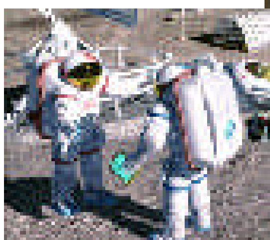
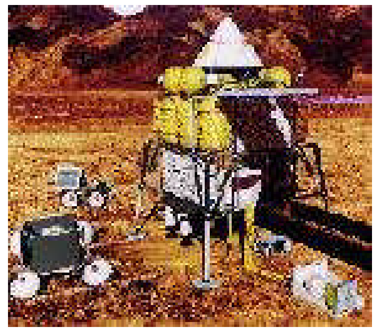
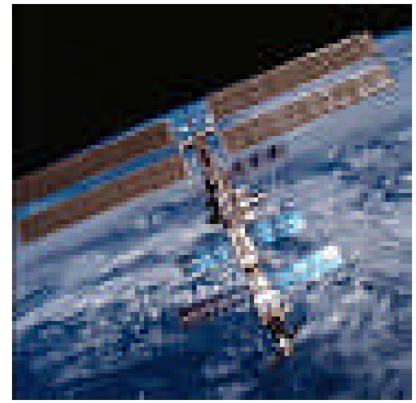
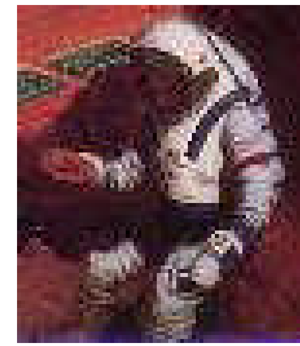
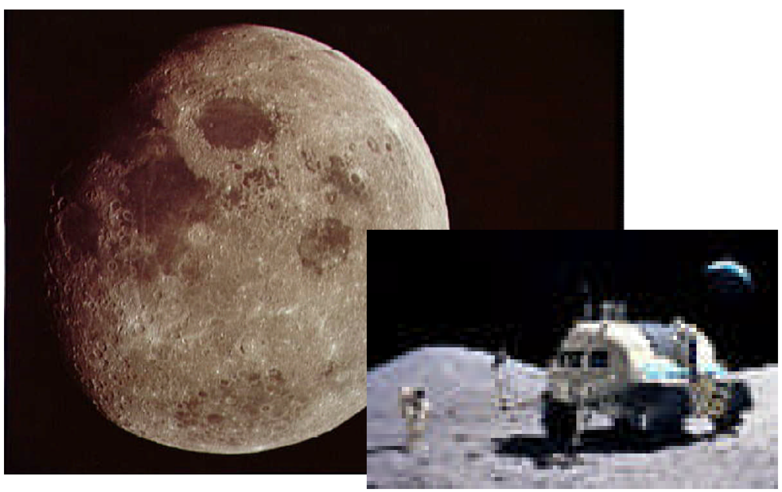
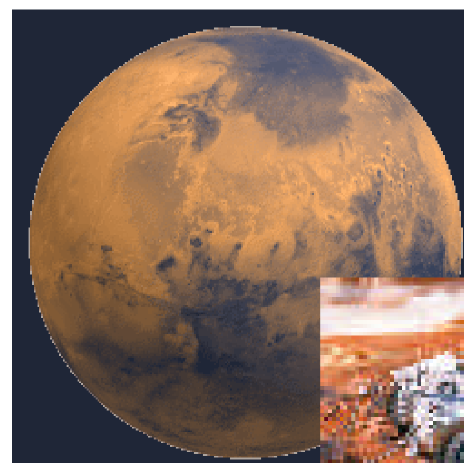
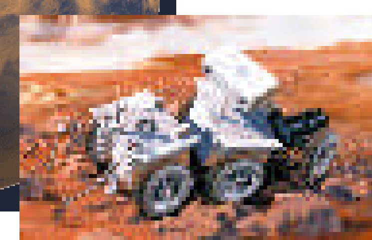
Capability 9.1
Exploration

Presenters: Rick Eckelkamp, Team Coordinator
Jim Blacic

9.1 Exploration Activities



Exploration Challenge

- To build an efficient, cost effective exploration infrastructure,
- To coordinate exploration robots & crews from multiple earth sites to accomplish science and exploration objectives, and
- To maximize self-sufficiency of the lunar/planetary exploration team.

Exploration Challenge Focused

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- The challenge is to preserve exploration and science participation by essential Earth-based personnel within the new context of an operationally efficient, crew-centered system.

- Efficiency and safety concerns dictate heavy use of automation and robots working in cooperation with humans.

- This summary pitch and the appendix material outline the capabilities required to accomplish these objectives.

Capability Breakdown Structure
9.1 Exploration

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9.1
Exploration Activities

- **9.1.1** Physical Access to Exploration Targets
- **9.1.2** Observation
- **9.1.3** Analysis
- **9.1.4** Operate
- **9.1.5** Command and Control Information

More details for all sections are given in the Appendix

Drivers/Assumptions for Exploration

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- Lunar missions will develop the capabilities to send humans to Mars (hence must be of long duration, > 6 months)
- Scientific exploration will require:
  - Advanced sampling techniques (surface and subsurface)
  - Analytical capability available on the Moon and Mars
  - Global access
- Power will be readily available (100s of KW available to bases)
- Communications – very high bandwidth will be provided at least locally
- Crew will need rapid access to large databases for both exploration and maintenance
- Robotic devices must be capable of significant autonomous operation
- Environment protection will be available for radiation (including solar flares), dust, and other environmental hazards on the Moon and Mars

Exploration Activities
Themes and Goals

- This sub-team treats three integrated themes:
  – What are the required elements/tools of lunar/planetary field science and field exploration? (9.1 - 9.3)
  – What kind of operational issues need to be addressed for exploration efforts? (9.4)
  – What are the associated elements of a command and control system? (9.5)

- Exploration Sub-team Goals:
  – Identify specific capabilities (hardware, software, techniques, and processes) that must be developed to achieve successful exploration.
  – Outline operations trades to accomplish exploration in an efficient and affordable manner.

Exploration Mission Evolution Flow

Earth-based control of multiple reconnaissance robots

Earth-based control of teams of infrastructure-building robots

Astronauts arrive and work in cooperation with robots.

- Building infrastructures
- Exploring
- (Astronauts' stays start with days; then, proceed to months)

The surface base comes online.

Remote site sorties begin, supported by surface base.

Exploration Activities Context

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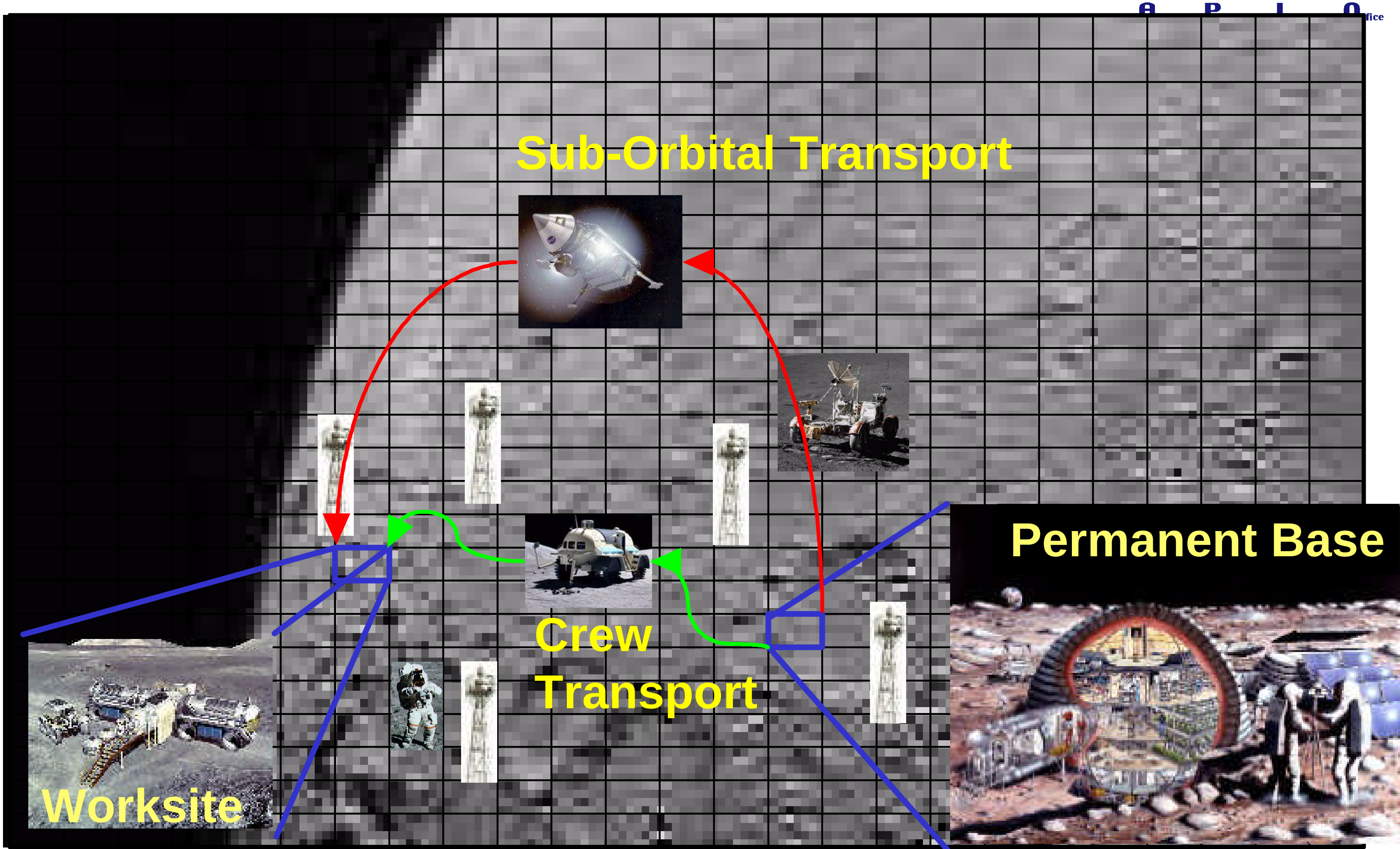
- The Capabilities presented herein are in the context of conducting lunar/planetary remote work missions with the following profile:
  - Earth-based operations performing strategic planning and on-call in-depth failure and contingency analysis
  - A permanent lunar/planetary base staffed with a large crew performing surface and remote site support functions
  - Field EVA personnel performing tasks at one or more remote sites
    - 3-4 crew per site, staying for up to two weeks
    - Remote crew housed in pressurized crew mobile unit with normal background radiation protection (rapid surface transport & early warning high radiation warning system assumed)
    - Substantial highly-automated operational capabilities in addition to rovers and robotic assistants
    - Automated mobile units can be sent to an unstaffed site ahead of the crew
    - Crew arrival via high-speed transport
- Missions are assumed to be as self-sufficient as possible.
  - Lunar Missions Operations are analogues for Mars Mission Operations

