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

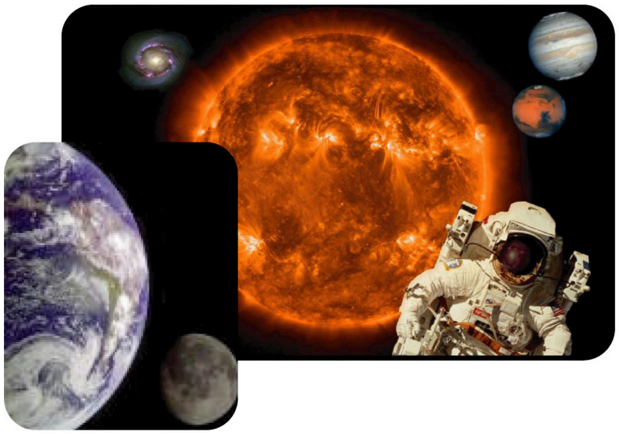
- The Science Instruments and Sensors roadmaps include capabilities associated with the collection, detection, conversion, and processing of scientific data required to answer compelling science questions driven by the Vision for Space Exploration and The New Age of Exploration (NASA's Direction for 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

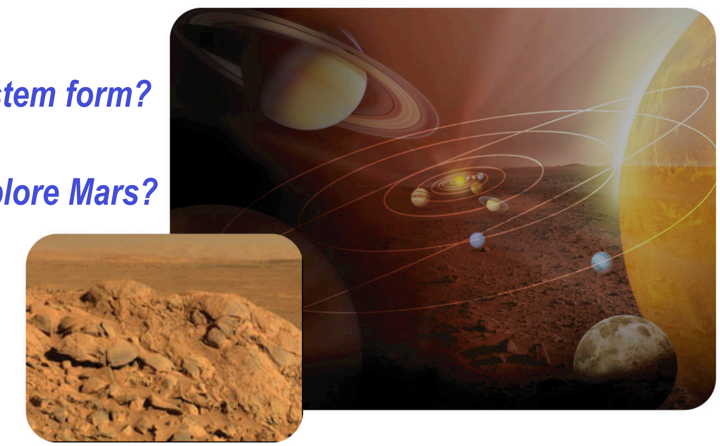
Compelling Science Questions

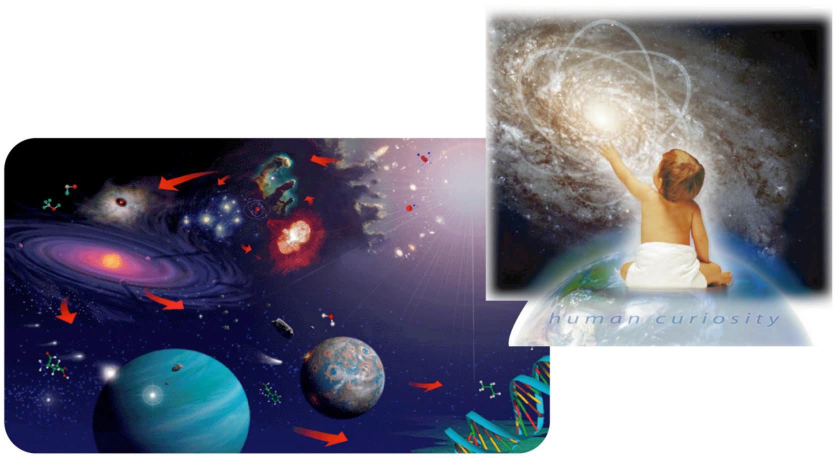
Answers to questions as old as human curiosity have always seemed beyond the reach of science..
UNTIL NOW!



- *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

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 Images
- 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

- 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

Capability Roadmap Team Kickoff 9/28/04

Establish Team

* Collect team member recommendations from NASA, academia and industry

Preliminary Planning Activities

* Develop Capability Breakdown Structure, Roadmap Development Plan, Budget, and Schedule

Public Workshop 11/30/04

* 112 People Registered for the Science Instruments and Sensors Session
* 67 White Papers Submitted
* 23 Capability Presentations
* Follow-up Activity with Presenters

First Team Workshop @ JPL 12/8-9, 2004

* Review Planning Documents
* Capability Breakdown Structure
* Science and Technology Presentations
* Roadmap Development Process

Sub-Team Activities

* Define Capability Breakdown Structure: Level 2
* Develop Science Traceability Spreadsheets
* Review Strategic Reference Documents

GSFC Workshop Jan. 4-6, 2005

* Science Vision, Science Capability & Technology Presentations
* Science Traceability
* CRM Connection points

MIT Workshop Feb. 2-4, 2005

* Capability Breakdown Structure: Level 4
* NRC Presentation
* Review Science Traceability
* Identification of High Priority Capabilities

Deliver NRC Products 3/7/05

* HQ Team Dry Run (3/1/05)

NRC Dialogue 3/16/05

* A Clear Pathway to Capability Development?
* Technology Maturity Level?
* Metrics for measuring Technical Maturity Advancement?
* Connection Points to Other Roadmaps?

Develop First Draft of Roadmaps

* Capability Priorities
* Integration with Other Roadmaps
* SRM Interaction

Review SRM Draft Products 4/15/05

Final Workshop

* Strategic Roadmap Alignment
* Capability Roadmap Integration

NRC Summary Review

Final Product Delivery 6/05

Strategic Traceability

Advanced Planning & Integration Office

- 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)

