA SP-6105) that is only sporadically followed • no NASA-wide policy on systems engineering exists • NASA, DoD, and contractor teams use different processes and terminology	• A systems engineering policy, guidelines, and implementation strategies based on national standards and NASA/DoD/contractor best practices has been developed • Annual audits of NASA's systems engineering process model ensures best practices are used and distributed • A systems engineering certification program requiring continual education and training has been institutionalized • A knowledge management system for capturing and reuse of best practices and knowledge repository for cost, reliability, validated systems analyses and simulations, software, and hardware has been initiated • A completely digital product life-cycle management system for systems engineering and management for program/project control has been developed	• A collaborative / distributive advanced engineering environment for product life-cycle engineering and management has been developed based on system engineer and management processes for systems development and workforce training • Systems engineering, life-cycle cost, risk, and safety have been integrated for robust solutions of complex systems-of-systems development • All NASA centers have achieved the top level of systems engineering maturity • A certified (educated, trained, and experienced) systems engineering staff exists for engineering, management, and decision making • the organization interfaces and throughput is optimized through dynamic simulations	• an expert system for systems engineering exists to aid in the training and use of the validated advanced engineering environment for complex systems-of-systems developments • Knowledge management has revolutionized the startup of new programs with reuse of processes and tools • All decisions are based on validated simulations and virtual and surgical physical testing for performance, cost, safety, uncertainty, and risk (and politics!!) • a completed integrated international organization is optimized for the collaborative distributed environment

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Skills (Workforce)

Systems Engineering Architect/Specialist

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- Definition of a Systems Engineering Architect/Expert
  - Architect network centric and systems of systems
  - System Integrator
  - Drives next generation of mission solutions
- Attributes
  - Experienced technical leader
  - Experienced in working with the customer, understand their needs and customer value and to serve as the customer's primary technical interface
  - Expert in fundamentals – cost, schedule, risk, processes
  - System lifecycle experience from pre-proposal to logistics support
  - Understand hardware, software, mission and big picture
  - Solid interpersonal skills, verbal and written communications
- Lack of senior level experienced systems engineers/architects
  - Many self-proclaimed systems engineers
  - Exists both in industry and government

US R&D Scientists and Engineers

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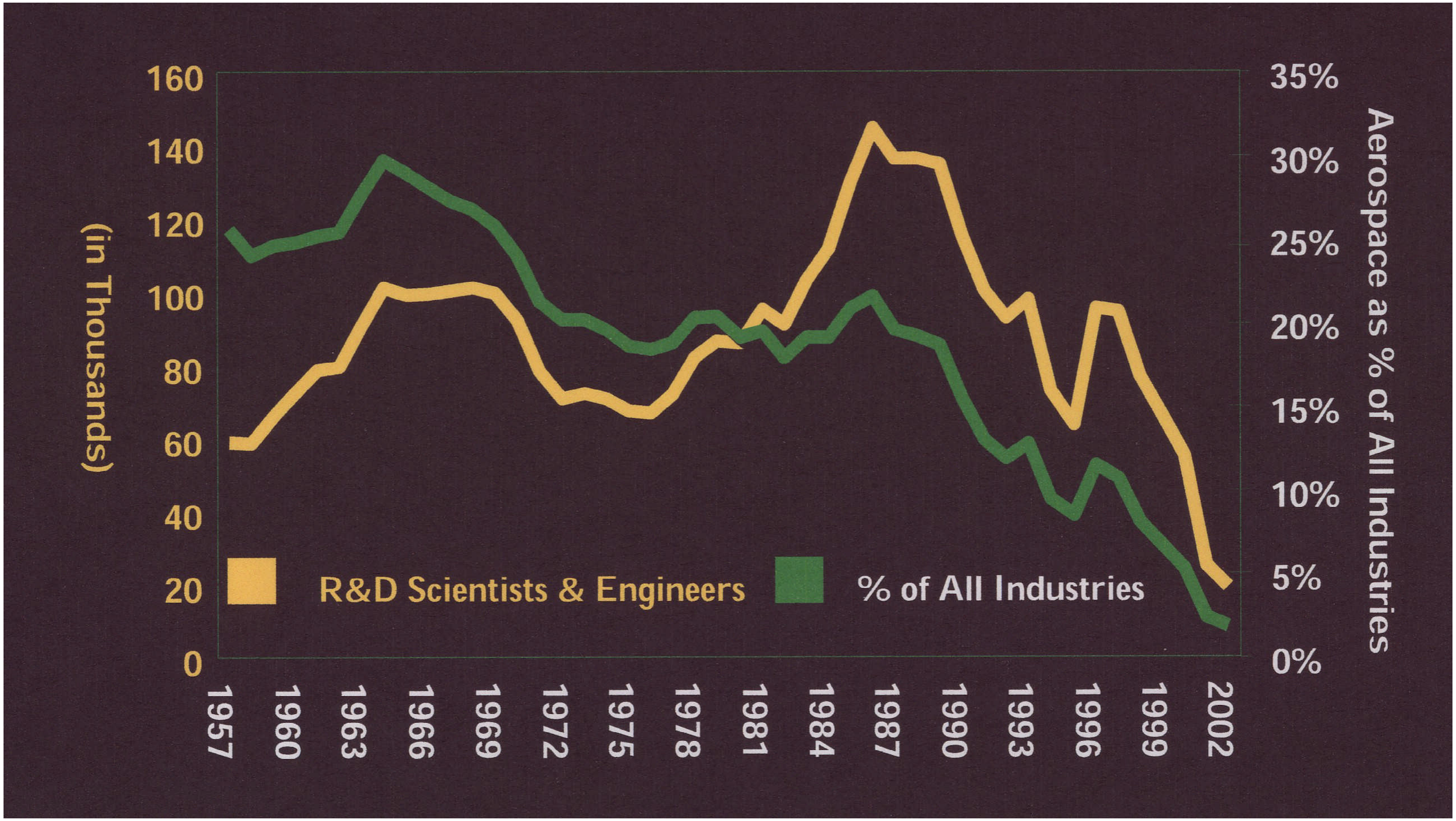

Degreed workforce is a shrinking pool.

The Resource Picture

- Degreed workforce is a shrinking pool
  - Many graduates are not US citizens
  - Total engineering enrollments continue to decrease
- 20-30 year cycle between major system developments and 10 year development cycle
  - Lack of SE experience on large complex systems
  - Experienced SE engineers are retiring faster than being trained
- NASA systems engineering for human spaceflight has eroded and systems of systems is particularly acute (NRC 2004 NASA Systems Integration Study)
- Existing university / industry partnerships are not having enough impact
  - SE is not a standard discipline (EE, ChemE, ME etc.)
  - More penetration at undergraduate level
- Need new ways to attract and develop system engineers
  - Additional learning
  - On-the-job experience
  - Virtual simulation

NRO SE Certification Requirements

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Level	Experience	Training
I	2 yrs. SE	SE-501 Acquisition Systems Engineering and SE-502 Designing Space Missions *or* 6 SE-related graduate credits *or* SPRDE Level II Certified
II	4 yrs. SE	Complete 4 from below: Requirements Development/Management Risk Management Measurement & Analysis Concept & Architecture Development Formal Decision Making Integration, Verification & Validation *or* 12 SE-related graduate credits or 6 after Level 1 *or* SPRDE Level III Certified
III	7 yrs. SE	INCOSE Certification or *or* 18 total SE-related graduate credits or 6 after Level 2

NASA needs to develop a SE certification program to develop systems engineering to meet future program requirements.

NASA SE Workforce Program

Advanced Planning & Integration Office

- Establish SE development policy including SE certification requirements for promotions
- Establish Government, industry, and academia SE education, training, and job experience partnerships
- Develop guidelines and process for SE graduated certification. Include integration with program management education and training
- Measure progress in SE workforce development and changes in program SE metrics

Workforce and Education Assessment and Vision

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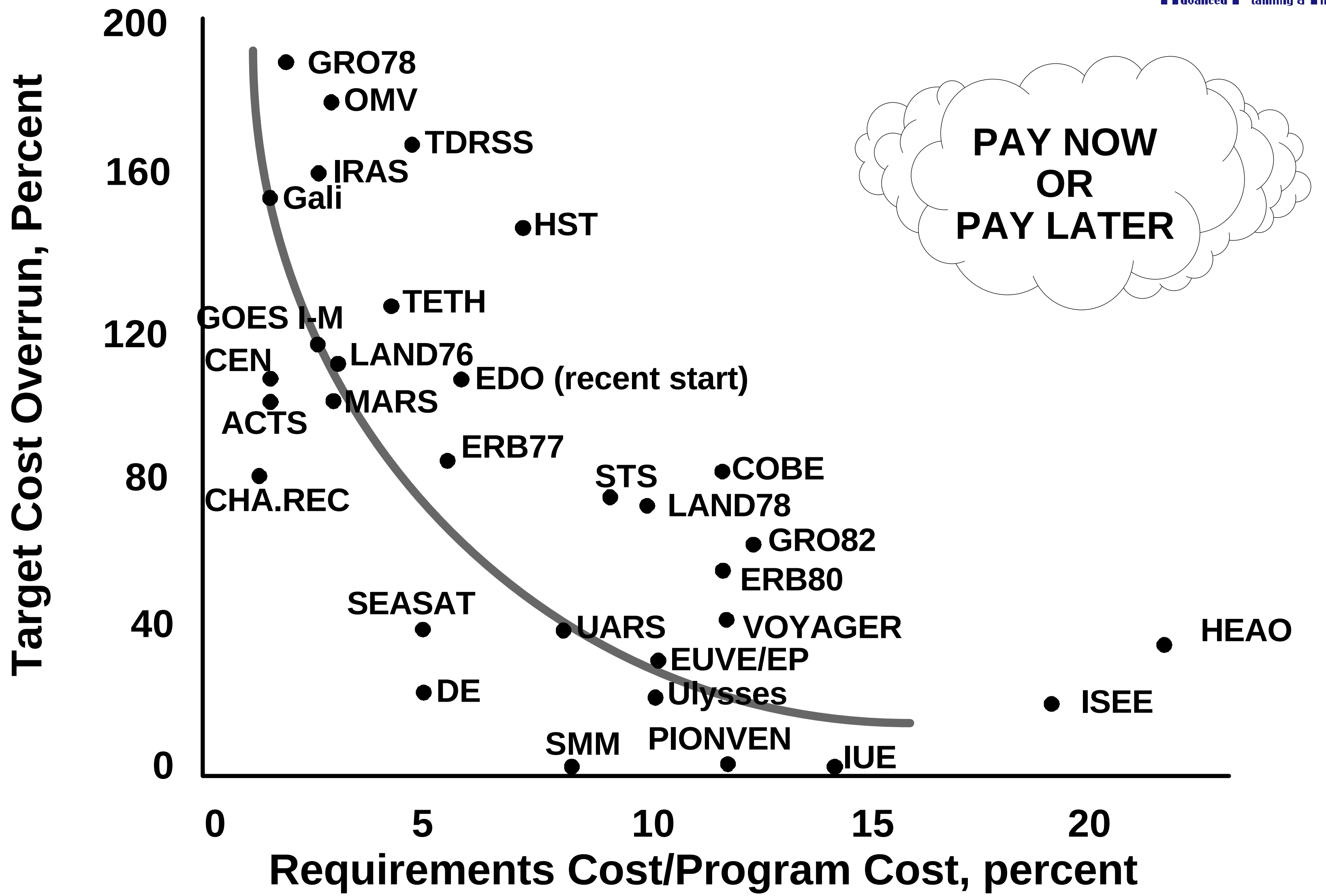
Typical Today	5-Year Vision	10-year Vision	15-Year Vision
• "erosion of knowledge, experience and skills" in "systems engineering, project management discipline, cost, schedule management, and technology management". "particularly acute" for systems of systems integration. (NRC Systems Integration for Project Constellation, 2004) • DOD has "essentially eliminated its systems engineering capability". (NRC, 2004) • only a single capstone design course in undergraduate engineering • courses taught in traditional classrooms • some video and Web-based Courses	• A systems engineering certification program requiring continual education and training has been institutionalized • just-in-time training via intelligent tutoring and advisory systems • training support using standard NASA and enterprise product and process models • focused training tuned to new opportunities and the best match with different employee skills and working styles	• Technological obsolescence of workforce virtually eliminated by a certified (educated, trained, and experienced) systems engineering staff for engineering, management, and decision making • learning centers at each of NASA's Collaborative Engineering Environment facilities • university use of collaborative, distributed- learning consortia • practical experience of new engineers using validated system simulations • technological obsolescence of workforce virtually eliminated	• Systems Engineering experience gained through simulation and on-the-job training • Advanced Engineering Environment technologies and systems replicated at the university and used for maintaining a strong fundamental core course structure, with simultaneous links to the math and science departments and virtual links to industry and government laboratories • national team teaching in engineering, math, science, management, and the humanities • personal learning experience emphasized —anytime, anywhere via an advanced Internet with high bandwidth • just-in-time personal/virtual training and tutoring

Adopted from: "Design in the New Millennium: Advanced Engineering Environments", NRC 2000

Systems Engineering Tools and Methods

Effect of Requirements Definition Investment on Program Costs



The Systems Engineering Process
(Ref. ANSI 499)

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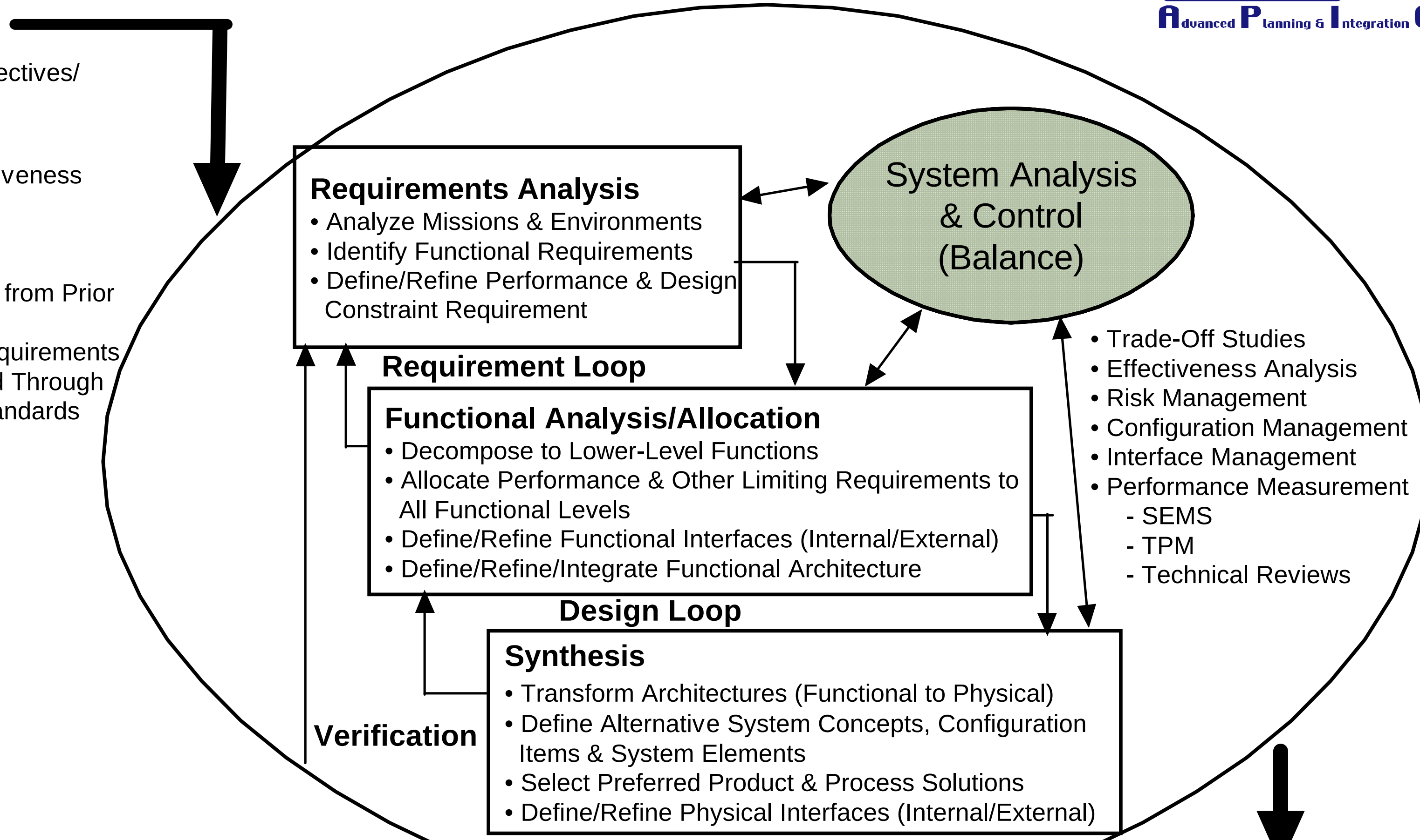
Process Input

- Customer Needs/Objectives/ Requirements
  - Missions
  - Measures of Effectiveness
  - Environments
  - Constraints
- Technology Base
- Output Requirements from Prior Development Effort
- Program Decision Requirements
- Requirements Applied Through Specifications and Standards

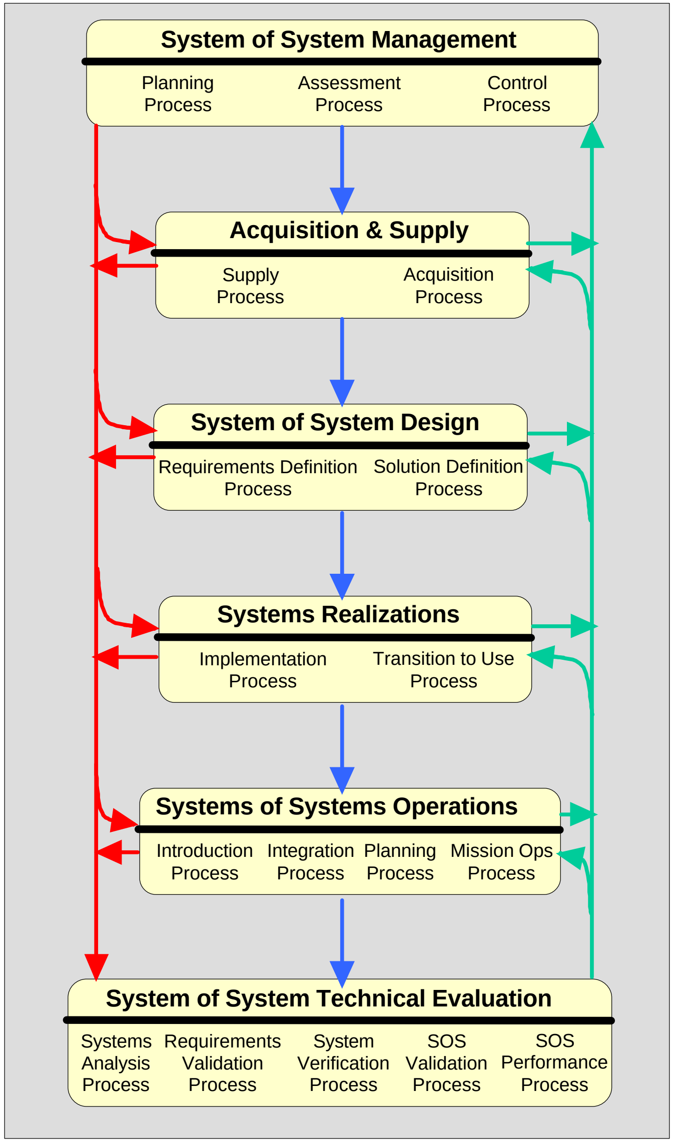


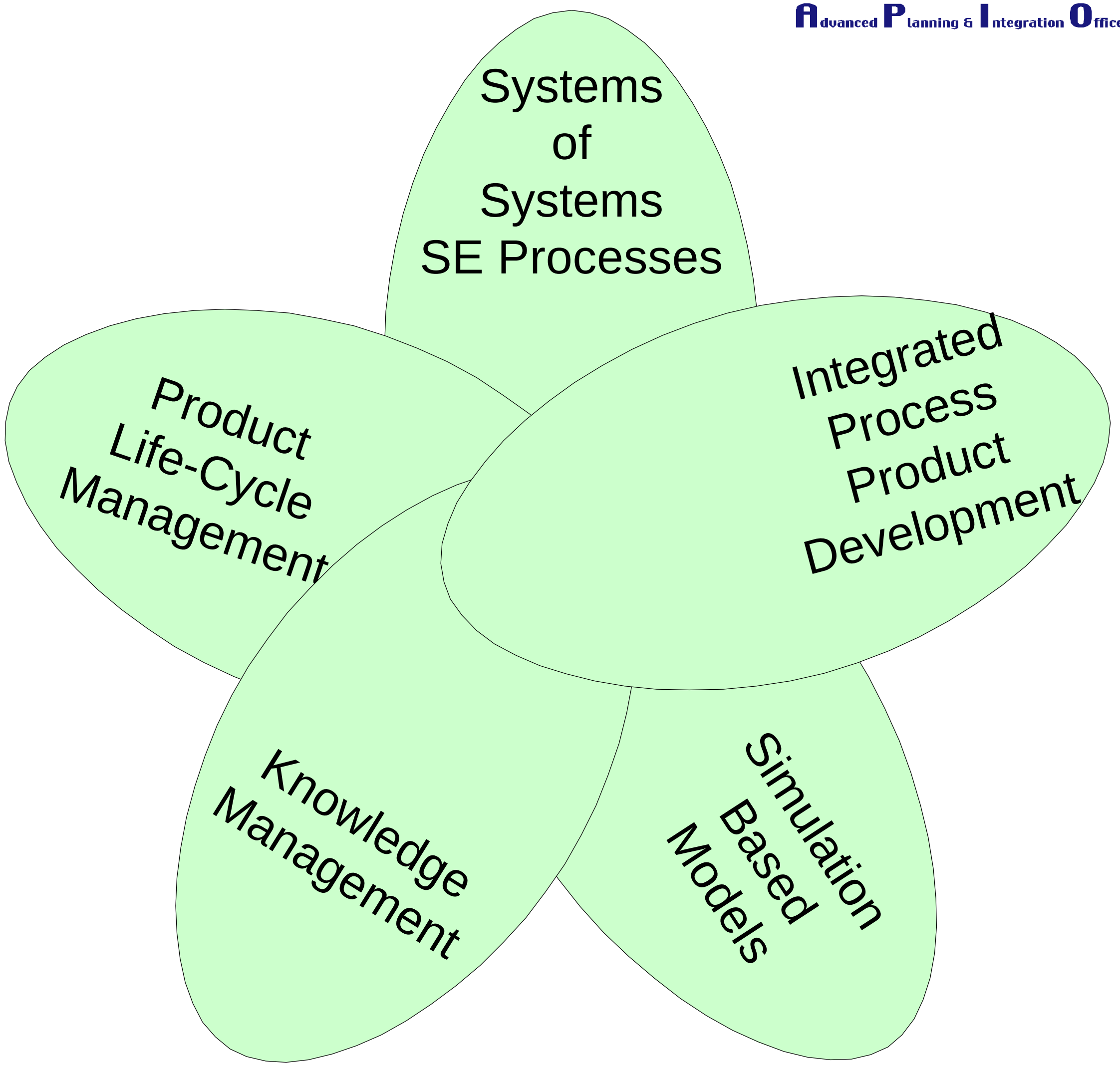
Process Output

- Development Level Dependant
  - Decision Data Base
  - System/Configuration Item Architecture
  - Specification & Baseline