Exploration Mission Context



Summary of Strong needs for Surface Exploration

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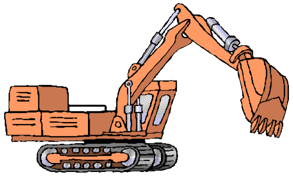
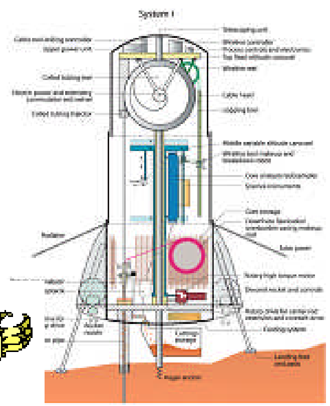
Capabilities in most need of development:



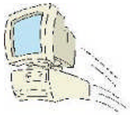
- Early teleoperated or equivalent machine(s) to construct large trenches for habitat “cut and cover” and to move dirt in general



- Drilling and subsurface sampling at depths beyond 1 m
- Other advanced planetary science tools and techniques

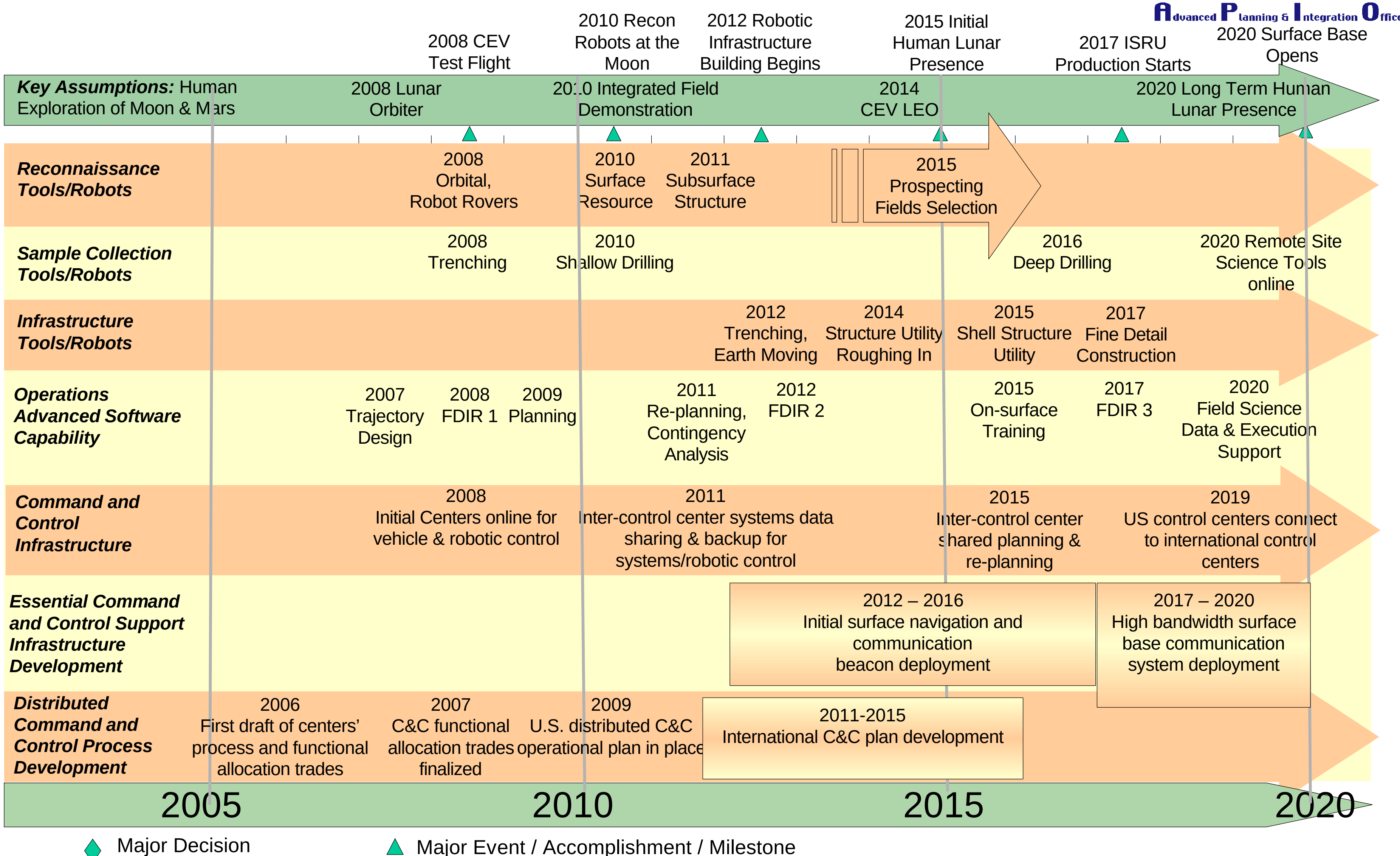
- Multi-sensor field exploration robots, human assistant robots, and other construction robots

- Robust space-qualified computers and advanced operational software



- <u>Robust human exploration operations control architecture</u>

9.1 Exploration Summary Roadmap



Explorations Cost Advisory: NASA Programs' Budget History

- Due to yearly budget pressures, NASA has historically concentrated mostly on vehicle hardware development and low initial costs.

- The focus has not been on providing efficient operational systems that would lower total lifetime costs.

- As a result, high operations costs have prevented NASA from sponsoring many worthwhile programs.

- A sustainable exploration program should allocate funds from the onset to develop an efficient operational exploration system.

- Besides saving money, an efficient operational system will be essential for Mars operations.

Additional Detail 9.1 Exploration

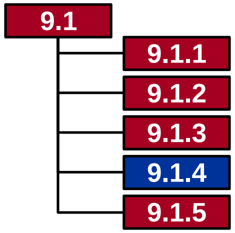
9.1.4
Operate

- 9.1 Exploration Activities
  - 9.1.4 Operate
    - 9.1.4.1 Plan/Re-Plan
    - 9.1.4.2 Setup/Teardown
    - 9.1.4.3 Train
    - 9.1.4.4 Perform
    - 9.1.4.5 Recover
    - 9.1.4.6 Maintain
    - 9.1.4.7 Document

9.1.4 Operate

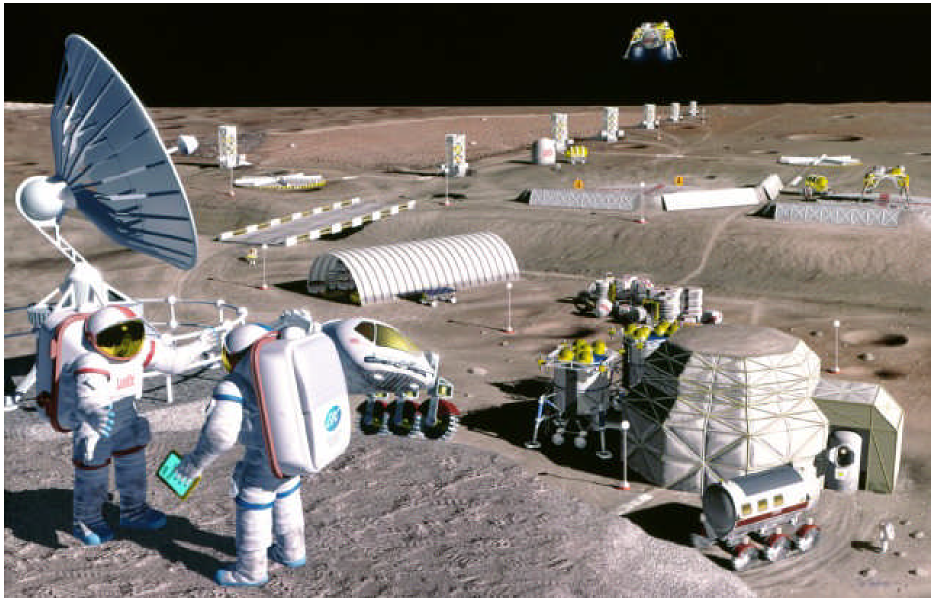
- **<u>Description</u>:**
  - "Operate" is the full-life cycle of an activity from concept to close-out for Assembly, Science and Exploration.

- **The crew performs Exploration Activities to;**
  - Study geologic features
  - Explore for resources
  - Install scientific equipment
  - Conduct engineering activities
  - Explore the environment



9.1.4 Operate

- **The Crew/System must operate these activities in a self-sufficient manner**
  - Plan/Replan
  - Setup/Teardown
  - Train
  - Perform
  - Recover
  - Maintain
  - Document



9.1.4.1
Plan/Replan (Surface IVA/Earth)

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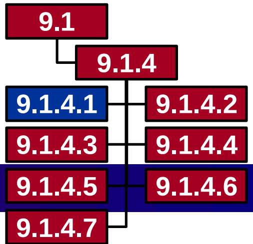
- **Description**:
  - Define missions, suites of activities
  - Perform pre-mission contingency analyses
  - Construct trajectory profiles, activity timelines, automated process scripts, supporting data
  - ***Examples***:
    - On-board crew activity scheduler/resource planner
    - Robotic failure contingency planning

- **Benefits**:
  - Ability to manage activities against limited resources (power, time, consumables, etc).
  - Identify significant contingent plans (strategic/tactical)

- **Figures of Merit**:
  - number of crew tasks done in a work day; rate of resource use; number of planning personnel

- **General Assessment**:
  - Mostly manual processes requiring many personnel; no off-earth capability; promising partial prototypes exist

- **Development Required**: Medium



9.1.4.2
Setup/Teardown (EVA/IVA)

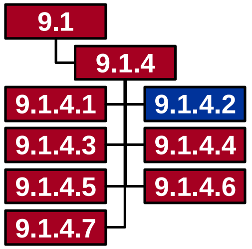
- **<u>Description</u>**:
  - Identify areas of exploration
  - Deploy tools/support equipment and consumables
  - Tear-down and retrieve equipment, pack samples
  - ***<u>Examples</u>***:
    - Deploy navigation/communications surface beacons
    - Robots prepare in-space EVA site before crew egresses
    - Robotic planetary surface reconnaissance

- **<u>Benefits</u>**:
  - Timely preparation for exploration activities, use of robots increases crew EVA efficiency

- **<u>Figures of Merit</u>:**
  - Amount of crew EVA time and resources needed, number of parallel activities accomplished per unit time

- **<u>General Assessment</u>:**
  - Some planetary & ISS robotic successes, more progress needed in robot autonomous activity control

- **<u>Development Required</u>**: **Medium**



9.1.4.3
Train (IVA/Earth)

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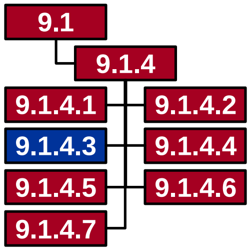
- **Description**:
  - Preparing for an activity by practicing activities using equipment and/or computer models, virtual reality (VR), etc.
  - ***Examples***:
    - **On-board “just-in-time” training for science activities**
    - **Planetary surface system refresher training**
    - **Human tele-robotic robot training**
    - **Inter-robot task training transfer**

- **Benefits**:
  - Ability to familiarize the crew with work processes and practices, efficient training of robots

- **Figures of Merit:**
  - Time required to train crew and robots, ability to field new equipment & experiments without requiring crew training on Earth

- **General Assessment:**
  - 1&2) NSTS & ISS have some onboard training devices; ground-based VR training exists; 3) tele-robot training used in some industries; 4) robot-to-robot training in experimental stage



- **Development Required: 1 & 2 – Low; 3 & 4 - Medium**

9.1.4.4
Perform (EVA/IVA)

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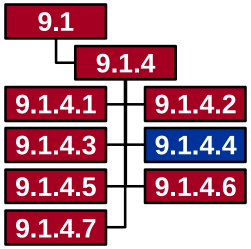
- **Description**:
  - To perform the activity that has been planned
  - Crew or robots using a repertoire of software aids, hardware tools, and vehicles
  - ***Examples***:
    - Automatic execution of scripted robotic activity plans
    - Surface-based resource planner
    - Crew Situational Awareness System
    - Robust data access systems for the EVA crew

- **Benefits**:
  - Actual achievement of science and exploration goals

- **Figures of Merit:**
  - Time to achieve activity completion per task; ability to manage multiple tasks at the same time; situational understand of the Crew about the activity; safety of the Crew during EVA/IVA

- **General Assessment:**
  - Tightly managed schedules and processes for most activities, Single sequential activities are the norm. Situational Awareness and Multi-modal interfaces limited.