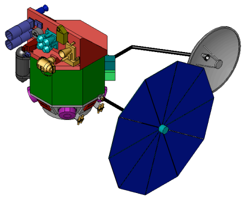
Advanced Planning & Integration Office

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

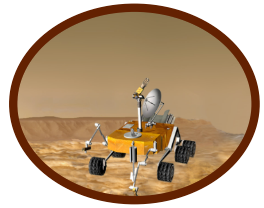
Advanced Planning & Integration Office

Lunar Recon. Orbiter

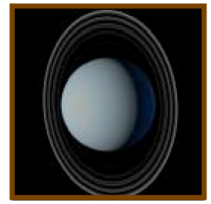


Constellation-X

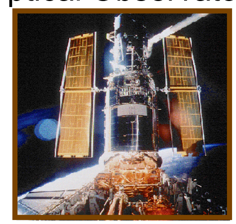
Astrobiology Field Lab



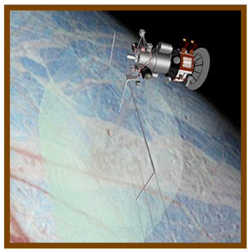
Uranus Orbiter with Probes



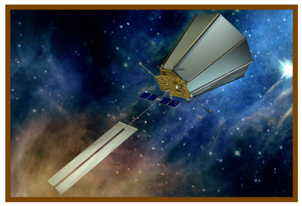
Large-Aperture UV/ Optical Observatory



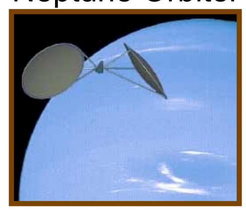
Europa Geophysical Orbiter



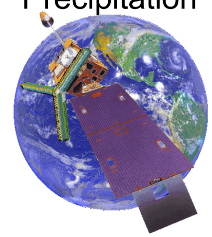
TPF-C



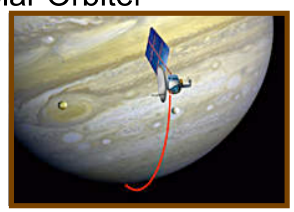
Neptune Orbiter



GEO Global Precipitation

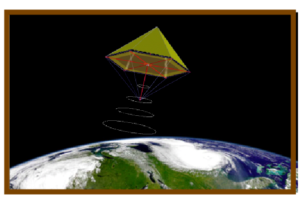


Jupiter Polar Orbiter w/ Probes

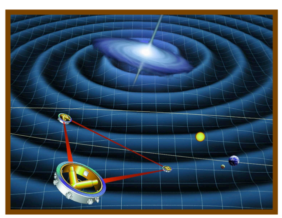


Mars Sample Return

GEO/MEO InSAR

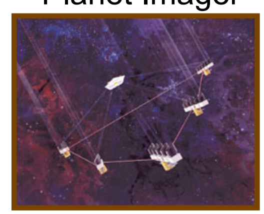


LISA



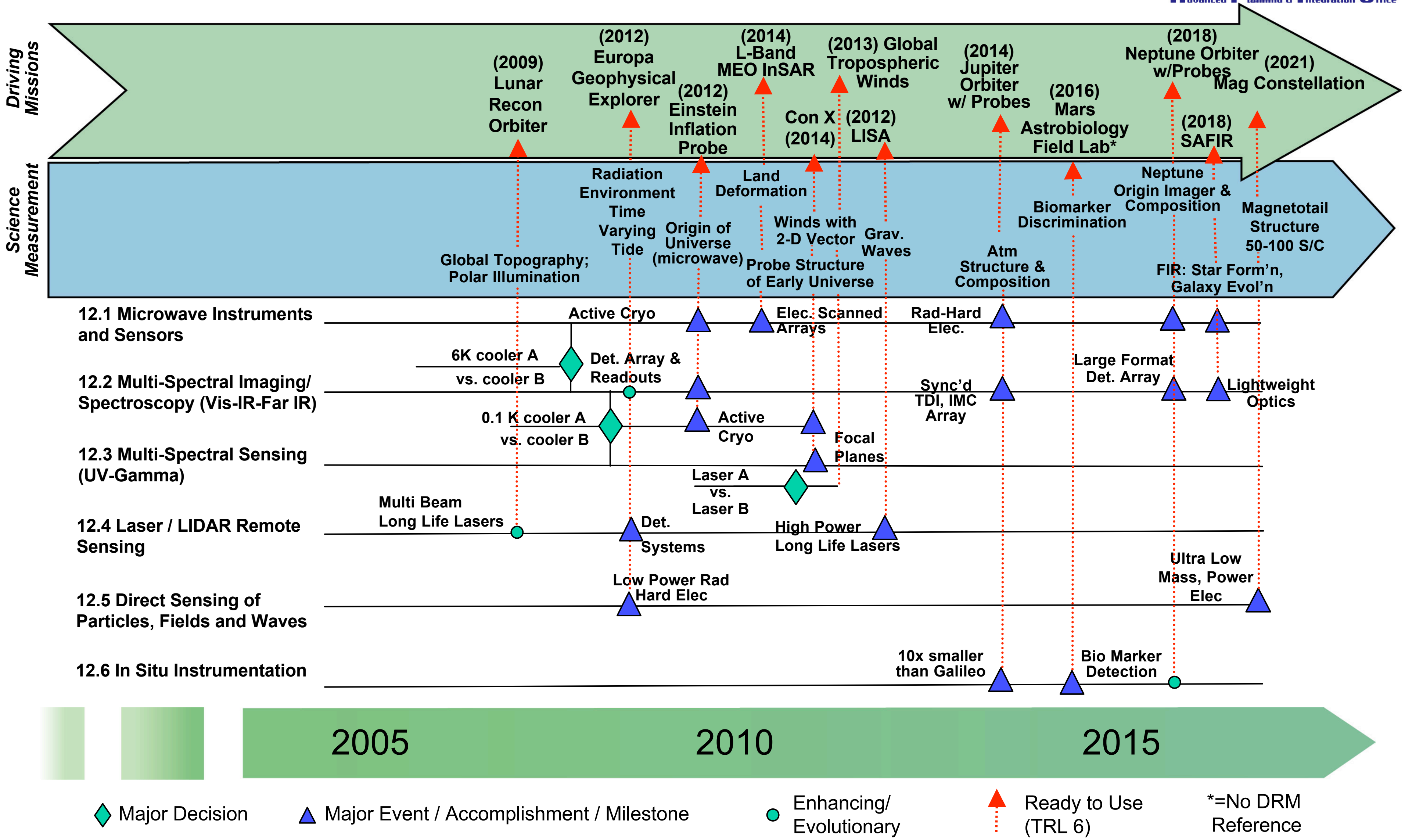
SAFIR

Planet Imager

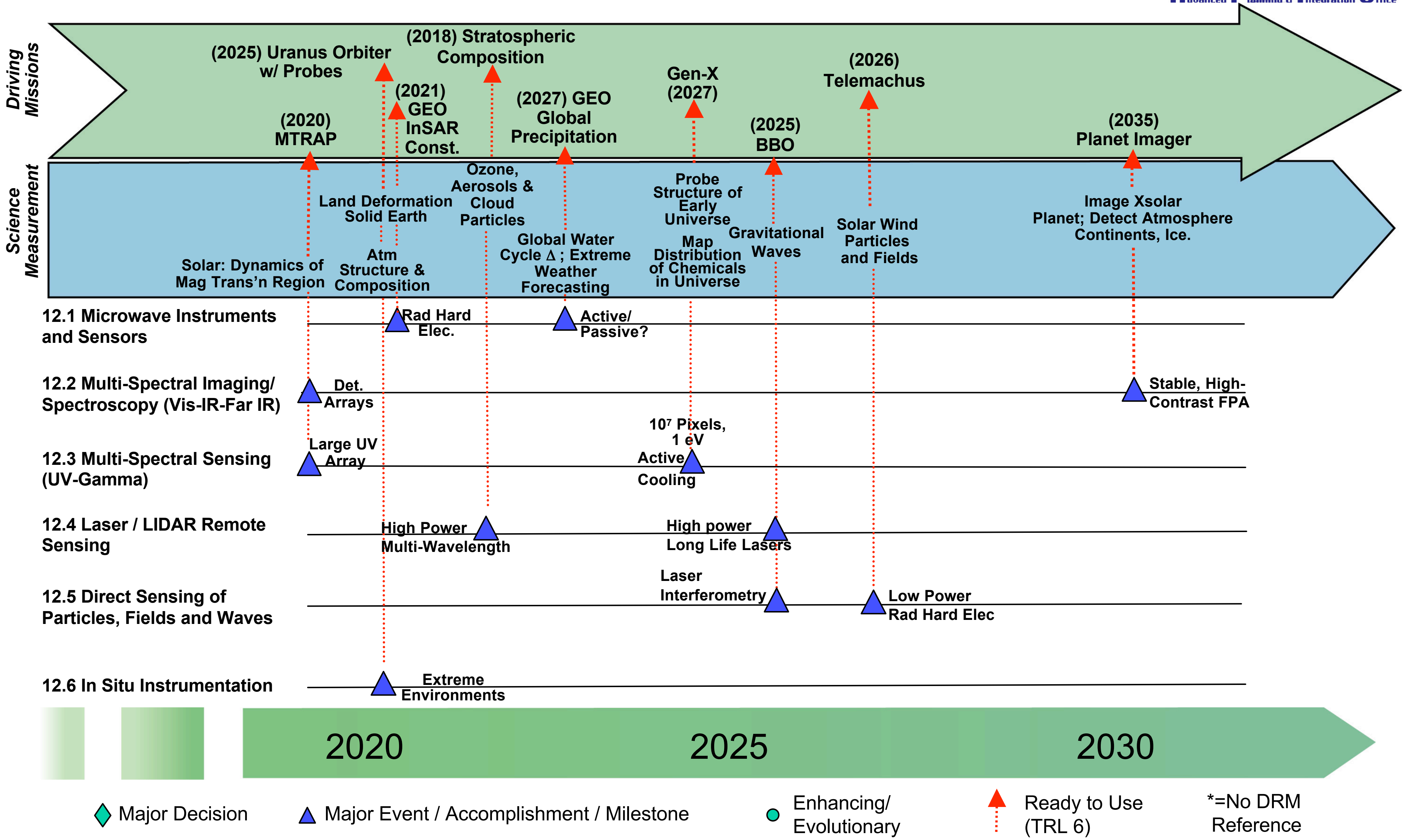


2010 2020 2030

Science Instruments and Sensors
Near Term Capability Roadmap



Science Instruments and Sensors
Far Term Capability Roadmap



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

	Strategic Roadmap	Connection Points
	1. Lunar: Robotic and Human Exploration	Minimal Design Reference Missions
	2. Mars: Robotic and Human Exploration	Presented at Meeting #1 and MEPAG follow up. MEPAG reference missions provide strategic guidance.
	3. Solar System Exploration	Design Reference Missions are defined and strategic guidance documentation has been reviewed.
	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)
	6. International Space Station	
	7. Space Shuttle	
	8. Universe Exploration	Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed. . (POC: Kathy Flanagan)
	9. Earth Science and Applications from Space	Design Reference Missions are defined and strategic guidance documentation has been reviewed. (POC: Azita Valinia)
	10. Sun-Solar System Connection	Presented at Meeting #1. Design Reference Missions are defined and strategic guidance documentation has been reviewed.
	11. Aeronautical Technologies	
	12. Education	
	13. Nuclear Systems	

	No Relationship
	Critical Relationship
	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

Science Instruments and Sensors 12.0

Microwave Instruments and Sensors 12.1

Chair: Soren Madsen, JPL
Co-Chair: Chris Ruf, UM

- Radar Altimetry 12.1.1
- Real Aperture Radar 12.1.2
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- Passive Microwave Sounder 12.1.8
- GPS - Radio time-of-Flight triangulation 12.1.9
- Other Technology 12.1.10

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

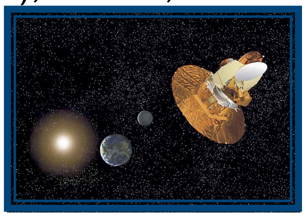
What isn't covered

– 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

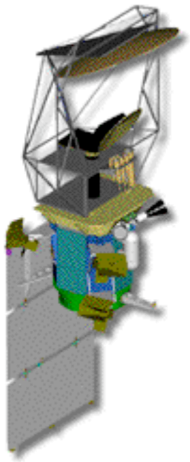
Planetary Science: Pioneer, Apollo–17, Magellan, Cassini, MARSIS