Systems Analysis and Simulation drive the entire Systems Engineering Process

Integrated Systems Engineering and Life-Cycle Management





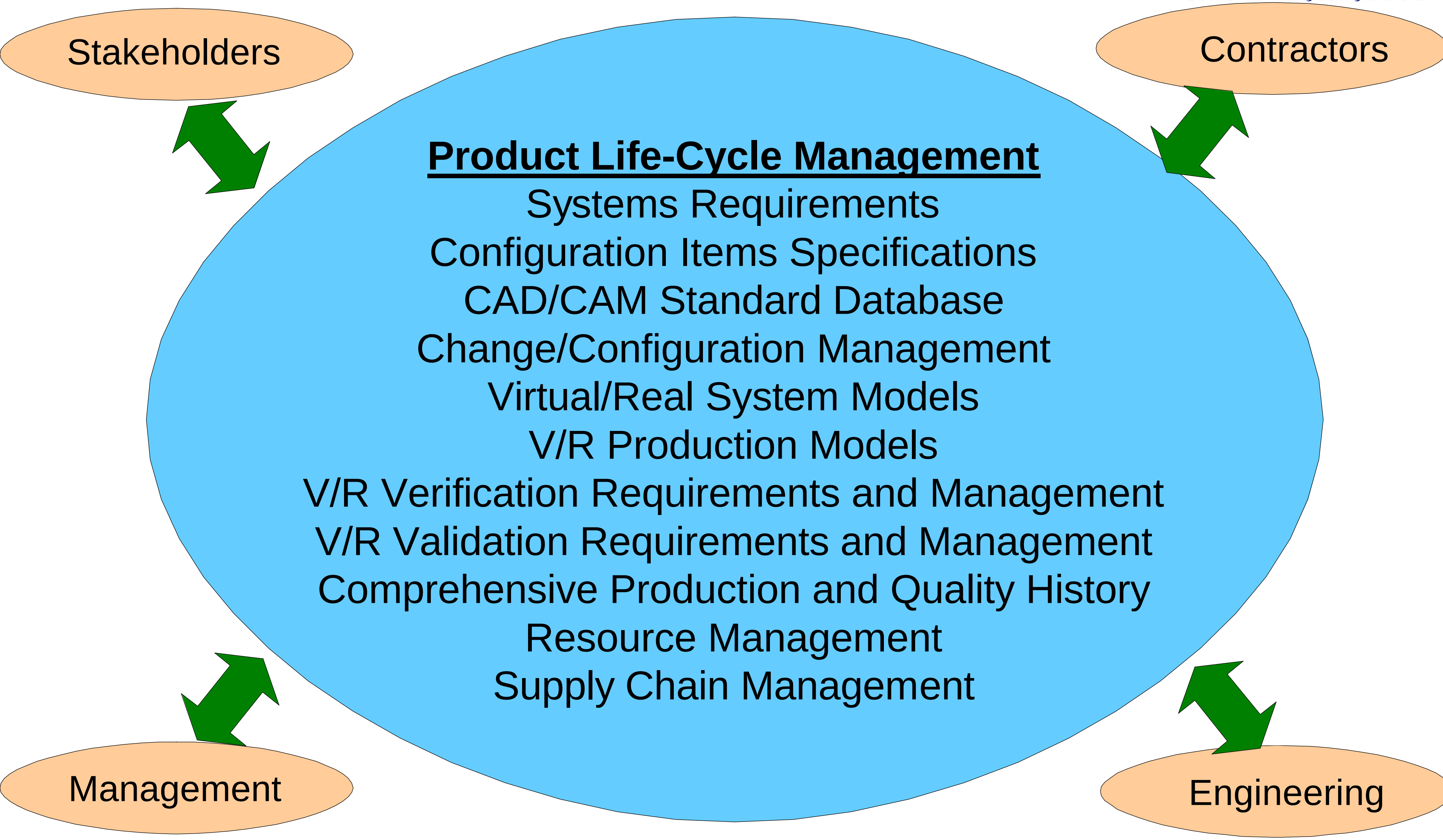
Product Life Cycle Engineering and Management Focus

Integrated Product Process Development

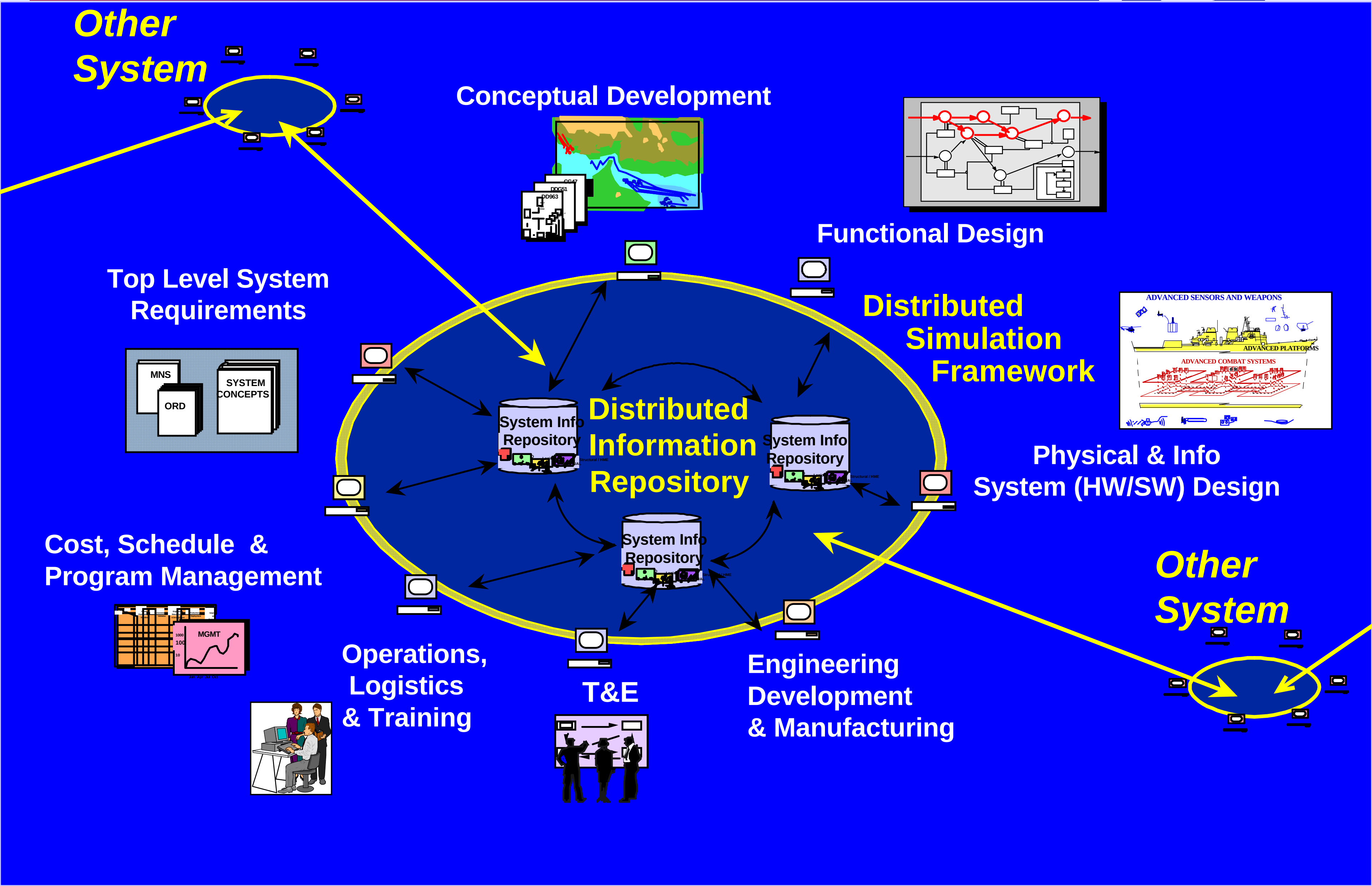
IPPD Defined: A management process that integrates all activities from product concept through production/field support, using a multi-functional team, to simultaneously optimize the product and its manufacturing and sustainment processes to meet cost and performance objectives. Its key tenets are as follows:

- **Customer Focus**
- **Concurrent Development of Products and Processes**
- **Early and Continuous Life Cycle Planning**
- **Maximize Flexibility for Optimization**
- **Use of Contractor Unique Approaches**
- **Encourage Robust Design and Improved Process Capability**
- **Event Driven Scheduling**
- **Multidisciplinary Teamwork**
- **Empowerment**
- **Seamless Management Tools**
- **Proactive Identification and Management of Risk**

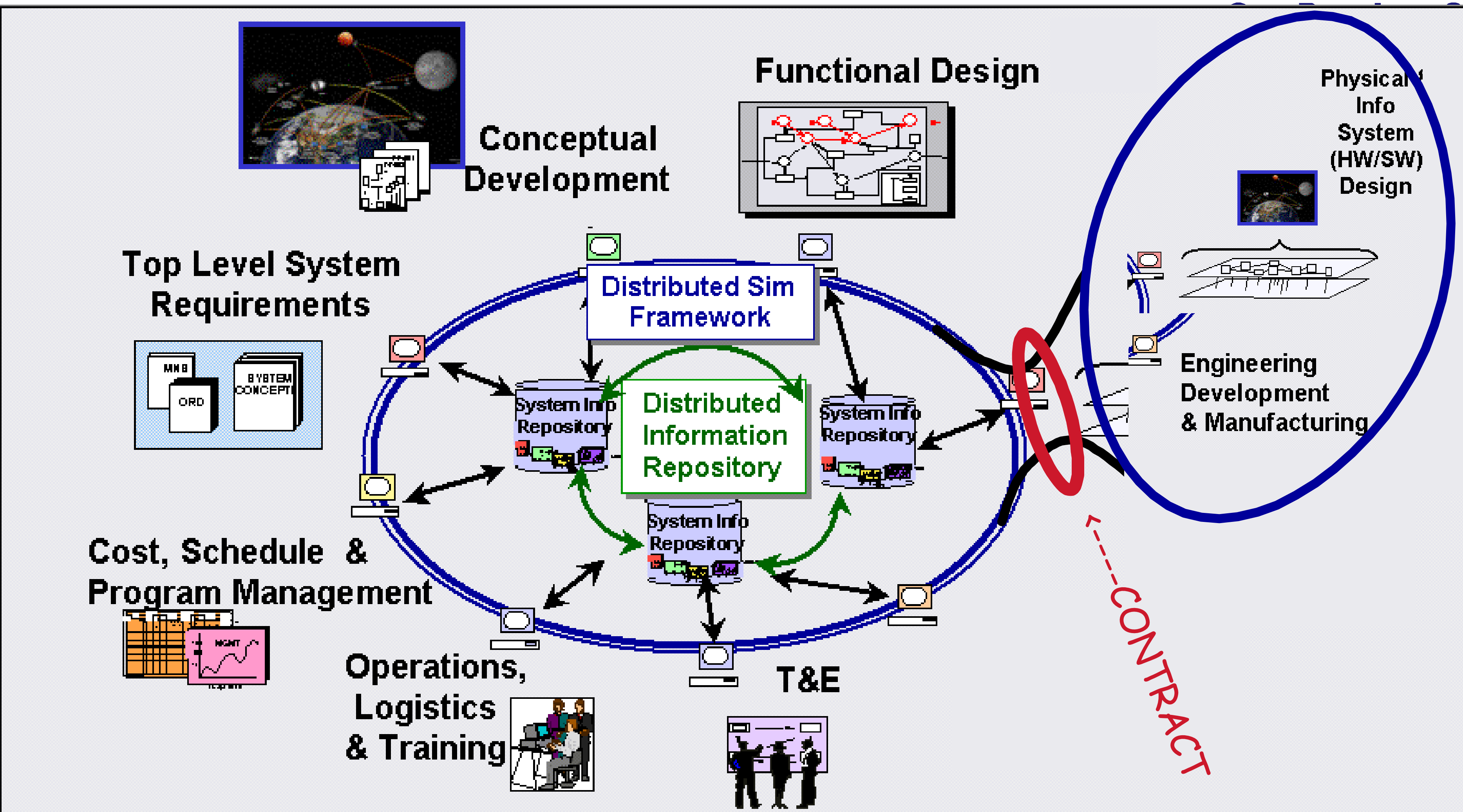
Product Lifecycle Management (PLM)



Simulation Based Systems Engineering



SBSE: The Challenge of Contracted Elements



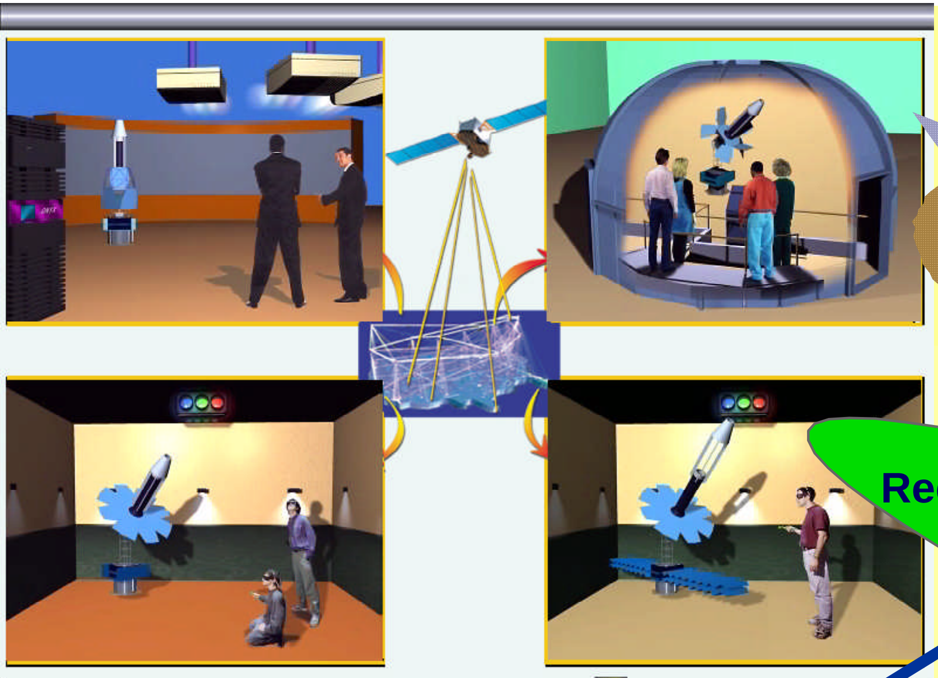
Fully Integrate Total NASA/Industry Systems Engineering and Management

Systems Engineering Tools and Gaps

Engineering Discipline Tools	- Mostly very good for detailed analysis; however needs standards for multidisciplinary integration for design and speed increases for optimization and uncertainty analyses.	
Specialty Engineering ("ilities") Tools	- Little confidence in prediction of causal relationships for reliability, maintainability, supportability, operability, availability, safety, etc.	
Life Cycle Cost	- NASA has continually underestimated the life-cycle cost (technology, development, production, operations, logistics). Needs causal models to assist engineering system and lifecycle design.	
Program/Project Management	- Many excellent tools available for cost, schedule, and configuration management; needs total integration including risk and engineering mitigation planning	
Product Life-cycle Management	- Many new COTS capabilities are being developed. Need to assess and select for NASA applications. Integration with simulation based SE modeling required. NASA wide and industry integration required.	

Critical Gap	
Significant Gap	
No or Minor Gap	

Systems Engineering/Robust Design



Requirements, Flowdown, Trades, Sensitivities, and Validation

Risk
Sustainability
Cost
Schedule
Informed Decisions
Performance
Safety
Reliability

Requirements
Concept Development
Design/Development
Test
Manufacturing
Integration/Verification
Ops/Maintenance
Disposal

System of Systems
Life-Cycle Simulation and Modeling

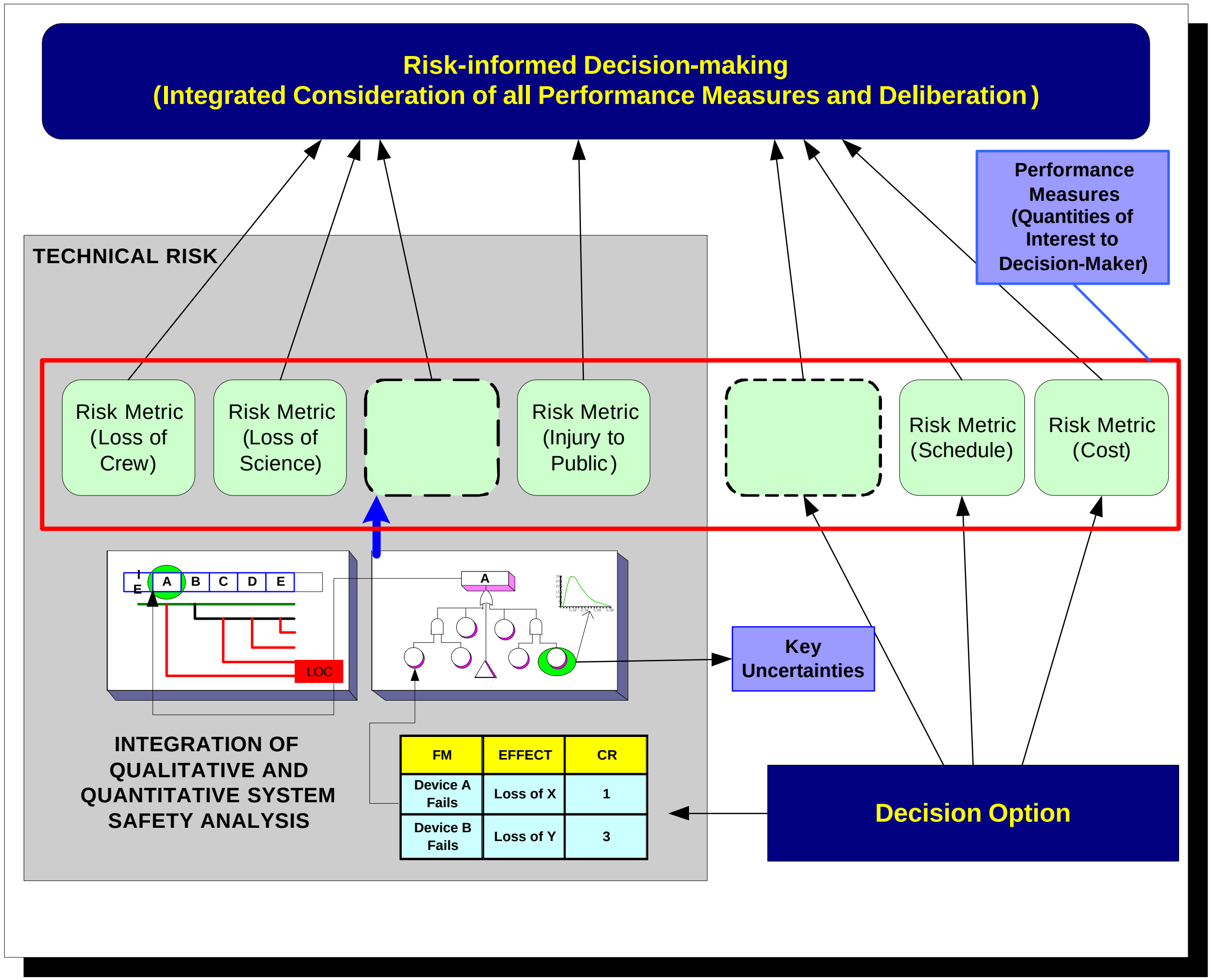
Advanced Tools and Processes

- High Fidelity Numerical Simulations
- Non-Traditional Methods
- Rapid Synthesis Methods
- Life Cycle Frameworks
- Life Cycle Cost Simulations
- Risk Simulations

Integrated Decision-Making

Integration of risk analysis with decision processes

Systems Engineering



Apollo Decision FOM Matrix (1962)

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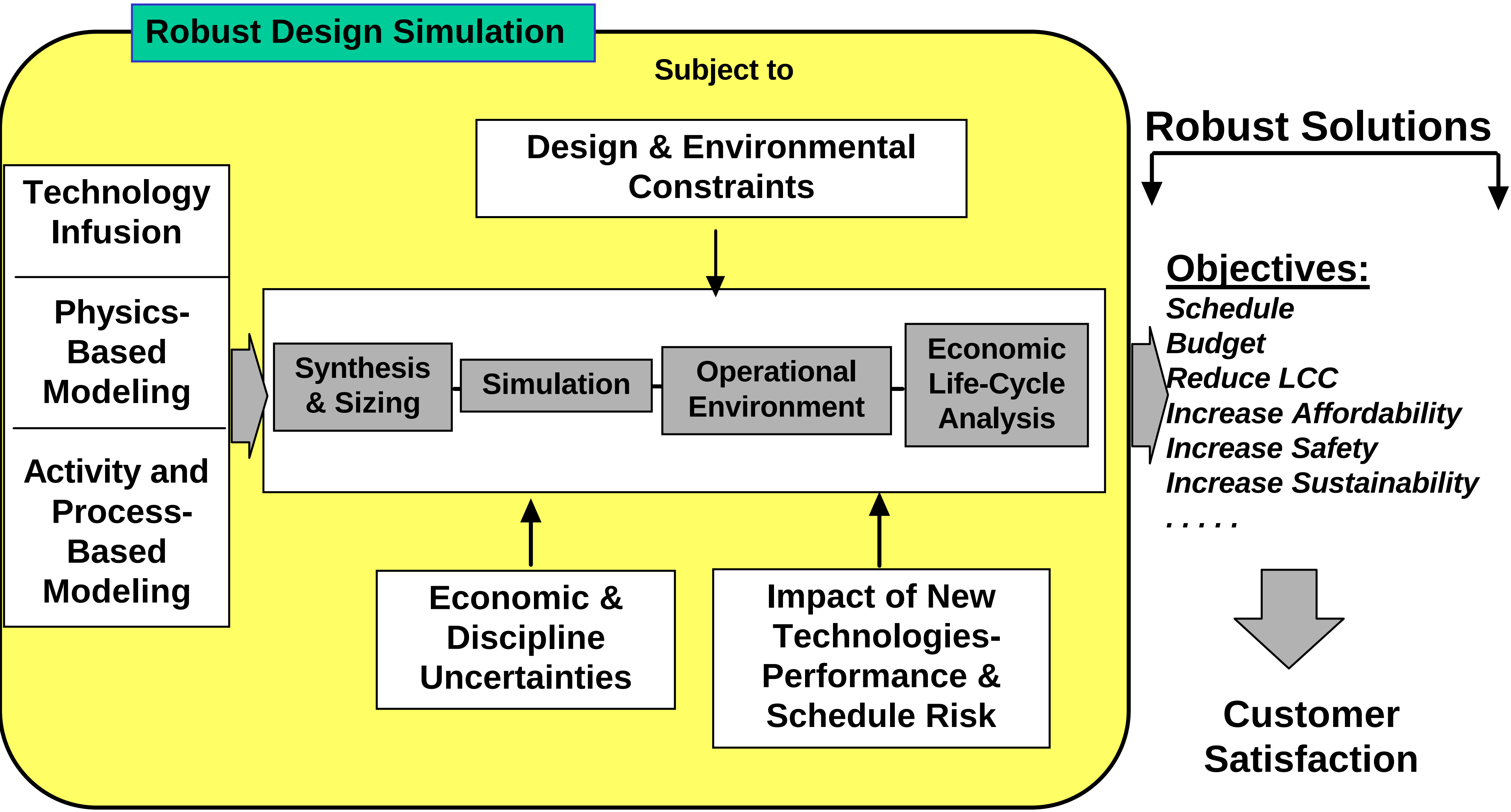
	Performance	Probability of Success	Schedule	Safety	R&D Costs	Ops Costs	Growth Potential	Delivery Costs	Critical Development Problem Areas
EOR	15300	14.5 (w/spare)	Aug 1969	18.2	$6490 E6	$1240	12	$88.4 E6	a. Earth orbit rendezvous b. propellant transfer c. C-5 launch vehicle d. standard apollo capsule
LOR	12,600 5,000 LEM	19.1	Feb 1969	16.1 (CM) 22.0 (LEM)	$5840 E6	$620	10*	$77.4 E6*	a. lunar orbit rendezvous b. LEM and personnel transfer c. C-5 launch vehicle d. standard apollo capsule
C-5 Direct	9210	21.9	Oct 1968	16.7	$5690 E6	$510	12	$61.4 E6	a. high energy return b. light weight capsule c. C-5 launch vehicle
Nova Direct	15300	25.3	May 1970	18.0	$6160 E6	$630	15	$55.4 E6	a. Nova launch vehicle b. standard apollo capsule