- **Development Required**: Medium



9.1.4.5
Recover (EVA/IVA)

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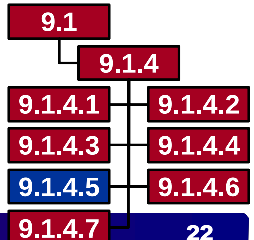
- **<u>Description</u>**:
  - To be able to adapt to a change in the activity or equipment status
  - To be able to implement backup/contigencies in a time-critical fashion
  - *<u>Examples</u>*:
    - Human and system health monitoring, fault detection, and reconfiguration
    - Invocation of contingent plans
- **<u>Benefits</u>**:
  - To continue an activity in the presence of changing requirements, system health, and environmental conditions.
  - Identify significant contingent plans (tactical/immediate)
  - Improves safety to systems and crew
- **<u>Figures of Meri</u>**t:
  - Time to diagnose a problem, and modify plan accordingly
- **<u>General Assessment</u>**:
  - After-the-fact analysis is very robust; Real-Time Systems Health Management is limited by the on-board sensing capability (weight and power concerns). Caution and warning events require human expertise to resolve. Inflexible recovery schemes (typically scripted failover to backups).
- **<u>Development Required</u>**: **High**



9.1.4.6
Maintain (EVA/IVA)

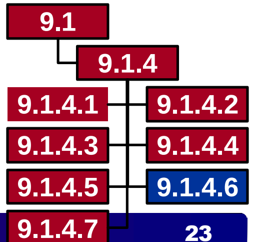
- **<u>Description</u>:**
  - To perform needed support, reconfiguration or repairs
  - ***<u>Example</u>*:**
    - On-line documentation, procedures, manuals, videos
    - Embedded sensors for health management

- **<u>Benefits</u>:**
  - Ability to repair a defective system in-the-field
  - Reduced maintenance costs through adoption of condition-based maintenance policies
  - Faster turnaround of reusable systems

- **<u>Figures of Merit</u>:**
  - System down time; logistics required to maintain operations; Human intervention time required; # of replacements vs repairs required

- **<u>General Assessment</u>: Informed Logistics:**
  - Limited built-in troubleshooting aids in components and subsystems.
  - Condition-based maintenance (instead of fixed schedules) gaining ground in DoD and commercial aviation.
  - Early investigations into prognostics (notably JSF and 777).

- **<u>Development Required</u>: High**



9.1.4.7
Document (EVA/IVA)

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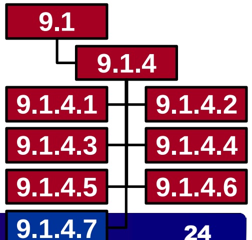
- **Description:**
  - To capture and record the results of activities that are occuring (or have occurred)
  - ***Examples*:**
    - Automated Audio/visual capture and information linkage of Crew state and samples
    - Intelligent telemetry documentation
    - Spoken language recording/recognition

- **Benefits**:
  - Ability to share the Full context and record of all scientific and explorations activities; Ability for the Crew to stop and restart activities efficiently

- **Figures of Merit:**
  - % of the information and context recorded for every Exploration activity; time needed to understand what occurred in the activity by a 3rd party

- **General Assessment:**
  - Current SOA in space is recorded voice and video loops; manual digital pictures; Automated context recording systems are in initial development. Limited

- **Development Required**: Medium - High



Maturity Level –
Capabilities for 9.1.4 Operate

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Capability / Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.4.1 Plan/Re-Plan. *Key Tech: Crew-centered tactical planning and adaption*	Ground-based: Timeplanner, MAPGEN, SPIFE	*6*	An on-board capability to plan activities and schedules against resources / time	2005	2010	5
9.1.4.2 Setup/Teardown *Key: Automated construction and site preparation*	Automated Bulldozers, Unfolding tents	*3*	Cooperative automation assembling and constructing systems	2009	2014	2
9.1.4.3 Train *Key: Just-in-time training for Crew while in field*	ISS systems; Military systems	*5*	VR and Multimodal portable training syetem. Human factors	2008	2012	5
9.1.4.4 Perform *Key: Coordinated human automation interaction*	Hubble repair; N/A	*3*	EVA Crew and Robotics coordinating together and with ground on common tasks	2009	2014	2
9.1.4.5 Recover *Key: Systems being able to gracefully degrade and reconfigure*	Ground-based after the fact.	*5*	Prognostic and onboard diagnosis and health management	2007	2010	4
9.1.4.6 Maintain *Key: In-situ repair and support of systems*	RFID, and military	*5*	Design and Logistics for Maintenance and common parts	2007	2010	4
9.1.4.7 Document *Key: Automatically capturing the complete record of all Crew and system actions*	Video, and Audio clips	*5*	Focus at depth Volatile capture mechanism	2007	2012	4

9.1.5
Command and Control & Information

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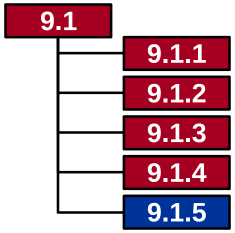
9.1
Exploration Activities

9.1.5
Command and Control & Information

9.1
9.1.1
9.1.2
9.1.3
9.1.4
9.1.5

9.1.5 Command and Control

- **<u>Description</u>**:
  - To control the timing and execution processes of exploration activities
  - Includes communication, procedural, software, and process methods
  - ***<u>Examples</u>***:
    - Lunar/planetary surface robot control
    - Communications reconfiguration
    - Sharing of exploration data among control centers
- **<u>Benefits</u>**:
  - Provides essential operational infrastructure that enables accomplishment of mission objectives
- **<u>Figures of Merit:</u>**
  - number of ground personnel required to:
    - control and plan operations and
    - maintain operational capabilities
  - cost per accomplished exploration objective
  - number of exploration objectives met
- **<u>Development Required</u>**: **Medium to HIGH**



Change is Necessary

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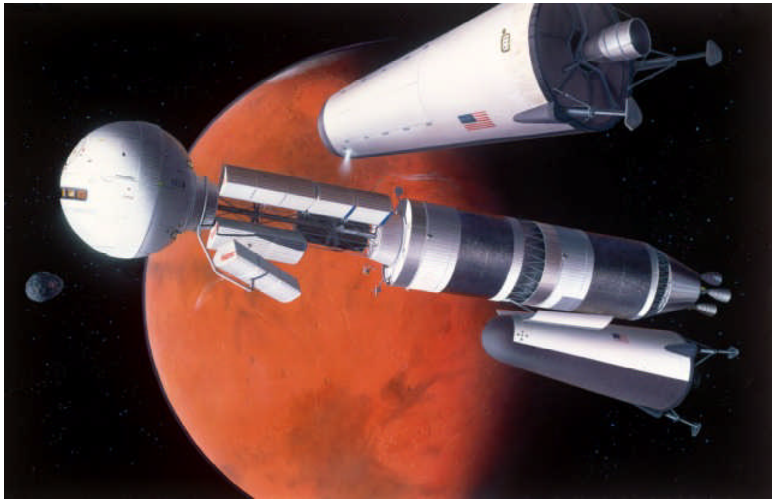
To have a successful and flourishing exploration program, we must make a "Earth-shaking change" in how we perform command and control.

- **From <u>ground-centered</u> control to <u>crew-centered</u> control**
- **"They that begin a program with a large marching army continue that program with a large marching army."**
- **Sheer economics and competition demand this change.**

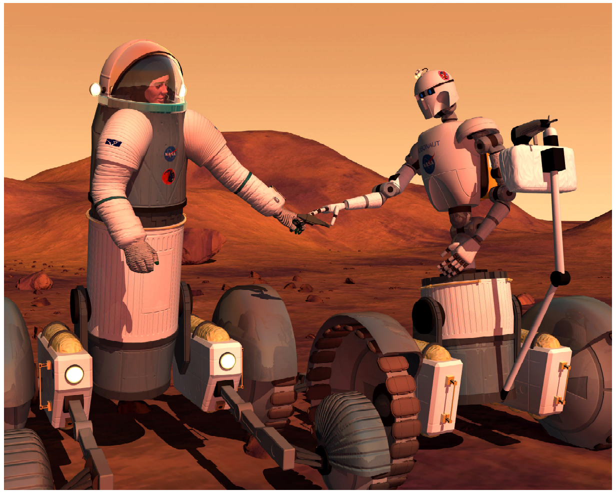
9.1.5 Command and Control

From today's ground-centered concept of Command and Control to a Crew-centered concept of Control



Mission Management Systems
- *Routine systems management*
- *Anomaly response and recovery*
- *Vehicle & mission level awareness*

Human-automation interaction
- *Adaptive decision support*
- *Situation awareness displays*
- *Crew Caution & Warning alerts*



