Recommendations from the Workshop on Science Associated with the Lunar Exploration Architecture, Tempe, Arizona, 2/27-3/2, 2007

LEAG Meeting
October 2007, Houston

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NAC Science Committee

Workshop Goals

- Ensure that NASA's exploration strategy, architecture, and hardware development enable the best and appropriately integrated science activities.
- Bring diverse constituencies together to discuss & assess science activities and priorities for science enabled by the architecture.
- Identify needed Science Programs and Technology Developments.

Workshop Participation

- **Primarily a NAC Science Subcommittee Activity**
  - Astrophysics
  - Earth Science
  - Heliophysics
  - Planetary Protection
  - Planetary Science
  - Ad-hoc Outreach Committee
- **Supplemented with invited topical experts**
- **SMD, ESMD, LAT personnel: key participants**
- **Open meeting, science community participation**
  - 112 white papers, 48 posters, 250-180 attendees

Workshop Report / Results

- Prioritization of science objectives
- Workshop presentations and white papers posted on LPI web site
- Workshop Synthesis Report
  - Subcommittee workshop reports
- Recommendations via the NASA Advisory Council
  - Drawn from Synthesis Report

Synthesis Report and associated recommendations:
http://www.hq.nasa.gov/office/oer/nac/recommendations/Recommend-5-07.pdf

Workshop Archive Website

http://www.lpi.usra.edu/meetings/LEA/

Lunar and Planetary Institute

Meeting Archive

Presentations

White Papers

Workshop on Science Associated with the Lunar Exploration Architecture

February 27–March 2, 2007

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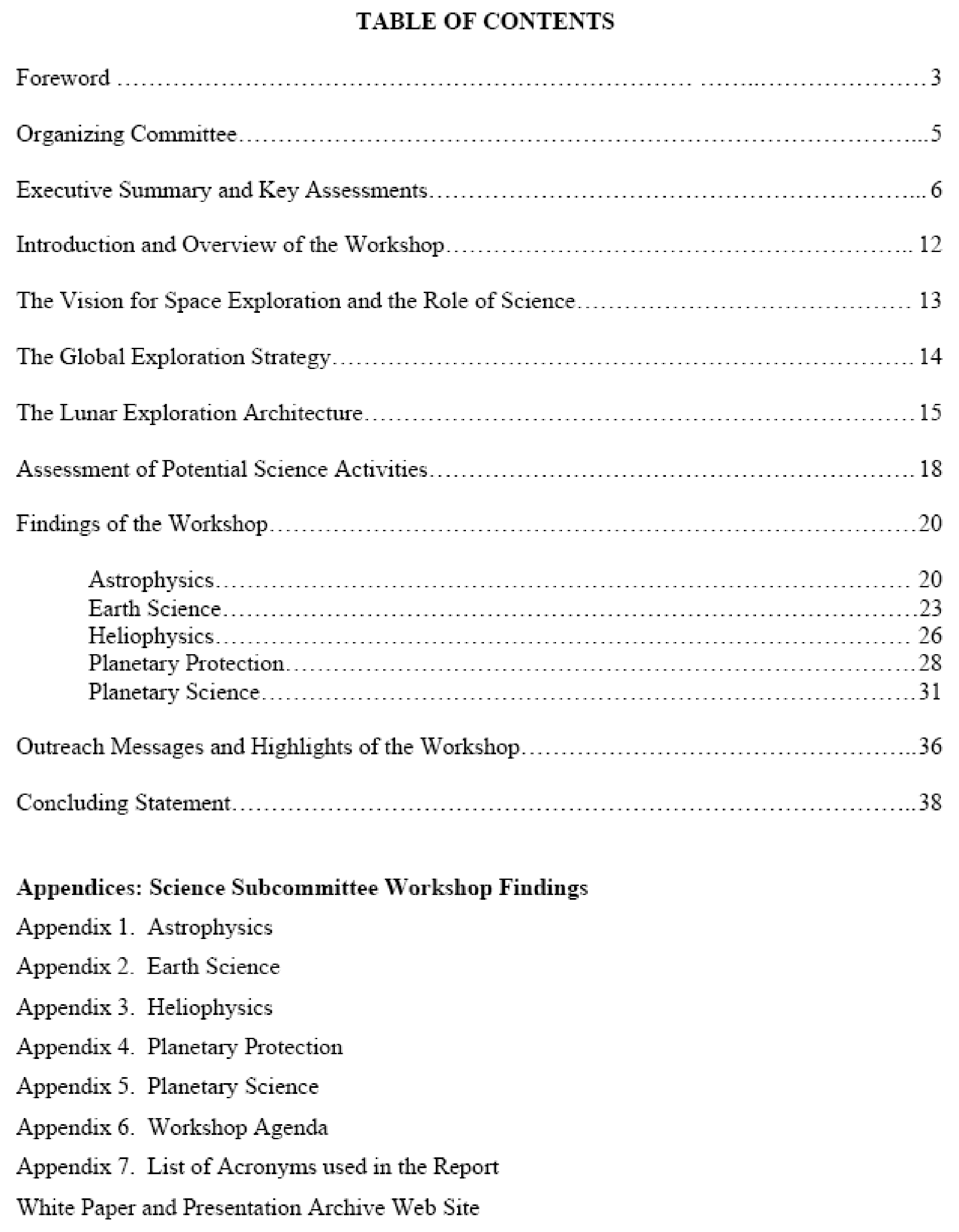
NAC Timeline, 2007

- NAC Workshop, Feb 27-Mar 2, 2007
- April 19: NAC briefing on workshop results, development of recommendations.
  - Findings/recommendations briefed to Sci. & Expl. Committees.
  - Council discussed recommendations in public session.
- May 18: Recommendations derived from the Tempe Workshop and subsequent considerations by the Science Committee (35) delivered to NASA Administrator.
- July 17-18 NAC meeting: First briefing of LAT II and process for response to recommendations.
- October 17 NAC meeting: Review responses to recommendations as part of LAT II development.

NAC Meeting April 19, 2007, KSC

- Synthesis report details the top priority science objectives as determined at the workshop.
  - These objectives represent the most promising lines of scientific enquiry for activities associated with return-to-the-Moon exploration.
  - Assessment of objectives from the workshop did not attempt to place specific activities into a sequence nor did it try to measure relative costs, risks, and scientific rewards among the objectives.
  - Workshop results not intended to supplant recommendations of Decadal Surveys; workshop participants reaffirmed importance of Decadal Surveys.