Roadmap to Affordability Through Robust Design Simulation



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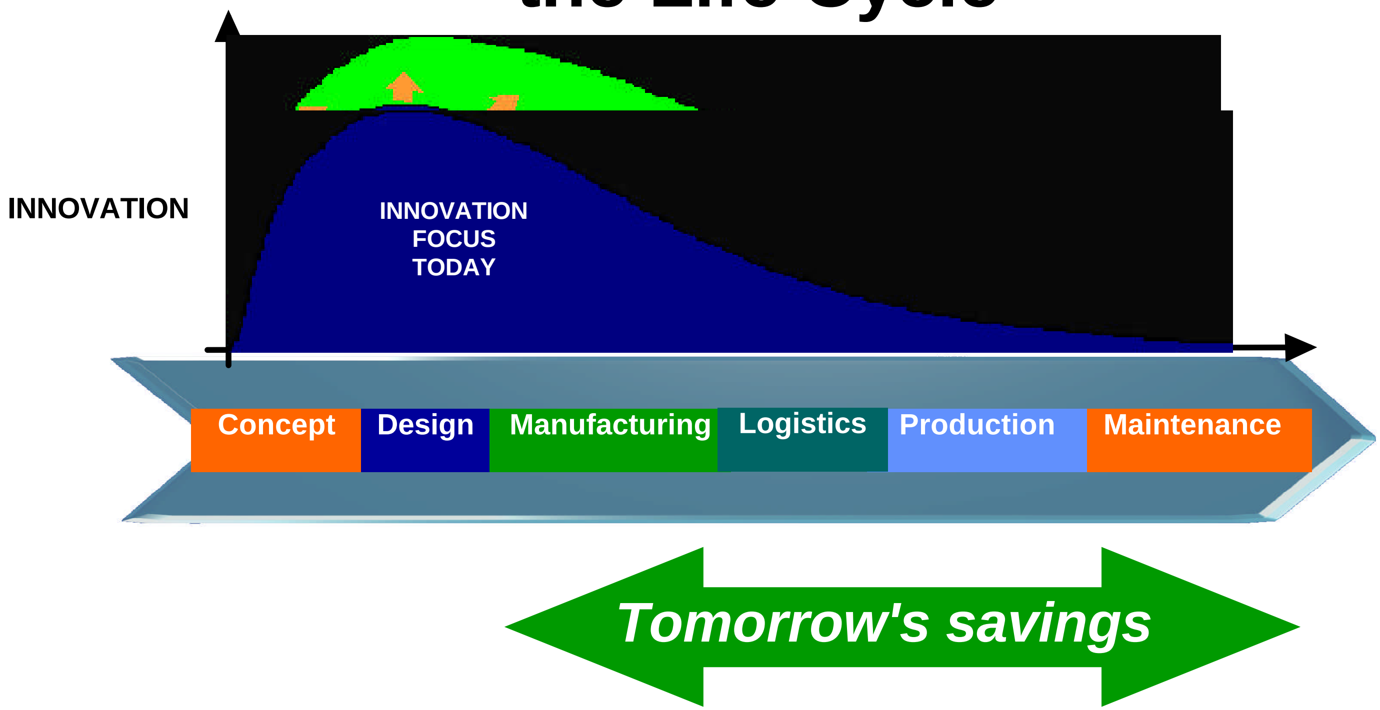
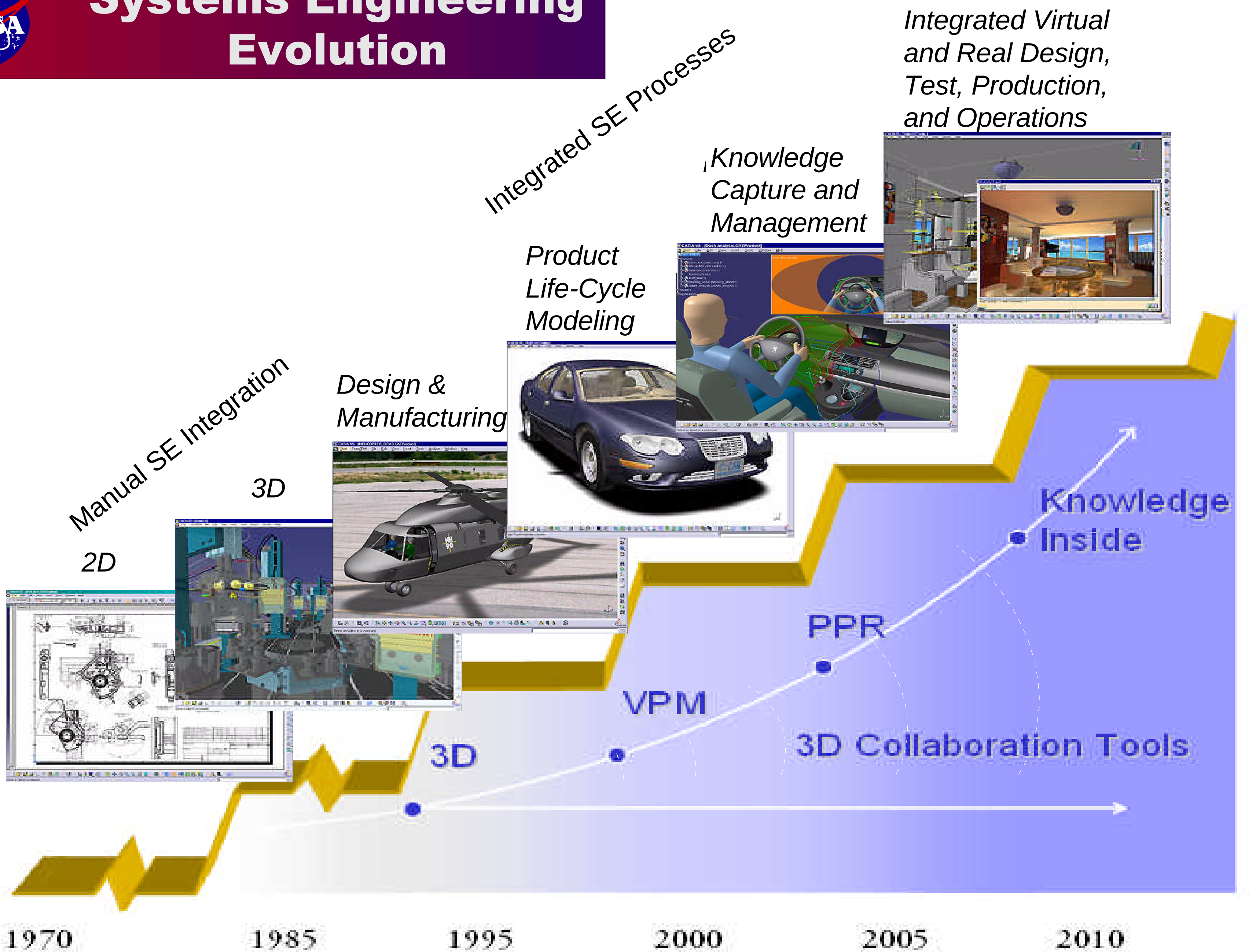
Innovation Focus Throughout the Life Cycle



Optimizing the re-use of Data and Corporate Knowledge

Systems Engineering Evolution



Rapid (Virtual and Real) Prototyping

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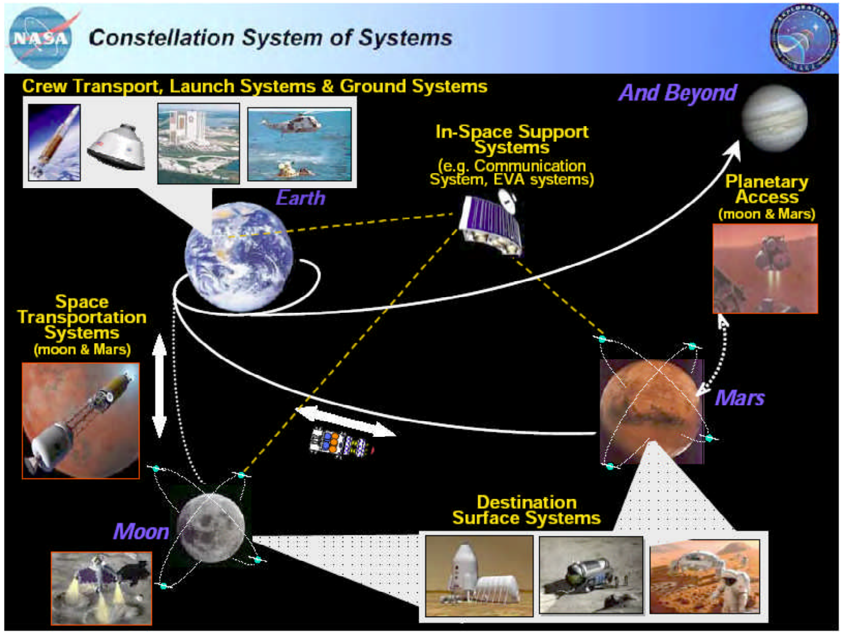
- Early Requirements Development
- Analysis of Alternatives
- Reconfigurable Designs
- Real/Virtual Integration
- Human/Machine Performance
- Safety, Reliability, Cost Trades



- Systems of System Integrated Performance and Decision Analysis

Rapid Validation of Virtual Models for Confident Decision Analysis

Define, Monitor, and Control the Physical World

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VIRTUAL

PHYSICAL

Product & Process Knowledge

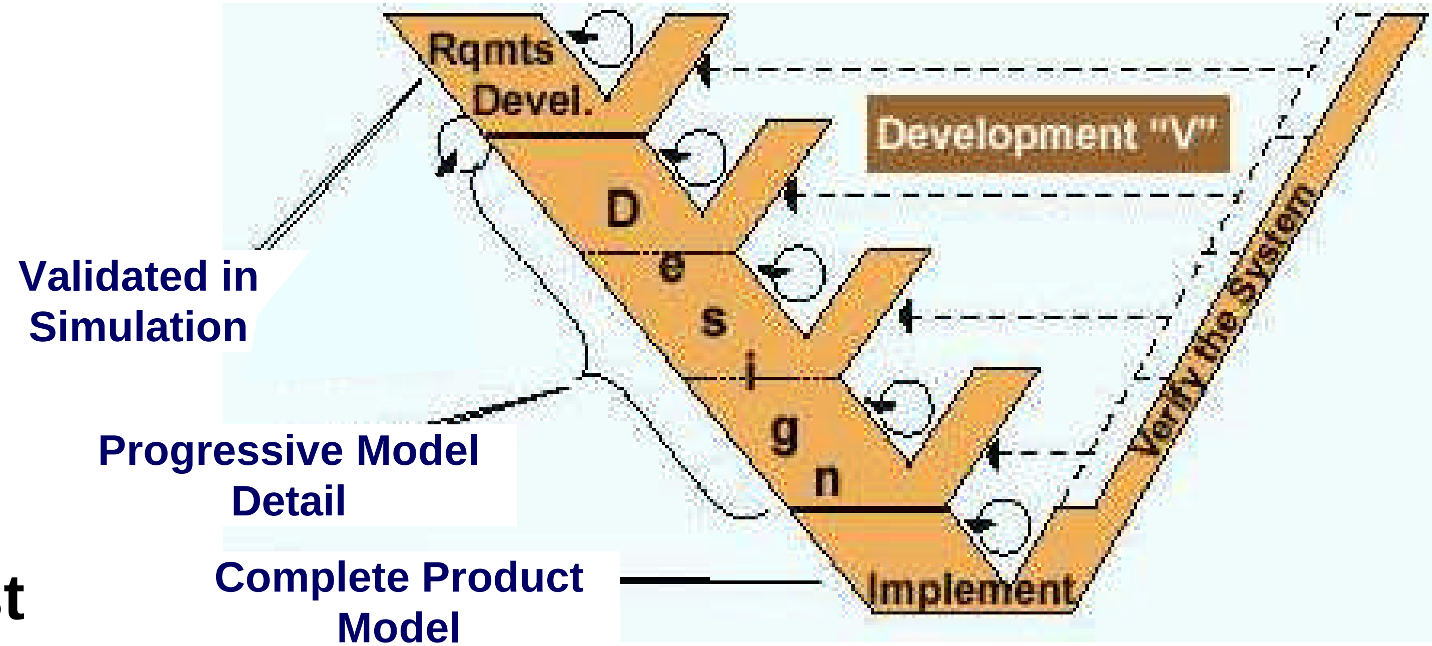
Production

INTELLECTUAL PROPERTY

REAL OPERATIONS

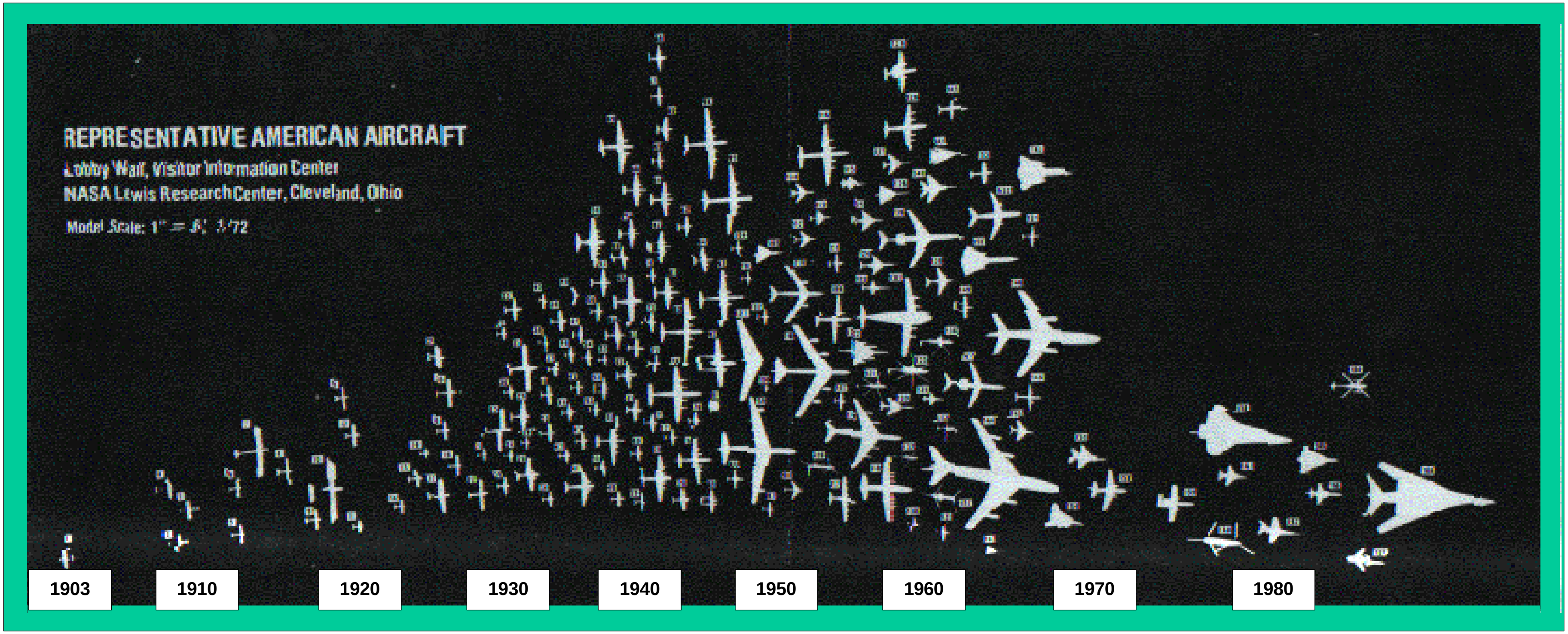
SBSE Integration with Systems Engineering

- **Design is Authored as Models**
- **Simulation Verifies the Design**
- **Physical Test Verifies the Simulation**



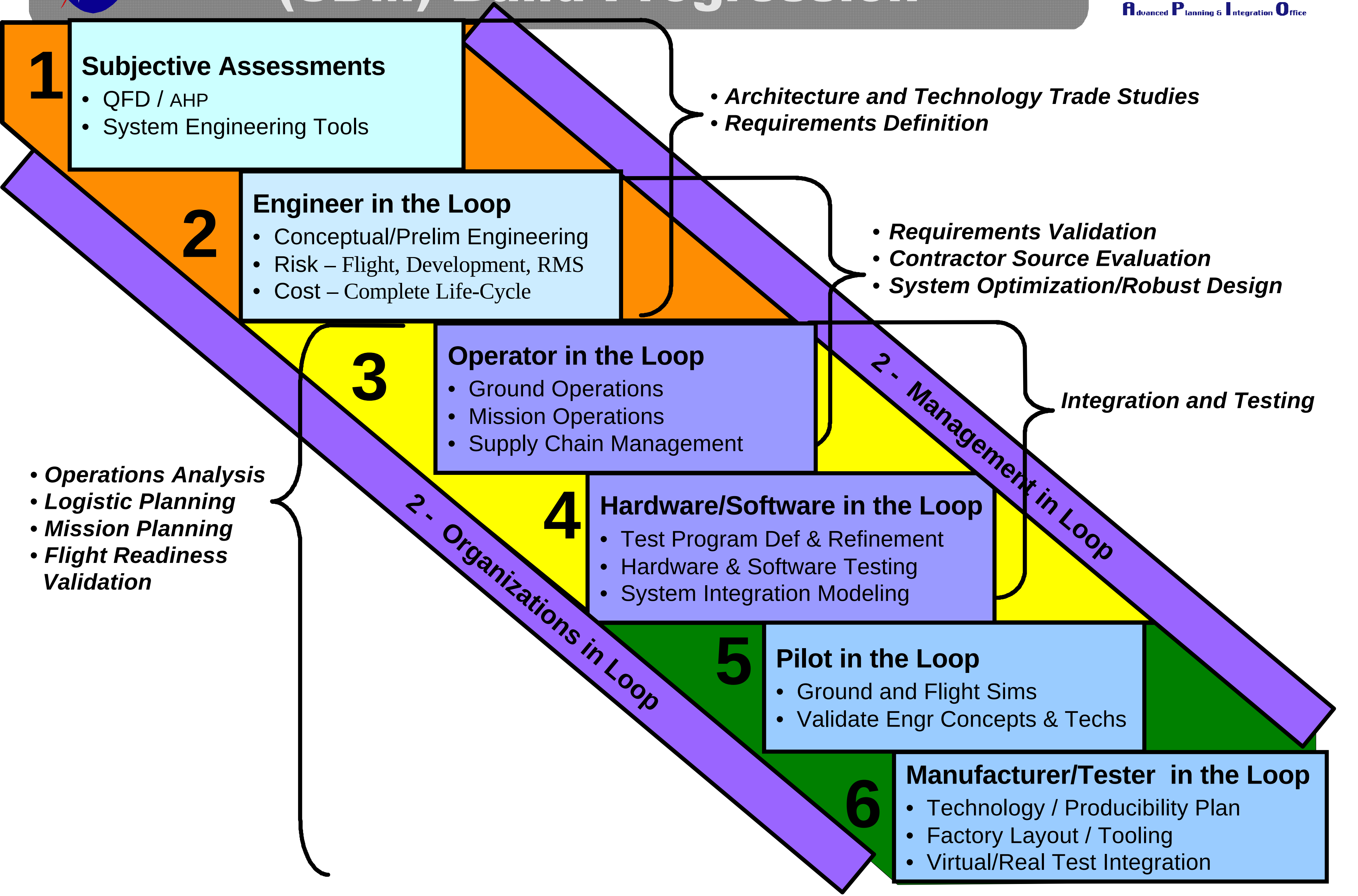
Better Decisions / Shorter Development Times

Virtual Simulation to Keep and Reuse Workforce Knowledge



Validated virtual simulation may compensate for lack of physical Systems Engineering experience.

Simulation Based Modeling (SBM) Build Progression



Collaboration/Distributive Environment

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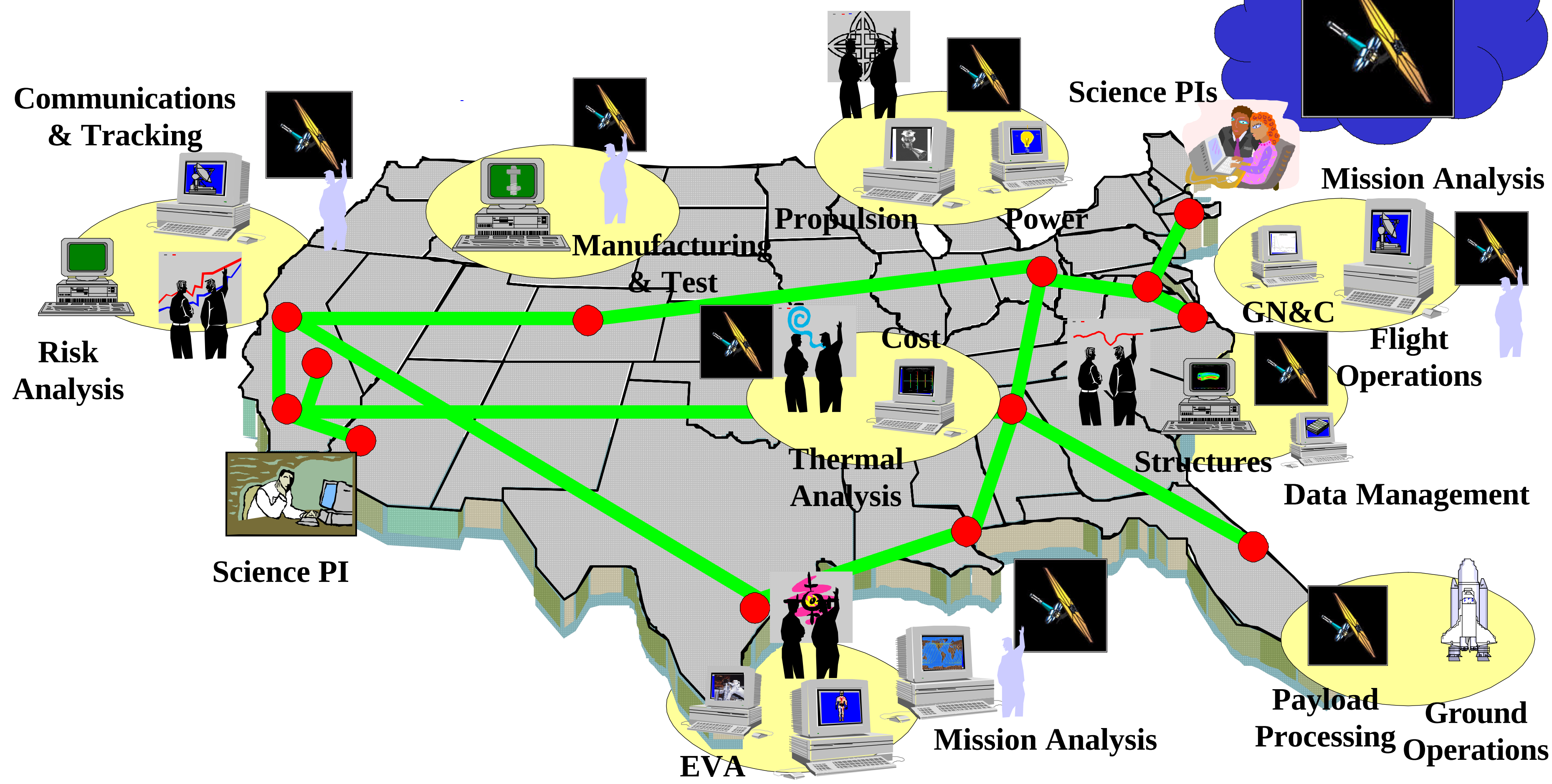
A geographically distributed, integrated, secure, collaborative environment which enables life cycle design and analysis capability, enabling world-class engineering and science applications



Modeling Management Structure
For STS Logistics, Management and Planning ~70%

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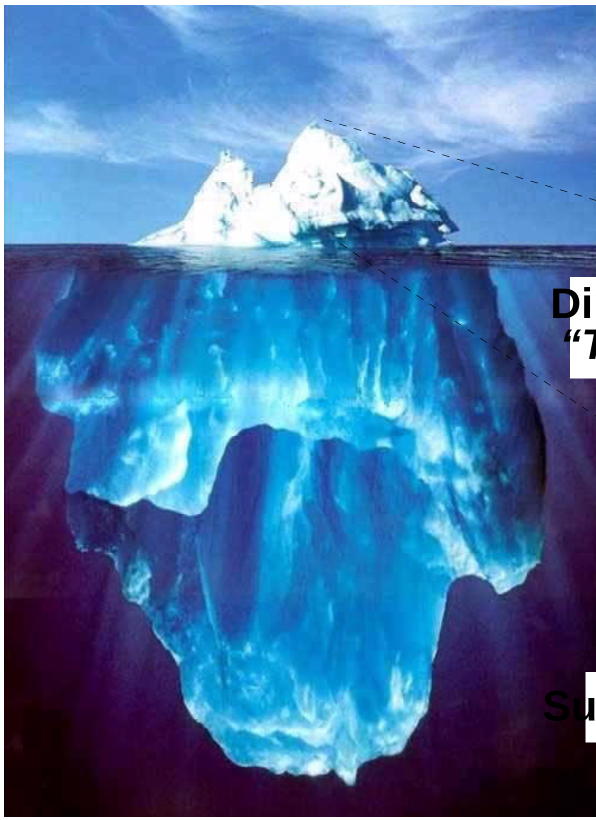

Direct (Visible) Wor
“Tip of the Iceberg

+
Support (Hidden)

Recurring
Ops

STS Budget "Pyramid"
(FY 1994 Access to Space Study)

Generic Operations Function	Total $M FY94	*Total (%)*	
Elem. Receipt & Accept.	1.4	*0.0%*	~10%
Landing/Recovery	19.6	*0.6%*	
Veh Assy & Integ	27.1	*0.8%*	
Launch	51.5	*1.5%*	
Offline Payload/Crew	75.9	*2.3%*	
Turnaround	112.3	*3.3%*	
Vehicle Depot Maint.	237.5	*7.1%*	~20%
Traffic/Flight Control	199.4	*5.9%*	
Operations Support Infra	318.6	*9.5%*	
Concept-Uniq Logistics	842.7	*25.1%*	~70%
STS Ops Plan'g & Mgmnt	1477.4	*43.9%*	
Total ($M FY94)	**3363.4**	***100.0%***	
Percent	**100.0%**		

CM McCleskey/NASA KSC

Organizational Simulation

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- Management and Organization integration is a major percentage of program costs
- Information flow, decision paths, and process graphs can be stochastically modeled for duration, human capital, and impact on total program costs.
- Currently, no organizational model has been developed to analyze NASA program organizational performance.
- Validated organizational simulations may have as much impact as system simulation and optimization

Systems Engineering Tools and Methods Assessment and Vision

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Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
1. Mission Requirements Analysis/Product System Strategy • high-level systems engineering analysis • stakeholder/mission requirements definition	• traditional systems engineering methods / non-standard application across NASA • little integration and reuse of engineering analyses • late trades of requirements versus system specs, performance, and cost	• establishment of NASA-wide policy and guidelines for systems engineering • integrated life-cycle analysis tools for system and requirements trades for acquisition	• integrated systems engineering and management systems for technical and programmatic risk • validated life-cycle simulation of all mission requirements • seamless transitioning of technical simulations to management and control simulation • systems of systems requirements are understood and validated	• all life-cycle engineering functions are seamlessly integrated for system design, development, manufacture, and operation • all mission and enterprise requirements can be traded with functional and physical models for the systems of systems environment • complete emersion of stakeholder in the design/requirements process
2. Product Specification • product strategy • voice of the customer • environmental and other regulatory requirements • planned product specification	• competitive comparisons • projections of future products • interviews and focus groups of customers and others • demonstrations • output is written documentation	• complete linkage of customer requirements, functional requirements, physical architecture, and operational requirements • virtual prototypes for specification validation • strategic decision models and analyses based on uncertainty and risk • product life-cycle model for management of complete digital product database	• knowledge base for construction of systems analyses for a proposal with a "selected" level risk • reliable specifications even for first-of-a-kind products • systems of systems impact of specifications are known	• reliable “batch of one” methods for unique products • product created on demand • ability to write in preferences and requests • maximum reuse of hardware, software, infrastructure, and knowledge for the enterprise