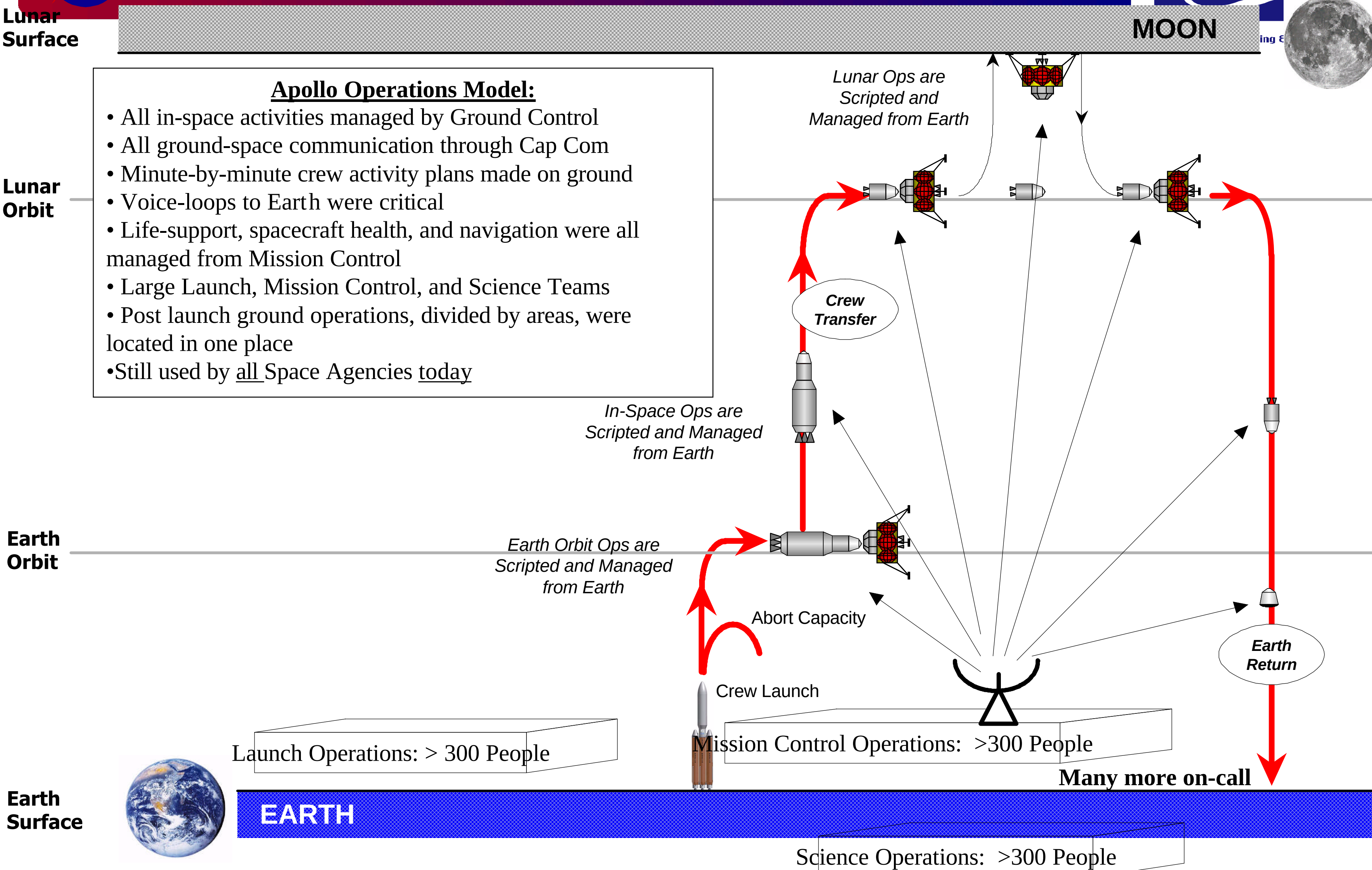
Robotic Systems Management
- *Human-machine multi-agent coordination*
- *Real-time activity planning and sequencing*

Networked Communication Infrastructure
- *Adaptable Communications to bring information to/from the Crew*

Apollo-Style Mission Operations

Apollo Operations Model:

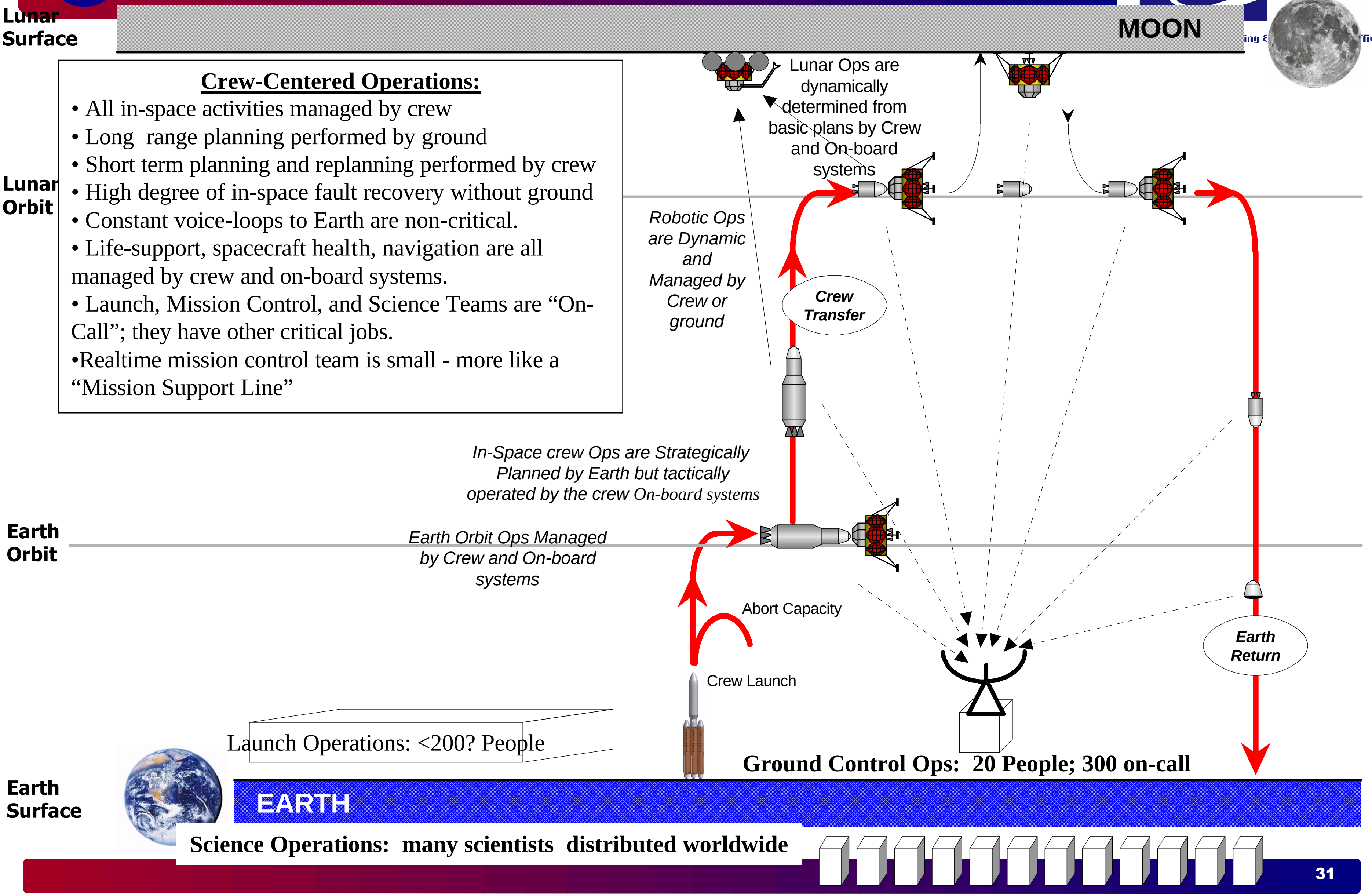
- All in-space activities managed by Ground Control
- All ground-space communication through Cap Com
- Minute-by-minute crew activity plans made on ground
- Voice-loops to Earth were critical
- Life-support, spacecraft health, and navigation were all managed from Mission Control
- Large Launch, Mission Control, and Science Teams
- Post launch ground operations, divided by areas, were located in one place
- Still used by all Space Agencies today



The Goal: Crew-Centered Operations

Crew-Centered Operations:

- All in-space activities managed by crew
- Long range planning performed by ground
- Short term planning and replanning performed by crew
- High degree of in-space fault recovery without ground
- Constant voice-loops to Earth are non-critical.
- Life-support, spacecraft health, navigation are all managed by crew and on-board systems.
- Launch, Mission Control, and Science Teams are “On-Call”; they have other critical jobs.
- Realtime mission control team is small - more like a “Mission Support Line”



Mission Control becomes Mission Support

Distributed ground-flight support is the communication lifeline between crew, robotics, and earthbound operations.

- **The crew needs to**
  - **Perform scientific and engineering activities, and**
  - **Be at the center of command and control activities**
  - **Manage in-space facilities**
  - **Manage deployment of scientific/engineering equipment**
- **The ground is the support to enable this to happen.**

Robotic Control

Robotic Control	Earth	Surface Base	Field
Telerobotic Commanding			
Single-Joint	Yes	Yes	Yes
Coordinated Multi-Joint	Yes	Yes	Yes
Scripted Control			
Hand-Built Script Writing	Prime	Backup	No
Training-Method Script Writing	Yes	Yes	Yes
Script Execution	Yes	Yes	Yes
Voice/Visual Commanding			
Single/Multi-Joint Commanding	No	Backup	Prime
Auto-Sequence Control	Backup	Shared	Shared
Higher-Level Task Initiation	Backup	Shared	Shared
Autonomous Operations Monitoring	Backup	Shared	Shared
Reconnaissance Robot Control			
Long Duration	Prime	Backup	No
Short Duration	Backup	Prime	Backup
Field Robot Crew Assistant Control	No	Backup	Prime

Crew Operations Support

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Crew Operations Support	Earth	Surface Base	Field
Activity Planning			
Yearly/Monthly Planning	Yes	No	No
Contingency Planning	Yes	No	No
Weekly Planning	No	Prime	Support
Daily Planning	No	Shared	Shared
Detailed Activity Schedule Building	No	Backup	Prime
Daily Activity Monitoring	No	Support	Prime
Systems Monitoring	On-Call Expertise	Support	Automated
System Failure Analysis and Reconfiguration	On-Call Expertise	First Aid	Support

9.1.5 Requirements for Efficient Operations/Control

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To accomplish efficient operations and control requires:

- Substantial advances in some areas of autonomous systems, robots, and robotic control,
- Development of methods to perform crew-centered and integrated robot-human operations, and
- Space communications and computer structures that enable multiple Earth-based control centers to:
  - control lunar/planetary robots,
  - perform inter-center voice, data, and video exchanges
  - perform integrated command and control of in-transit and lunar/planetary operations.