Synthesis Report



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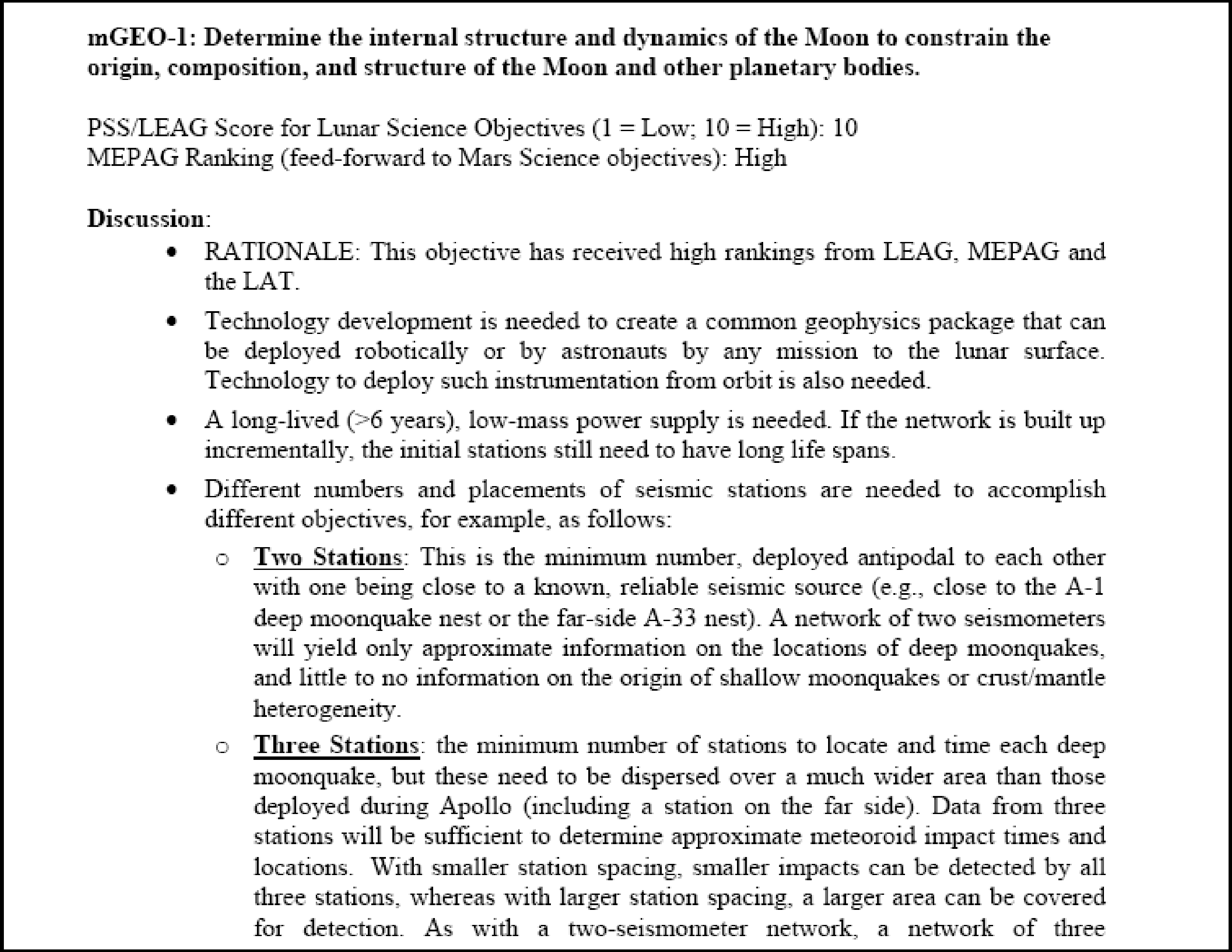
Appendices: Science Subcommittee Workshop Findings

PSS Workshop Report, example



mGEO-1: Determine the internal structure and dynamics of the Moon to constrain the origin, composition, and structure of the Moon and other planetary bodies.

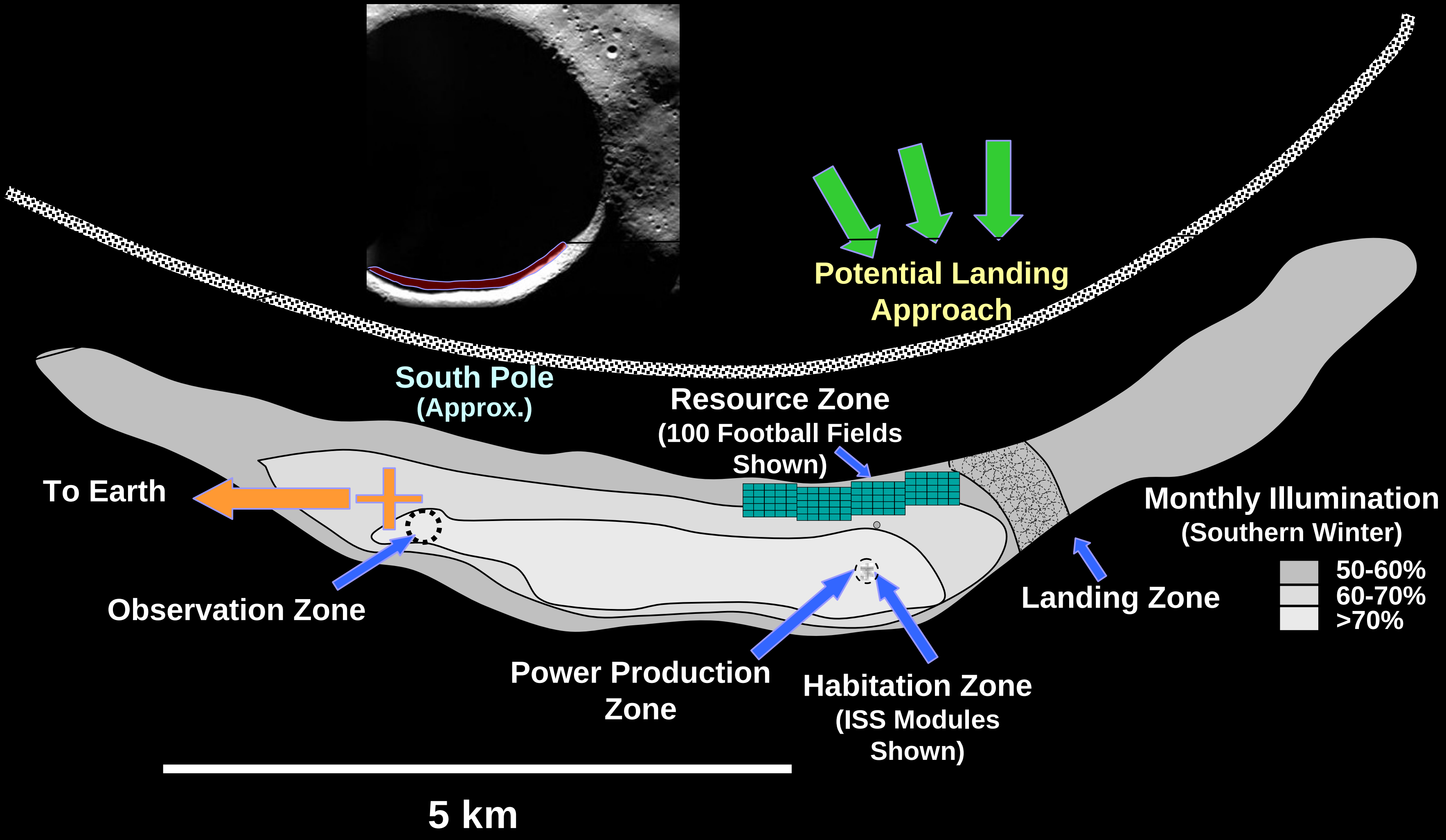
PSS/LEAG Score for Lunar Science Objectives (1 = Low; 10 = High): 10
MEPAG Ranking (feed-forward to Mars Science objectives): High