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

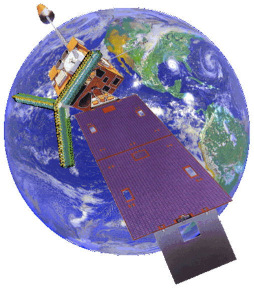
Mission/Strategic Drivers

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



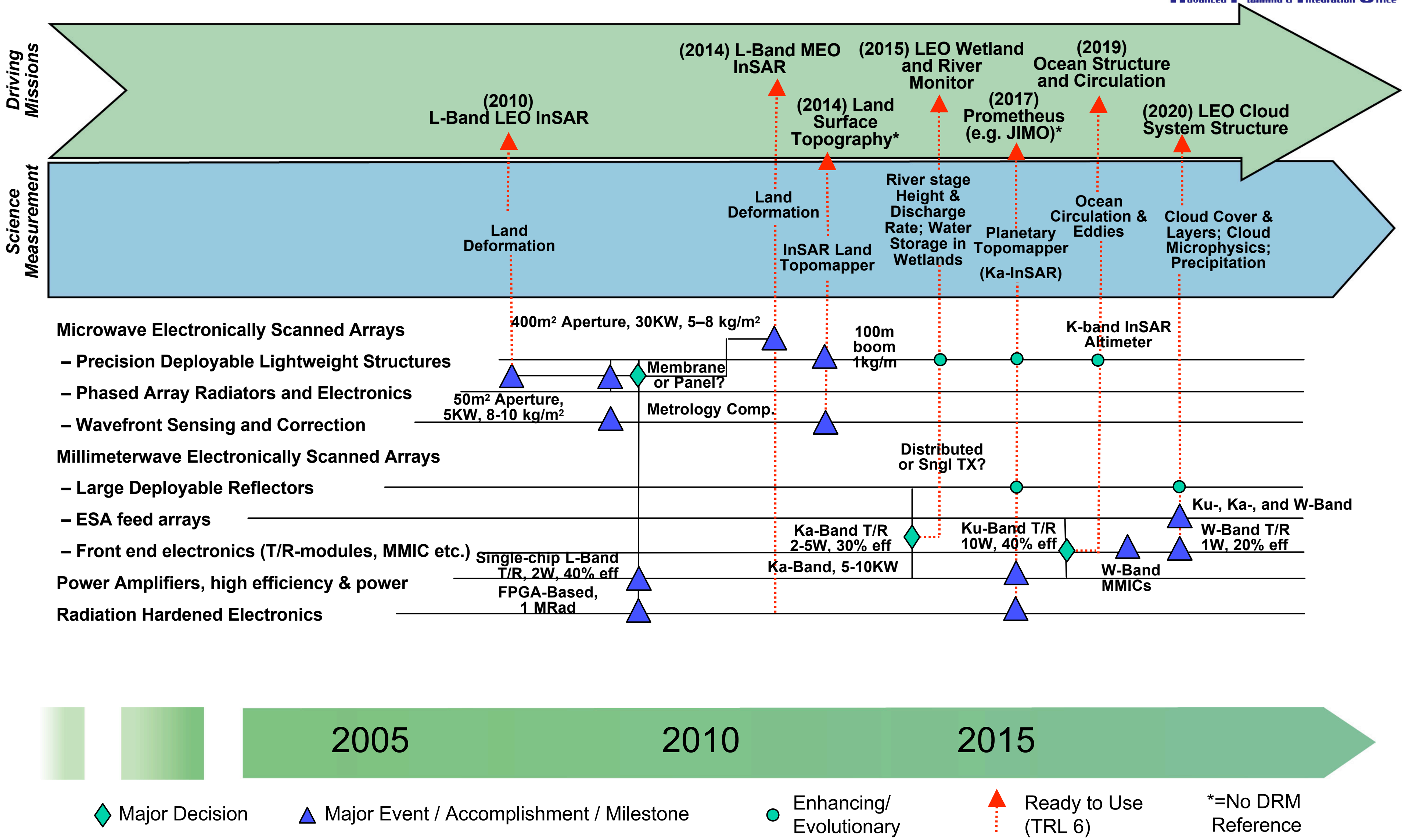
GEO Global Precip

12.1 Capability Need/Gap Assessment

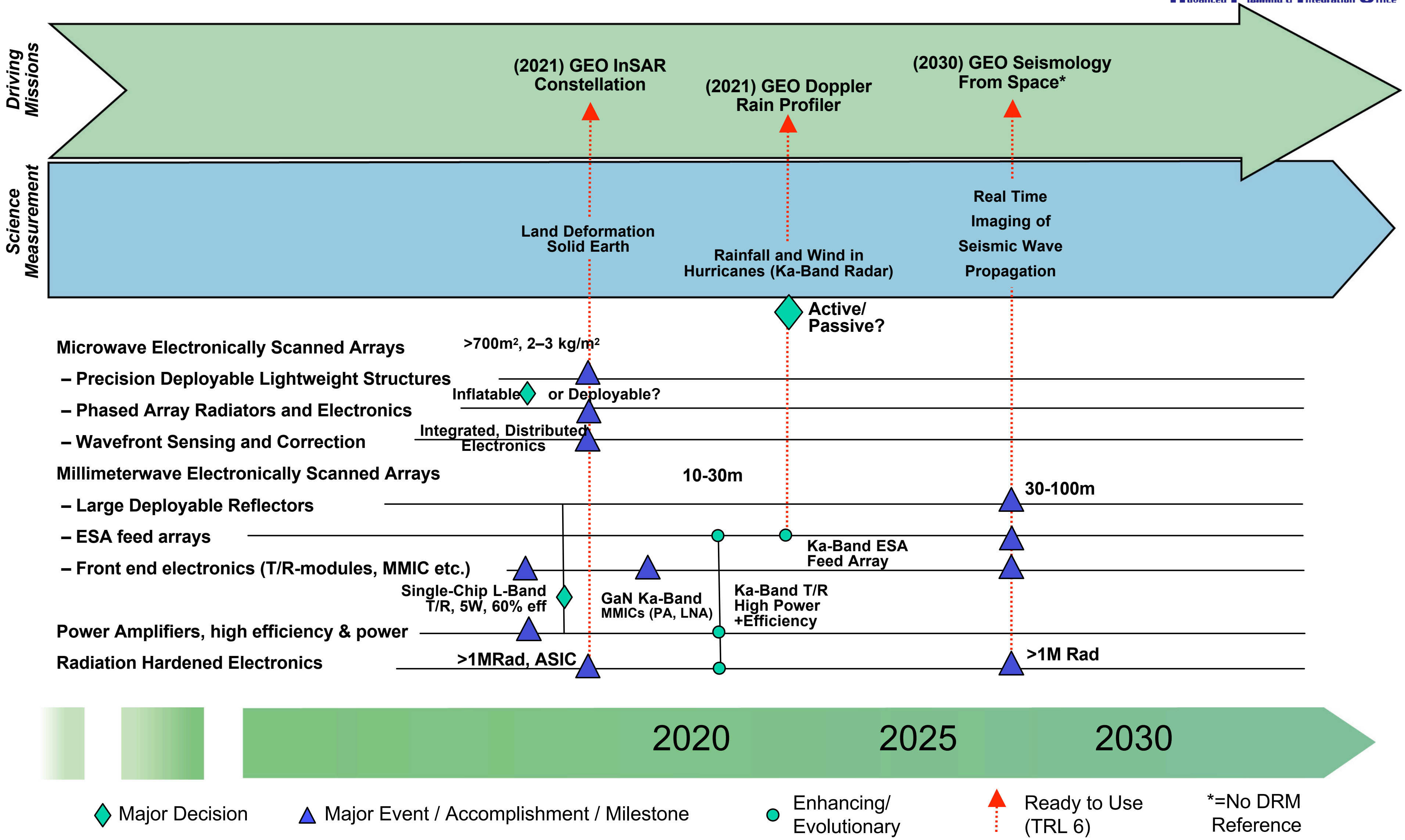
Sub Capability	Figures of Merit	Current Technology	Needed Technology
Interferometric SAR	Temporal and Spatial Resolution, swath width	Moderate High efficiency L-band T/R modules, Moderate ~30m^2 antennas	Large (400–700m^2), deployable antennas, High efficiency rad-hard T/R modules, Digital Beam Formation (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