Maturity Levels for Command and Control

Capability/ Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
Order of magnitude faster computers	1800+ MIPS rad. hardened	5	Space qualify, upgradeable	2007	2009	4
Large distributed data bases	Exist today	9	Populate with exploration data	n/a	2011	5
100 MBPS space comm link	1 MBPS	2	Space qualify, upgradeable	2012	2015	2
Web-based/similar space network	Earth equivalent exists totoday	4	Space qualify, upgradeable	2009	2012	3
Inter-control center voice, data, video	Essentials in-place today	8	Upgrade protocols	n/a	2008	5
Exploration Vehicle autonomous nav	NSTS rendezvous, Apollo TL-TE optical, ISS GPS, grnd-based STDN	4	Lunar/planetary surface & orbital nav, TLTE/TP onboard nav	2008-2012	2010-15	3 4
Advances in ground-based robotic control	ISS rudimentary, Robonaut demo, MER control	2	Fast comm link, time delay abatement s/w	2008	2010	3
Autonomous FDIR	NSTS, various fighter jets, deep-space probes, Freedom ISE	4	Inter-system FDIR, AI trend analysis advances	2008-2012	2010-15	3 4

9.1
Exploration Activities

Advanced Planning & Integration Office

- **9.1 Exploration Activities**
  - **9.1.1 Physical Access to Exploration Targets**
  - **9.1.2 Observation**
  - **9.1.3 Analysis**
  - **9.1.4 Operate**
  - **9.1.5 Command and Control Information**

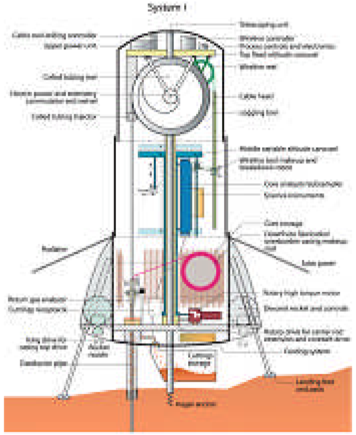
More details for all sections are given in the Appendix

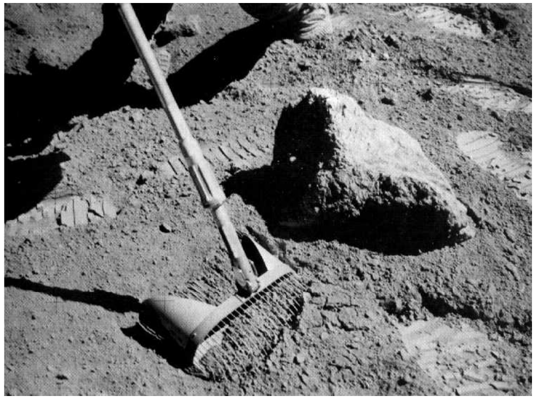
9.1.1Physical Access to Exploration Targets

Advanced Planning & Integration Office

9.1
Exploration Activities

9.1.1
Physical Access to
Exploration Targets





9.1.1.1
Sample Collection

9.1.1.2
Trenching

9.1.1.3
Drilling

9.1
- 9.1.1
- 9.1.2
- 9.1.3
- 9.1.4
- 9.1.5

9.1.1 PHYSICAL ACCESS TO XPLORATION TARGETS

9.1.1.1 Sampling

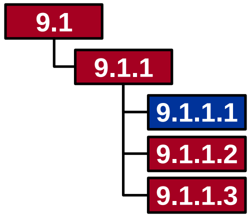
Description – Physical acquisition of planetary solid, liquid or gaseous materials for scientific/engineering characterization or ISRU assessment

Benefits – Enables more accurate, precise and complete characterization of planetary materials than can be done in the field or *in situ*. Creates archive for future study by a larger body of investigators

FOM – Mass, volume, degree of contamination

General Assessment – solid sampling is adequate; gas/liquid technology is inadequate

Development Needed -- Medium



9.1.1.2 Trenching

Description – Removal of planetary solid material to produce a linear space with vertical or sloping faces that exposes the subsurface for

a) sampling or *in situ* observation
b) placement of habitat modules
c) placement of utility conduits

Benefits – Exposes near-surface planetary materials for scientific investigations. Enables mass-efficient shielding of habitats or utility conduits by "cut and cover"

FOM – length, width, depth; time to construct

General Assessment – shallow trenching is adequate; deeper/longer trenching is inadequate

Development Needed -- a) Medium; b) High; c) Medium

9.1.1 PHYSICAL ACCESS TO EXPLORATION TARGETS

9.1.1.3 Drilling

<u>Description</u> – Removal of planetary solid material to produce a cylindrical hole and core of material. Used for depths beyond the capability of trenching.

- a) *Near-surface*: 10-100 cm in loose soils and 1-10 cm in hard rock
- b) *Shallow*: 10 cm – 10 m in all rock types
- c) *Intermediate*: 10 m- ~300 m in all rock types
- d) *Deep*: Beyond ~ 300 m in all rock types

<u>Benefits</u> – Exposes the planetary subsurface for scientific investigations and discovery; production of resources such as ground water

<u>FOM</u> – % retrieval of cuttings or core; degree of contamination

<u>General Assessment</u> – a) & b) prototypes under development; c) & d) = TRL 1

<u>Development Needed</u> --a) = Low; b) = Med; c) = High; d) = High

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9.1.1
Physical Access to Exploration Targets

Advanced Planning & Integration Office

Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.1.1 Sampling						
(a) Solid (regolith) *Key: sealing; cryogenic sample handling*	Apollo Viking	*9*	Retain volatiles; top-most layer of surface	-	2008	7
(b) Liquid (ground water) *Key: Well completion*	Terres-trial	*1*	Natural-state acquisition / handling;	2015	2030	0
(c) Gas (volatiles, atmosphere) *Key: GCMS, sealed sample container*	Viking	*4,2*	Natural-state acquisition / Handling	2008	2012	6
9.1.1.2 Trenching						
(a) Sampling Trench *Key: Scooping tools*	Apollo Viking MER	*9*		-	2008	7
(b) Habitat Trench *Key: Big “back hoe”, explosives*	Terres-trial	*2,2*	Equipment development; explosives technique/materials development	2012	2015	0

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9.1.1
Physical Access to Exploration Targets

Advanced Planning & Integration Office

Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
(c) Utility Trench *Key: Powered trencher*	Terr.	*2*	Equipment development	2012	2015	0
9.1.1.3 Drilling						
(a) Near-surface *Key: Very small coring drill*	Proto	*3*	Prototype testing in relevant environment	2008	2010	2
(b) Shallow *Key: Small drill, core capture*	Lab	*3,3*	Prototype testing in relevant environment; core acquisition development	2007	2012	2
(c) Intermediate *Key: Medium drill, core capture*	Terr.	*2,2*	Prototype development and testing	2010	2017	0
(d) Deep *Key: Big drill, core capture, hole completion*	Terr.	2,2,2	Prototype development and testing; well completion development	2018	2025	0

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Advanced Planning & Integration Office

9.1
Exploration Activities

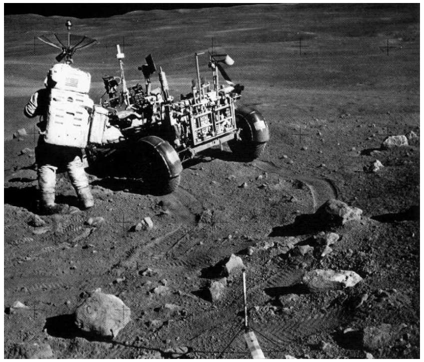
9.1.2
Observation

9.1.2.1
Orbital/Aerial Remote Sensing

9.1.2.2
Surface Sensing

9.1.2.3
Subsurface Remote Sensing

9.1.2.4
Surface Outward Observation



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9.1.2 OBSERVATION

Advanced Planning & Integration Office

9.1.2.1 Orbital /Aerial Remote Sensing

Descriptions -- a) Orbital: planet-wide imaging and sensing of composition, topography, gravity field, magnetic field; b) Suborbital/aerial: Imaging, composition & topography

Benefits – Determine elemental and mineralogic compositions, topography, geophysical fields; enable site evaluations and surface route planning

FOM – % of major/minor rock-forming elements; accuracy; precision; spatial resolution

General Assessment – Current flight instruments generally adequate; improvements in accuracy/precision and spatial resolution needed; suborbital/aerial platforms needed

Development Needed -- a) Low; b) High

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Advanced Planning & Integration Office

9.1.2.2 Surface Sensing

9.1.2.2.1 Direct Contact

Description – Placement of sensors and/or interrogation energy sources directly in contact with soil or rock surface

- ***Passive*: natural energy emanated or reflected from surface and measured in contact; e.g., natural g radiation spectrometer**
- ***Active*: artificial energy introduced to surface material by contact to produce a characteristic signal measured in contact; e.g., Mossbauer spectrometer**

Benefits – Maximizes the accuracy and precision of measurement location; minimizes the effects of intervening medium such as an atmosphere; allows more time for signal integration compared to orbital/aerial

FOM – Accuracy/precision of major rock-forming elements

General Assessment -- Existing flight instruments adequate; some improvement in accuracy and precision needed

Development Needed -- a) Low; b) Low

9.1.2 OBSERVATION

Advanced Planning & Integration Office

9.1.2.2 Surface Sensing

9.1.2.2.2 Stand-Off

Description – Placement of sensors and/or interrogation energy sources at some distance from the surface being interrogated

- ***Passive:*** **Natural energy emanated or reflected from surface and received at a distance; e.g., Vis/IR imaging spectrometer**
- ***Active:*** **Artificial energy transmitted to the surface material from a distance to produce a characteristic signal; e.g., laser-induced break-down spectrometer**

Benefits – Enables measurement at locations not directly accessible by contact, e.g., cliffs; enables simultaneous, contextual measurement of large areas from a single location

FOM – Accuracy/precision of major rock-forming elements

General Assessment -- Current passive flight instruments adequate; Active instruments inadequate

Development Needed -- a) Low; b) Medium

9.1.2.3.1 Sub-Surface Sensing Automated Image Processing

Advanced Planning & Integration Office

Description – Use automated techniques to recognize key surface features in voluminous photographic data sets and to interpolate or extrapolate surface features to probable location of key features below the surface:

- Example A: Exposed rock in steep crater walls shows regolith depth (and resources) that extend to surrounding subsurface areas
- Example B: Breached lava tubes (rilles / "skylights") locate intact sections under the surface (up to 300 m diameter; many km length)

Benefits

A) Automated location of exposed rock areas and mapping of expected regolith depth will assist plans to bury habitats (trenching).

B) Automated location of lava tubes (natural shelters from radiation, dust, heat, and cold) may avoid energy-intensive trenching operations

FOM – Depth and size of features mapped; accuracy of predictions

General Assessment -- Improves accuracy, consistency, cost (vs. human)

Development Needed -- Medium

9.1.2.3.2 Sub-Surface Sensing Radiation Interactions

Advanced Planning & Integration Office

Description – Assess sub-surface minerals by sensing secondary radiation (neutron, gamma ray/X-ray) from natural or artificial primary radiation interactions with subsurface material (up to ~ 1 meter depth).

Artificial radiation sources might potentially be integrated with radioisotope thermal generators (also used for electrical power or heat)

Benefits –

Neutron spectrometers on Lunar Prospector and Mars Observer located hydrogen and water which could have significant value for ISRU.

New instruments may allow rapid operation from a rover on the surface for precise mapping of resources for future human consumables (e.g., frozen H2O and other volatiles), and for propellant production.