Discussion:

- RATIONALE: This objective has received high rankings from LEAG, MEPAG and the LAT.
- Technology development is needed to create a common geophysics package that can be deployed robotically or by astronauts by any mission to the lunar surface. Technology to deploy such instrumentation from orbit is also needed.
- A long-lived (>6 years), low-mass power supply is needed. If the network is built up incrementally, the initial stations still need to have long life spans.
- Different numbers and placements of seismic stations are needed to accomplish different objectives, for example, as follows:
    - **Two Stations**: This is the minimum number, deployed antipodal to each other with one being close to a known, reliable seismic source (e.g., close to the A-1 deep moonquake nest or the far-side A-33 nest). A network of two seismometers will yield only approximate information on the locations of deep moonquakes, and little to no information on the origin of shallow moonquakes or crust/mantle heterogeneity.
    - **Three Stations**: the minimum number of stations to locate and time each deep moonquake, but these need to be dispersed over a much wider area than those deployed during Apollo (including a station on the far side). Data from three stations will be sufficient to determine approximate meteoroid impact times and locations. With smaller station spacing, smaller impacts can be detected by all three stations, whereas with larger station spacing, a larger area can be covered for detection. As with a two-seismometer network, a network of three

LAT-I South Polar site as notional Outpost

Shackleton Crater rim site with notional activity zones



Potential Landing Approach

South Pole (Approx.)

Resource Zone (100 Football Fields Shown)

To Earth

Monthly Illumination (Southern Winter)

- ▩ 50-60%
- ▩ 60-70%
- ▢ >70%

Observation Zone

Landing Zone

Power Production Zone

Habitation Zone (ISS Modules Shown)

5 km

PSS Workshop Report, Objective Assessment

Rating for polar outpost (1-5)