Advanced Planning & Integration Office

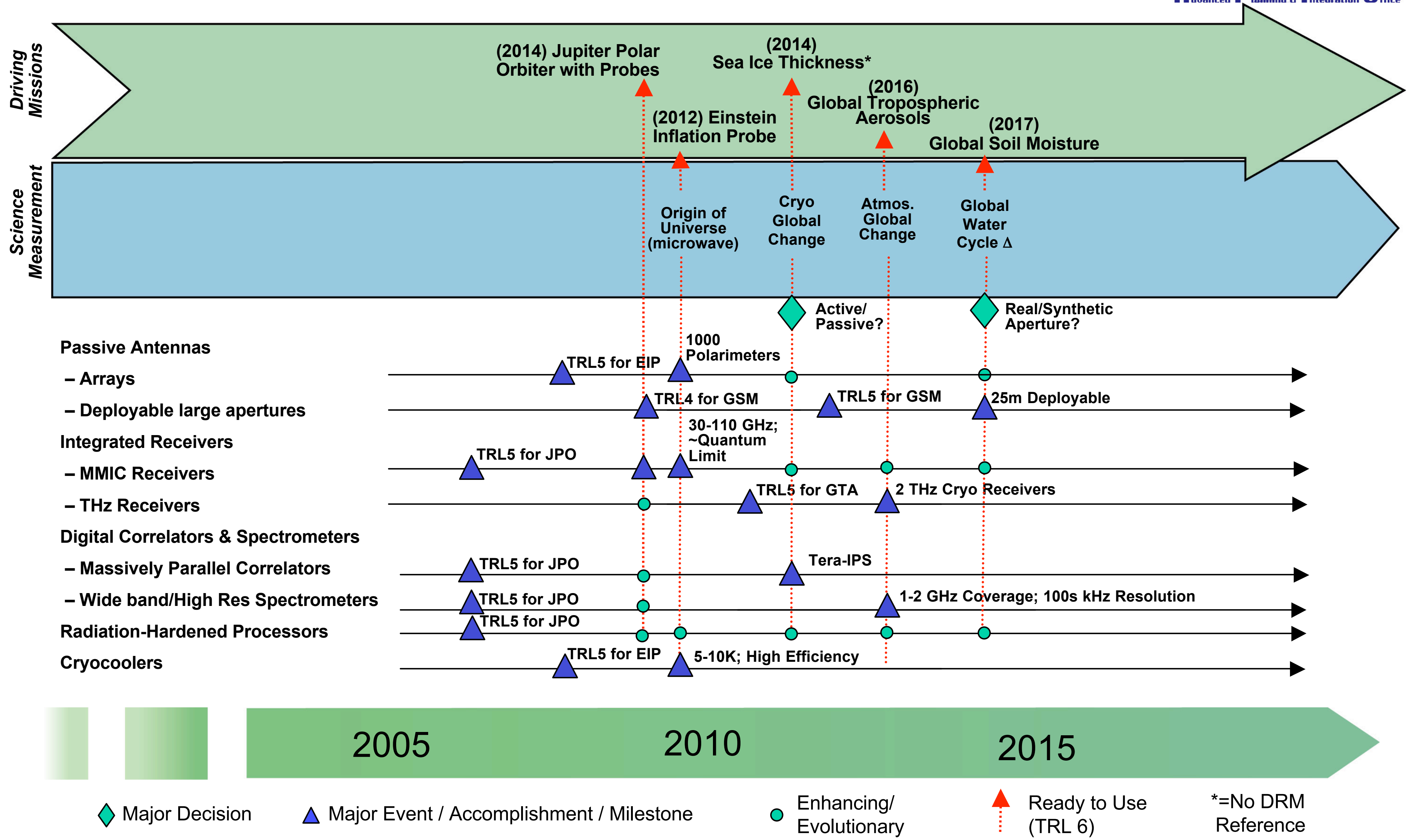


12.1 Microwave Instruments and Sensors (Active)
Far Term Capability Roadmap



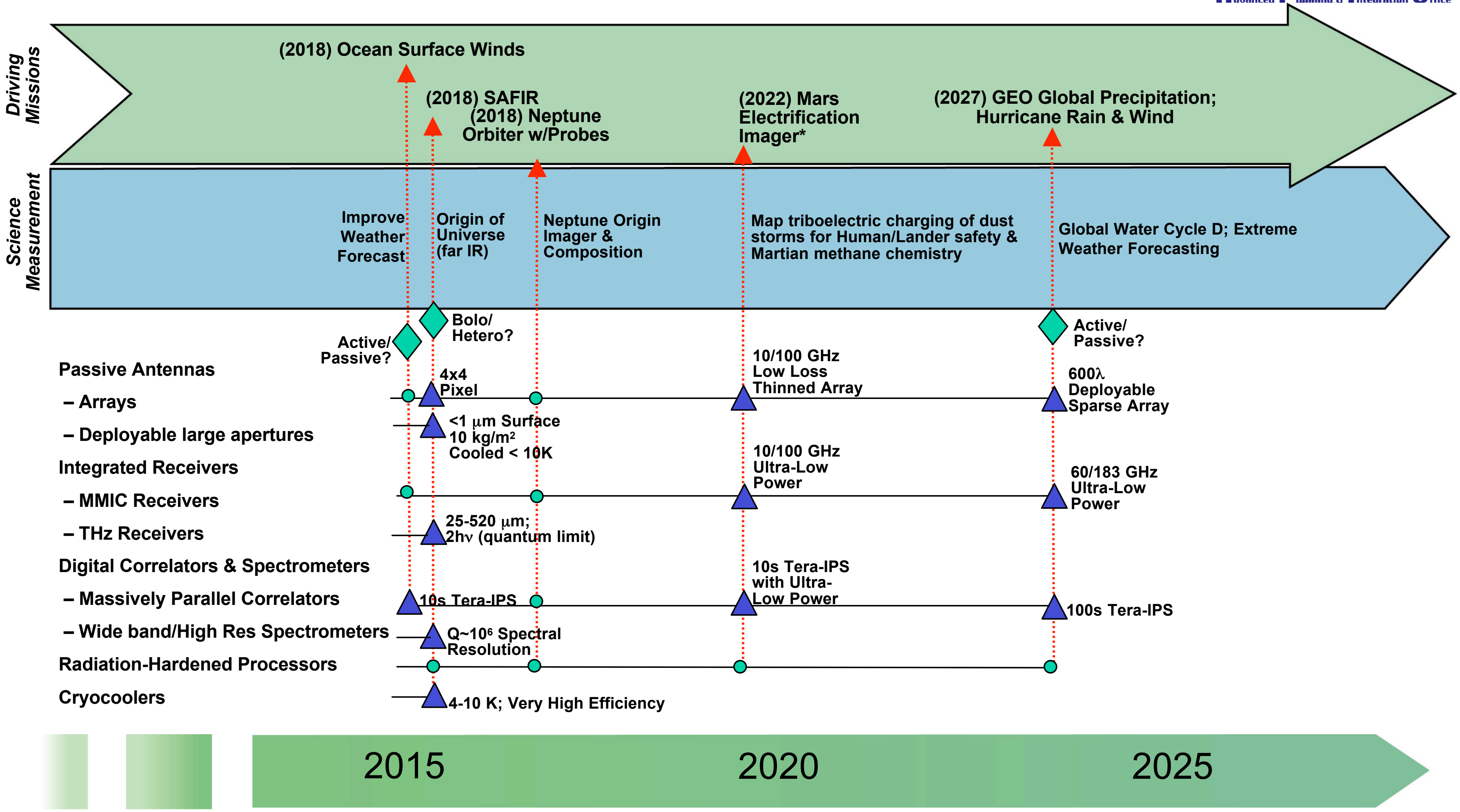
12.1 Microwave Instruments and Sensors (Passive) Near Term Capability Roadmap

Advanced Planning & Integration Office



12.1 Microwave Instruments and Sensors (Passive)
Far Term Capability Roadmap

Advanced Planning & Integration Office



Major Decision | Major Event / Accomplishment / Milestone | Enhancing/ Evolutionary | Ready to Use (TRL 6) | *=No DRM Reference

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

- 12.0 Science Instruments and Sensors
  - 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 Images, Photometers, Radiometers, Sounders
    - 12.2.5 IR/FIR Spectrometers/ Interferometers
    - 12.2.6 IR/FIR Spectral (& hyperspectral) Imagers

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):

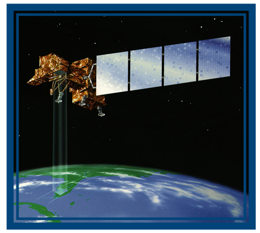
- Is there evidence of life in other planetary systems?
- How are planetary systems formed, & what are their properties?
- Did the early universe undergo a process of rapid expansion?

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)

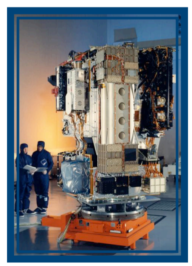
12.2 Multi-Spectral Imaging/Spectroscopy (Vis-IR-FIR)

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

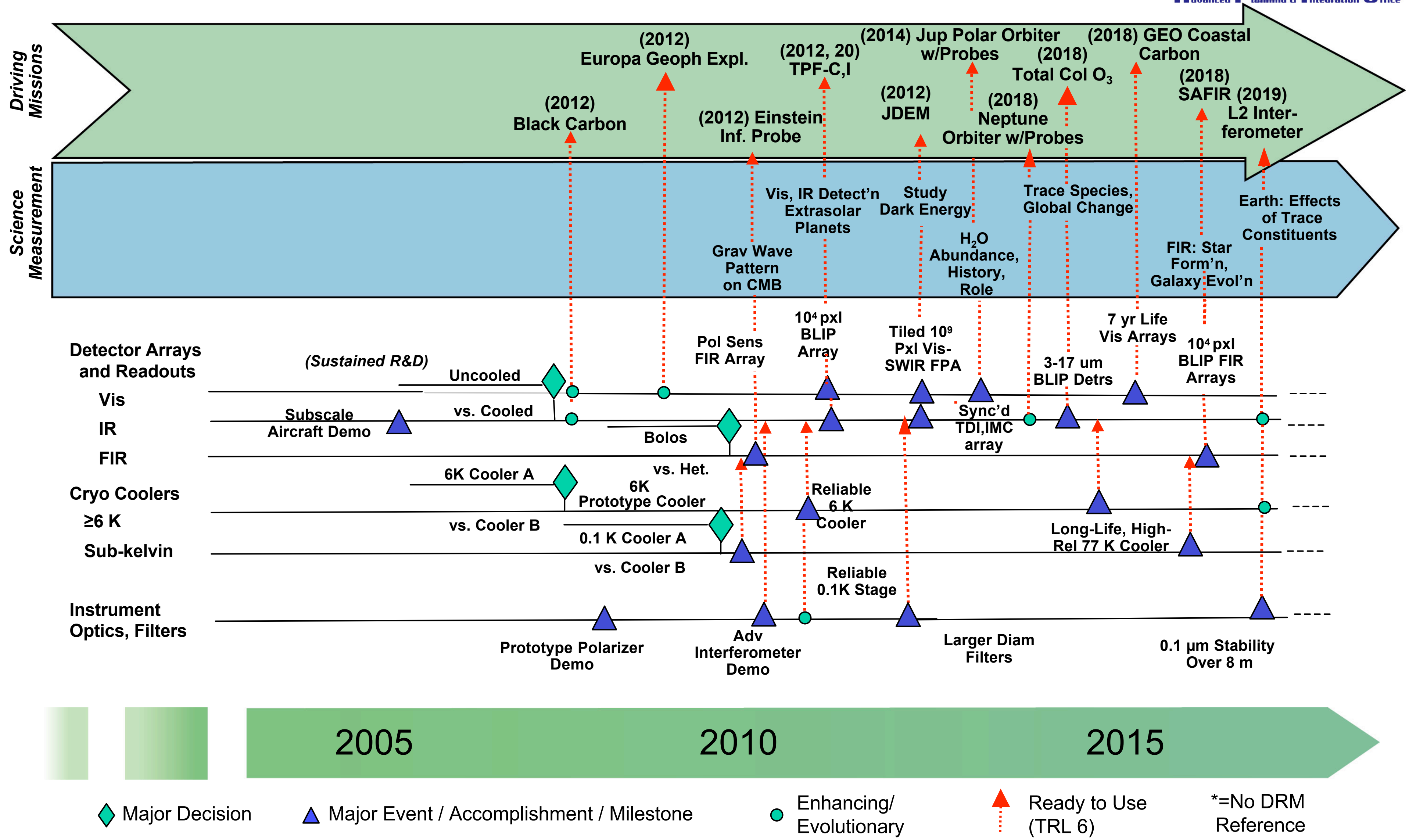
12.2 Capability Need/Gap Assessment

Advanced Planning & Integration Office

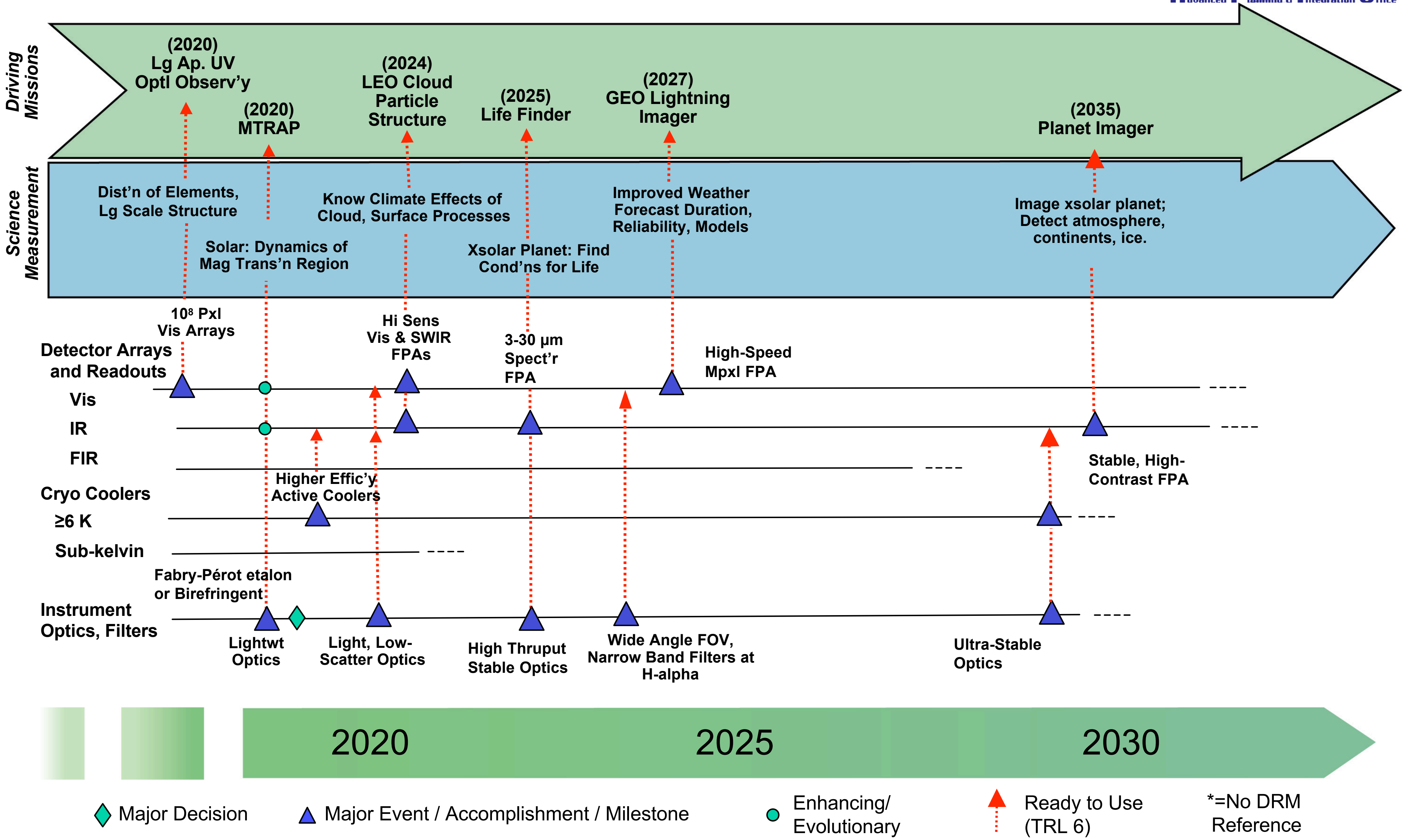
Sub Capability	Figures of Merit	Current Technology	Needed Technology
Visible Detector Arrays	Pixel Count, Uniformity Quantum Efficiency Noise Crosstalk	≤1 k x 2 k format Radiation degradation Transition (CCD <-> CMOS) Few, changeable foundaries	>2 k x 2 k format; mosaics Radiation tolerance Stable fabrication 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)