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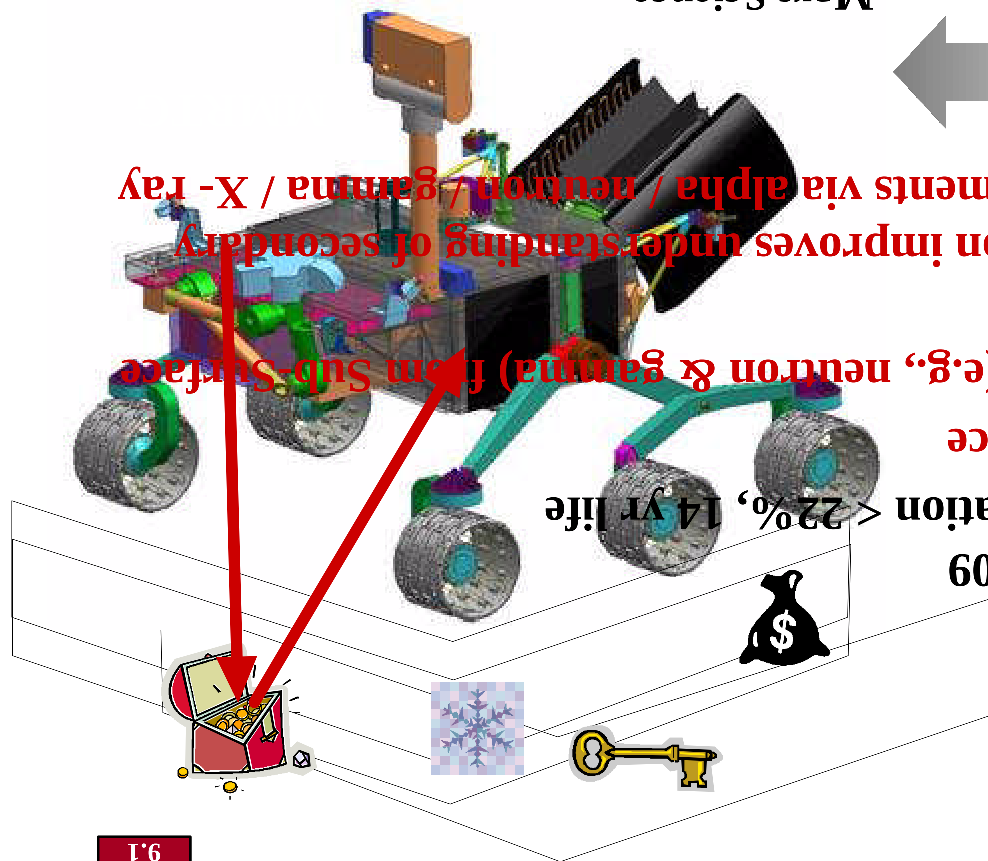
FOM – Depth of observation, energy required; accuracy & precision of data

General Assessment – Proven technique, integration with RTG is new

Development Needed -- Low

Sub-Surface Irradiation by "Multi-Mission Radioisotope Thermoelectric Generator"



Mars Science Laboratory (example use)

...2009

...adation < 22%, 14 yr life

...ource

...n (e.g., neutron & gamma) from Sub-Surface

...tion improves understanding of secondary

...elements via alpha / neutron / gamma / X- ray

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9.1.2.3.3 Sub-Surface Sensing Radar Observations

Advanced Planning & Integration Office

Description –Locate features and determine characteristics below the surface by illuminating areas of interest with radar. Radar may help locate key ISRU species (such as thick slabs of ice, which reflect circularly polarized radar with a high reverse circular polarization ratio)

A) Radar from Earth: High power, large apertures, long ranges (10^6 km)
B) Radar from Orbit: Intermediate power & aperture, Mid-range (10^2 km)
C) Radar on the surface: Low power, small aperture, short range (1 m)

Benefits –
A) Earth Radar finds ice in Mercury's polar craters (not yet on moon)
B) Orbital Radar (SAR) finds bedrock under dry soil, maybe metal ores (e.g., Chromite / Platinum Group Elements layers in impact melts)
C) Ground Penetrating Radar finds geotechnical features / strata

FOM – Depth of observation, energy required; accuracy & precision of data

General Assessment – Well characterized techniques

Development Needed -- low

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9.1.2.3.4 Sub-Surface Sensing Impact Observation (Ejecta)

Advanced Planning & Integration Office

Description – High velocity impact vaporizes material from below the surface, allowing spectroscopic observation to determine mineral content (like "LIBS", but with more energy):

A) Natural impacts (meteoroids)
B) Artificial impacts (penetrators, spacecraft components, explosions)

Benefits –Assesses minerals and resources for future human consumables (frozen H_2O and other volatiles) and propellant production

FOM –Knowledge of impact location, Energy used, Degree of contamination

General Assessment – Simple technique needs foresight and coordination

Development Needed -- low

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9.1.2.3.5 Sub-Surface Sensing Impact Sensing (Seismic)

Advanced Planning & Integration Office

Description – Network of seismic sensors to monitor and interpret surface waves following an impact / explosion on the surface or a "moonquake"

Use new "Spectral Analysis of Surface Waves" technique

Benefits –

- Improve prospects of physical access (e.g., avoid drilling into a subsurface boulder, with blocking and breaking of drill strings)
- Locate voids and deposits of lower density materials (e.g, natural caverns for shelter and condensed volatile deposits for ISRU)
- Potential to identify ice strata that record major comet impacts (and maybe even major Earth impacts) which brought water to the moon

FOM – Instrument mass, energy used; accuracy in lower density deposits

General Assessment -- Transfer geotechnical advances to spa ses

Development Needed -- Medium

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9.1.2.3.6 Sub-Surface Sensing Microwave Beam Interactions

Description –

- Generate and focus microwaves via a surface reflector to heat regolith at selected depth(s) (up to ~1 meter)
- Determine composition of released volatiles via spectroscopy (or capture on a cold plate / Quartz Crystal Microbalance)

Benefits –

- Assess location, extent and composition of volatile condensates important for ISRU (water, Argon, etc.) without requiring drilling (thereby reducing time, energy, mass, risk, etc.)
- Microwave beams may also assist in recovery of resources and to sinter lunar regolith and thereby create ISRU-derived structures

FOM – Depth, Instrument mass and energy needs; Accuracy of data

General Assessment – New technique, also beneficial for ISRU processes (suggested by L. Taylor) to sinter lunar regolith and create structures

Development Needed -- **HIGH**

9.1.2
Observation

Advanced Planning & Integration Office

Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.2.1 Orbital/Aerial Remote Sensing						
9.1.2.1.1 Orbital *Key: Hi-res instruments*	Mars Odyssey	*9*	Higher spatial resolution	-	2008	7
9.1.2.1.2 Suborbital/aerial *Key: Hi-res instruments*	Military UAV	*2*	Higher spatial resolution; vehicle development	2008	2012	0
9.1.2.2 Surface Sensing *Key: Specific instruments*		1-9		Variable	2008	1-6
9.1.2.2.1 Direct Contact (a) Passive *Key: Neutron spectrometer, g spectrometer*	Apollo; Robotic Landers	*9,9*	Higher data integration rate; higher accuracy/ precision	-	2008	6
(b) Active *Key: APXS, Mossbauer spectrometer*	MER	*9,9*	Higher data integration rate; higher accuracy/ precision	-	2008	6

9.1.2 OBSERVATION

Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.2.2.2 Stand-off **(a) Passive** ***Key: Vis-IR imaging spectrometer***	**Mars Odyssey,** **CRISM**	***9***	**Higher data integration rate; higher accuracy/ precision**	**-**	**2008**	**6**
(b) Active ***Key: LIBS***	**LANL LIBS**	***3***	**Flight prototype development**	**2005**	**2008**	**2**

9.1.2.3 SUB-SURFACE OBSERVATION

Advanced Planning & Integration Office

Capability	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.2.3.1 Auto. Image Process. *Key: Recognize surface features and extrapolate/interpolate*	CalTech JARTool; +human	*5*	Interpolate surface data to subsurface	-x	2008	7
9.1.2.3.2 Radiation Interaction *Key: Integration with powerful external radiation sources*	Neutron Detectors: MO&Lunar Prospector	*9*	Accelerate data rate via radiation Source integrated with Power/ Heat	-x	2008	7
9.1.2.3.3 Radar Observations *Key: Short wavelength circularly polarized for thin ice*	Arecibo & Goldstone	*9*	Higher spatial resolution; Access shadows	2008	2012	7
9.1.2.3.4 Impact Observation *Key: Coordinated observation during impact events*	"Deep Impact" mission	*7*	Coordination with astronomy and Japan's Lunar-A	x	2008	1-6
9.1.2.3.5 Impact Sensing *Key: Spectral Analysis of Surface Waves*	Geo-tech uses	*9*	Coordination with astronomy and Japan's Lunar-A	x	x	x
9.1.2.3.6 Microwave Beam *Key: Focus at depth, assessment (capture?) of volatiles*	Ovens on Earth	*4*	Focus at depth Volatile capture mechanism	-x	2008	6

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9.1.2.4 Platform Observations

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Description:

- The lack of a sensible atmosphere, the extreme stability of the surface, the low (but not too low) gravity, and the nature of its rotation make the lunar surface very useful for observations of objects or phenomena not associated with the Moon itself.
- Targets of Observations
  - The Universe
  - The Earth
  - The Sun
  - The space environment and phenomena in the Earth-Moon or Sun-Earth system such as interactions of the solar wind with the geomagnetic field.
  - Various experiments in the fields of physics and biology carried out in special facilities
- These functions may not be primary objectives for Exploration but would become attractive scientific investments as lunar surface capabilities and resources become available.
- The instruments would, for the most part, be described as telescopes in the sense that they would enable observations of distant phenomena.

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Advantages of Moon for Astronomy

Advanced Planning & Integration Office

- Ultra-high vacuum- effectively no atmosphere
  - Perfect transmittance; diffraction-limited imaging
  - Dark sky - no scattered light allowing daytime as well as nighttime observing and observing close to the Sun in the sky
  - Cold sky everywhere and very cold surface environments in certain crates with permanent shadowing, allowing radiative cooling of telescopes
  - No wind, allowing simple sunshades and lightweight structures
- High lunar mass
  - Enormous moment of inertia permits smooth tracking and easy pointing
  - Low but sensible gravity
    - No co-orbiting debris as with spacecraft
    - Dropped tools and parts easily retrieved; favorable work environment compared to zero-g
  - Mass of the Moon shields farside radiotelescopes from Earth “noise”
    - The farside is the only place in the solar system shielded from Earth interference
- Slow sidereal rate
  - Sky sources available continuously for 14 days
    - Long-uninterrupted observation of variable phenomena
    - Long sensor integration times for faint sources
- Very large-scale instruments may be feasible only on the Moon
  - Giant filled-aperture telescopes
  - Large baseline interferometers
  - Farside radio receiver arrays with large areal expanse

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Disadvantages of Moon for Astronomy
(As seen by scientific community)

Advanced Planning & Integration Office

- Expensive to operate human-tended or -emplaced observatories
  - Robotic soft landers cheaper overall although less capable
  - Dedicated human mission for observatory requires development of robotic cargo lander
  - Telescope itself is an expensive instrument (compared to freeflyer)
- Lack of solar power during lunar night
  - Energy storage solutions for lunar night have large mass (e.g., batteries)
  - Nuclear solutions required
    - RTG for small telescope
    - Reactor for large facility
- High radiation background - increased detector noise
- Day-night cycle limits efficiency of single observatory to 50% (compared to deep-space freeflyer)
  - If 100% of sky must be available 100% of time, 2 observatories required
  - Equatorial observatory sees whole sky but any single portion 50% of the time
  - Polar observatory sees 50% of the sky all the time
- Mobilized dust a concern for mirrors and moving parts over time