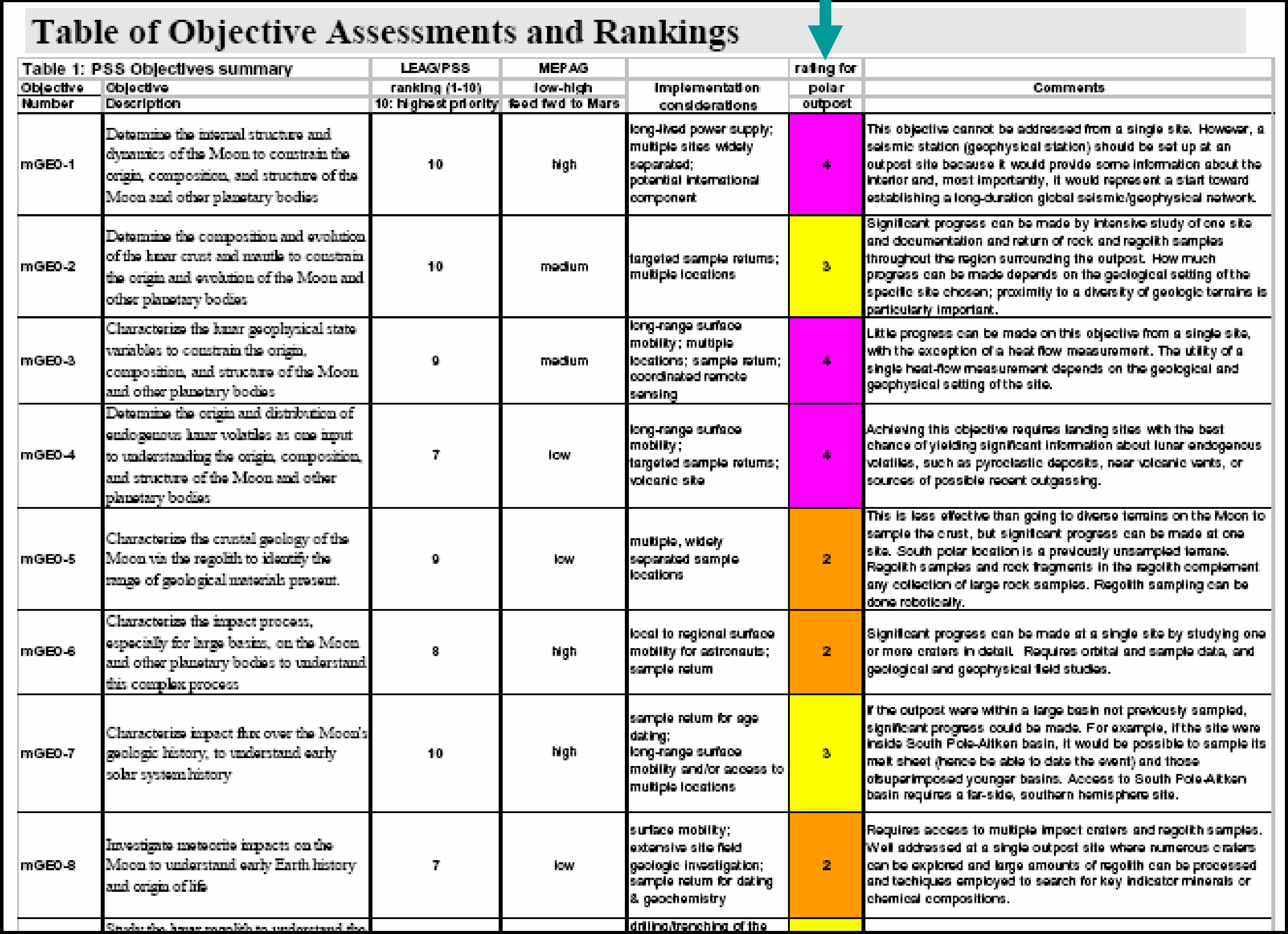


Table of Objective Assessments and Rankings

Table 1: PSS Objectives summary		LEAG/PSS	MEPAG		rating for	
Objective Number	Objective Description	ranking (1-10) 10: highest priority	low-high feed fwd to Mars	Implementation considerations	polar outpost	Comments
mGEO-1	Determine the internal structure and dynamics of the Moon to constrain the origin, composition, and structure of the Moon and other planetary bodies	10	high	long-lived power supply; multiple sites widely separated; potential international component	4	This objective cannot be addressed from a single site. However, a seismic station (geophysical station) should be set up at an outpost site because it would provide some information about the interior and, most importantly, it would represent a start toward establishing a long-duration global seismic/geophysical network.
mGEO-2	Determine the composition and evolution of the lunar crust and mantle to constrain the origin and evolution of the Moon and other planetary bodies	10	medium	targeted sample returns; multiple locations	3	Significant progress can be made by intensive study of one site and documentation and return of rock and regolith samples throughout the region surrounding the outpost. How much progress can be made depends on the geological setting of the specific site chosen; proximity to a diversity of geologic terrains is particularly important.
mGEO-3	Characterize the lunar geophysical state variables to constrain the origin, composition, and structure of the Moon and other planetary bodies	9	medium	long-range surface mobility; multiple locations; sample return; coordinated remote sensing	4	Little progress can be made on this objective from a single site, with the exception of a heat flow measurement. The utility of a single heat-flow measurement depends on the geological and geophysical setting of the site.
mGEO-4	Determine the origin and distribution of endogenous lunar volatiles as one input to understanding the origin, composition, and structure of the Moon and other planetary bodies	7	low	long-range surface mobility; targeted sample returns; volcanic site	4	Achieving this objective requires landing sites with the best chance of yielding significant information about lunar endogenous volatiles, such as pyroclastic deposits, near volcanic vents, or sources of possible recent outgassing.
mGEO-5	Characterize the crustal geology of the Moon via the regolith to identify the range of geological materials present.	9	low	multiple, widely separated sample locations	2	This is less effective than going to diverse terrains on the Moon to sample the crust, but significant progress can be made at one site. South polar location is a previously unsampled terrane. Regolith samples and rock fragments in the regolith complement any collection of large rock samples. Regolith sampling can be done robotically.
mGEO-6	Characterize the impact process, especially for large basins, on the Moon and other planetary bodies to understand this complex process	8	high	local to regional surface mobility for astronauts; sample return	2	Significant progress can be made at a single site by studying one or more craters in detail. Requires orbital and sample data, and geological and geophysical field studies.
mGEO-7	Characterize impact flux over the Moon's geologic history, to understand early solar system history	10	high	sample return for age dating; long-range surface mobility and/or access to multiple locations	3	If the outpost were within a large basin not previously sampled, significant progress could be made. For example, if the site were inside South Pole-Aitken basin, it would be possible to sample its melt sheet (hence be able to date the event) and those of superimposed younger basins. Access to South Pole-Aitken basin requires a far-side, southern hemisphere site.
mGEO-8	Investigate meteorite impacts on the Moon to understand early Earth history and origin of life	7	low	surface mobility; extensive site field geologic investigation; sample return for dating & geochemistry	2	Requires access to multiple impact craters and regolith samples. Well addressed at a single outpost site where numerous craters can be explored and large amounts of regolith can be processed and techiques employed to search for key indicator minerals or chemical compositions.
	Study the lunar regolith to understand the			drilling/trenching of the		

Astrophysics: Key Findings

- **Worthwhile astrophysical opportunities within Lunar Architecture**
  - Most promising: meter-wave radio telescopes on the lunar surface, and smaller "payloads of opportunity" competitively selected, that mesh well with the Lunar Architecture.