Advanced Planning & Integration Office

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

Advanced Planning & Integration Office

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
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  - Earth Science Research Plan: 6 Jan 2005 Draft
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- **Planetary Science**
  - New Frontiers in the Solar System: An Integrated Exploration Strategy (2003)
- **Sun-Solar System**
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  - 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

12.0 Science Instruments and Sensors

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

12.3 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

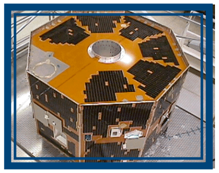
- Light-weight, high-resolution, grazing & normal incidence and diffractive optics, plus coatings, are covered by Advanced Telescopes and Observatories(CRM #4)
- Formation flying capabilities and necessary metrology are covered by CRM #4
- Cooling of large structures (including large-area detectors) 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

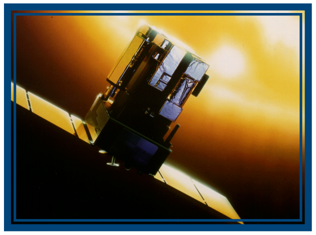
History/Current Missions

– ***Sun-Solar:***

SOHO (1995)
IMAGE (2000)
RHESSI (2002)
Solar-B (2006)
STEREO (2006)

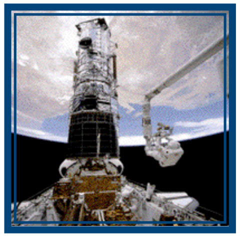


IMAGE


SOHO

– ***Universe & Origins:***

EUVE (1992)
HST (1990)
FUSE (1999)
Uhuru (1970)
Einstein (1978)
Chandra (1999)
Compton GRO (1991)
GLAST (2007/8)


HST

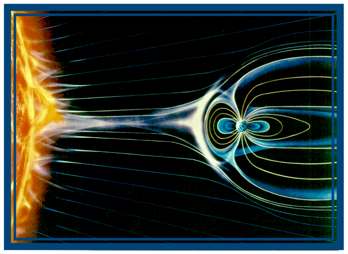

FUSE


Chandra

Mission/Strategic Drivers

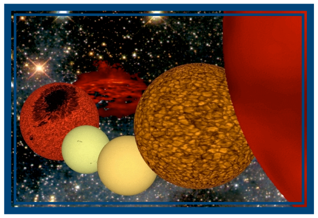
– ***Sun-Solar:***

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)