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
3. Concept Development • target setting • brainstorming on product and process alternatives • development of product and process concepts	• iterative, largely manual, bottom-up, non-optimized • expert opinion for concept initiation • rules of thumb • innovation relies on experienced practitioners	• integrated, predictive life-cycle cost and profitability models • optimization of shared resources • better models of cost and "ilities" for concept trades with customer requirements	• complete life-cycle optimizations trading safety, performance, life-cycle cost, technical/performance risk, and schedule • full automation of subsystem and component tracking and trade-offs • collaborative engineering environment for complete enterprise participation in engineering and management with contractors • virtual prototyping for manufacturing, integration, testing, ground and fight operations	**Steps 3, 4, and 5 combined** • concept is optimized to meet mission and enterprise requirements (hardware, software, and knowledge reuse known) - sensitivities, robustness, uncertainties are automatically generated for decision analysis • expert system generates alternatives • optimized, top-down concept development process • automatic analytical evaluation of all product and process attributes (including risk and uncertainty) • global collaborative engineering environment

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
4. Preliminary Product and Process Design • high-level definition of product and process designs • evaluation of product and process designs vs. targets • high-level system trade-offs	• iterative, largely manual, largely bottom-up, heuristic • derivations of existing designs • progressive definition • coarse definition, mostly manual from scratch • unequal levels of definition for new and reused parts • 20% of product and process attributes evaluated analytically using simplified models • reliance on physical prototypes	• rapid iteration of product and process design • object-oriented models scalable from macro to micro levels • single interoperable data set • automated process model creation • analytical evaluation of all attributes, including cost and producibility • multifunctional optimization	• some degree of iteration implied, but guided by optimization capability • analytical evaluation of all attributes, 200 to 300 times faster than current methods • integrated; single data source • full automation of subsystem and component tracking and trade-offs • virtual manufacturing	• single-pass product and process design and concurrent evaluation with multifunction optimization and automatic cascade to next lower level of design • automated generation of details about component and subsystem design and manufacturing details from high-level descriptions and desired attributes • single product life-cycle data source

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
5. Refinement and Verification of Detailed Product and Process Designs • development of designs for components, subsystems, and manufacturing processes • geometry creation • prediction and evaluation of all product and process attributes • tracking and trade-offs of subsystems and components	• detailed process and product definition mostly manual and from scratch • limited reuse of design geometries for new parts • analytical evaluation of one-third of product and process attributes using detailed models • some model sharing • reliance on physical prototypes • attribute prediction and evaluation partially automated, but not integrated with design evolution	• distributed, collaborative processes within NASA • physical prototypes essentially eliminated • real-time sharing of design information	• automatic configuration control and tracking of system and processes • distributed, collaborative processes (NASA and contractors) • design advisors • minimal, "surgical" testing • no late trade-offs and no errors	• automatic verification of the system and processes generated within the NASA advanced engineering environment • immersive design and evaluation environment from the total NASA/ contractor engineers, managers, and decision makers • international distributed, collaborative processes

Adopted from: "Design in the New Millennium: Advanced Engineering Environments", NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
6. System Prototype Development • experimental refinement of product attributes that do not meet targets	• analytical evaluation required for more than half of all product attributes • real and virtual prototypes available for form, fit, and function demonstrations and tests	• integrated database for development of rapid prototypes • virtual prototypes becoming the norm for NASA	• complete virtual prototyping of system, systems, manufacturing, integration, tests, and operations	• validated virtual models - limited experiments required
7. Production, Testing, Certification, and Delivery	• virtual shop floor modeled • discrete event optimized production flow • on-line statistical process control	• product life-cycle model used to integrate production with resources, supply chain, workforce, and management • products with 100% quality—getting it right the first time	• all production hardware, software, infrastructure, workforce, and processes developed and tested virtually • complete supply chain modeled and integrated with production • off-line robust design • lean, agile manufacturing • design for manufacturing: fewer parts, more compatibility, and easier assembly processes	• complete integrated virtual environment for supply chain, production, integration, verification, and validation • virtual design and manufacturing process with zero defects • only minor facility reconfigurations required for single product runs

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Systems Engineering Tools and Methods Assessment and Vision

Advanced Planning & Integration Office

Steps in the Design and Development of Products and Processes	Typical Today	5-Year Vision	10-year Vision	15-Year Vision
8. Operation, Support, Decommissioning, and Disposal	• sequential, historically based modeling approach • a lot of manual operations	• consideration of remanufacturing in design • limited autonomous systems • simulation models based on operational processes • improved automation of support activities • supply chain modeled for impacts on design	• autonomous systems • operations driven supply chain fully modeled and managed • design for easy repair • design for disassembly • design for reuse and remanufacture	• autonomous systems • self-healing • self-disassembly • self-disposal

Adopted from: “Design in the New Millennium: Advanced Engineering Environments”, NRC 2000

Capability 15.1 Systems Engineering Roadmap

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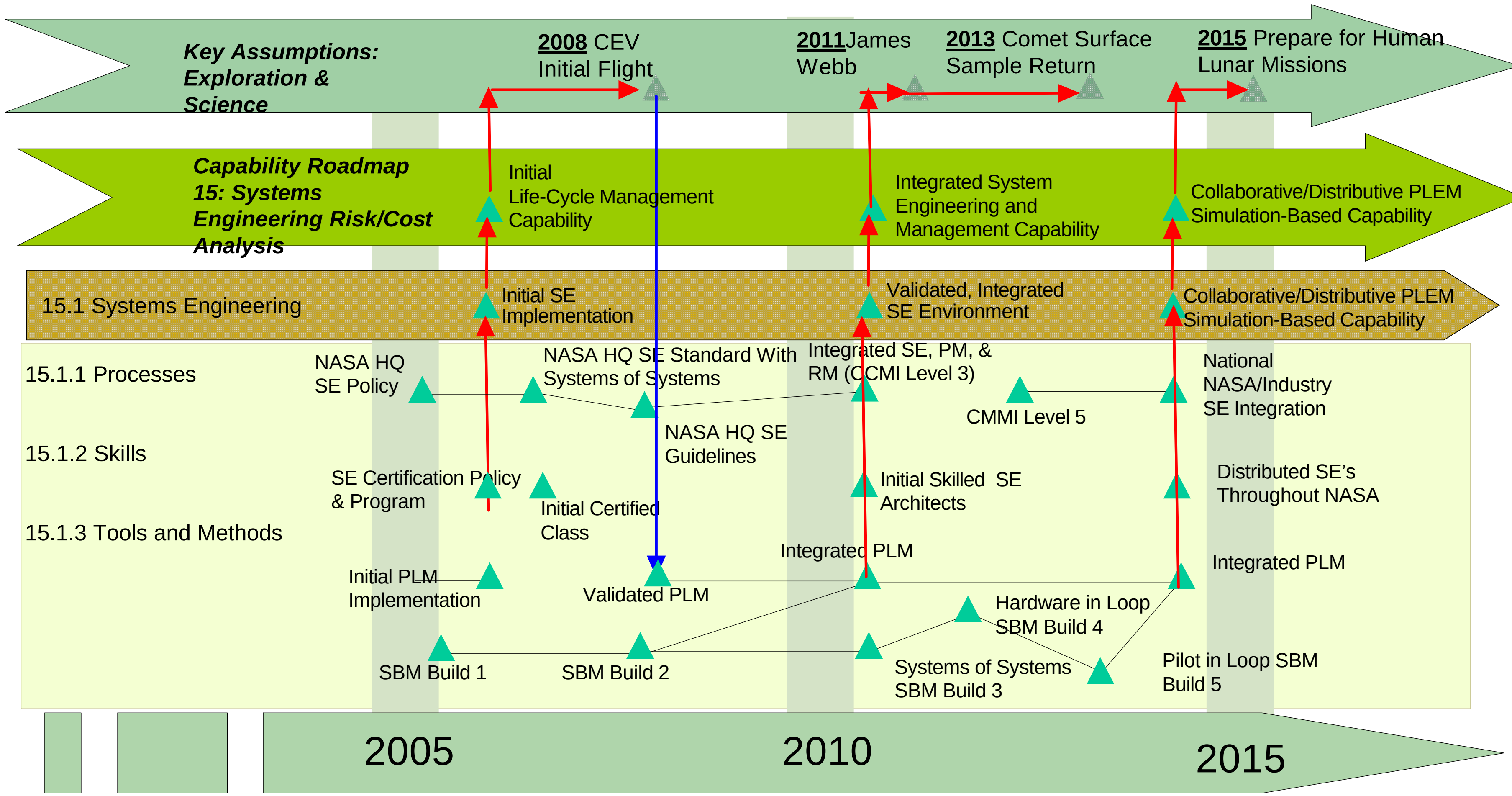


Major Decision

Major Event / Accomplishment / Milestone

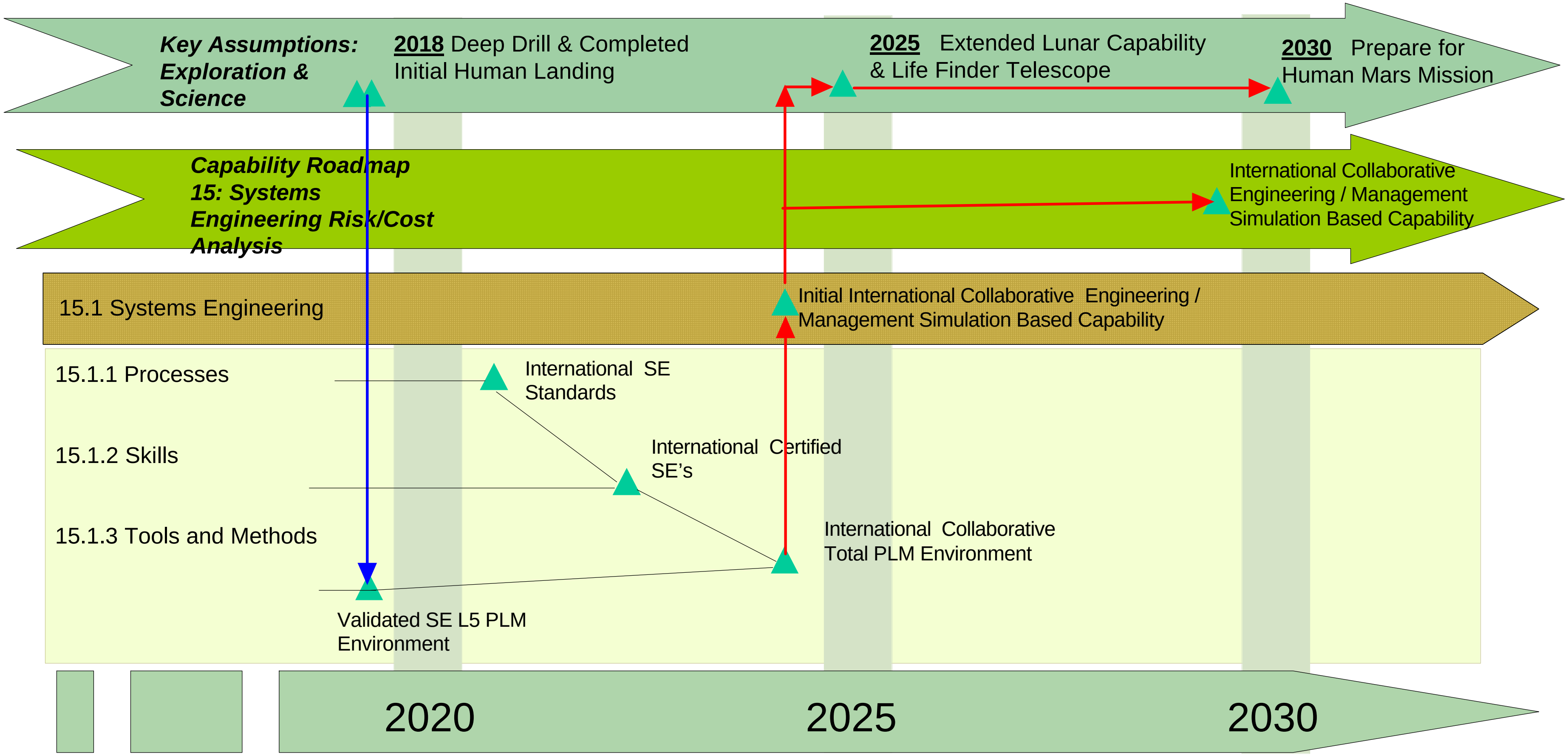
Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Capability 15.1 Systems Engineering Roadmap

Advanced Planning & Integration Office



Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Summary

- Systems Engineering in NASA needs to be improved for large complex systems of systems projects

- Standard system engineering policy needs to be developed at the Agency level for guidance to Centers

- The training and education of systems engineering needs to be institutionalized

- Advanced Engineering Environment can greatly enhance program execution, workforce training, and search for innovation and improved science

Capability - 15.2 Life Cycle Cost

Presenter:

Dr. David Bearden

What is a Life Cycle Cost (LCC)?

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- An integrated, process-centered, and disciplined approach to life cycle management of projects provides real and tangible benefits to all project stakeholders.

- A LCC estimate includes total cost of ownership over the system life cycle, all project feasibility, project definition, system definition, preliminary and final design, fabrication and integration, deployment, operations and disposal efforts.

- A LCC estimate provides an exhaustive and structured accounting of all resources necessary to identify all cost elements including development, deployment, operation and support and disposal costs.

*** Definitions provided by the NASA Cost Estimation Handbook, 2004**

Benefits of the Life Cycle Cost

- “Ensure cost realism and accuracy”
  - The President’s Commission
- Improve confidence in selection process
  - Enables better budgeting
- Predict cost impact of change
- Limit potential for significant overruns
  - Increases mission success
- Gauge economic impact of decisions

Cost Team Process

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- **Evaluated current Capability Readiness Level (CRL) of cost discipline, at the lowest cost team WBS level**
  - **Cost Analysts at NASA HQ, MSFC, JPL, SAIC and The Aerospace Corporation evaluated the readiness level and importance of the current State of the Practice**
  - **Scored Robotic Spacecraft and Human Space Flight separately**
- **Interviewed Agency cost estimating leaders for current status / initiatives**
- **Identified remaining near-term gaps after implementation of current initiatives**
  - **Recommended additional measures for near-term**
- **Envisioned ideal state for cost estimating**
  - **Five and twenty year horizons**

Current State-of-the-Practice for Life Cycle Cost

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- **Tools**
  - Primarily system level parametric models with broad application
  - Medium fidelity models for development and operations
  - Low fidelity requirements (Physics) based models for instruments
  - High fidelity component models limited in application
  - Immature technology development capability
  - Scattered, sparsely-populated databases deployed across centers and industry
  - Databases with limited content, pre full-cost accounting and not normalized

- **Skills**
  - Limited formal cost training in academia
  - Limited career path

- **Process**
  - Program costs rolled up from several models
  - Costs validated through comparison of bottom's up to parametric (top down)
  - Periodic intersection of cost estimation with project development
  - Immature linkage to Schedule Analysis
  - Minimal understanding of relationship of LCC to mission risk and safety

Maturity Level – State of the Practice for 15.2 Life Cycle Cost

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Robototic Spacecraft			
Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation			
Development			
Production			
Operations			

Human Spaceflight			
Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation			
Development			
Production			
Operations			

Critical Gap	
Significant Gap	
No or Minor Gap	

Results indicate a strong need for Technology Maturation Cost Estimation Capabilities

Observations on Maturity

- Capability ratings trended higher for Robotic Spacecraft than Human Spaceflight primarily because of better data availability (function of more recent, relevant missions)

- Capability ratings for Technology maturation cost estimating low in all areas

- Production and Development estimating limited by data available in Human Spaceflight area

- Operations cost estimating readiness low due to less mature tools and processes and availability of fewer estimators

Requirements/Assumptions for Life Cycle Cost

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- Missions Driving Requirements
  - Primarily driven by ESMD
    - Prometheus
    - Crew Exploration Vehicle
    - Human Exploration of Moon/Mars
  - Large SMD Projects
    - James Webb Space Telescope
  - Scale of large ESMD and SMD projects increases budgetary impact of overruns, poor estimation, and requirements creep

- Additional reports that drive capability
  - 2004 Aldridge Commission Recommendations On NASA Cost Estimating
  - 2004 GAO Report on NASA Cost Estimating
  - NPR 7120.5C
  - 2004 NASA Cost Estimating Handbook

Elements of LCC Roadmap

- **Tools**
  - One NASA Cost Engineering (ONCE) Database
  - Technology Development Estimation Capability
  - Integrated Cost, Risk, & Schedule Models
  - Integrated Life Cycle Models with Improved Operations Models
  - Requirements (Physics) based Models
  - Economic Modeling
- **Skills**
  - Continuous Development
  - Formal Academic Education
- **Process**
  - CADRe (Cost Analysis Data Requirement) feeds data to ONCE
  - CCRM (Continuous Cost Risk Management)
  - Standard WBS
  - CAIG-like (Cost Analysis Improvement Group) implementation

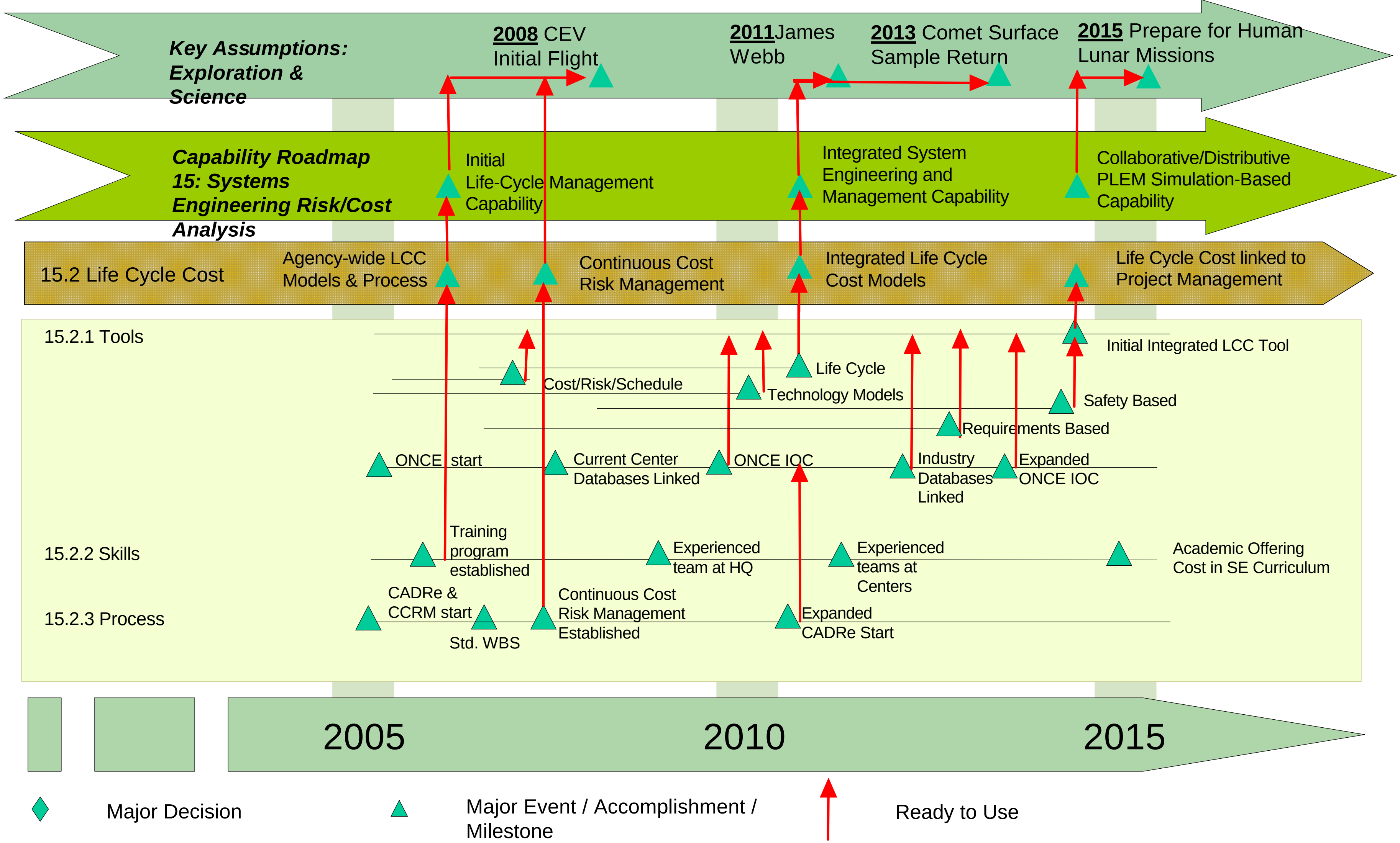
Cost Estimating 5 Year Vision

"Enable a more agile cost estimating capability that interacts effectively with the project management function"

- Improved models
  - Representative Initiative: Integrated Life Cycle parametric system level models
  - Remaining Gap: Importance of accurate cost information justifies more investment to build higher fidelity integrated models
- Improved database
  - Representative Initiative: CADRe -> ONCE
  - Remaining Gap: Better coordination and cooperation by data owners (data sharing by centers/ involved parties), data availability is a long-term problem
- Enhanced process to enable use of LCC estimating as an input to the project management function
  - Representative Initiative: CCRM
  - Remaining Gap: CCRM implementation will be challenging

Capability 15.2 Life Cycle Cost Roadmap

Advanced Planning & Integration Office



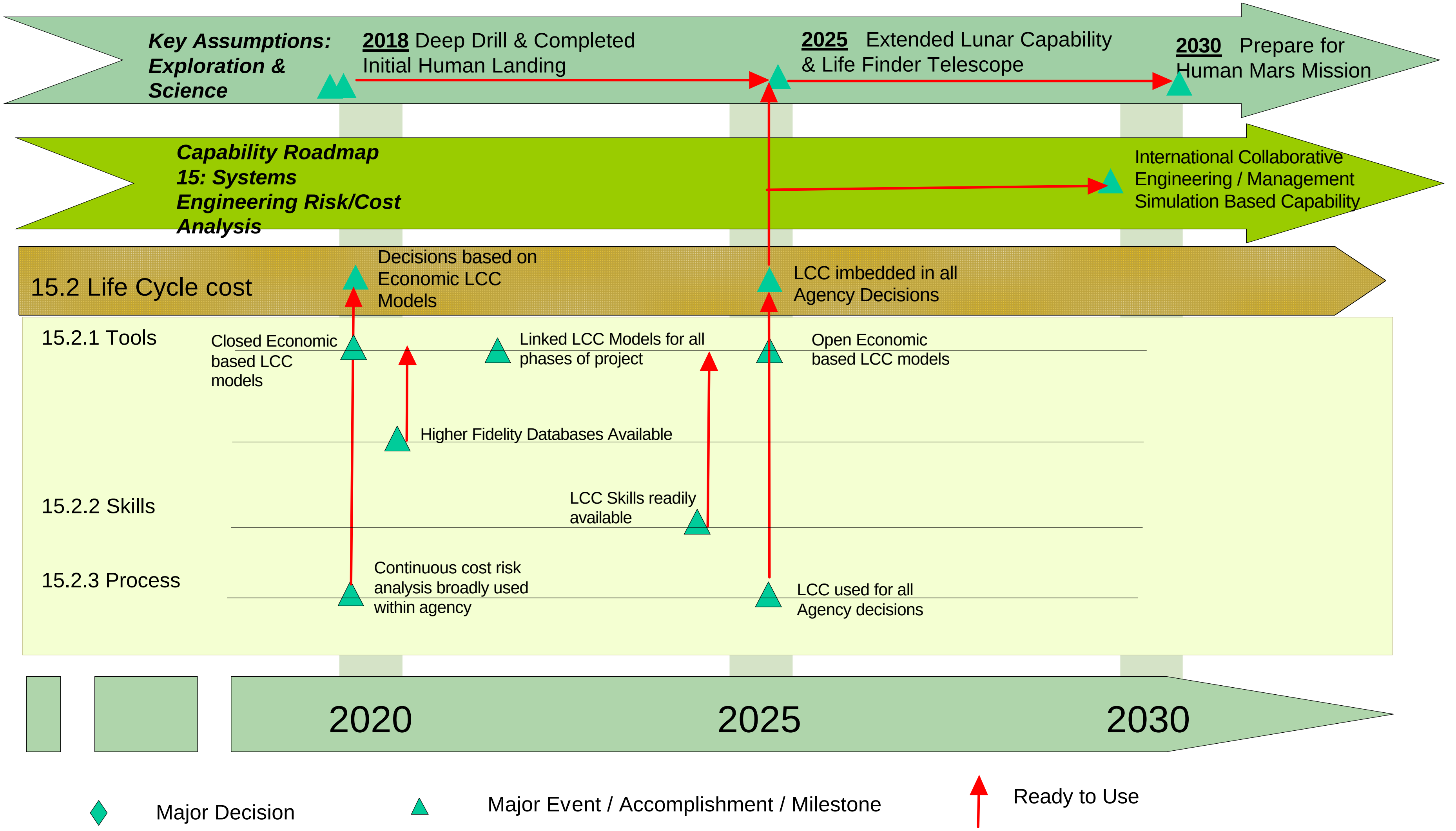
Cost Estimating 20 Year Vision

Advanced Planning & Integration Office

"Create a cost estimating capability that simulates the economic system and interacts seamlessly with management and systems engineering throughout the project"

- **Understand the whole economic system and simulate to understand the effects of design and programmatic decisions have at the industry base level**
  - **Model not only design solution, but economic business case for industry**
- **Link the project management and systems engineering process with cost analysis**
  - **Simulate technology changes, process changes, etc.**
- **Improve tools and databases to allow for high-fidelity analysis**
  - **Cost as a function of safety, risk, schedule, and technology**

Capability 15.2 Life Cycle Cost Roadmap



Life Cycle Cost Goals

Advanced Planning & Integration Office

Capability	Year 5	Year 10	Year 25
MODELS			
Cost Accuracy	30%	20%	10%
Schedule Accuracy	30%	20%	10%
DATABASE			
% of Programs w/ Complete CADRe	50%	90%	100%
SKILLS			
% Staff w/ Formal Training within NASA	50%	75%	90%
PROCESS			
% Programs implementing full CCRM process	30%	60%	90%

Summary

- Evaluated current capability of cost estimation discipline
- Envisioned ideal future state for cost estimating
- Performed gap analysis taking into account current initiatives
- Developed roadmap from current state-of-practice to envisioned state

Capability – 15.3 Risk Management

Presenter:

Theodore Hammer

Capability – Risk Management

- **Risk Management identifies potential problem areas early enough to allow development and implementation of mitigation strategies. This includes contingency planning, descope approaches, and qualitative and quantitative assessments. As complexity of systems grows the importance of risk analysis increases in managing cost, schedule and mission success.**

- **The Risk Management sub-element needs to be thoroughly integrated with other aspects of systems engineering**

- **Risk management includes tools, processes, and skills**

Key Points/Benefits

Advanced Planning & Integration Office

- **Risk Management most effective when integrated with program/project and technical management**
- **Gaps exist within the present risk management state of the practice**
- **First End State targets elimination of existing gaps**
- **End States target delivery of capabilities five years prior to a milestone**
- **Regular evaluation critical**
- **A formal integrated risk management capability benefits implementation of highly complex systems by**
  - Enabling cost effective implementation and problem avoidance
  - Increasing probability of mission success
  - Reducing programmatic problems (e.g., cost and schedule)

Current State-of-the-Practice for Risk Management Within NASA

Advanced Planning & Integration Office

- Risk Management policy and requirements exist
- Conduct annual NASA Risk Management conference
- Risk Management planning widely used
- Assessments are highly qualitative
- Quantitative assessments using such tools as PRA are limited
- Risk mitigation planning and implementation widely used, but not well integrated into the project planning (e.g., cost/work breakdown, integrated schedules)
- Various risk management tools have been used, however , based on NASA trade studies ESMD has selected a state-of-the-art risk tool as the Directorate standard: Active Risk Manager (Strategic Thought, LLP)
- Formal risk management training exists based on Software Engineering Institute risk management process

Evaluation based on OSMA and NASA Center RM POC assessments.