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Examples of Optical Observatory Instruments

Advanced Planning & Integration Office

9.1.2.4.1 Telescopes with Optical Elements (i.e., mirrors)

9.1.2.4.1.1 Large-Aperture UV/Optical/IR (UVOIR) Telescope
- Search for life and detection of Earth-like planets
- Formation & evolution of the early universe

9.1.2.4.1.2 IR and Sub-mm Interferometers
- Studies of forming and evolved extrasolar planetary systems
- Processes and structure of galactic nuclei and quasars

9.1.2.4.1.3 Optical Interferometer
- Imaging nearby stars
- Validating distance scales in the universe

9.1.2.4.1.4 2-Meter Class UVOIR Telescope for Solar System Studies
- Origin of the solar system
- Properties of small bodies, particularly in the Kuiper Belt
- Dedicated study of Mars with monitoring of atmospheric phenomena

9.1.2.4.1.5 Solar monitor facility
- Solar flare physics and prediction
- Solar interior through heleoseismology

9.1.2.4.1.6 Nearside Earth Synoptic Earth Observation Facility
- Continuous monitoring of planetary-scale phenomena
  - Global radiation budget including albedo variation
  - Global climate modeling
  - Geomagnetic storms and aurorae
- Continuous monitoring of LEO and GEO
- Earth surface observation and surveillance

Examples of Observatory Instruments Not Based on Standard Optics

Advanced Planning & Integration Office

9.1.2.4.2 Radio Telescopes

- Low-frequency observations not possible from Earth
- Long-baseline interferometer
- Shielding from terrestrial radio interference

9.1.2.4.3 Large-Aperture X-ray and Gamma-ray Telescopes

- Physics of neutron stars and black holes
- Stellar accretion disks

9.1.2.4.4 Solar-terrestrial physics facility

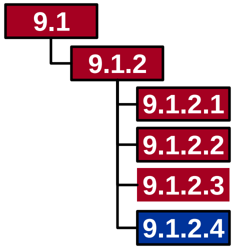
- Direct solar wind measurement
- Reconnection events in the geotail

9.1.2.4.5 Particle Physics, Cosmology, and Gravitational Waves

- Cosmic ray measurements
- Neutrino telescope
- Gravitational wave detector
- Moon-scale particle accelerator using ambient vacuum

Details and Benefits of 9.1.4.1: Optical Observatory Instruments

- *Description*: Much of the observation of other bodies from the Moon will be done at wavelengths ranging from ultraviolet to far infrared where telescopes having reflective optics can be used.
- *Examples*:
  - **Optical interferometer.**
  - **Nearside Earth Synoptic Earth Observation Facility.**
- *Benefits*: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate in synchronicity with its orbital velocity about the Earth. These characteristics are favorable for a variety of scientific observation and research.
- *FOM*: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
- *General Assessment*: Sophisticated instrumentation exists in terrestrial observatories and aboard robotic spacecraft. Instruments must be adapted for use in lunar setting. In some cases, this will be easy. In others, challenges exist to operate autonomously and continuously in the lunar environment.
- *Development needed*: LOW



Details and Benefits of 9.1.4.2: Radio Astronomy

Advanced Planning & Integration Office

- *Description*: Radiotelescopes and interferometers, particularly those operating at low frequencies can observe the universe in unique ways**.** Interferometers can be designed with elements on the Moon and on the Earth, providing baselines at solar system scales.
- *Examples*:
  - **Low-frequency radiotelescope.**
  - **Long-baseline Moon-Earth radio interferometer**.
- *Benefits*: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate in synchronicity with its orbital velocity about the Earth. The lunar farside is the only location in the solar system that is perfectly shielded from terrestrial interference. These characteristics are favorable for a variety of scientific observation and research.
- <u>*FOM*</u>: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
- *General Assessment*: Antenna design is a highly advanced art. Adaptation to lunar conditions should present few problems.
- *Development needed*: LOW

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Details and Benefits of 9.1.4.3: X-ray & Gamma-ray Telescopes

Advanced Planning & Integration Office

- *Description*: The lack of an atmosphere on the Moon allows observations of high energy photons using instruments with large throughput.
- *Examples*:
  - **X-ray radiotelescope.**
  - **Gamma-ray radiotelescope**.

- *Benefits*: The Moon is an airless body with an extremely stable surface and a slow sidereal rotation rate. The gravity field and extremely stable surface will permit construction of unique instruments for research into the high energies in the electromagnetic radiation from the universe.
- *FOM*: Angular resolution; detection sensitivity; available integration time; wide spectrum; environmental stability.
- *General Assessment*: The design of such telescopes is well understood, but the shipment and assembly of large apertures on the lunar surface will require careful operations. Adaptation to lunar conditions should present few problems.
- *Development needed*: MEDIUM

Details and Benefits of 9.1.4.4: Solar-terrestrial physics

- *Description*: The lack of an atmosphere on the Moon allows direct access to the solar wind. The Moon fortuitously sits at a distance where reconnection occurs in the Earth's magnetic geotail. Observations at radio frequencies and data from satellite constellations anchored to the Moon can provide 3-dimensional information on the interaction between the solar wind and the geomagnetic field.
- *Examples*:
  - **The European Cluster mission.**
- *Benefits*: Continuous, long-term observation of the Earth-Sun interactions will permit greater sophistication in modeling the effects of solar events on the Earth's magnetic field, ionosphere, and climate.
- <u>*FOM*</u>: Continuous monitoring; simultaneous in-situ measurements of the solar field at the Earth.
- *General Assessment*: The technology for making these observations is well in hand.
- *Development needed*: LOW

Details and Benefits of 9.1.4.5: High-energy Physics & Relativity

Advanced Planning & Integration Office

- *Description*: Gravity wave detectors, very large particle accelerators, neutrino telescopes, and cosmic ray measurements are some of the possibilities for advances in cosmology and high-energy physics using research facilities on the lunar surface.
- *Examples*:
  - **LIGO**.

- *Benefits*: The lunar surface vacuum and the extreme surface stability allow new designs for research in high-energy physics and relativity.
- *FOM*: Long-term observations; extreme environmental stability; ready availability of vacuum environment.
- *General Assessment*: Lunar research facilities in these fields of study may well take on new forms from similar facilities on Earth. The scale of the facilities may be a challenge.
- *Development needed*: MEDIUM

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9.1.4: Facilities for Observation from the Moon

Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.4.1 Optical Observatory Instruments						
(a) Telescope (reflective optics) *Key: sensor; optics; data processing; construction; operation*	Hubble	*6*	Adapt to lunar setting; integrate into lunar ops	2019	2025	
(b) Interferometric arrays *Key: Optical fiber networks; precision alignment*	Earth facilities	*5*	Space qualification; ops in lunar setting	2024	2030	
(c) *Key:*						
9.1.4.2 Radio Astronomy						
(a) Antenna design; data processing *Key: Frequency response; detector sensitivity; signal reconstruction*	Earth facilities; S/C comm	*6*		2019	2025	
(b) Interferometric arrays *Key: Element communication; timing precision; ops*	Earth facilities	*5*		2024	2030	

9.1.4: Facilities for Observation from the Moon

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Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.4.3 X-ray & Gamma-ray telescopes						
(a) Optics design; sensor development ***Key: sensor; optics; data processing; construction; operation***	**Chandra; Compton**	***6***	**Adapt to lunar setting; integrate into lunar ops**	**2019**	**2025**	
9.1.4.4 Solar-terrestrial physics						
(a) Solar telescope ***Key: Long-term, uninterrupted imaging of Sun***	**Earth facilities**	***6***	**Adapt to lunar setting; integrate into lunar ops**	**2019**	**2025**	
(b) Array of spacecraft monitoring of solar wind interactions ***Key: Orbital coordination; communication; operations***	**CLUSTER**	***7***	Mission design	**2019**	**2025**	
9.1.4.5 High-energy Physics & Cosmology						
(a) Various research facilities ***Key: Innovative utilization of lunar environment; use of lunar mass (e.g., shielding and neutrino detection)***	**Earth facilities**	5	Facility concept and design; construction on Moon	2029	2035	

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- **9.1 Exploration Activities**
  - **9.1.3 Analysis**
    - 9.1.3.1 InSitu Analysis
    - 9.1.3.2 Analysis at Base
    - 9.1.3.3 Sample Curation
    - 9.1.3.4 Sample Transport to Earth

- 9.1
  - 9.1.1
  - 9.1.2
  - 9.1.3
  - 9.1.4
  - 9.1.5

Description of 9.1.3: Tools of Measurement & Observation

Description:

- Scientific investigations on the lunar surface will require some sort of measurement or characterization of lunar materials.
- Some observations or characterizations can be done on materials where they are found using robotic and/or human observers.
- Some observations are too complex or require too much time for in situ analysis and must be done at the base on selected samples.
- A limited number of special samples will be returned to Earth for curation by NASA and study by scientists around the world. These returned samples must be handled and documented by special procedures in accordance with NASA policy. :

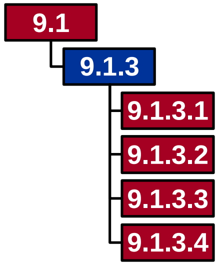
Major categories of activity are the following:

9.1.3.1 In Situ Analysis

9.1.3.2 Analysis at Base

9.1.3.3 Sample Curation

9.1.3.4 Sample transport to Earth



Details and Benefits of 9.1.3.1: In-Situ Analysis

- *Description*: Measurements and/or observations will be taken at a lunar surface site by teleoperated robots or human/robot field teams.
- *Examples*:
  - Spectral analysis of materials in a geologic formation
  - Measurement of soil compressibility with penetrometer
  - Documentation of geologic context of deposits or formations
- *Benefits*: Analysis tools built into a teleoperated robot allow reconnaissance for planning human traverses to a site of interest; acquire information for decisions in real time where spacesuit constraints limit the time available at the location.
- *FOM*: Ability to extract scientific information at high spatial resolution and high signal-to-noise from object of study; low mass, power, volume
- *General Assessment*: Instruments exist in laboratories and in flight-qualified form. Principal challenge is integration of sensors and data management in mobile platforms for lunar surface environment.
- *Development needed*: LOW

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Details and Benefits of 9.1.3.2: Sample Analysis at the Base

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- *Description*: In-situ analysis capability will be limited. Some samples deemed scientifically significant will require in-depth study. Analytical capability may be included at the base, subject to limits on mass, volume, technology, and crew time.
- *Examples*:
  - Optical microscopy of prepared geologic thin sections.
  - Elemental analysis by x-ray diffraction.
- *Benefits*: Lab environment permits sample preparation that is impossible in the field. Analysis at the base would facilitate planning scientific excursions, e.g., by allowing informed input by terrestrial support teams. It would provide information for selecting samples to be returned.
- <u>*FOM*</u>: Ability to extract information on chemical composition and physical state at submicroscopic dimensions high accuracy and sensitivity from a sample; low mass, power, volume
- *General Assessment*: Sophisticated instrumentation exists in terrestrial laboratories. Instruments must be adapted for use in lunar setting. In some cases, this will be easy. In others, challenges exist to reduce mass, power, and volume.
- *Development needed*: MEDIUM