Meter-wave radio observations require only lightweight dipoles

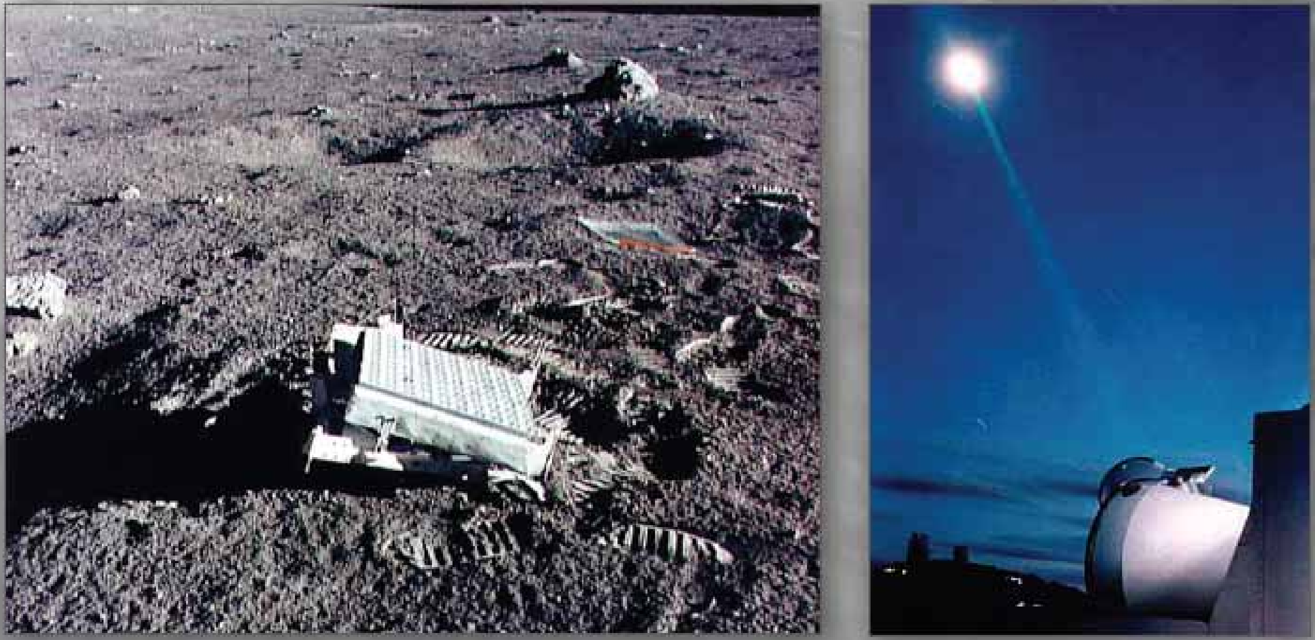
Astrophysics: Possible Activities

Lunar Ranging Experiments and Theories of Gravity

Measurements of lunar perihelion precession with an accuracy of $\delta\Phi = 1.4\text{x}10^{-12}$ to test alternatives to general relativity.

Currently accuracy is $2.4\text{x}10^{-11}$.

Placing a carefully designed array of transponders expected to achieve desired accuracy.



Earth Observations from Moon

- A lunar observatory provides a unique, stable, serviceable platform for global, continuous full-spectrum view of the Earth to address a range of Earth Science issues over the long-term:
  - time-dependent atmospheric composition (global mapping of emissions, long range transport of pollution plumes, greenhouse gases sources and sinks)
  - changes in the cryosphere (ice sheet disintegration, sea ice change, snow cover cycles)
  - Earth and ecosystem monitoring (volcanic eruptions, wildland fires, health and structure of vegetation, drought and land degradation)
  - radiation balance and solar variability influence on climate

Earth Observation Issues

- Communications across satellite platforms (LEO, GEO, GPS)
- Numerous limb occultation opportunities from visible (stars) to microwave (GPS) to VHF (communications)
- maximize full-disk Earth viewing
  - > 50% acceptable
  - > 90% desirable
- anywhere on near side would be acceptable
- minimize day-night thermal variability
- minimize dust influence

2/07

5/07

8/07

11/07

Heliophysics Science at the Moon

Heliophysics Science community defined four themes:

1) Space Weather, Safeguarding the Journey

2) Heliophysics Science *of* the Moon

3) The Moon as an Historical Record

4) The Moon as a Heliophysics Science Platform

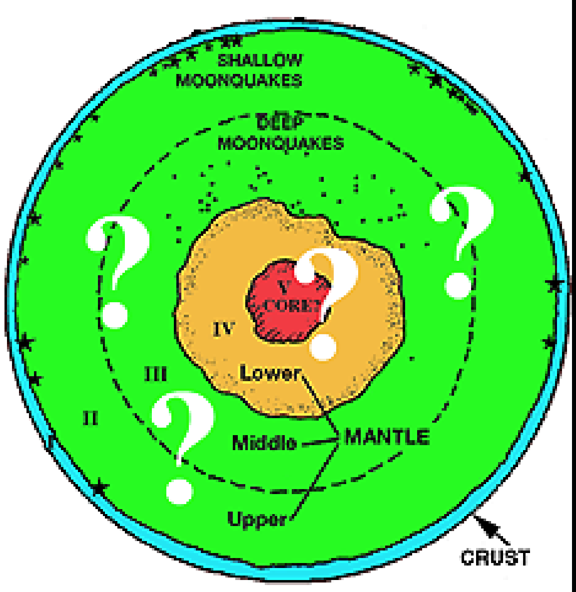
Solar and Space Physics at the Moon: Summary

- The lunar surface and lunar orbits provide good vantage points for investigating the lunar environment, particularly crustal magnetization and dust-plasma interactions.
- Excavation of the lunar regolith could provide unique and unprecedented data on the particle and irradiance history of the Sun.
- The lunar surface and lunar orbits offer good vantage points for imaging of the Sun, Geospace, and the boundaries of the heliosphere.
- Lunar-based instrumentation would allow measurements of plasma transport in the magnetotail and would provide important space weather monitoring capabilities in support of exploration missions.

Planetary Science Themes

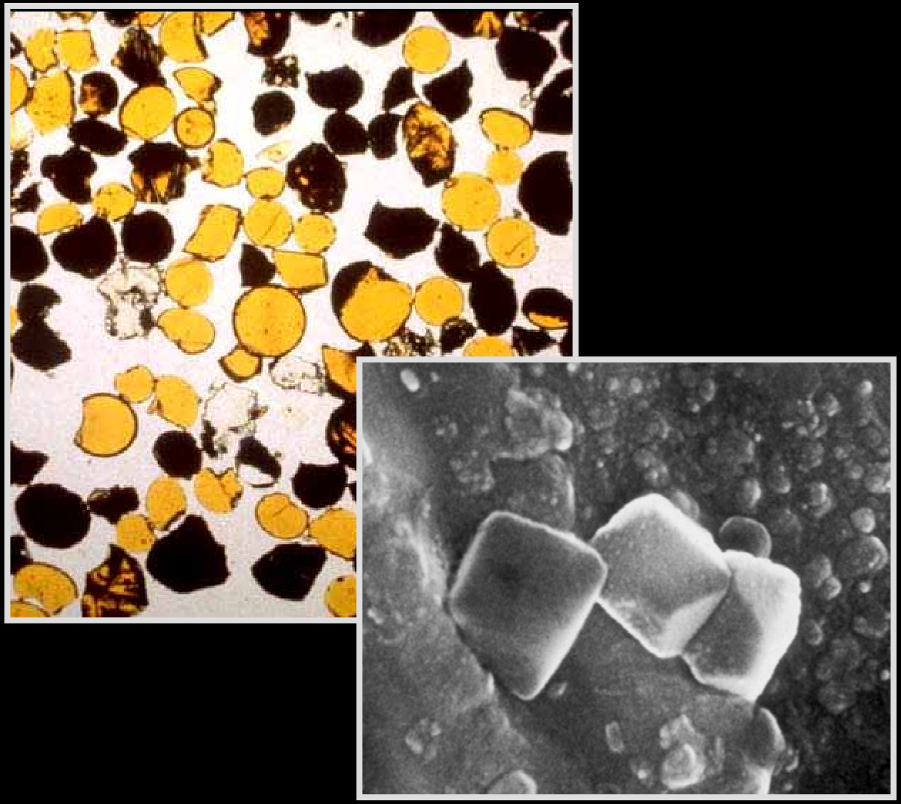
- The Moon is the keystone recorder of early solar system processes, especially those pertaining to the Earth-Moon system.
- The most important processes on the Early Earth that shaped the environment in which life originated are recorded on the surface of the Moon and are accessible.
  - Impact, Volcanism
  - Return to the Moon provides the potential to access the record.