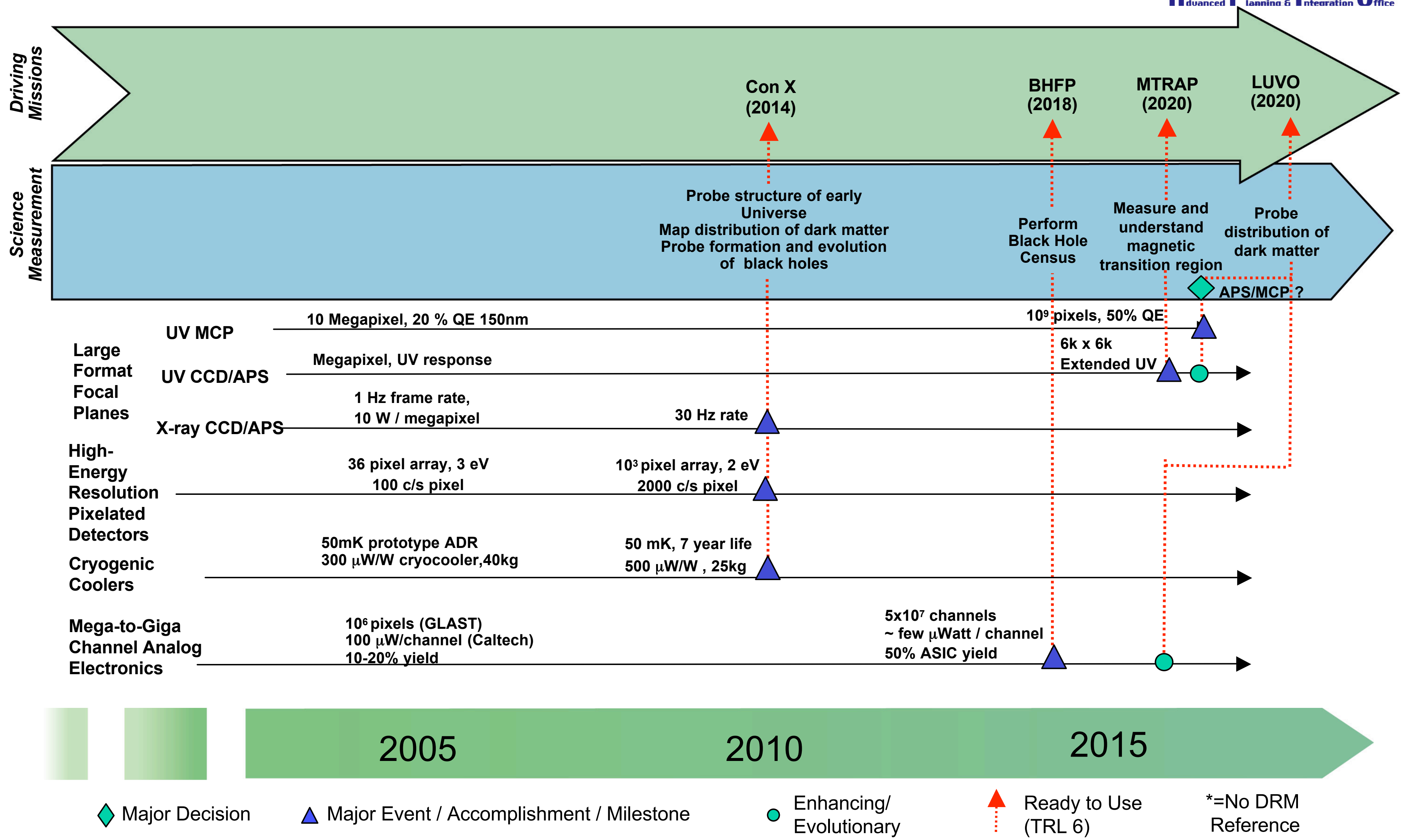


12.3 Capability Need/Gap Assessment

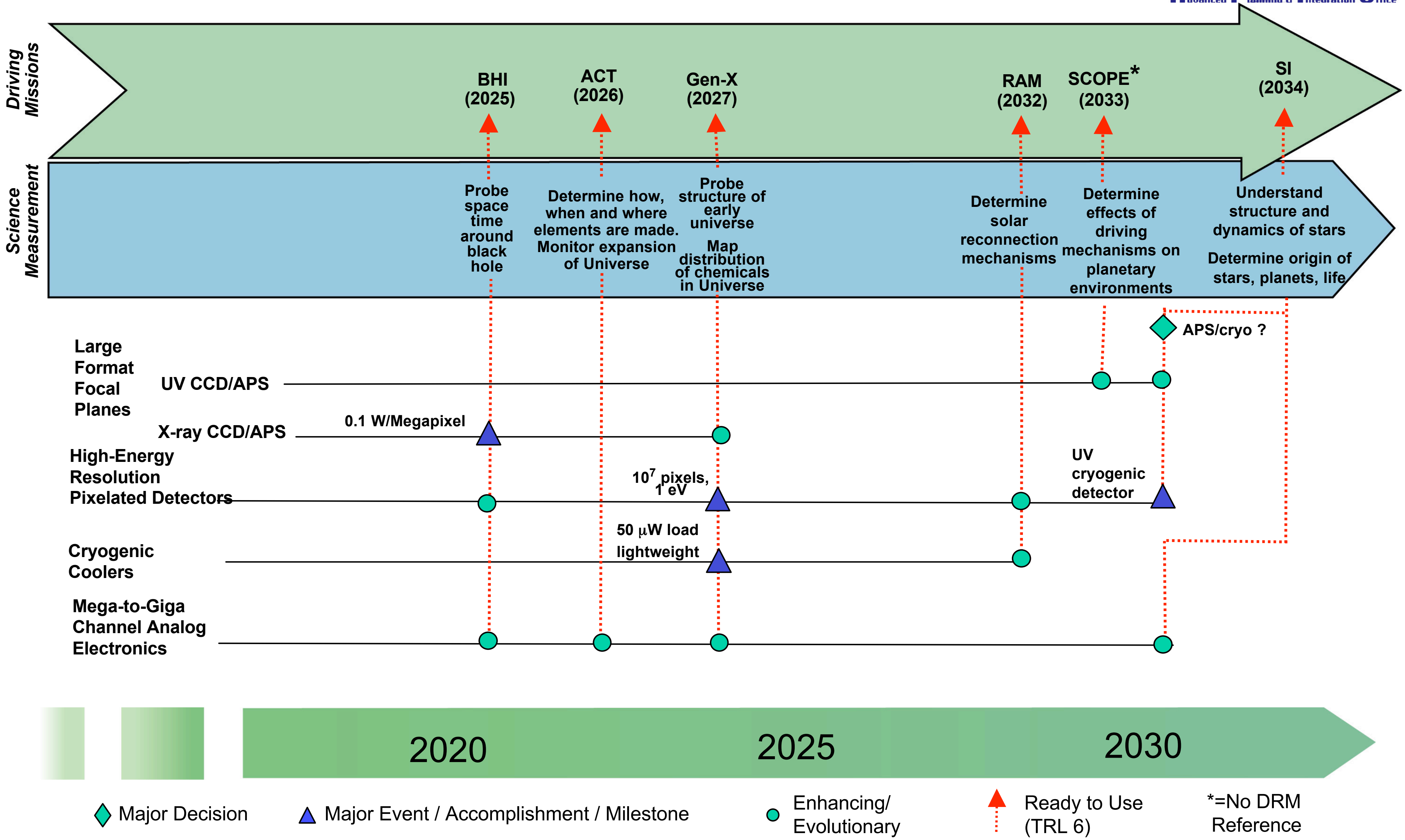
Advanced Planning & Integration Office

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 Quantum efficiency	10^7 pixels 10-15%	10^9 50%	LUVO LUVO	2016 2016
UV & X-Ray Imaging and Spectrometry.	Large Format Focal Plane Detectors : CCDs and Active Pixel Sensors	Total pixels Pixels / chip Power Resolution Readout speed Response	Megapixel Megapixel 10 W / Megapixel 120 eV @ 6 keV 1 Hz > 150 nm, below ~ 6 keV	> 10^8 (UV) 6k x 6k, buttable (UV) 4k x 4k, 4-side buttable (X-ray) 0.1 W / Megapixel < 120 eV 30 Hz Extended UV response X-ray response above 6 kev	MTRAP MTRAP BHI BHI BHI Con-X MTRAP Gen X	2016 2016 2021 2021 2021 2010 2016 2023
X-Ray Imaging and Spectrometry	High-Energy-Resolution Pixelated Detectors	Energy resolution Number of pixels Count rate capability	6 eV , 6 keV ASTRO-E 2.7 eV in lab 36 pixels array (ASTRO-E) 100 c/s per pixel	2 eV (Con-X), 1eV (Gen-X) 10^3 pixel 10^7 pixel > 10^3 c/s-pixel	Con-X Gen-X Con-X Gen-X Con-X	2010 2023 2010 2023 2010
	Cryogenic Coolers	Temperature Load Operation Lifetime Efficiency	50 mK 5 μW Continuous ADR lab prototype 300 μW/W (cryocooler)	50 mK 5 μW ~ 50 μW Continuous or duty cycle > 95% 7 year 500 μW/W	Con-X Con-X Gen-X Con-X Con-X Con-X	2010 2010 2023 2010 2010 2010
Gamma-Ray Imaging and Spectrometry	Mega-to-Giga Channel Analog Electronics	Number of channels Power/channel Noise/channel Yield	10^6 (GLAST) 100μW / channel (Caltech) 200 e rms (no interconnects) 10-20%	5.10^6-10^8 100μW-2μW /channel < 300 e rms with interconnects/coupling 50% for 10^4 ASICs	BHFP BHFP BHFP BHFP	2014 2014 2014 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.***

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

Advanced Planning & Integration Office

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

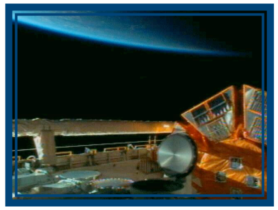
- Receiver optics and infrastructure also addressed by Advanced Telescopes and Observatories Capability Roadmap.
- Agency will support risk reduction activities, including aircraft and ground-based prototype testing.
- Sensors must reach technical maturity 3-5 years before launch.
- Some Earth science 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

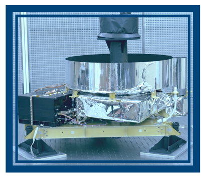
12.4 Laser/LIDAR Remote Sensing

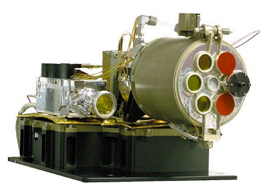
Advanced Planning & Integration Office

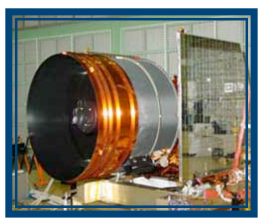
Past/Current Missions

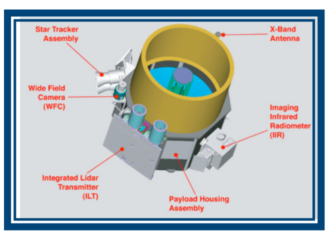
- Clementine LIDAR -- 1994
- LITE -- 1994
- NEAR NLR -- 1997
- MGS MOLA -- 1999
- SLA 1 & 2
- Icesat/GLAS -- 2003
- MESSENGER MLA -- launched 2004
- CALIPSO/CALIOP -- 2005 launch
- ALADIN/AEOLIS ADM -- 2007 launch
- LRO LOLA -- 2008 launch

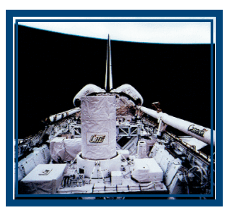












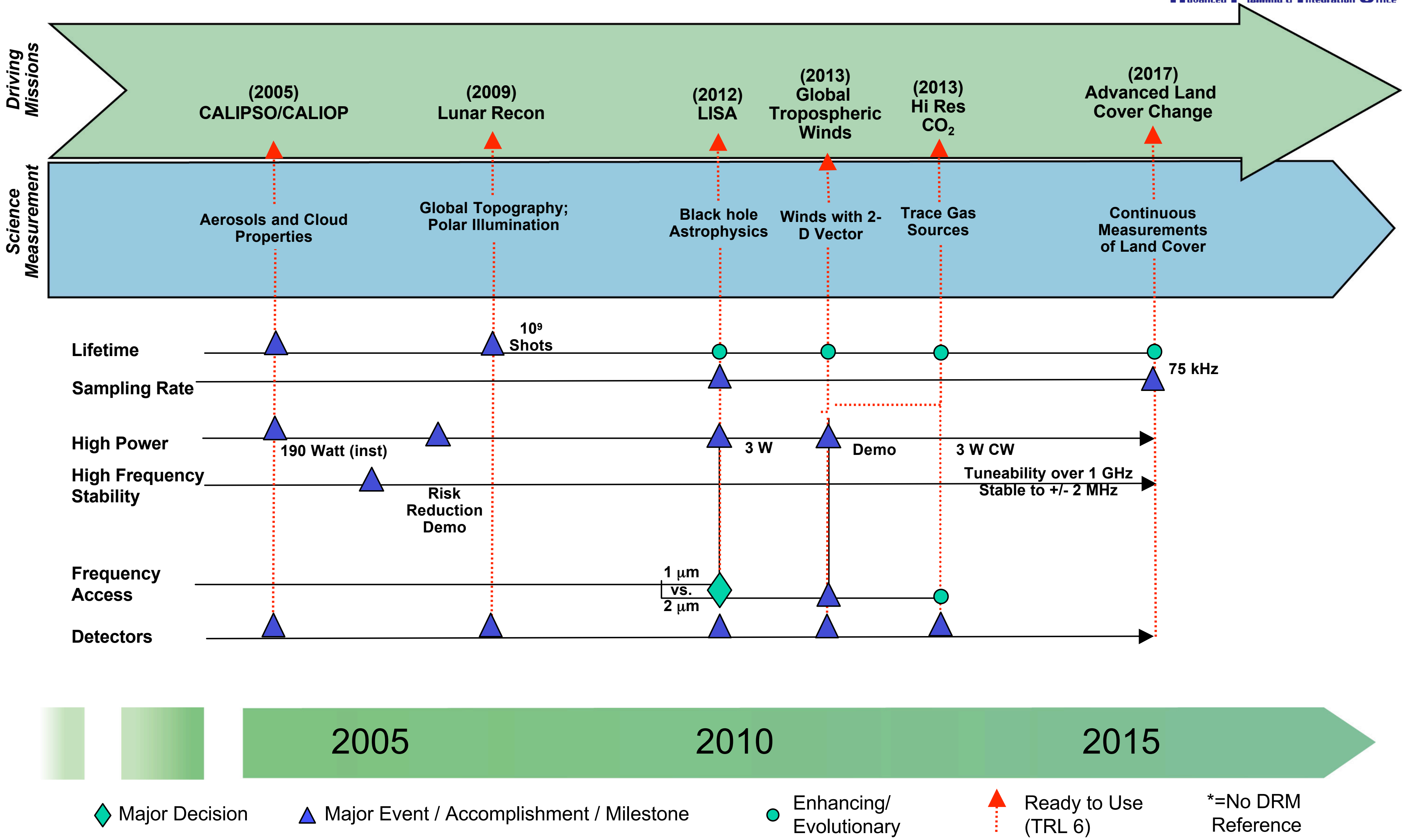
Future Driving Missions

- **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

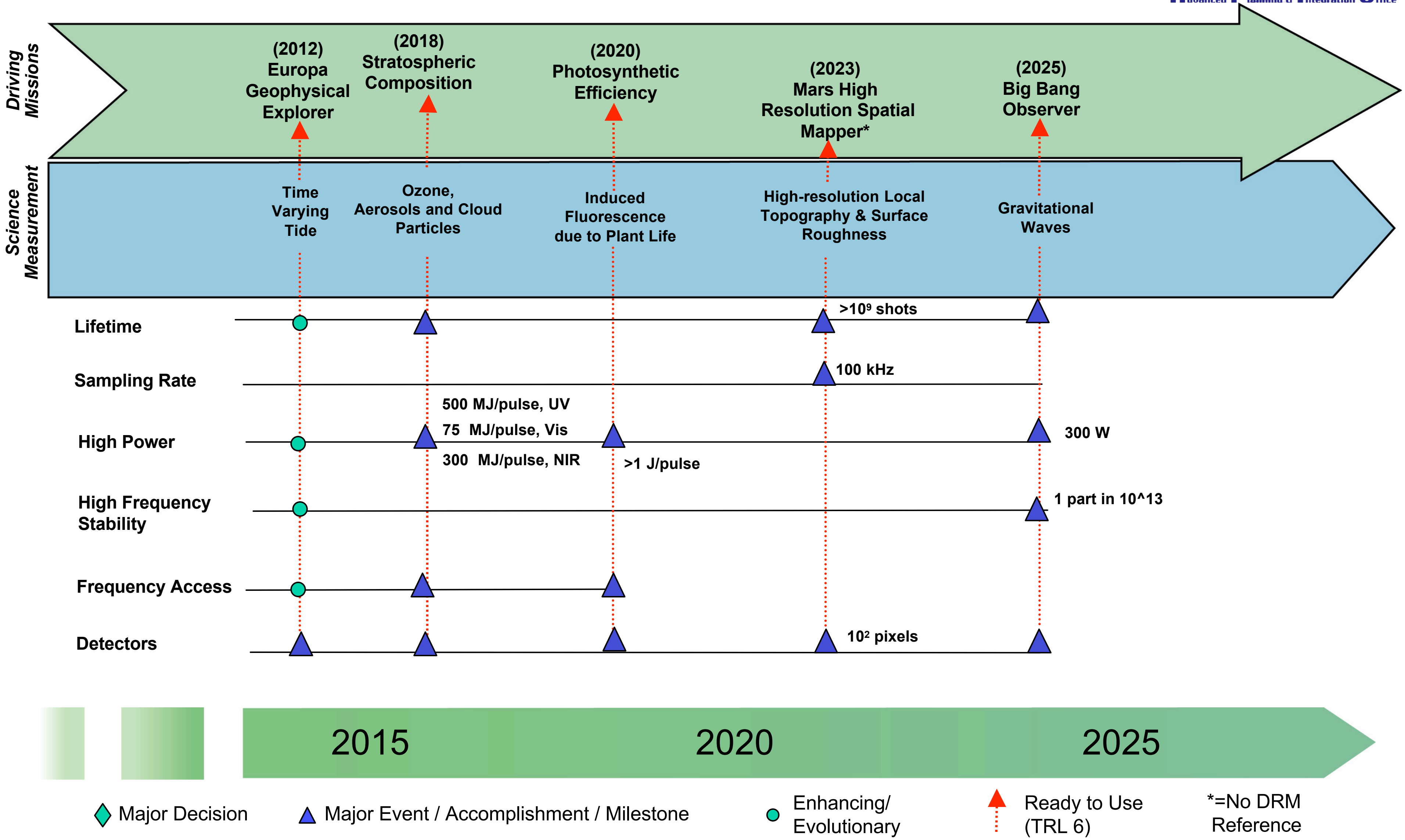
12.4 Capability Need/Gap Assessment

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



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)

- 12.0 Science Instruments and Sensors
  - 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

12.5 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.