Evaluation of Risk Management State of the Practice

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Risk Management

	Skill	Tool	Process
Prepare for Risk Management			
Determine Risk Sources and Categories			
Define Risk Parameters			
Establish a Risk Management Strategy			
Identify and Analyze Risks			
Identify Risks			
Quantitative			
Qualitative			
Evaluate, Categorize, and Prioritize Risks			
Planning			
Track/Control/Communicate			
Mitigate Risks			
Develop Risk Mitigation Plans			
Implement Risk Mitigation Plans			

Critical Gap	
Significant Gap	
No or Minor Gap	

Gaps

- **Prepare** R
  - Insufficient level of integration of risk management and risk assessment with other capabilities
  - Lack of regular collection of data to assess the level of compliance and practice of risk management and assessment
  - Limited skill, tools and process for in-depth identification of risk sources
  - Limited skill, tools and process for an integrated risk strategy
- **Identify** R
  - Lack of standardization in risk management tools used
  - Inconsistent level of skill and knowledge for Risk Management practioners
  - Insufficient application of quantitative techniques to identify risks, and limited qualitative assessment skills
  - Insufficient skills and tools for a consistent approach to monitoring, tracking, control/feedback and communication (e.g., external) of risks
- **Mitigate** Y
  - Limited skill and tools for mitigation planning
  - Limited skill, tools and process for the implementation of mitigation activities

Requirements/Assumptions for 15.3 Risk Management

- Key Assumption is capability to support key milestones must be in place 5 years prior:
  - 2011 James Webb Telescope
  - 2015 Prepare for Human Lunar Missions
  - 2018 Initial Human Lunar Landings
  - 2025 Extended Lunar Capability
  - 2030 Prepare for Human Mars Mission
- Requirements and assumptions for increased risk management capabilities
  - Increased complexity of systems
  - Increased inter-dependency of complex systems
  - Distributed implementing organizations
  - Environment uncertainty
  - Longer mission durations/complex logistics requirements
  - Tougher science requirements
  - Challenge of implementation and verification of advanced instrument technology (e.g., increased detector sensitivity)
  - Increase future IT capabilities at lower costs

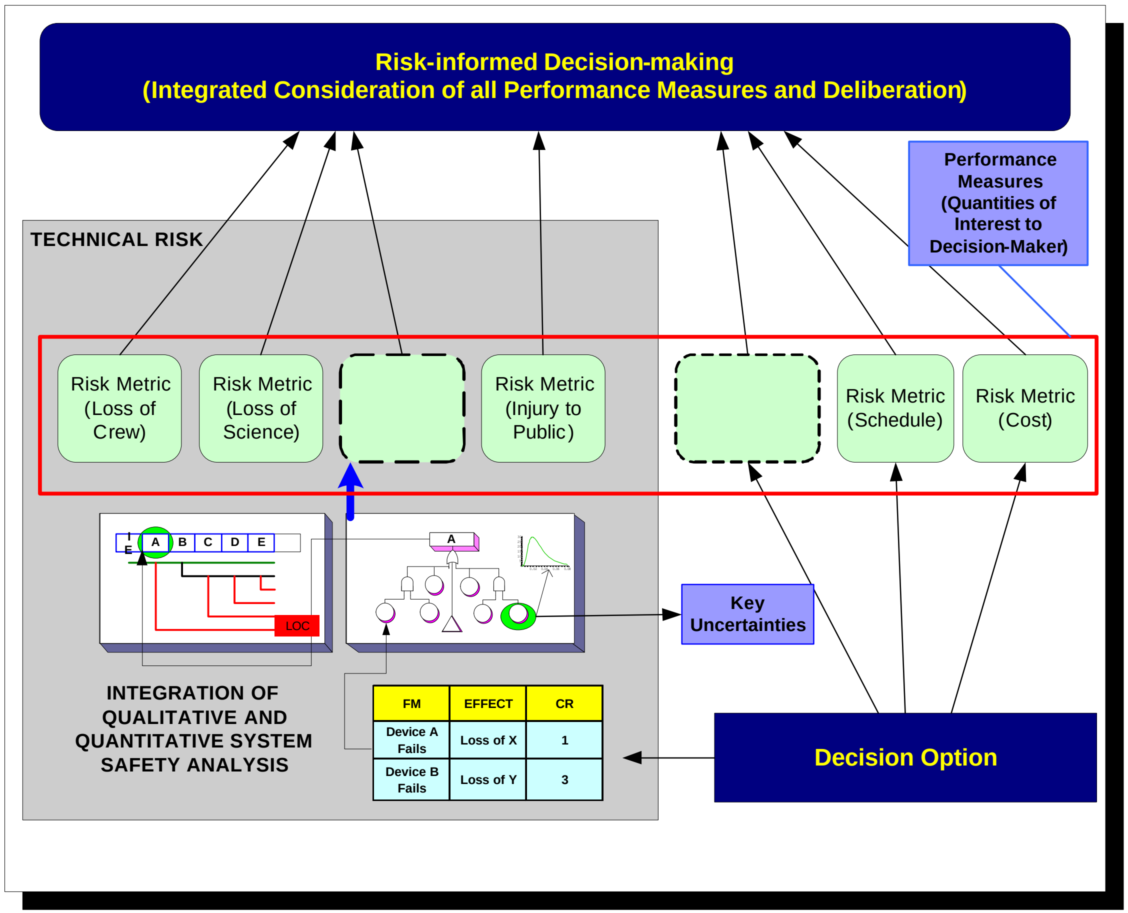
End States

FY 2010 Lunar Support

- **Prepare**
  - Change process and skills to effect integration of risk management
  - Regular collection of self assessment data
  - Institute skills, tools and process for:
    - In-depth identification of risk sources
    - Integrated risk strategies
- **Identify**
  - Standardize risk management tools used
  - Define skills/knowledge criteria for risk practioners; conduct training
    - Including quantitative techniques
  - Institute skills, tools: Monitoring, tracking, control/feedback and communication (e.g., external) of risks
- **Mitigate**
  - Institute skill and tools for mitigation planning
  - Institute skill, tools and process for the implementation of mitigation activities

Top Level Objective of RM 2009 End State

Integration of risk analysis with decision processes



End States (Continued)

FY 2014 Human Lunar Landing Support

- **Prepare**
  - Improved risk source identification; expanded to include routine operational environment challenges
  - Risk sensitivity analysis for interdependent complex systems
- **Identify**
  - Simulation-based risk identification
  - Increased depth and fidelity of quantitative techniques
  - Improved risk communication, including risk uncertainties
- **Mitigate**
  - Integration of mitigation activities into project schedules

End States (Continued)

FY 2020 Extended Lunar Support

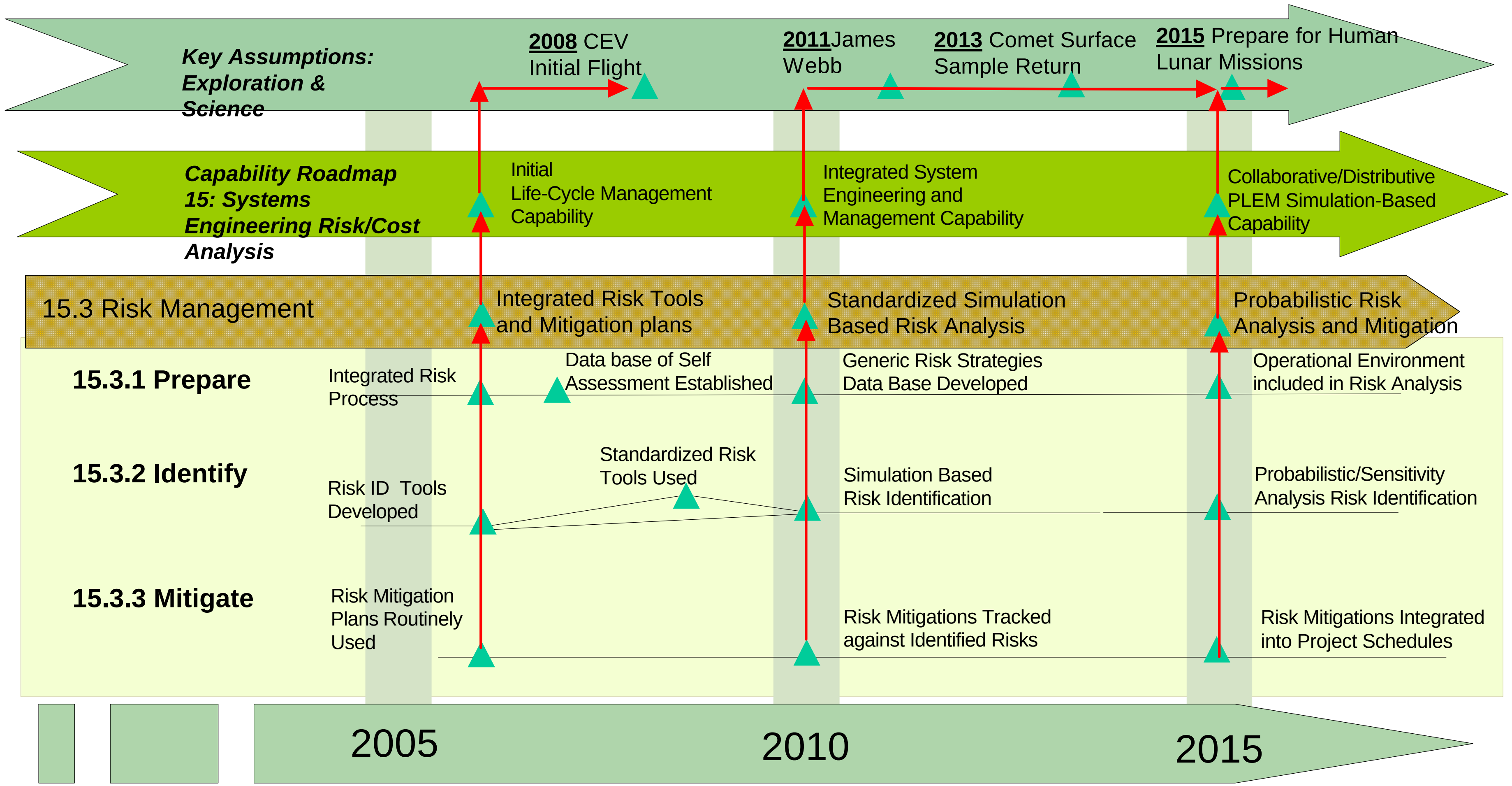
- **Prepare**
  - Risk sensitivity analysis techniques for interdependent systems
  - Improved risk source identification; plans for expanded extended lunar operational environment challenges
- **Identify**
  - Predictive risk capability and tools
  - Interactive risk identification; knowledge based providing a connection to risk decisions made in the past
- **Mitigate**
  - Capture of risk mitigation successes/failures to predict mitigation approach probability

End States (Continued)

FY 2025 Human Mars Support

- **Prepare**
  - Improved risk sensitivity analysis techniques for interdependent complex systems
  - Improved risk source identification; plans for expanded Mars operational environment challenges
- **Identify**
  - Improved predictive risk capability and tools

Capability 15.3 Risk Management Roadmap



Major Decision

Major Event / Accomplishment / Milestone

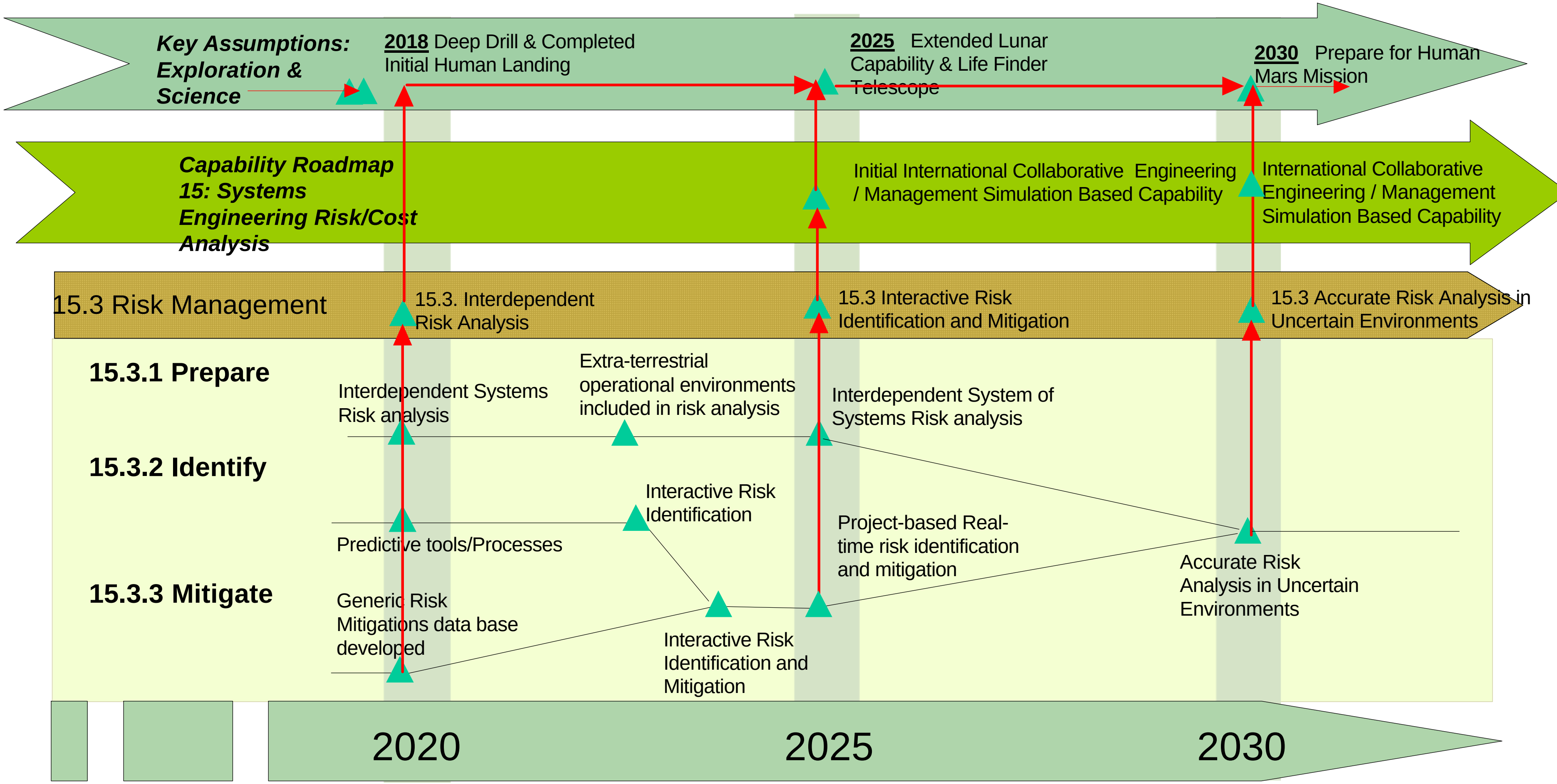
Ready to Use

Legend

PLM – Product LC Management
SBM – Sim. Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment

Capability 15.3 Risk Management Roadmap

Advanced Planning & Integration Office



Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product LC Management
SBM – Sim. Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment

Maturity Goals

RISK MANAGEMENT

	2009	2015	2020	2025
Prepare for Risk Management				
Change process and skills to effect integration of RM	6	7	7	7
Regular collection of self assessment data	1/YR	1/YR	1/YR	1/YR
Institute skills, tools and process	80%	100%	100%	100%
Improved risk source identification		6	7	7
Risk sensitivity analysis for interdependent complex systems		6	7	7
Sensitivity analysis techniques for interdependent complex systems			6	7
Improved risk source id; extended lunar operations			6	7
Improved risk source identification; expanded Mars ops				6
Identify and Analyze Risks				
Standardize risk management tools used	6	7	7	7
Define skills/knowledge criteria for risk practioners	6	7	7	7
Institute skills, tools: Monitoring, tracking, control/feedback and communication	6	7	7	7
Simulation-based risk identification		6	7	7
Increased depth and fidelity of quantitative techniques		6	7	7
Improved risk communication, including risk uncertainties		6	7	7
Predictive risk capability and tools			6	7
Interactive risk identification; knowledge based connection to risk decisions made in the past			6	7
Improved predictive risk capability and tools				6
Mitigate Risks				
Institute skills and tools for mitigation planning	6	7	7	7
Institute skill, tools and process for the implementation of mitigation activities		6	7	7
Integration of mitigation activities into project schedules		6	7	7
Capture of risk mitigation successes/failures to predict mitigation approach probability			6	7

Summary

- Risk Management most effective when integrated with program/project and technical management
- First End State targets achieving RM integration with program/project and technical management, and elimination of existing gaps
- End States target delivery of capabilities five years prior to milestone that would benefit most from those capabilities
- Regular evaluation critical to determining capability maturity and success in meeting end state objectives

Capability - 15.4 Safety & Reliability Analysis

Presenter:

Homayoon Dezfuli, Ph.D, NASA

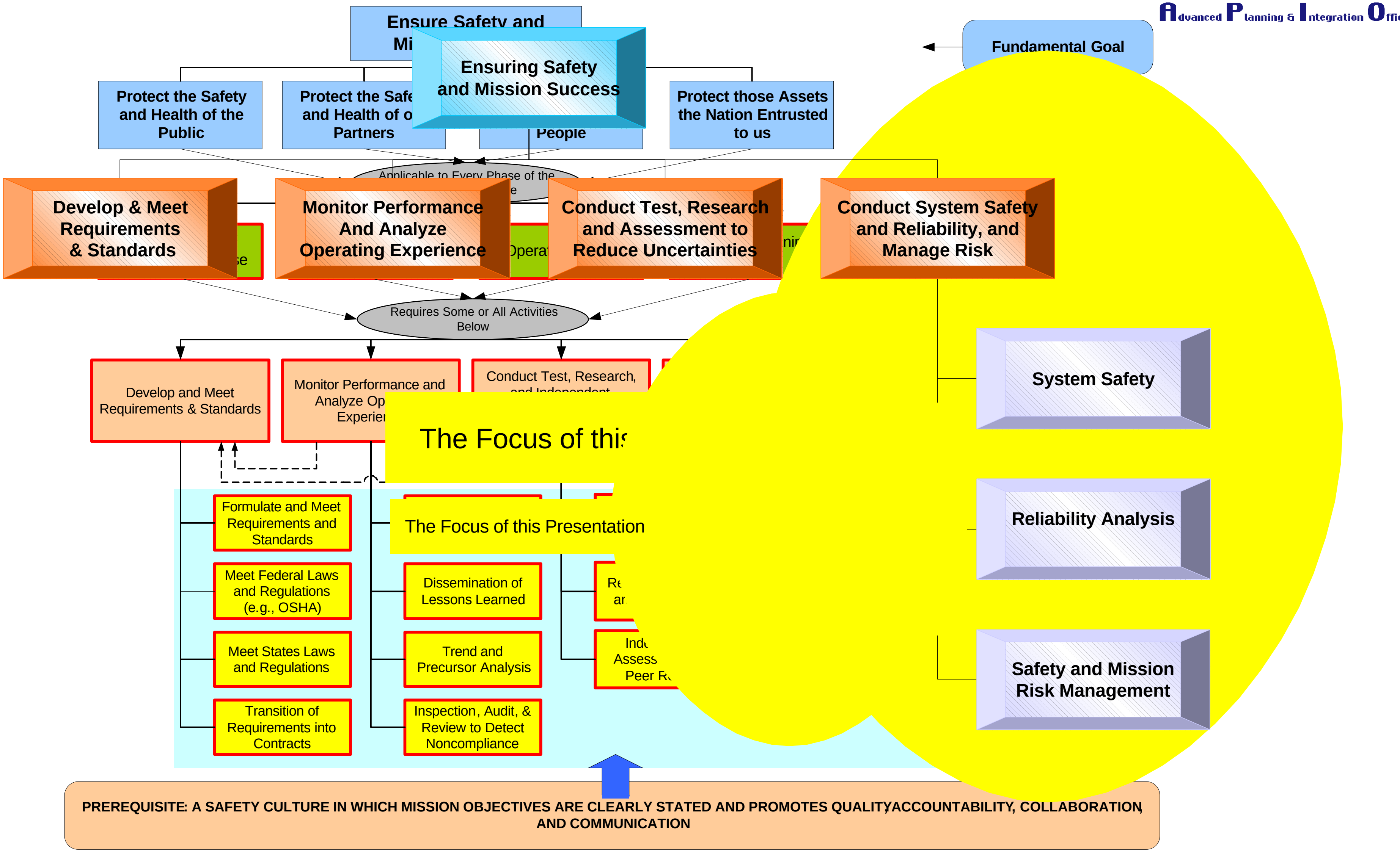
Team Lead

Objectives of System Safety & Reliability Analysis

Advanced Planning & Integration Office

- **Evaluation and management of**
  - Safety risk
  - Mission success
- **Includes processes and techniques used to provide organized, disciplined approach to:**
  - Identify and resolve risks as effectively as possible
    - Personnel
    - Equipment
    - Mission success
  - Assess safety and reliability through all phases of the life cycle
  - Risk-informed management of safety & reliability
- **Assessment tools and processes should provide integrated evaluation of the entire system:**
  - Hardware
  - Software
  - Physical environments
  - Operations
  - Human
  - Interactions of systems

Ensuring Safety and Mission Success in an Ideal Decision-making Framework



Benefits of Safety & Reliability Analysis

Advanced Planning & Integration Office

- Benefit: Ensure safety and mission success while affordably meeting program objectives

- This benefit will be realized when safety, reliability and risk analyses are standardized and are integrated with decision processes under a single decision-making framework
  - Integrate information on safety, reliability and risk under one umbrella (integration)
    - Elimination of organizational and process barriers
  - Systematize the hazard identification process (modeling standardization)
  - Analyze safety and mission risk (measurement of safety and mission performance)
    - Assessment of aggregate risks
    - Identification of weaknesses and vulnerabilities
    - Identification and assessment of uncertainties
  - Manage safety and mission risk (decision-making)
    - Performance of trade-off studies
    - Development of risk reduction strategies