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Details and Benefits of 9.1.3.3: Sample Curation

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- *Description*: Some samples will be determined to have sufficient scientific importance as to be preserved and returned to the Earth for study by the global scientific community (as are the Apollo samples and Antarctic meteorites collected by U.S. expeditions).
- *Examples*:
  - Identification in the field of candidate samples for curation
  - Documented collection of samples for potential curation
    - Establish geologic context through photography, orientation, and location (selenographic coordinates).
    - Appropriate packaging for transport to base
  - Bonded storage at the base under lunar environmental conditions for candidate return samples
  - Analytical capability and communication for consultation to decide which candidates should actually be returned
- *Benefits*: The scientific integrity of returned samples must be preserved through strict adherence to documented collection, storage, and packaging procedures.
- *FOM*: Peer-reviewed configuration control processes acceptable to the scientific community.
- *General Assessment*: Well understood. Must be incorporated into mission requirements.
- *Development needed*: LOW

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Details and Benefits of 9.1.3.4: Sample Transport to Earth

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- *Description*: While properly documented and executed procedures are necessary to maintain scientific integrity of returned samples, the containers and packaging are also important.
- *Examples*:
  - The number of materials with which scientific lunar samples can come into contact is <u>severely</u> restricted.
  - Sealing containers under lunar vacuum in the presence of dust is challenging, particularly given material restrictions.
  - Containers must be physically robust while lightweight.
  - A variety of containers may be needed to return different types of sample.
  - Containers must be designed to be easily opened in the appropriate terrestrial lab environment where curation will take place (lesson learned from Apollo).
- *Benefits*: The scientific integrity of returned samples must be maintained through strict adherence to documented collection, storage, and packaging procedures.
- <u>*FOM*</u>: Peer-reviewed configuration control of processes and materials acceptable to the scientific community.
- *General Assessment*: Well understood. Must be incorporated into mission requirements.
- *Development needed*: LOW

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9.1.3: Tools of Measurement & Observation

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Capability /Technology	SOA	TRL	Needs	Need TRL 6	Capability Date	CRL
9.1.3.1 In-situ Analysis						
(a) Remote sensing (incl. imaging) *Key: sensor; optics; data processing*	MER	*8*	Adapt to lunar setting; integrate into lunar ops	-	2010	7
(b) Local measure. of physical state *Key: Ops environment*	Apollo, Lunakhod	*1*	Natural-state acquis-ition / handling;	2015	2030	0
(c) *Key:*		*4,2*	Natural-state acquisition / Handling	2008	2012	6
9.1.3.2 Sample Analysis at Base						
(a) Analytical Instrumentation *Key: Packaging current state of art*	Earth labs; ISS	*9*		-	2008	7
(b) Sample preparation equipment *Key: safety issues re habitat life support (e.g., dust, oil)*	Earth labs	*2,2*		2012	2015	0

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Appendix

US Manned Space Program Relative Cost

	Apollo	ASTP	Skylab	NSTS	ISS	Exploration
Vehicle Development	High	Low	Moderate	High	High	High
Ops Systems Development	High	Low	Moderate	Moderate	Low	High
Vehicle Sustaining Eng./yr.	Low	N/A	N/A	Moderate	Low to Moderate?	?
Ops Systems Sustaining Eng./yr.	Low	Low	Low	Low	Low	?
Ops costs/yr.	High	High	High	High	High	?
# of years	2	1	1	38 +	5 +	50 +
Total program cost						

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US Robotic Space Program Relative Cost

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	Viking	Hubble	Pathfinder	MER	Exploration
Vehicle Development	High	High	Moderate	High	High
Ops Systems Development	Low	Low	Low	Low	High
Vehicle Sustaining Eng./yr.	n/a	High	n/a	n/a	?
Ops Systems Sustaining Eng./yr.	Low	Low	Low	Low	?
Ops costs/yr.	High	High	High	High	?
# of years	2 years	10	90 days	1-2 years	50 +
Total program cost					

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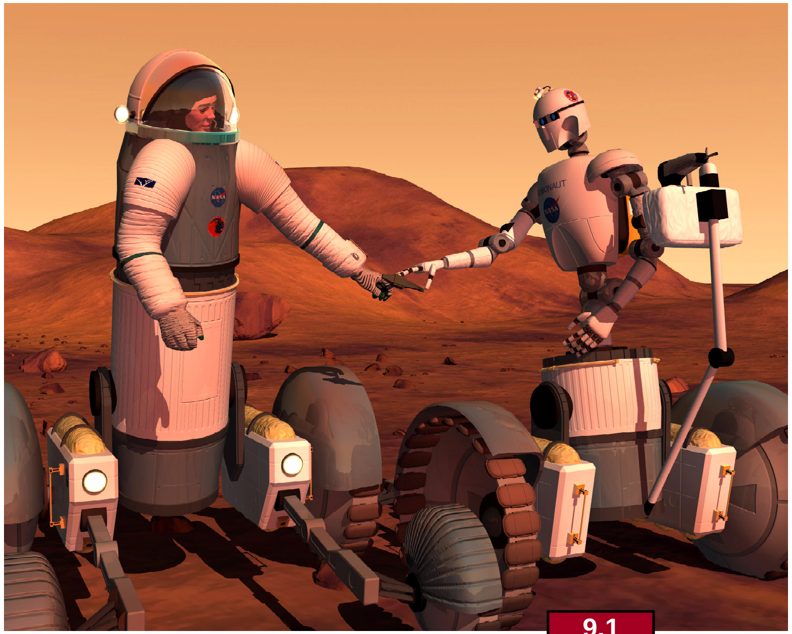
Concept of Operations: Robotic assistants explore while people monitor and control from safe havens



Machine systems

- physical strength, power, reach
- computational power, analysis
- communications
- continuous performance
- automation as a team player

People

- Active scientific discovery
- Hypothesis testing
- Creative problem-solving
- Strategic decision-making / Replanning
- First-hand experience and Communications to earth

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Lunar Mission Operations Functional Trade Space

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Lunar Mission Scenarios

- Global Surface Access, 7 Day Duration
- South Pole Region, 30-90 Day Duration

Lunar Network & Vicinity Operations

System Monitoring & Control
Earth-based vs. On-board *

Science & Payload Ops
Earth-based vs. On-board *

Element Trades (Decision and Analysis Categories)

- Communications
- Crew Activity Planning
- Life Support
- Robotic Activity Planning
- Vehicle Monitoring & Control
- Surface Asset Monitoring & Control

Earth-Moon Transit Operations

System Monitoring & Control
Earth-based vs. On-board *

Trajectory Management & Ascent / Descent
Earth-based vs. On-board *

- Communications
- Crew Activity Planning
- Vehicle Monitoring & Control
- Life Support

Earth Network & Vicinity Operations

System Monitoring & Control
Earth-based vs. On-board *

Ascent / Descent & Landing
Earth-based vs. On-board *

- Communications
- Crew Activity Planning
- Life Support
- Trajectory Management
- Vehicle Monitoring & Control

* Combined Options Allowed

9.1.5 Mobility/Hybrid Human/Robotic Control Roadmap

Technology	SOA TRL	Years to Develop to TRL 6: 1	2	3	4	5	6	7	8	9	10
Hybrid human/autonomous mobility: proximity/long range traverse*	**4-5**										
Fused control sensor suite	**4**										
S/W control architecture	**5**										
Autonomous fault ID/management and early propagation detection	**2-3**										
Autonomous resource management	**4**										

Note: *While it is understood that both the Apollo rover (human controlled) and MER (semi-autonomous) are TRL8, the redesign of both systems to accommodate seamless hybrid control has not been achieved and will require significant design and integrated testing—this is somewhat reflected in the other critical technology development roadmaps.

Some Lunar Base Need Candidates

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Power generation, transmission, and storage

Fuel and water generation, transmission, and storage

Environmental control

Dust control

Communications

Building materials production

Dirt movement

Construction - buildings, roads, landing port, science/industrial facilities

Maintenance

Navigation

Surveying

Human and materials transportation

Exploration Robotic Design Principles

Redundancy – one more massive and expensive large capacity robot to do the job or several smaller less expensive and robots who together could do the job in the same time or the same job in a longer time in the presence of failures

Interoperability – using components of robotics in multiple machines, e.g., power supplies, computers, end effectors, …

COTS based – web-based packet communications, standard interfaces (e.g., USB, Firewire, data and mechanical connection), commonly-available components and subunits

Exploration Robotic Design Principles continued

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Generalized workers – robots that can perform a variety of tasks

Standardization – develop and use new international robotic standards

Alterability – be re-programmable and physically alterable for new tasks or to recover from unplanned events or failures

Controllability - autonomous operations with override capability and provisions for tele-robotic control

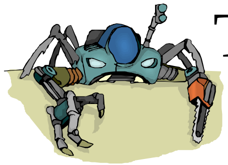
Potential Lunar Robot Examples

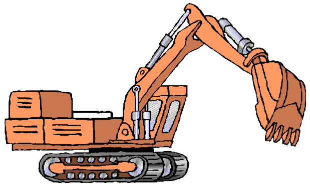
Scout

Dirt mover

For Hire

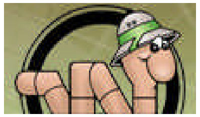
Transport

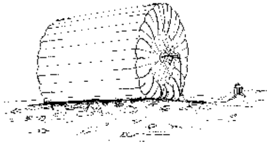




Trencher

Burrower





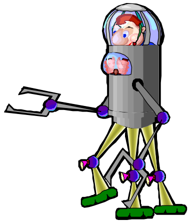
Lunar dirt settler

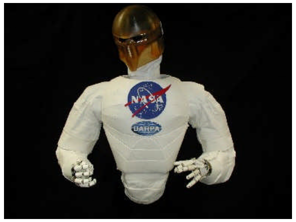
Dirt solidifier

Plumber/Wirer

Crew assistant

Crane





Challenges for Exploration Robotics

- Qualify robotic designs for outer space environments
- Minimize time latency effects for earth-based ground control methods
- Conduct surface robot operations near lunar noon
- Conduct surface robot operations during Martian blowing dust times
- Make further advances in perception and “cognition”
  (see examples next page)
- Secure and redundant command paths

Needed Perception and "Cognition" Advances

•Intake of visual, auditory, and tactile sensory inputs → rapid recognition of objects

•Physical path planning in presence of many multiple types of constraints

•Logical layering of hierarchical control mechanisms

dumb behaviors building up to complex behaviors

[e.g., single joint movement …basic skill (grasp) … tasks with multiple skills (go fetch panel)]

•Transformation of high level commands to a sequence of skills including constraints checking and intelligent reaction to these constraints

•Inter –robot information and skill transfer

•Operating in the environment of non-cooperative agents (e.g., robots avoiding interference with the actions of other robots and with carbon-based units)

•Self-starting actions based on perceived needs (within constraints)