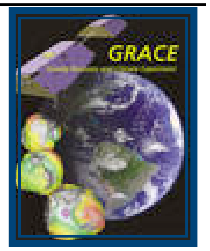
Miniaturization and reduction in mass and power needs are shared with the in-situ and remote-sensing teams, and for spacecraft avionics.

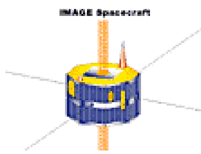
Advanced Planning & Integration Office

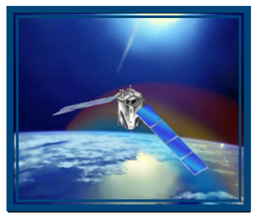
Past / Current Missions

Terrestrial

GRACE
Polar
IMAGE
TIMED
Cluster

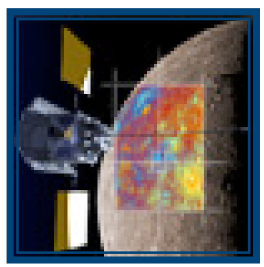






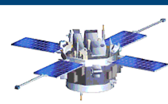
Planetary

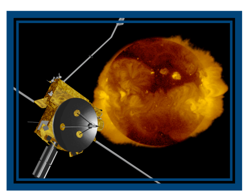
Galileo
Cassini
Messenger



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

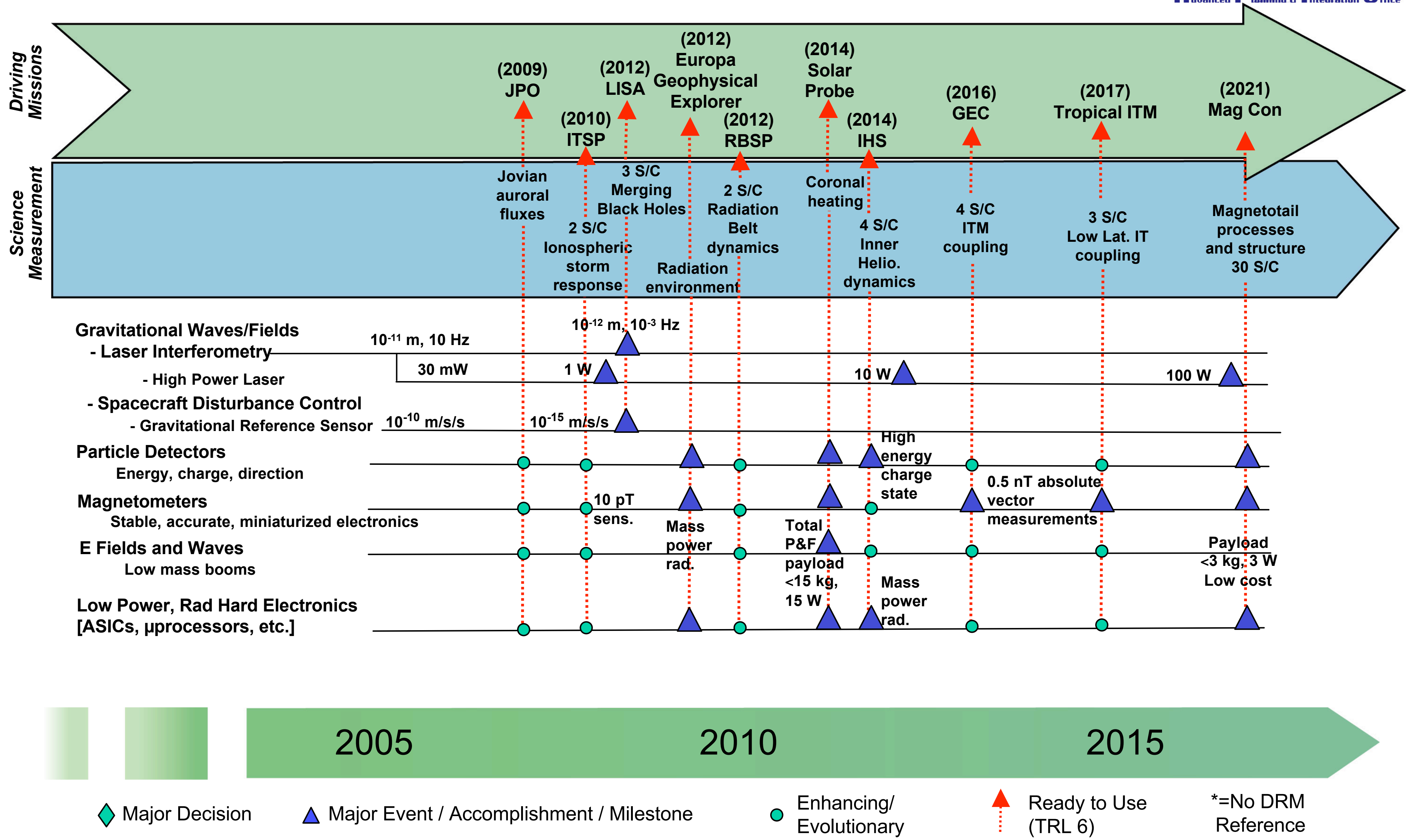
Heliospheric: Solar Probe (SP), Inner Heliosphere Sentinels (IHS), Telemachus, Interstellar Probe (ISP), Heliospheric Imager and Galactic Observer (HIGO)

Astrophysics: Laser Interferometer Space Antenna (LISA), Big Bang Observer (BBO)

12.5 Capability Need/Gap Assessment

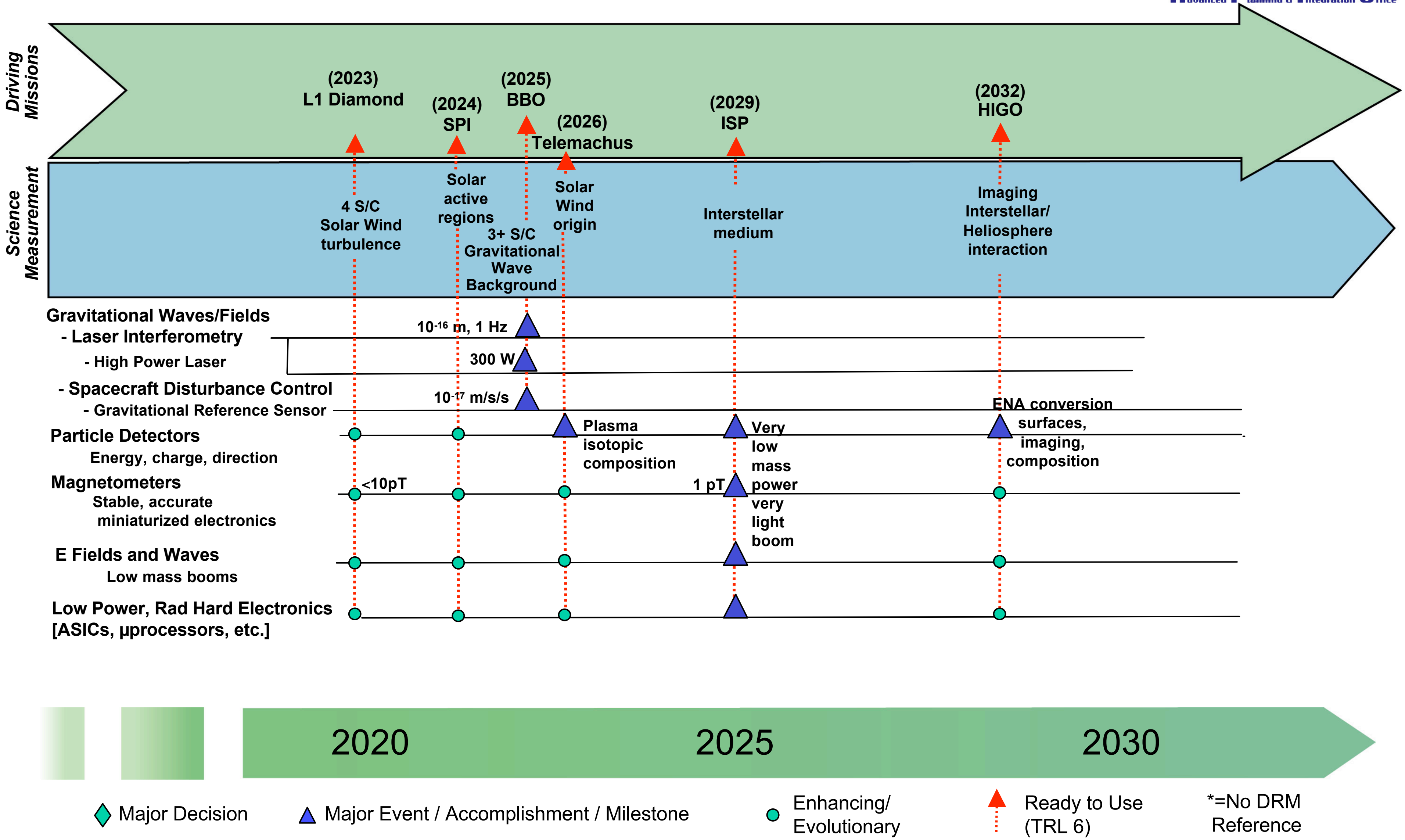
Sub Capability	Figures of Merit	Current Technology	Needed Technology
Gravitational Waves and Fields	High sensitivity to low frequency (10^{-3} – 1 Hz) relative displacement of proof masses	Laser Interferometry	High power, stable, long-life lasers; Interferometer system; Disturbance compensation system (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