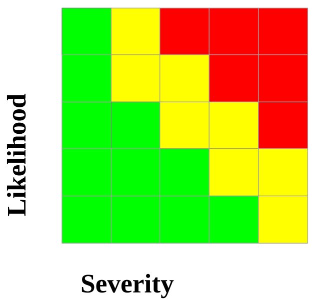
Current State-of-the-practice for 15.4 Safety & Reliability Analysis

Advanced Planning & Integration Office

- **Hazard analysis is widely used**
  - Focuses on specific contributors
  - Limited applicability to complex systems-of-systems
    - generally the result of brainstorming
- **Fault Tree Analysis and Failure Modes and Effects Analysis are widely used**
  - Typically applied when completed design information is available
  - Primarily applied at subsystem level
  - Limited ability to affect early design decisions
- **Risk Matrix is widely used**
  - Applied to top-level risk issues
  - Interaction between risk items is difficult to discern
  - Is unsuitable for combining risks to obtain aggregate risk
  - Uncertainties are not formally accounted for

Example Application of Risk Matrix

- **A Typical State-of-Practice System Safety Assessment Technique**
  - Analyst postulates a failure or a deviation and assesses its consequences
    - Typically one failure or deviation is analyzed at a time
  - Analyst qualitatively judges how often a failure or deviation can occur
  - Analyst qualitatively judges the severity of the outcome or assumes the worst-case outcome
  - Analyst maps each analyzed failure into one of three risk categories (**Green**, **Yellow**, **Red**)



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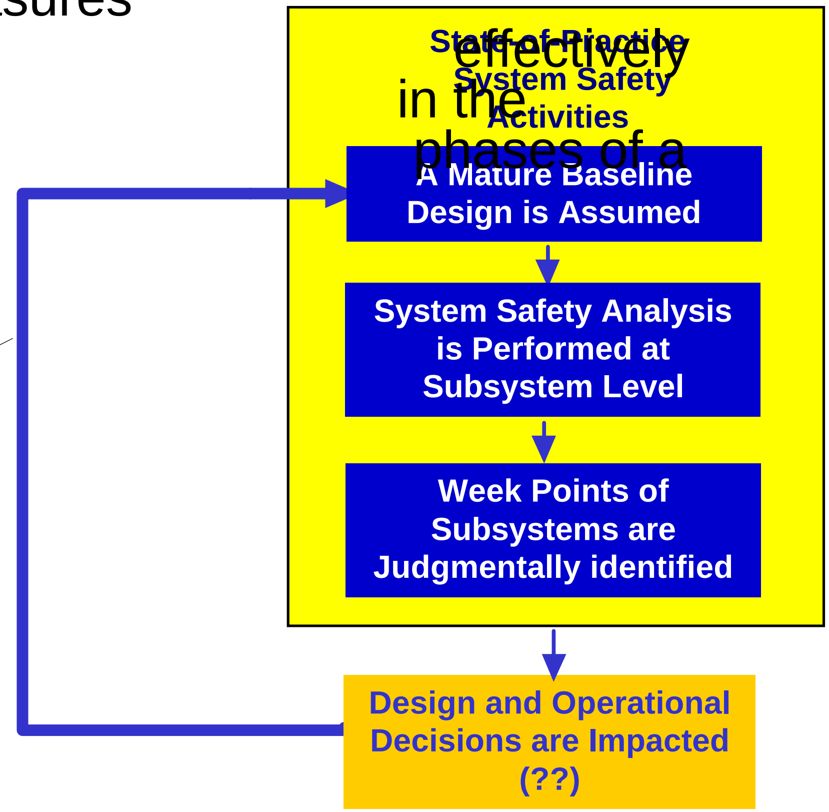
- **The state-of-practice safety analyses does not readily reveal whether safety is improving, declining or staying the same**
  - Not designed to measure safety
  - Without safety performance measures (safety risk metrics) one cannot effectively manage safety risk in the design and operational phases of a system



System safety and risk analyses are organizationally remote from design

They are add-on to traditional engineering analysis

CAIB Report Finding F7.4-4 (Volume I, page 193)

Advanced Planning & Integration Office

"System safety engineering and management is separated from mainstream engineering, is not vigorous enough to have an impact on system design, and is hidden in the other safety disciplines at NASA Headquarters."

Current State-of-the-practice for 15.4 Safety & Reliability Analysis (Continued)

Advanced Planning & Integration Office

- **NASA has begun applying probabilistic risk assessment (PRA) techniques for evaluating safety performance**
  - PRA is shown to be an effective tool
    - To integrate qualitative and quantitative safety models
    - To quantify risk metrics relating to the likelihood and severity of events adverse to safety or mission success including gaining an understanding of uncertainties
- **Probabilistic risk models have not yet been used for design decisions**
  - Models for software-intensive systems, unique space environment, and human decision-making and human-automation interactions have not been fully developed
  - Model developments are hampered by lack of PRA skills and limited and fragmented safety-related reliability databases

Requirements/Assumptions for 15.4 Safety & Reliability Analysis

Advanced Planning & Integration Office

- **Robust and effective Safety and Reliability Assessment will be necessary to safely and affordably meet all the goals in the mission framework**
  - ~ 14 launches FY05 -FY10 (not including Shuttle and ISS)
  - Over a hundred launches between FY10 - FY 30
  - Planetary missions using nuclear technology
  - Human mission to Mars by 2030
  - Sample & return missions to Mars in 2014
  - Potential for 3 month stay on the Moon
  - Complex science missions (telescopes and solar exploration)

- **Not limited to human safety and crew survival,**
  - Must include loss of mission, loss of equipment, and adverse environmental impacts

Maturity Level – Capabilities for 15.4 Safety & Reliability Analysis

Advanced Planning & Integration Office

	Skills	Tools	Processes
Risk and Safety Management			
Risk Tradeoffs, Risk Acceptance and Risk Communication	Yellow	Yellow	Yellow
Appreciation and Quantification of Uncertainties	Red	Red	Red
Mishap Investigation	Green	Yellow	Green
Trend and Precursor Analysis	Red	Red	Red
Dissemination of Lessons Learned	Green	Yellow	Yellow
Systems Safety			
Qualitative Systems Safety Analysis (hardware, **software, phenomenological, human**)	Yellow	Yellow	Yellow
Quantitative Systems Safety Analysis (hardware, **software, phenomenological, human**)	Red	Yellow	Yellow
System Reliability			
Reliability Prediction Models	Green	Yellow	Yellow
Reliability Database	Yellow	Yellow	Red

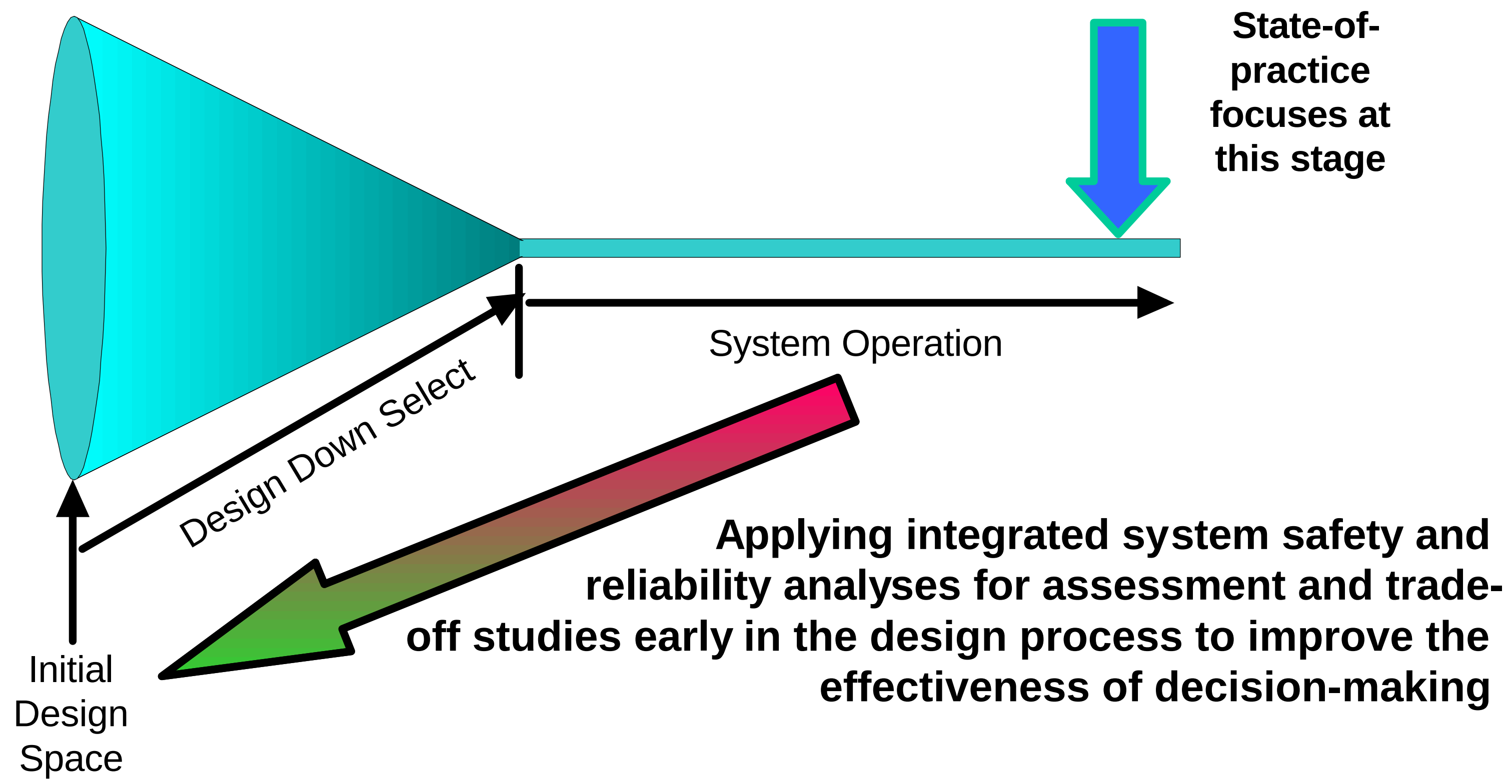
Key:

Green	Minor or No Gap
Yellow	Significant Gap
Red	Critical Gap
Text in red indicates a gap	

Top-level Objective for FY10
15.4 Safety & Reliability Analysis

Advanced Planning & Integration Office

- **Objective: Integration of qualitative and probabilistic methods to support design evaluation**
  - **Integrated qualitative and probabilistic methods are usually not conducted until late in the system life-cycle**

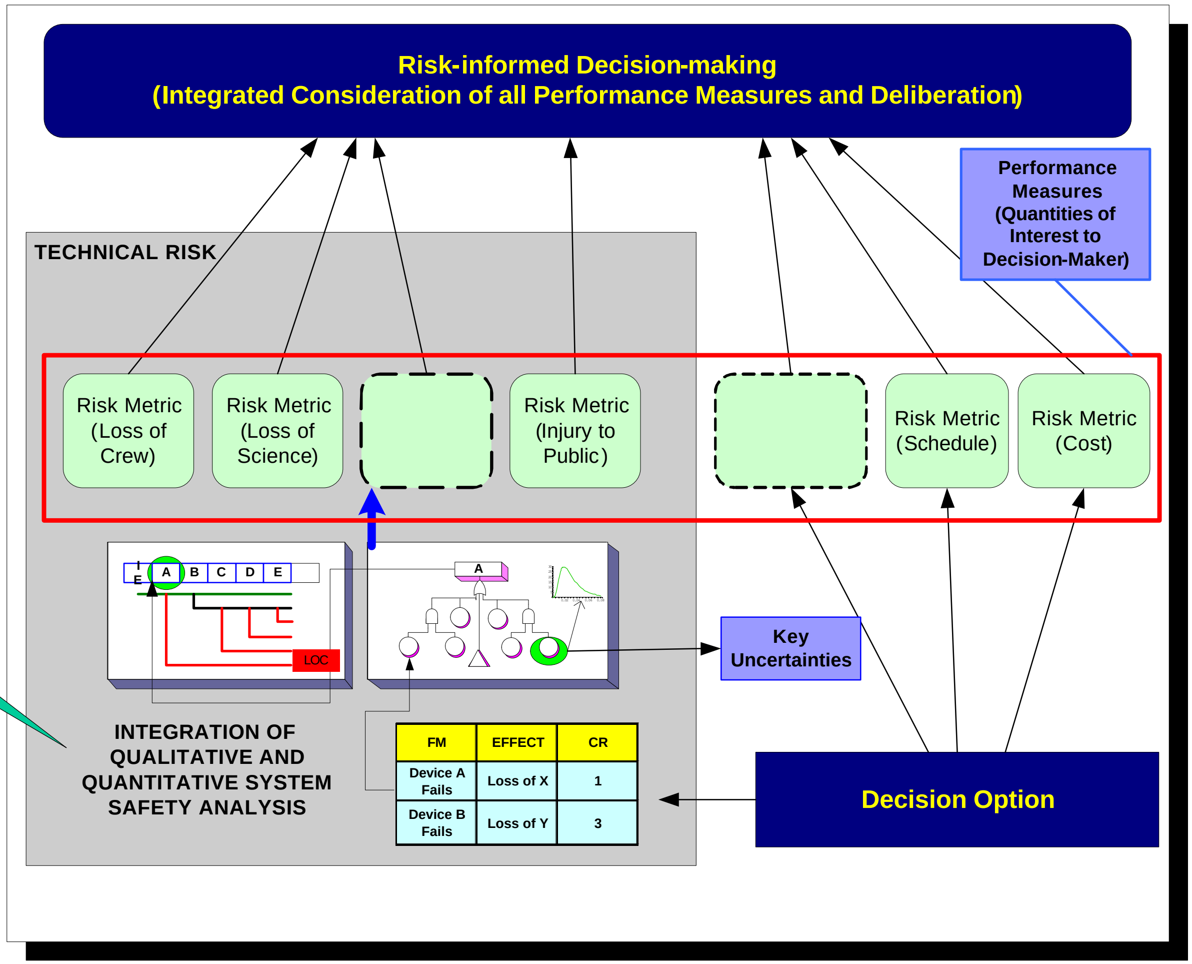


Top-level Objective for FY10 15.4 Safety & Reliability Analysis (Continued)

Advanced Planning & Integration Office

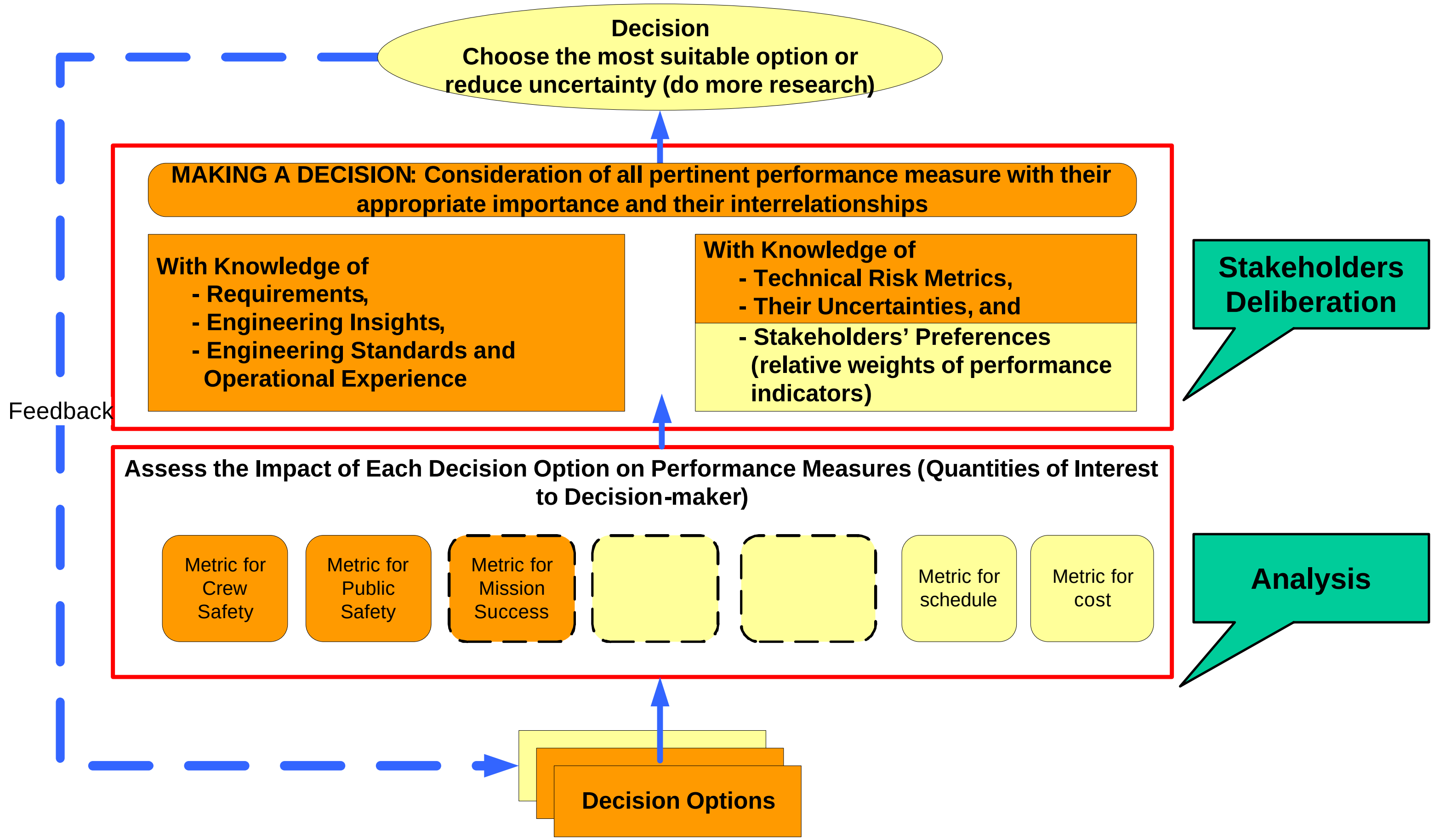
Integration of risk analysis with decision processes

FY10



Top-level Objective for FY10 15.4 Safety & Reliability Analysis (Continued)

Advanced Planning & Integration Office



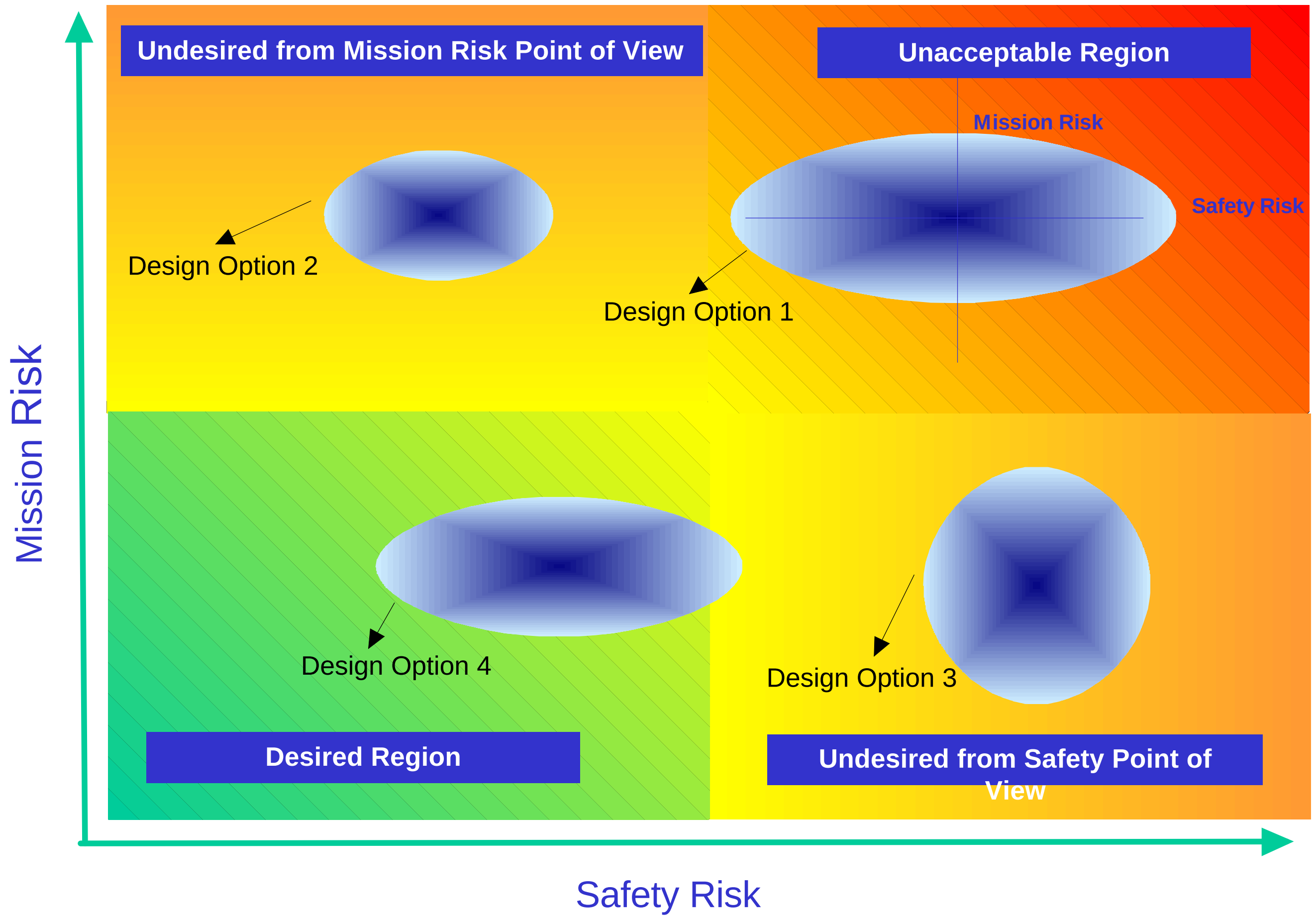
FY15 Vision for 15.4 Safety & Reliability Analysis

Advanced Planning & Integration Office

- **Safety, consistent with mission requirements, is designed into the system in a timely and cost-effective manner**
  - Standardization of safety and reliability analyses and processes and their integration with systems engineering process
  - Ability to trade safety & reliability against performance, cost, design options, diverse management paths
  - Extend analysis philosophy to development stages of system design
  - Developing risk acceptance process and criteria
  - Ability to assess and quantify uncertainties
  - Ability to perform trend and precursor analysis
  - Systems knowledgeable safety experts

- **Physics-based Probabilistic Risk Assessment Models that fully integrate all elements of risk; including technical, organizational, and cost**
  - Centralize existing safety, reliability, system design/operating limitations, and risk focused database
  - Assessing expected performance of a design / operational strategy, based on probabilistic simulation of time histories and explicit evaluation of performance (risk) metrics for those time histories
  - User-friendly, intuitive safety & reliability tool interfaces
  - Risk models linked directly to database with automated evaluation updates