Planetary Science Objectives



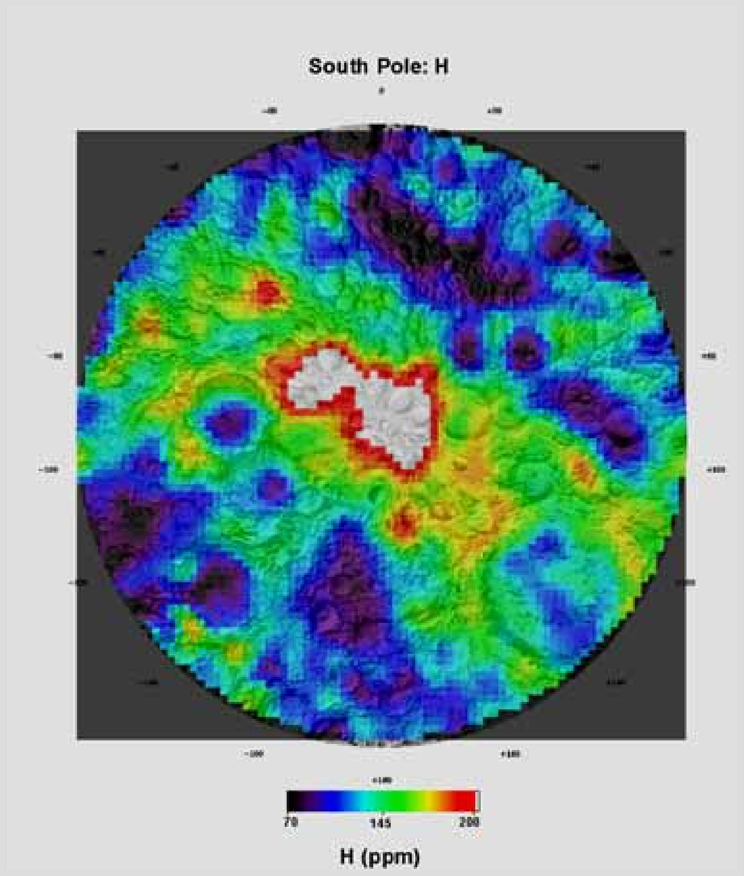
- Key Objectives
  - Impact history, especially understanding heavy bombardment
  - Planetary differentiation
    thermal, magmatic, volcanic
    history & processes,
    crustal diversity and evolution
  - Understand Moon’s interior
    (geophysical network: seismology, heat flow)
  - Characterizing polar volatile deposits
  - Characterizing other lunar resources and In-situ-resource utilization (ISRU) science

Search for resources involves study of areas of scientific interest.