Advanced Planning & Integration Office



12.5 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)
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

Advanced Planning & Integration Office

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

Science Instruments and Sensors 12.0

- In Situ Instrumentation 12.6

  Chair: Tim Krabach, JPL
  Co-Chair: Rich Dissly, BATC

  - Imaging/Microscopy 12.6.1
  - Mineralogical/Elemental Analysis 12.6.2
  - Chemical Detection and Identification 12.6.3
  - Isotope Analysis/ Age Dating 12.6.4
  - Biological Detection and Identification 12.6.5
  - Geophysical Measurements 12.6.6
  - Sample Handling and Preparation 12.6.7
  - In Situ Instrument Engineering 12.6.8

12.6 In-Situ Instrumentation

Advanced Planning & Integration Office

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

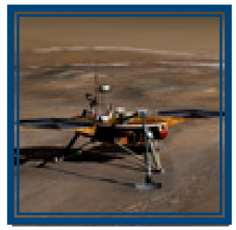
- Vis-IR far-field sensing, or measurements outside of planetary atmospheres, covered by **Multi-spectral Imaging subteam**
- In-situ measurements of interplanetary plasmas covered in **Particles, Fields and Waves subteam**
- In-Situ sensors for astronaut health and safety are **not** covered by this 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

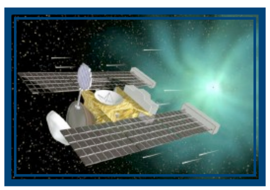
–**Mars**

_Viking
_Pathfinder
_MER
_Phoenix
_MSL



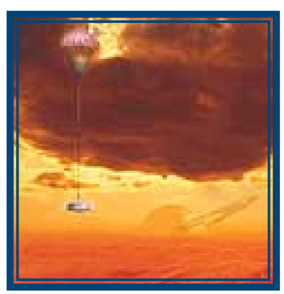
–**Sample Return**

_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

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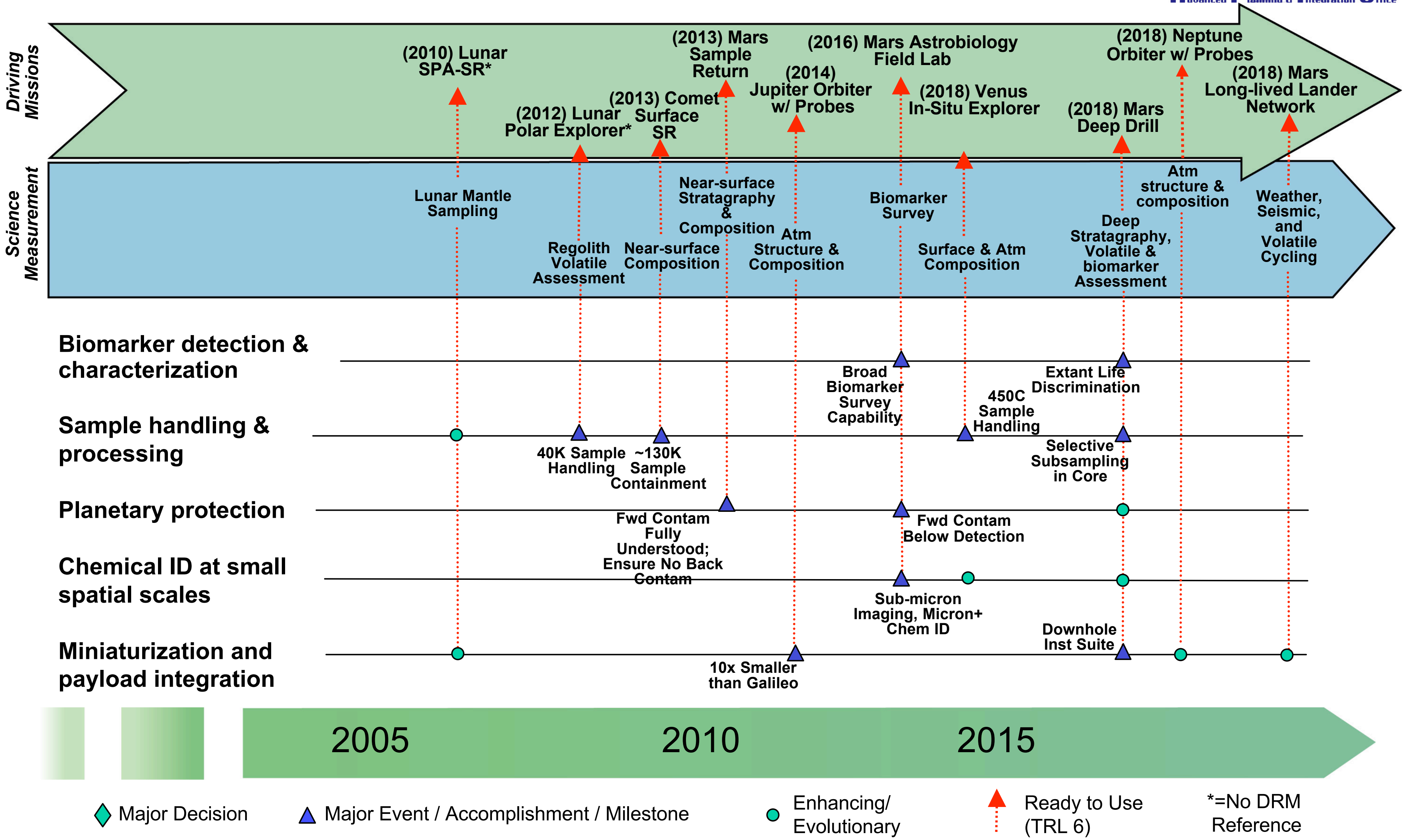
Sub Capability	Figures of Merit	Current Technology	Needed Technology
Biomarker Detection and Characterization	• Sensitivity • Selectivity • Contamination ID and quantification	• Characterization of viable organisms that can be cultured • Terrestrial contamination exceeds detection limits	• Quantitative 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

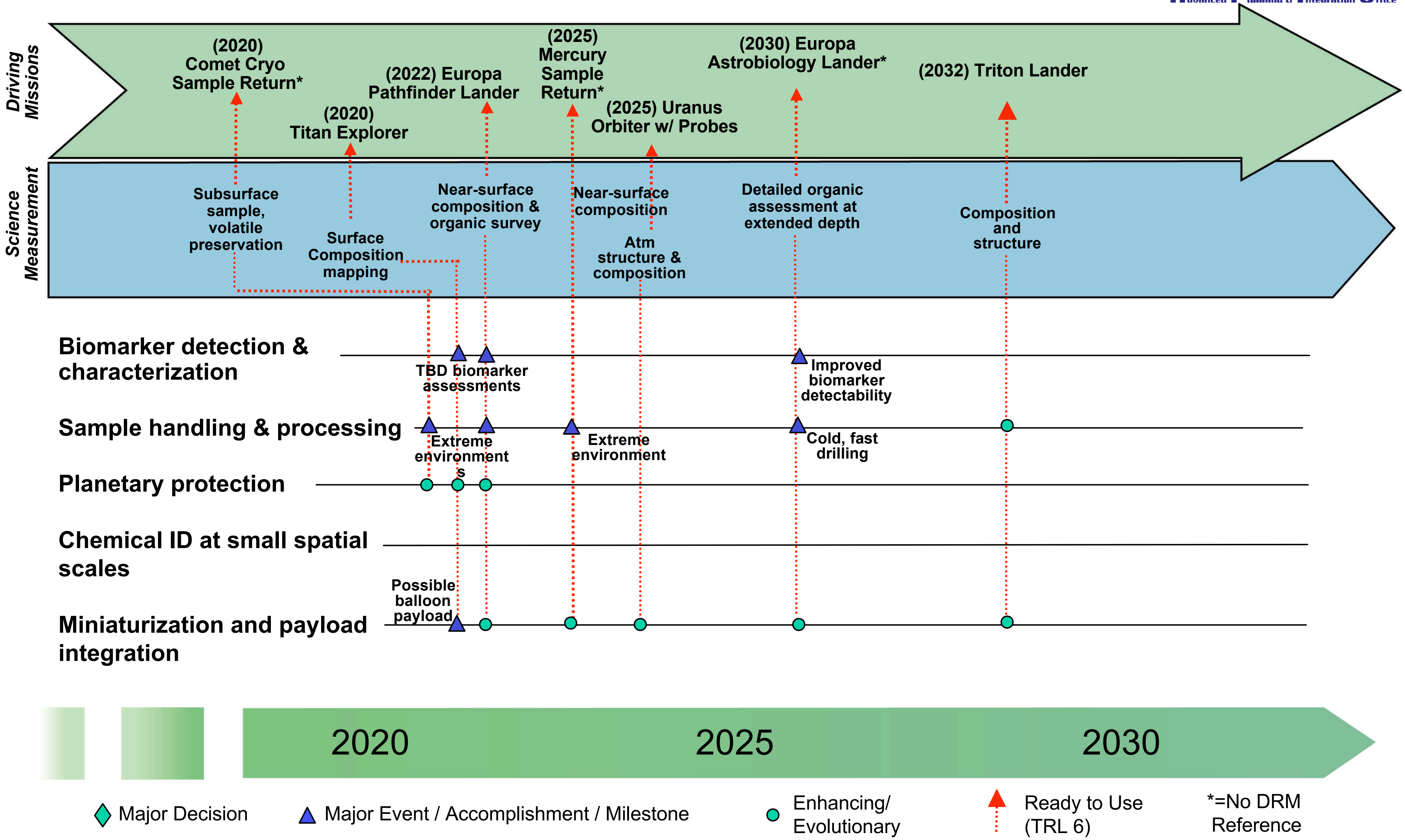
Capability 12.6 In-Situ Instrumentation Near Term Roadmap

Advanced Planning & Integration Office



Capability 12.6 In-Situ Instrumentation Far Term Roadmap

Advanced Planning & Integration Office



12.6 Capability Maturity Assessment

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

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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

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- **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

Advanced Planning & Integration Office

- 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.

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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

	* 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)

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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)

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
Interstellar 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

Advanced Planning & Integration Office

- 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

- 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

Advanced Planning & Integration Office

- 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

- 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