Top-level Objective for FY15
15.4 Safety & Reliability Analysis



Defining acceptable risk regions specific to the program

Risk assessment of decision options

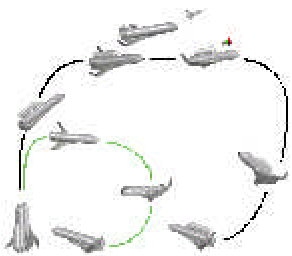
Assessment of uncertainties

consideration of risk results including their uncertainties in decision-making

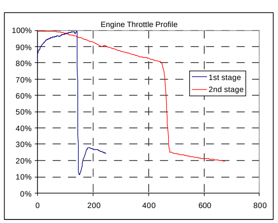
Example Integrated Future Capability

Architecture Definition

Mission Profile

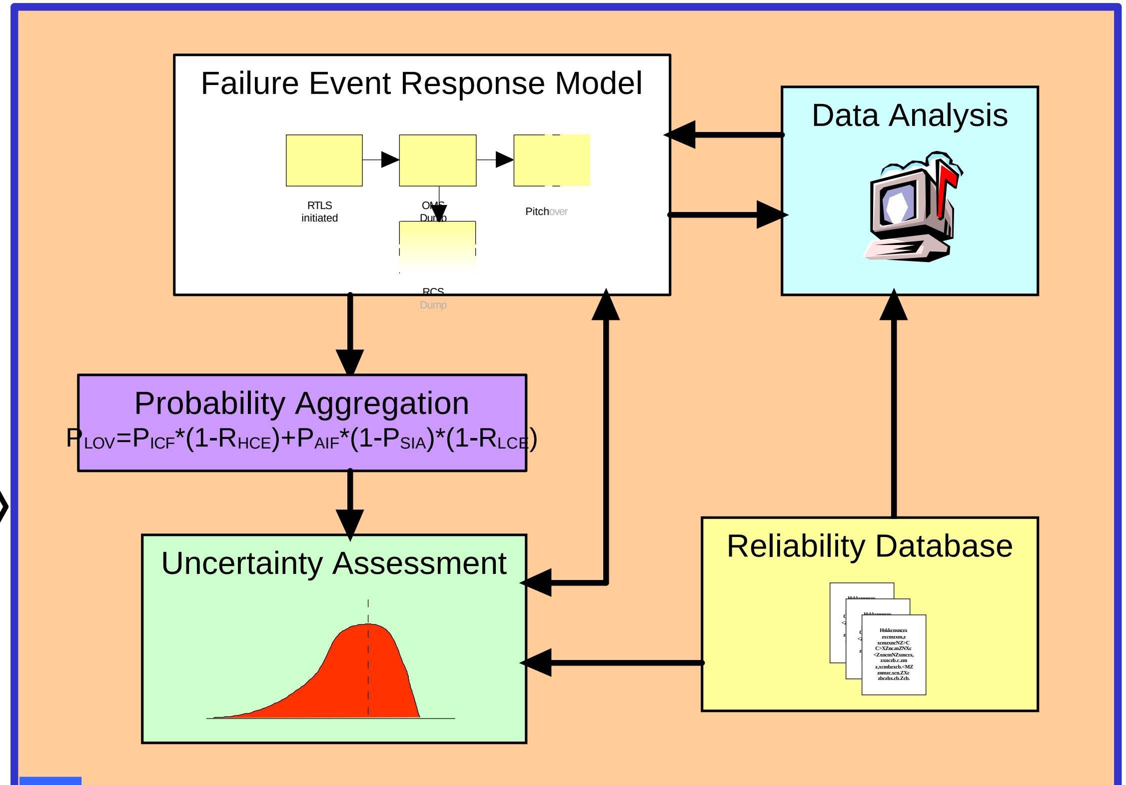


Operational Parameters



Inputs

Failure Modeling



Outputs

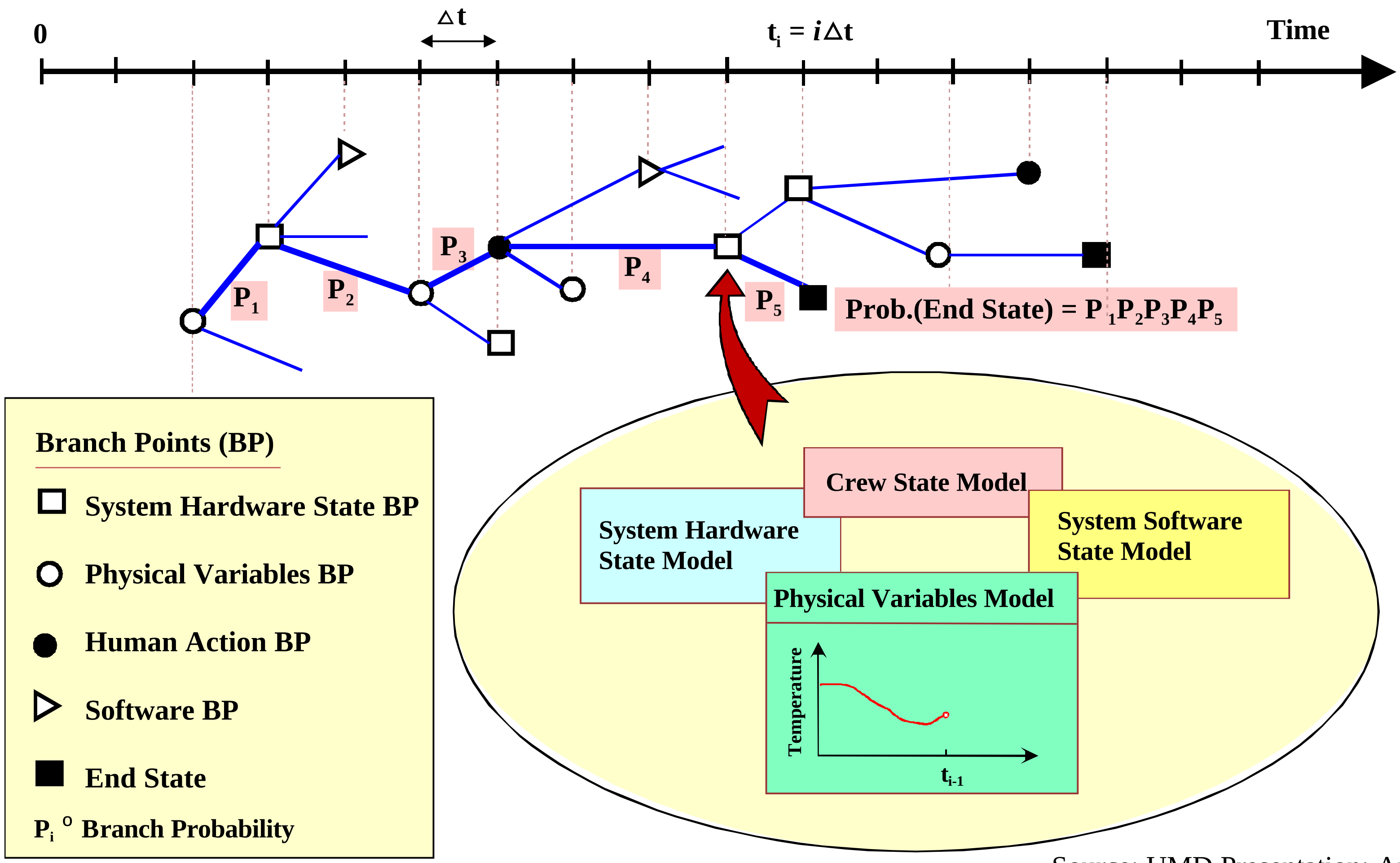
- Loss-of-Crew (LOC) Probability Distribution
- Loss-of-Vehicle (LOV) Probability Distribution
- Loss-of-Mission (LOM) Probability Distribution
- Other Risk Metrics

FY30 Vision for 15.4 Safety & Reliability Analysis

- **System safety and reliability activities incorporated in a risk-informed decision-making framework, capable of**
  - Responding to mishaps in real time
  - Allocating resources (presents solutions, evaluates mitigation options)
  - Effective communication of safety issues
  - Monitoring performance using well defined risk metrics

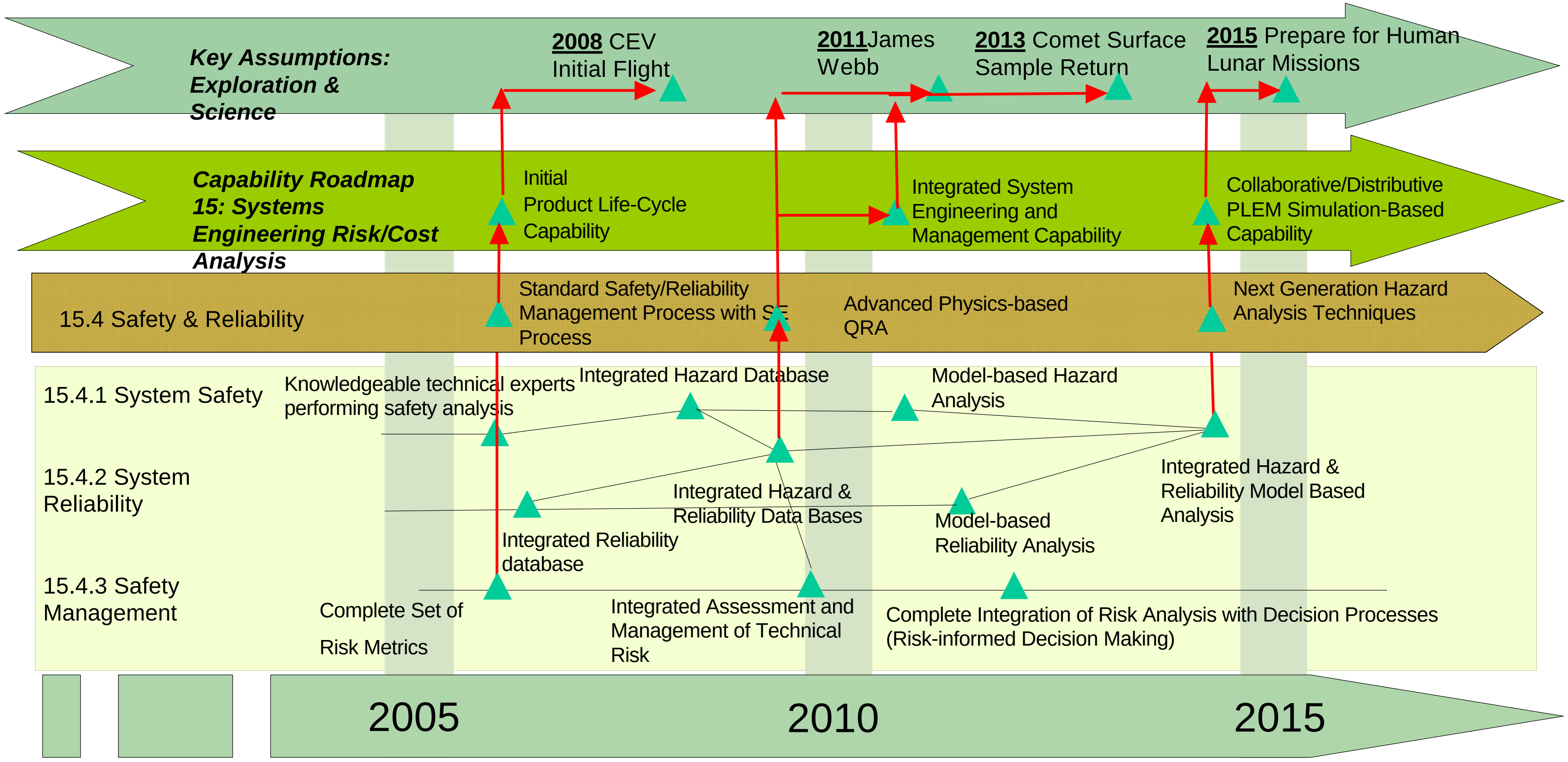
- **Virtual life-cycle simulation model of safety & reliability**
  - Next-generation hazard analysis techniques that evaluate
    - New hardware technology
    - Software
    - human performance
    - Organizational factors
  - Safety and reliability models that interface with
    - Quality control processes
    - Testing processes
    - Assembly and manufacturing
    - Maintenance and operational processes

Example of a Simulation-based Risk Model



Source: UMD Presentation: April 04

15.4 Safety & Reliability Analysis



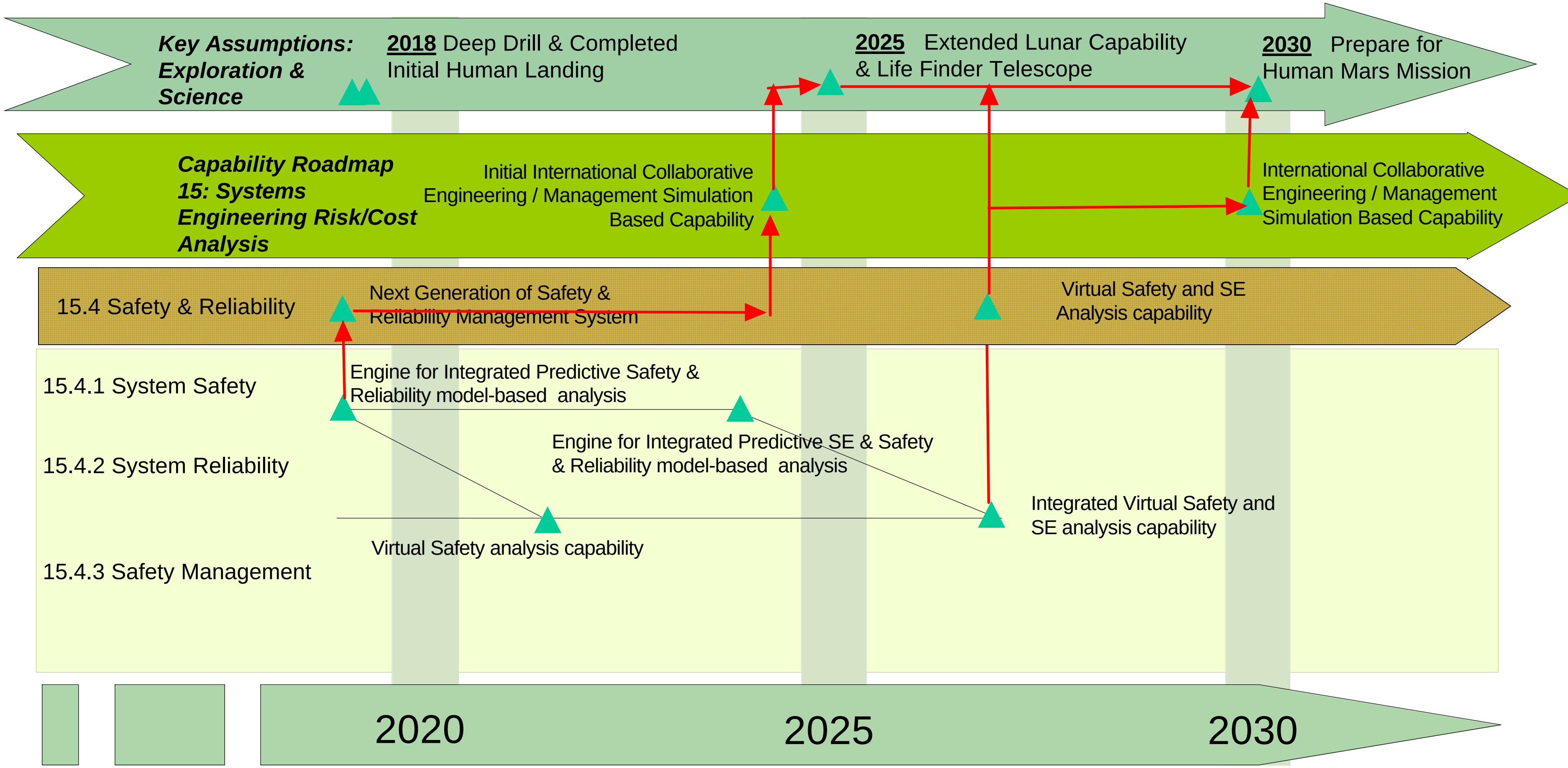
- ◆ Major Decision
- ▲ Major Event / Accomplishment / Milestone
- ↑ Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

15.4 Safety & Reliability Analysis

Advanced Planning & Integration Office



Major Decision

Major Event / Accomplishment / Milestone

Ready to Use

Legend

PLM – Product Life Cycle Management
SBM – Simulation Based Modeling
CMMI – Capability Maturity Model Integration
QRA - Quantitative Risk Assessment
LCC - Life Cycle Cost

Concluding Summary

Presenter:

Stephen Cavanaugh

Capabilities Current State

Systems Engineering

SE-CMMI		Team Assessment
ENGINEERING		
	REQUIREMENTS DEVELOPMENT	Red
	REQUIREMENTS MANAGEMENT	Red
	TECHNICAL SOLUTION	Yellow
	PRODUCT INTEGRATION	Yellow
	VERIFICATION	Yellow
	VALIDATION	Yellow
PROJECT MANAGEMENT		
	PROJECT PLANNING	Red
	PROJECT MONITORING AND CONTROL	Red
	SUPPLIER AGREEMENT MANAGEMENT	Yellow
	INTEGRATED PROJECT MANAGEMENT FOR IPPD	Red
	RISK MANAGEMENT	Red
	INTEGRATED TEAMING	Red
	INTEGRATED SUPPLIER MANAGEMENT	Yellow
	QUANTITATIVE PROJECT MANAGEMENT	Yellow
SUPPORT		
	CONFIGURATION MANAGEMENT	Green
	PROCESS AND PRODUCT QUALITY ASSURANCE	Green
	MEASUREMENT AND ANALYSIS	Green
	DECISION ANALYSIS AND RESOLUTION	Red
	ORGANIZATIONAL ENVIRONMENT FOR INTEGRATION	Green
	CAUSAL ANALYSIS AND RESOLUTION	Green
PROCESS MANAGEMENT		
	ORGANIZATIONAL PROCESS FOCUS	Green
	ORGANIZATIONAL PROCESS DEFINITION	Green
	ORGANIZATIONAL TRAINING	Green
	ORGANIZATIONAL PROCESS PERFORMANCE	Green
	ORGANIZATIONAL INNOVATION AND DEPLOYMENT	Green

Life Cycle Costing

Robototic Spacecraft

Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation	Red	Red	Red
Development	Green	Green	Green
Production	Green	Green	Green
Operations	Yellow	Green	Green

Human Spaceflight

Estimate Life Cycle Cost	Tools	Skills	Process
Technology Maturation	Red	Red	Yellow
Development	Yellow	Green	Yellow
Production	Yellow	Green	Green
Operations	Yellow	Yellow	Yellow

Risk Management

	Skill	Tool	Process
Prepare for Risk Management	Red	Yellow	Yellow
Determine Risk Sources and Categories	Yellow	Yellow	Yellow
Define Risk Parameters	Green	Green	Green
Establish a Risk Management Strategy	Red	Yellow	Yellow
Identify and Analyze Risks	Red	Yellow	Yellow
Identify Risks			
Quantitative	Red	Yellow	Yellow
Qualitative	Yellow	Yellow	Yellow
Evaluate, Categorize, and Prioritize Risks			
Planning	Green	Green	Green
Track/Control/Communicate	Yellow	Yellow	Green
Mitigate Risks	Yellow	Yellow	Yellow
Develop Risk Mitigation Plans	Yellow	Yellow	Green
Implement Risk Mitigation Plans	Yellow	Yellow	Yellow

Safety & Reliability Analysis

	Skills	Tools	Processes
Risk and Safety Management			
Risk Tradeoffs, Risk Acceptance and Risk Communication	Yellow	Yellow	Yellow
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System Reliability			
Reliability Prediction Models	Green	Yellow	Yellow
Reliability Database	Yellow	Yellow	Red

Critical Gap	Red
Significant Gap	Yellow
No or Minor Gap	Green

Key:

Green	Minor or No Gap
Yellow	Significant Gap
Red	Critical Gap
Text in red indicates a gap	

Systems Engineering Cost/Risk Analysis Roadmap Metrics

Advanced Planning & Integration Office

- Development Metrics (process, skills, tools)
  - Annual SE NASA modified CMMI audit of maturity (levels 1-5) and capability readiness (levels 1-5)
  - Number of NASA certified engineers in Systems Engineering, Life-Cycle Costing, Risk Management, and Safety
  - Percentage of programs using integrated Systems Engineering, Project Management, Life-Cycle Costing, Risk Management, and Safety tools

- Performance Metrics (implementation)
  - Number of cancelled programs and termination reviews per year
  - Average percent cost of overrun per year
  - Accuracy of cost and schedule predictions
  - Percent of program cost dedicated to Systems Engineering
  - Number of mission failures per total number of missions
  - Number of hits (requests) from Knowledge Management databases in Cost, Reliability, Safety, Risk, and Systems Engineering

- Do the Capability Roadmaps provide a clear path way to technology and capability development?
  - Yes. All Roadmap sections address skills, tools (including Database creation from which Models are developed to address current gaps), and new process.
- Are technology maturity levels accurately conveyed and used?
  - Yes. CRL were assessed by the community, and programs created to address areas with low level CRLs.
- Are proper metrics for measuring advancement of technical maturity included?
  - Yes. The development and performance metrics assigned are appropriate to measure progress towards increasing the validity of the discipline, and reflect current Government criticism.
- Do the Capability Roadmaps have connection point to each other when appropriate?
  - Yes. The capability is a discipline which connects to all other roadmaps.

NASA Systems Engineering Cost/Risk Analysis Roadmap Team Summary

- **An active Senior Sponsor is *absolutely essential* due to the complexity of future NASA Exploration missions**
- **Develop an Integrated organization of Systems Engineering, Cost, Risk, & Safety**
  - **Application needs to be strategic and tactical implementation**
  - **Capability to integrate across Agency are currently uneven**
- **Develop a Systems Engineering, Cost, Risk and Safety Professional Certification program to develop a qualified skill base**
  - **Require SE certification level for all SE positions**
  - **Require as a performance objective in personnel reviews**
  - **Reward progress**
- **Establish an independent review process for each program that provides a gate keeping processes to ensure project success**
- **Create a centralized archival database with best practices, skill base, processes, and lessons learned**

The state of systems engineering as practiced at NASA needs to be improved to successfully achieve the Exploration Vision.

DoD Partnering Possibilities

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- Both part of the U.S. government with all the general rules, regulations and procedures that entails
- Share a common industrial base
- Anticipate a large turn over of the workforce in the near future
- Funding constraints, including uncertainties from budget cuts
- Moving towards capabilities-based acquisition and evolutionary development
- Increasing complexity with more system-of-systems and families-of-systems
- Share some technology overlap
- Need a strong role of Systems Engineering Systems Engineering, Cost, Risk and Safety within our programs to be successful

Opportunity exists to collaborate with DoD & NROs Systems Engineering Professional Development Program and the established Systems Engineering Education programs at DAU & AFIT.

Next Steps/Forward Work

- Make changes to roadmaps based on NRC feedback
- Review and Assess all applicable Strategic Roadmaps and their requirements for Systems Engineering capabilities
  - Suggest possible opportunities for Strategic Roadmaps
- Make changes to roadmaps to ensure consistency with Strategic Roadmaps requirements
  - Additional metrics to determine if achievements will be reached
- Continue to work with other Capability roadmaps to ensure consistency and completeness
- Develop rough order of magnitude cost estimates for the Systems Engineering, Cost, Risk and Safety Capability Roadmap
- Prepare for 2nd NRC Review which will address 4 additional questions:
  - Are there any important gaps in the capability roadmaps as related to the strategic roadmap set?
  - Do the capability roadmaps articulate a clear sense of priorities among various elements?
  - Are the capability roadmaps clearly linked to the strategic roadmaps, and do the capability roadmaps reflect the priorities set out in the strategic roadmaps?
  - Is the timing for the availability of a capability synchronized with the scheduled need in the associated strategic roadmap?