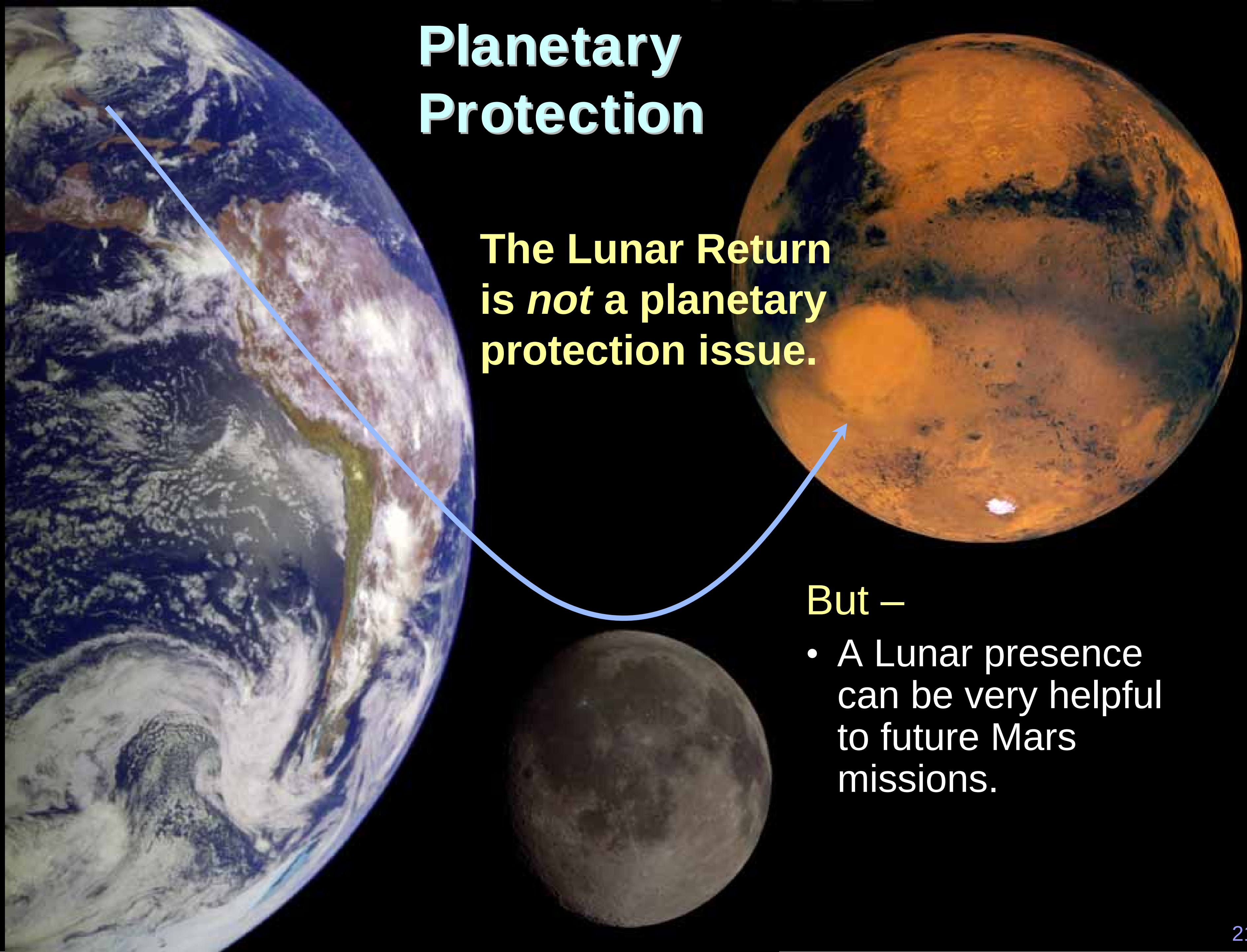


Volcanic Processes

H_2O in Polar Regions



Planetary Protection



The Lunar Return is *not* a planetary protection issue.

But –

- A Lunar presence can be very helpful to future Mars missions.

Planetary Protection lunar objectives

GOAL 1) Use of the Moon and lunar transit / orbits as test beds for Planetary Protection procedures and technologies involved with implementing human Mars mission requirements.

GOAL 2) Prepare for human exploration of Mars through the use of new technologies on the Moon.

Operations on the Moon are not constrained by current Planetary Protection restrictions.

- This makes the Moon an optimal location to establish the magnitude of contamination associated with human exploration
- The lunar return can facilitate development and testing of equipment and technologies designed to limit human-associated contamination.

Recommendations derived from Workshop findings

- The 35 recommendations stemming from workshop deliberations deal largely with how to accomplish the priority science within constraints of the lunar exploration architecture.
  - Some recommendations deal with modifications or augmentations to the architecture that would further enable high-priority science.
  - Others recommend studies that would explore trade space and associated costs and risks.

S-07-C-1, Scientific input to landing sites and other operational decisions

- **Scientific analysis and input should be integral components of the decision-making process for a lunar outpost** or any lunar mission relative to landing-site targets, exploration planning and execution, and continuous post-mission evaluation and feedback.
- Regular reviews of major decisions that will influence science outcome and legacy of lunar exploration should be carried out by the Council Science Committee and its Subcommittees, with their findings and recommendations transmitted to the Council.

Reasons for recommendation:

- Scientific knowledge, although only one of six major exploration themes within the exploration strategy, is key to each of the other themes. Topics for Council reviews should include:
- Options for full access to important sites on the Moon (low, mid, and high latitudes; nearside and farside; polar).

S-07-C-2, Evaluation and Prioritization of Science Activities

- Science activities enabled by lunar exploration should continue to be evaluated and prioritized within the science community by the Decadal Survey and science road-mapping processes, with periodic reviews by the Council.

Major reasons for the Recommendation

- Lunar science assessments formulated at Council workshops are not intended to supercede the decadal survey process, but should be considered as input to the next NRC Decadal Surveys and NASA Science Roadmaps as well as to NASA's architectural planning process.
- The NASA Science Mission Directorate has a well-validated process for establishing science priorities within their resource allocations.

S-07-C-3, Architecture should enable the highest priority science

- The architecture should enable the highest priority science activities as long as this is not cost-prohibitive and does not compromise other key objectives.

Major reasons for the Recommendation

- Because science activities in space are usually competed and normally not set forth in a specific programmatic way, the exploration architecture should be designed to enable and to not preclude, if possible, the kinds of activities that are listed as being of potentially high scientific priority, even though some of these activities may never actually be undertaken.
- This approach proved to be highly advantageous and flexible for Apollo during which most of the high priority science objectives were accomplished in addition to a number that were introduced subsequent to the first comprehensive lunar science conference in 1965.

S-07-C-4, Regular reviews of Lunar Exploration Architecture decisions

- Regular reviews (e.g., through the NASA Advisory Council structure) of major lunar architecture decisions that may directly or indirectly influence the science productivity of lunar missions should be conducted.

Major reasons for the Recommendation

- Lunar science assessments formulated at Council workshops and follow-on reviews can be of significant value in refining the evolving lunar architecture, providing operational vetting against known and probable scientific parameters, and in assuring the maximum potential scientific return from sortie and/or outpost missions.

S-07-C-5, CEV-SIM Bay

- The Crew Exploration Vehicle service module should have a capability conceptually similar to the Apollo science instrument module (SIM) to facilitate scientific and operational measurements and the deployment of payloads from lunar orbit.

Major reasons for the Recommendation

- The SIM Bay of the CEV service module could be used to deploy orbital sensors for Astrophysics, Heliophysics, and Earth Science experiments; to make orbital imaging, geodetic, geochemical, geophysical, mineralogical, photographic, and structural measurements of the Moon; and to deploy network stations to a variety of locations on the lunar surface.

S-07-C-6, Comparison study for potential non-polar Outpost sites

- NASA should conduct a study to evaluate options to determine if Outpost sites other than polar sites might compare favorably in terms of costs and potential to address key objectives of the Vision for Space Exploration, including prioritized science objectives.

Major reasons for the Recommendation

- LAT Phase 1 focused on a notional south polar site, including detailed assessment of capability to meet science objectives at such a site.
- A detailed assessment to fully explore the possibilities offered by a site or sites at lower latitudes is needed to determine the potential of other sites to enable achievement of objectives across all theme areas and to compare to the notional polar site.
- Potential for direct full-disk Earth observation, access to new and diverse geologic terrains and the testing of current lunar science hypotheses, and good ISRU potential are high priority science objectives for alternate sites. Such a study should include consideration of alternative power sources such as combined solar-power/fuel-cell technologies and nuclear power. Now that the notional polar outpost is well defined, trade studies relative to other sites should be relatively straight-forward and would require a relatively small team of diverse analysts.