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SE Back Up Slides

Capability Readiness Level Rating

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7 – Commercial processes/tools widely used by industry and NASA

6 – Commercial processes/tools sparsely used by NASA

5 – Specialized NASA developed processes/tools used in current programs

3 – Processes/tools under development for existing projects/programs

1 – Ideas of processes/tools that could enhance NASAs Systems Engineering

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National Research Council Dialogue to Assess Progress on

NASA's Title of CRM Capability Roadmap Development

General Background and Introduction

Julie A. Crooke
Nanotechnology APIO Coordinator
March 8, 2005

Agenda

Advanced Planning & Integration Office

- General Background and Introduction of Capability Roadmaps "Title"
  - Agency Objective
  - Strategic Planning Transformation
  - Advanced Planning Organizational Roles
  - Public Involvement in Strategic Planning
  - Strategic Roadmaps and Schedule
  - Capability Roadmaps and Schedule
  - Purpose of NRC Review
- Capability Roadmap Development (Progress to Date)

Agency Goals and Objectives

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National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**	
National Objectives	Implement a sustained and affordable human and robotic program to explore the solar system and beyond.	Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
NASA Objectives	Undertake robotic and human lunar exploration to further science, and to develop and test new approaches, technologies, and systems to enable and support sustained human and robotic exploration of Mars and more distant destinations. First robotic mission no later than 2008. (SRM 1)	Return the Space Shuttle to flight and focus its use on completion of the ISS, complete assembly of the ISS, and retire the Space Shuttle as soon as assembly of the ISS is completed, planned for the end of this decade. Conduct ISS activities consistent with U.S. obligations to ISS partners. (SRM 6, 7)
	Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. (SRM 2)	Develop a new crew exploration vehicle to provide crew transportation for missions beyond low Earth orbit. First test flight to be by the end of this decade with operational capability for human exploration NLT 2014. (SRM 5)
	Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources. (SRM 3)	Focus research and use of the ISS on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. (SRM 6)
	Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. (SRM 4)	Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020. (SRM 1)
	Explore the universe to understand its origin, structure, evolution, and destiny. (SRM 8)	Conduct human expeditions to Mars after acquiring adequate knowledge about the planet using robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. (SRM 2)

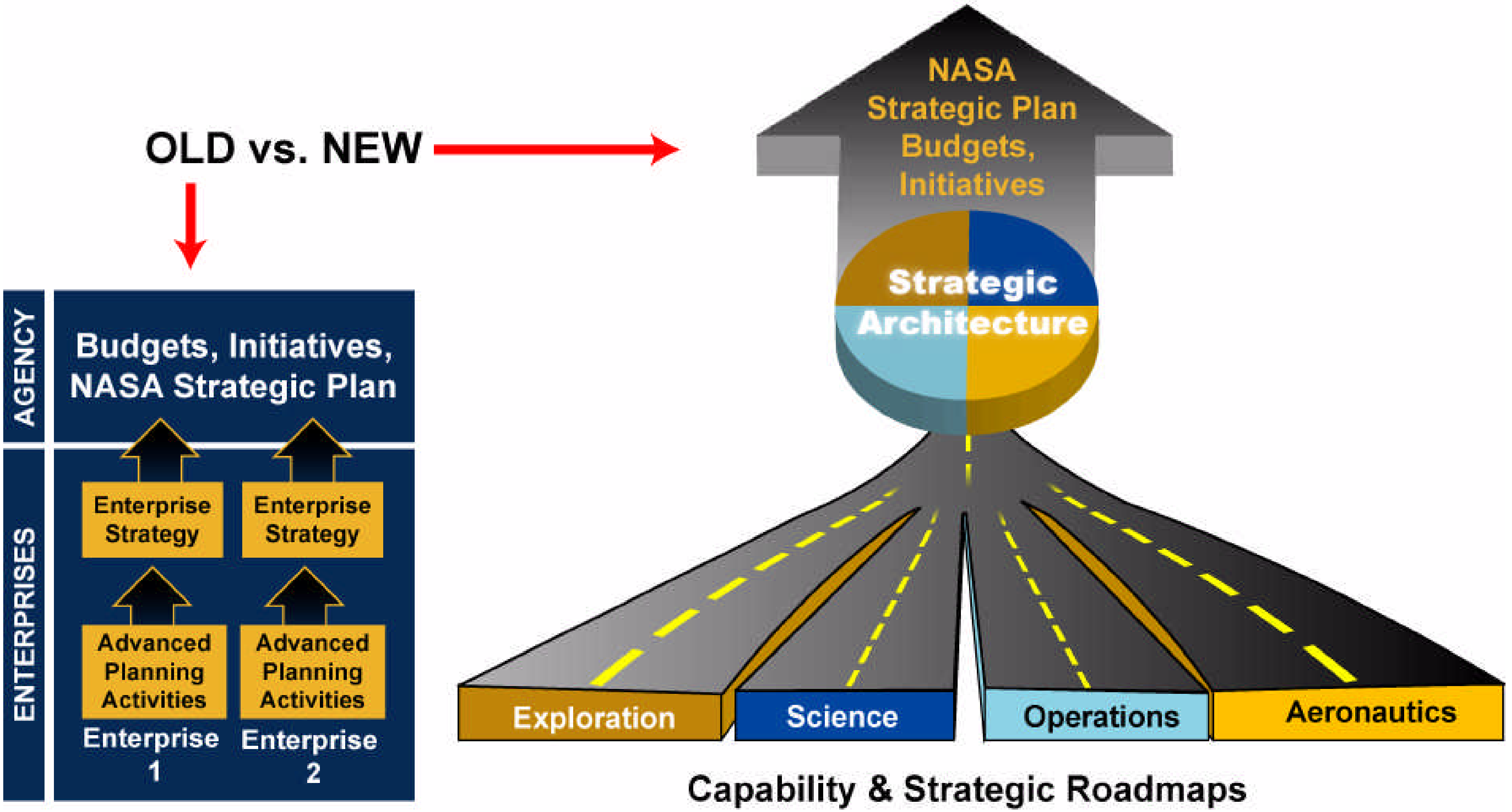
Agency Goals and Objectives

Advanced Planning & Integration Office

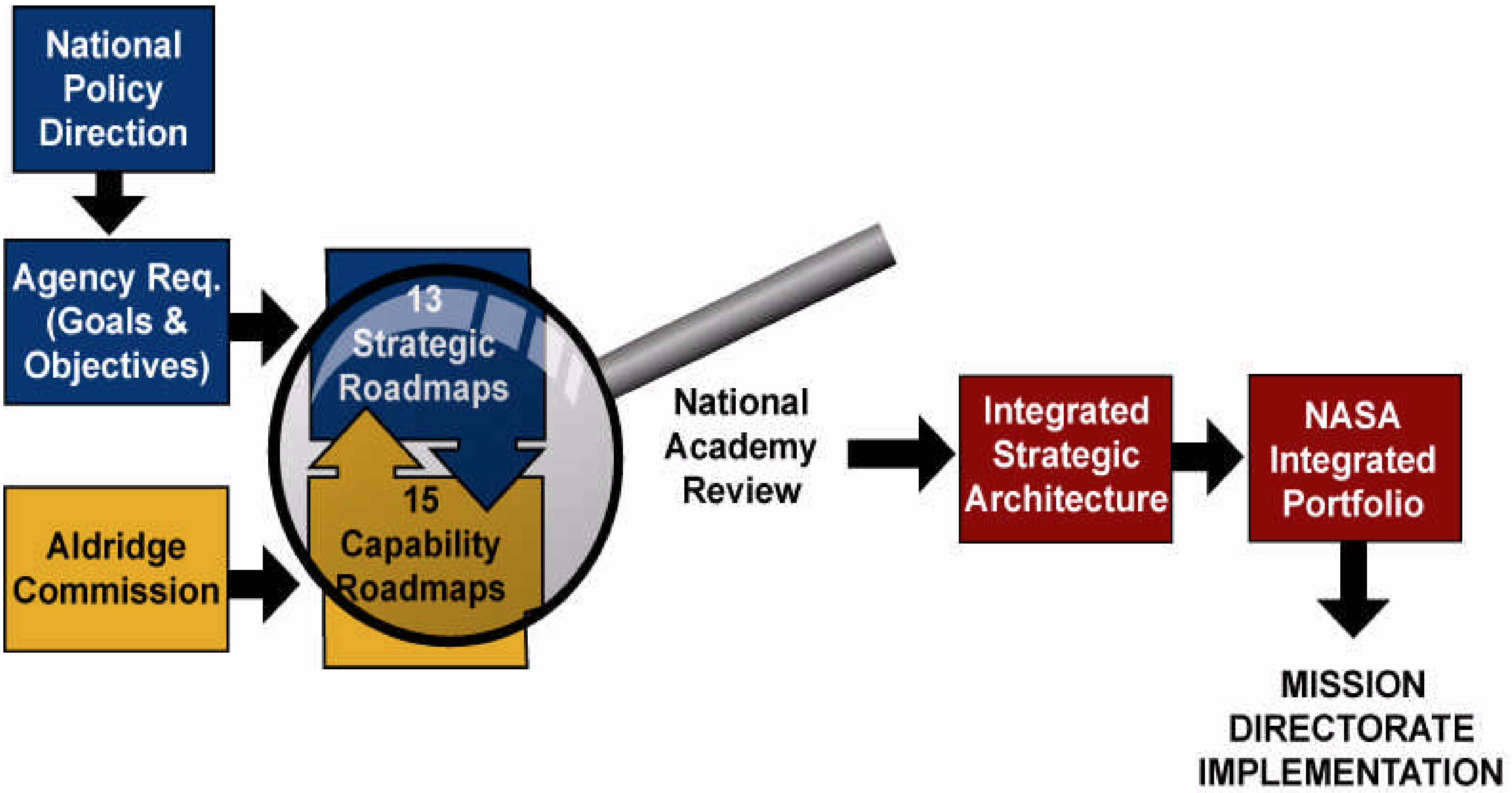
National Goal	**Advance U.S. scientific, security and economic interests through a robust space exploration program.**		
National Objectives	Develop innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.	Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.	Study the Earth system from space and develop new space-based and related capabilities for this purpose.
NASA Objectives	Develop and demonstrate power generation, propulsion, life support and other key capabilities required to support more distant, more capable, and/or longer duration human and robotic exploration of Mars and other destinations. (SRM 13 and Capability Roadmaps)	Pursue opportunities for international participation to support U.S. space exploration goals. (All SRMs)	Conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems. (SRM 9)
	Provide advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. (SRM 11)	Pursue commercial opportunities for providing transportation and other services supporting International Space Station and exploration missions beyond Earth orbit. Separate to the maximum extent practical crew from cargo. (SRM 5, 6, 7)	Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational Earth observation systems. (SRM 10)
	Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation. (SRM 12)	Use U.S. commercial space capabilities and services to fulfill NASA requirements to the maximum extent practical and continue to involve, or increase the involvement of, the U.S. private sector in design and development of space systems. (SRM 5,6,7)	

Strategic Planning Transformation

ACHIEVING THE VISION



Strategic Planning Transformation - continued



Advanced Planning Organizational Roles

- NASA Strategic Planning Council (Chair, NASA Administrator)
  - Agency-level strategic decisions & NASA Strategic Plan
- NASA Operations Council (Chair, NASA Deputy Administrator)
  - Implementation of strategies through integrated Agency tactical & operational activities
- Director for Advanced Planning (Charles Elachi)
  - Develops input, options, & assessments for Strategic Planning Council
- Associate Deputy Administrator for Systems Integration (Mary Kicza)
  - Tracks & assesses integrated schedules, progress towards goals, Agency needs, strategic investments
- Advanced Planning & Integration Office (Dir. APIO, Bernie Seery)
  - Provides staff to the Director for Advanced Planning and the Associate Deputy Administrator for Systems Integration
- Mission Directorates (Craig Steidle, Al Diaz, Victor Lebacqz, William Readdy)
  - Technical knowledge & expertise to implement overall Agency architecture(s)

Public Involvement in Strategic Planning

Advanced Planning & Integration Office

- NASA wants:
  - A broad community perspective when doing its strategic planning
  - Best strategies and most creative and innovative ideas from across the nation to implement the Vision
  - To provide opportunities for community input
    - RFI for Capability and Strategic Roadmap Input
      - Public workshop held in Washington DC on November 30th for Capability Roadmaps (509 people attended, 514 white papers submitted)
      - White Papers submitted for Strategic Roadmaps
    - Roadmap team members drawn from NASA, other Government Agencies, Academia, and Industry
    - Review by the National Research Council (NRC)
    - Presentations to professional societies, workshops, and conferences

Strategic Roadmaps

- Strategic Roadmap
  - One of thirteen elements of the NASA Strategy that will explore options and establish pathways for implementing the Vision for Exploration.

Roadmaps will include:

- Broad human and robotic science and exploration goals, priorities, anticipated discoveries
- High-level milestones, options, and decision points
- Implementation approaches, suggested missions

Strategic Roadmaps - continued

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Roadmap	Chairs (HQ Directorate, Center)	External chair
Robotic and Human Lunar Exploration	Adm. (Ret.) Craig Steidle (HQ/ESMD) and William Readdy (HQ/SOMD) Gen. (Ret.) Jefferson Howell (JSC)	Gen. (Ret.) Tom Stafford
Robotic and Human Exploration of Mars	Al Diaz (HQ/SMD) Dr. Charles Elachi (JPL)	Tom Young (Lockheed Martin, Ret.)
Solar System Exploration	Orlando Figueroa (HQ/SMD) Scott Hubbard (ARC)	Dr. Jonathan Lunine (Uni. of Arizona)
Search for Earth-Like Planets	Dr. Ghassem Asrar (HQ/SMD) Dr. Charles Beichman (JPL)	Dr. Adam Burrows (Uni. of Arizona)
Exploration Transportation System	Adm. (Ret.) Craig Steidle (HQ/ESMD) Jim Kennedy (KSC)	Gen. (Ret.) Charles Bolden
International Space Station	Mark Uhran (HQ/SOMD) Bob Cabana (JSC)	Adm. (Ret.) Tom Betterton
Space Shuttle	*Deferred*	*Deferred*

Directorate and APIO Coordinators Also with Each Team

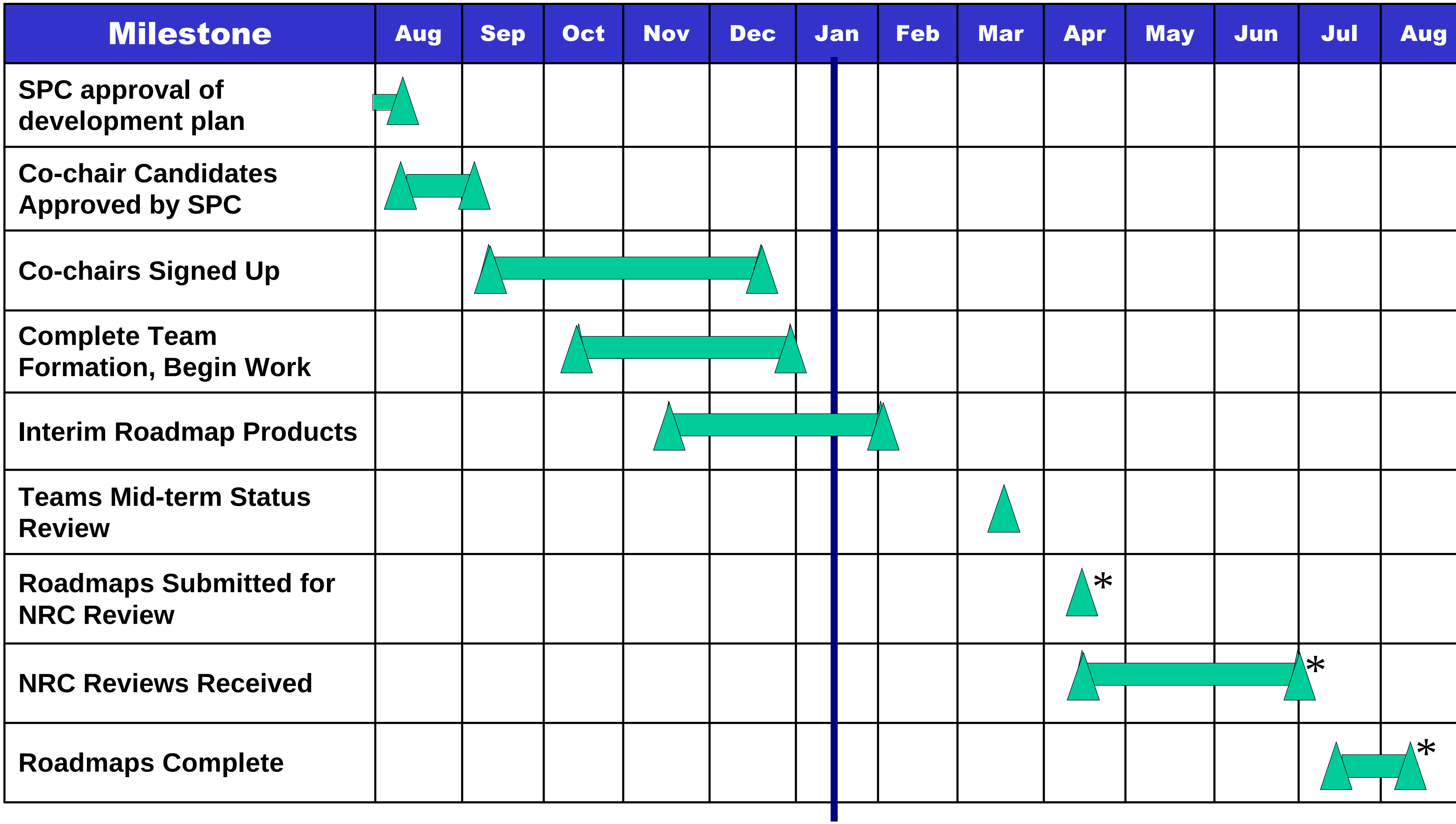
– DoD Participation

Strategic Roadmaps - continued

Advanced Planning & Integration Office

Roadmap	Chairs (HQ Directorate, Center)	External Chair
Universe Exploration	Dr. Anne Kinney (HQ/SMD) Dr. Nick White (GSFC)	Dr. Kathy Flanagan (MIT)
Earth Science and Applications from Space	Orlando Figueroa (HQ/SMD) Dr. Diane Evans (JPL)	Dr. Charles Kennel (UCSD/Scripps)
Sun-Solar System Connection	Al Diaz (HQ/SMD) Dr. Franco Einaudi (GSFC)	Dr. Timothy Killeen (NCAR)
Aeronautical Technologies	Terry Hertz (HQ/ARMD) None (Center)	James Jamieson (Boeing)
Education	Dr. Adena Loston (HQ/Office of Education) Dr. Julian Earls (GRC)	Dr. France Cordova (Uni. of Cal., Riverside)
Nuclear Systems	Adm. (Ret.) Craig Steidle (HQ/ESMD) Chris Scolese (GSFC)	Dr. John Ahearne (Duke Uni.)

Strategic Roadmaps Schedule



Capability Roadmaps

- Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.

- Capability Roadmap is a description of the developments (including alternate paths and options) required to achieve the capability.

Capability Charter

- **NASA, in response to the Presidential Commission recommendations, will prepare roadmaps and related implementation plans that define national capabilities needed to meet the Agency's strategic roadmaps. The roadmap titles are based on the Presidential Commission's recommendation of seventeen technologies, updated by the NASA Strategic Council.**
- **The capability roadmap development process will be accomplished in two phases.**
  - **Phase 1 will be the development of capability roadmaps and associated technical products.**
    - **During this phase, technical experts both internal and external to NASA will provide the technical knowledge and expertise in the development of roadmaps which identify the capabilities that are needed to meet the missions of the Agency. The capability roadmap team will identify and analyze each of the associated technologies and assess the capability performance afforded by the current state of the art, the performance level needed by the strategic mission and trace the development required.**
  - **Phase 2 will be the development of Investment Plans.**
    - **During this phase, a NASA team will develop investment plans for the capability roadmaps. This team will be working to determine the critical capabilities that are identified on the roadmaps and to develop an investment plan for each individual roadmap area to include schedules and yearly budgets. The activity of the Investment Plan Teams consists of using the perspectives and values described by the Capability Roadmaps and selecting and then formulating an optimized development plan suitable for consideration by the Agency in its budget submissions.**

Method and Timing of Integrating Capability Roadmaps with Strategic Roadmaps

- Strategic roadmaps are being developed in parallel with the Capability roadmaps
  - Assumptions were made to begin the Capability roadmap development.
    - Created a missions assumptions framework
    - Provided a set of design reference missions
- The Capability roadmaps being presented today are based on mission assumptions which will be updated by the agency strategic roadmap effort
- This dialogue review is, therefore, a work in progress
- Another NRC review in the June through August timeframe will include the integrated strategic and capability roadmap product

Process for Team Selection

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- **Guidelines for Team Member Selection**
  - **Small teams of 12 -15 members with participation from:**
    - **1/3 Industry**
    - **1/3 NASA & other Government Agencies**
    - **1/3 Academia**
- **Strategic Planning Council assigned roadmaps to Mission Directorate**
- **Mission Directorates assigned a NASA Chair with roadmap expertise**
- **NASA Chairs chose team members from industry, academia, other Government & within NASA who are recognized experts**

Capability Roadmaps - continued

Capability	NASA chair	External chair
◤ High-Energy Power and Propulsion	Joe Nainiger (GRC)	Dr. Tom Hughes (Penn State Uni.)
◤ In-Space Transportation	Paul McConnaughey (MSFC)	Col. Joe Boyles (US Air Force SMC)
◤ Advanced Telescopes and Observatories	Lee Feinberg (GSFC)	Dr. Howard MacEwen (SRS Technologies)
◤ Communication and Navigation	Bob Spearing (HQ/SOMD)	Michael Regan (DoD)
Robotic Access to Planetary Surfaces	Mark Adler (JPL)	Dr. Robert Braun (Georgia Tech)
Human Planetary Landing Systems	Robert Manning (JPL)	Dr. Harrison Schmitt
Human Health and Support Systems	Dennis Grounds (JSC)	Al Boehm (Ret, Hamilton-Sundstrand)
◤ Human Exploration Systems and Mobility	Chris Culbert (JSC)	Dr. Jeff Taylor (Uni. of Hawaii)

Directorate and APIO Coordinators Also with Each Team

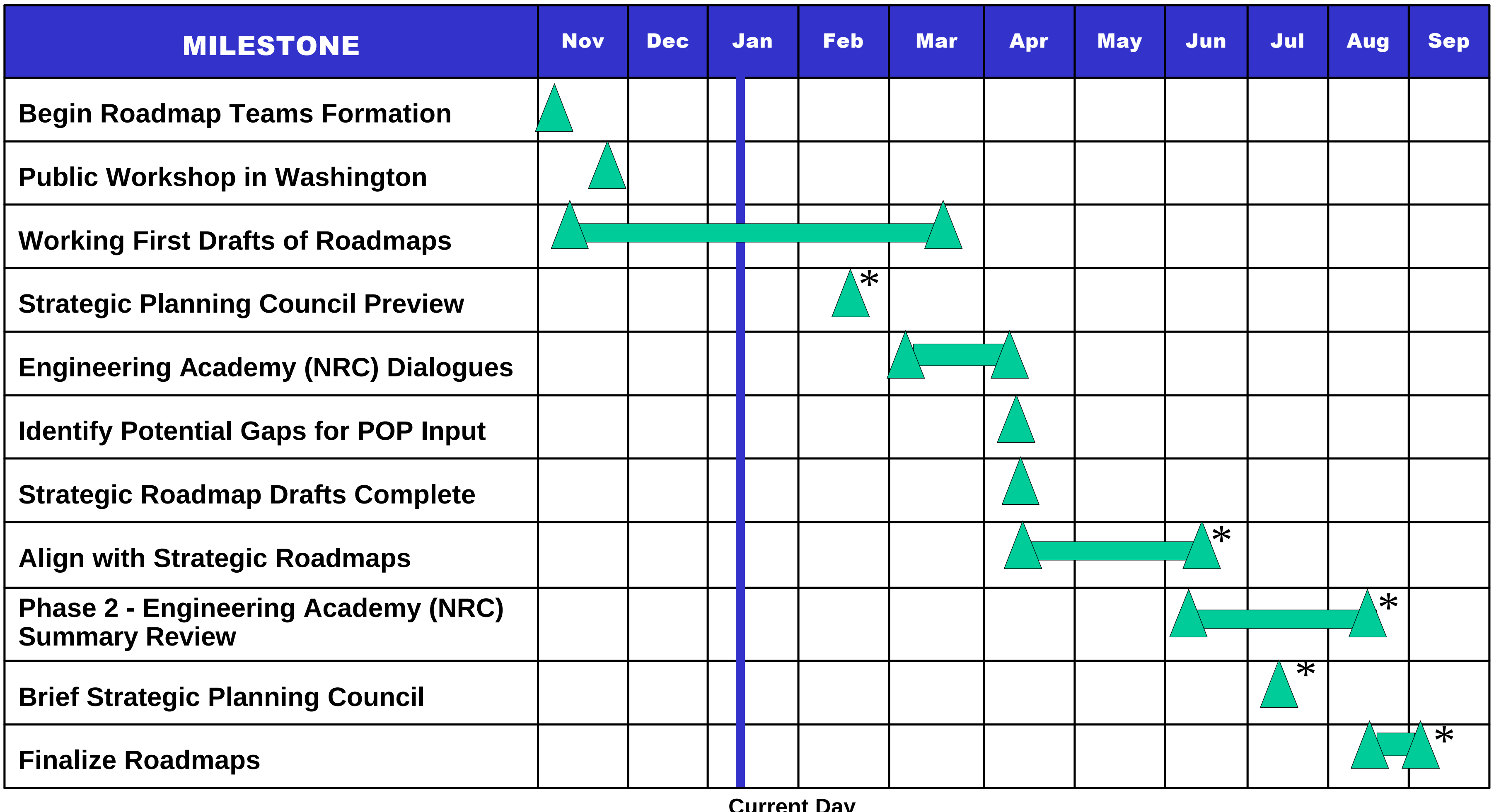
◤ = DoD Participation

Capability Roadmaps - continued

Capability	NASA chair	External chair
Autonomous Systems and Robotics	Dr. Steve Zornetzer (ARC)	Doug Gage (Ret. DARPA)
Transformational Spaceport/Range	Karen Poniatowski (HQ/SOMD)	Gen. (Ret.) Jimmy Morrell Col. Dennis Hilley (OSD)
Scientific Instruments/Sensors	Rich Barney (GSFC)	Dr. Maria Zuber (MIT)
In Situ Resource Utilization	Jerry Sanders (JSC)	Dr. Mike Duke (Colorado School of Mines)
Advanced Modeling, Simulation, Analysis	Dr. Erik Antonsson (JPL)	Dr. Tamas Gombosi (Uni. Of Michigan)
Systems Engineering Cost/Risk Analysis	Steve Cavanaugh (LaRC)	Dr. Alan Wilhite (Georgia Institute of Technology)
Nanotechnology	Dr. Murray Hirschbein (HQ/ARMD) and Dr. Minoo Dastoor (HQ/ESMD)	Dr. Dimitris Lagoudas (Texas A&M)

Capability Roadmap Development Schedule Overview

Advanced Planning & Integration Office



*Schedule under review.

Purpose of NRC Review

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- NASA wants the National Research Council (NRC) to review Capability Roadmap products and assess progress in four areas:

Four NRC Questions:

Do the Capability Roadmaps provide a clear pathway to (or process for) technology and capability development?

Are technology maturity levels accurately conveyed and used? (Note: Maturity levels will be evaluated using Technology Readiness Levels (TRLs) and Capability Readiness Levels (CRLs) or other appropriate methodologies)

Are proper metric for measuring advancement of technical maturity included?

- Do the Capability Roadmaps have connection points to each other when appropriate

Technology Readiness Levels

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- **9** Actual System Proven in Operation
- **8** Actual System Qualified by Demonstration
- **7** System Prototype Demonstration in an Operational Environment
- **6** System/Subsystem Model or Prototype Demonstration in a Relevant Environment
- **5** Component and/or Breadboard Validation in a Relevant Environment
- **4** Component and/or Breadboard Validation in a Laboratory Environment
- **3** Analytical and Experimental Critical Functions Characteristic Proof-of-Concept
- **2** Technology Concept and/or Application Formulated
- **1** Basic Principles Observed and Reported

Capability Readiness Levels

Advanced Planning & Integration Office

7 Capability Operational Readiness

6 Integrated Capability Demonstrated in an Operational Environment

5 Integrated Capability Demonstrated in a Relevant Environment

4 Integrated Capability Demonstrated in a Laboratory Environment

3 Sub-Capabilities* Demonstrated in a Relevant Environment

2 Sub-Capabilities* Demonstrated in a Laboratory Environment

1 Concept of Use Defined, Capability, Constituent Sub-capabilities* and Requirements Specified