S-07-C-7, Options for human and robotic sortie missions

- Keep open the possibility of <u>sortie missions</u> (human or robotic) <u>prior to establishment of the Outpost site</u>.

Major reasons for the Recommendation

- Precursor missions beyond LRO would help determine the value and reduce risks associated with a polar or other Outpost site. A landed mission with local mobility and in-situ analysis capabilities may be needed to characterize and thus “prove” the local resource potential of polar H and other potential volatile deposits, and to plan for appropriate mining and extraction technologies. The polar deposits may prove not to be the ready water resource that some anticipate although hydrogen and probably other solar wind volatiles are clearly more abundant than in near-equatorial regions.
- This issue has implications for in-situ resource utilization at and sustainability of the Outpost as well as commercial applications and partnerships, and public interest. Other priority mission activities would be to characterize the potential seismic or long-term impact hazards at a proposed Outpost site.

S-07-C-8, Return payload capabilities

- The Lunar Architecture should include a strategy to maximize the mass, at least 300 kg, and diversity of geological, biological, engineering and other samples (rocks and soils) returned from the Moon, whether through Outpost missions or through Sortie missions.

Major reasons for the Recommendation

- Achieving many of the highly ranked science objectives (Planetary Science and Planetary Protection, and possibly Biomedical), as well as engineering objectives, requires development of a strategy to maximize the mass and diversity of returned lunar samples.
- The 100 kg total return payload mass allocation (including containers) in the current exploration architecture for geological sample return is far too low to support the top science objectives. At the request of the PSS at the Tempe Conference, CAPTEM has analyzed this issue with respect to returned lunar materials and supports this conclusion (see May 1, 2007, CAPTEM Document 2007-01, “Analysis of Lunar Sample Mass Capability for the Lunar Exploration Architecture” at http://www.lpi.usra.edu/captem/).
- As recommended in the CAPTEM report, the notional return payload mass total should be on the order of 300 kg, pending further analysis of all potential demands for such payload. Analysis of this issue should continue so that all returned material requirements can be included in spacecraft design considerations.

S-07-C-9, Sample collection, documentation, containment, and curation

- NASA should establish well-defined protocols for the collection, documentation, containment, return, and curation of lunar samples of various types and purposes, with maximum mass and diversity of location, to optimize the scientific return while protecting the integrity of the samples.

Major reasons for the Recommendation

- Collection, return to Earth, and proper curation of lunar samples are needed to achieve planetary and other space science objectives, including materials science in support of exploration objectives. The overall sample strategy should integrate new field-exploration and sample documentation technologies as well as lessons learned from Apollo and the robotic exploration of Mars.
- Of critical importance will be post-mission evaluations of on-going sample analyses as well as frequent “lessons learned” reviews with feed-back into the near-term operational and exploration planning for follow-on lunar missions and feed-forward into architectural planning for Mars missions.

S-07-C-10, Roles and capabilities of astronauts

- The selection, roles, and capabilities of astronauts in the deployment, operation, and servicing of science activities, sampling, instruments, and facilities within the context of the planned architecture are critically important and need to be clearly defined and supported.

Major reasons for the Recommendation

- Much experience exists through Apollo, Skylab, Shuttle, Spacelab, Hubble Servicing, and International Space Station, as well as in scientific activities on Earth, to understand the roles of astronauts in space operations. Specific anticipated roles and capabilities within the context of the lunar architecture, however, need to be clearly defined.
- Many of the science objectives will necessarily require, for example, involvement of a Scientist Astronaut as an integral part of specific science experiments and/or as a field geologist.

S-07-C-11, Astronaut exploration training

- Development of crew selection criteria and a program of astronaut exploration training should be initiated as integral parts of the lunar exploration architecture and of the quality and quantity of returns from its implementation.

Major reasons for the Recommendation

- For further background information see the Field Exploration and Analysis Team (FEAT) White Paper at http://www.geo.utexas.edu/courses/660/FEAT_white_paper_v2.pdf. Important points include:
- Training should include, but not be limited to, geological, geochemical, and geophysical field exploration as well as critical factors in experiment deployment and/or operation.
- Training should involve experts and experience from the science community as well as NASA personnel with experience in field exploration and space-mission planning and execution.
- The training program developed for the Apollo 13-17 missions should be considered a starting point for training future astronauts.
- Crews for future lunar missions should include astronauts with professional field exploration experience.
- Research, operational simulations, and training are needed to determine how robots can best be used to assist astronauts in activities associated with the lunar exploration architecture.

S-07-C-12, Improved EVA suits

- A vigorous program is needed to significantly improve astronaut capabilities in EVA suits, specifically suit agility and glove dexterity must be significantly enhanced relative to Apollo and current ISS EVA suits. Other areas of suit-related improvement should include automated documentation of samples, automatic astronaut 3D position determination, and interaction with robotic assist technologies.

Major reasons for the Recommendation

- Apollo-era suits made many operations difficult, such as those involving finger, arm and shoulder motions, bending, and gripping and manipulation using the glove. Further, sample documentation, position determination, and navigation along with experiment deployment took inordinate amounts of astronaut time. Increased astronaut efficiency during EVAs directly impacts both scientific and operational returns from space missions.
- Integration of state-of-the-art technologies, such as heads-up displays and voice activation command and control should be investigated.

S-07-C-13, Integration of orbital data sets

- Lunar orbital data sets should be geodetically controlled and accurately co-registered to create cartographic products that will enable fusion, integration, and manipulation of all past and future data relevant to lunar exploration.

Major reasons for the Recommendation

- This recommendation results from considering how best to integrate the various data sets (US and international) that will be returned from the Moon in the next 5-8 years as well as those previously obtained. Improved positional accuracy for locations around the globe and for accurate co-registration of all available data sets is needed to maximize safety, reliability and efficiency in lunar human and robotic exploration operations.

S-07-C-14, Electromagnetic and charged dust environment

- Instruments and procedures should be developed and used to understand the <u>in-situ electromagnetic and charged-dust environment at a potential Outpost</u> or other lunar site.

Major reasons for the Recommendation

- Understanding the electrostatic charging and dust environment may have a direct impact on mission operations both with respect to potential hazards and to means of eliminating any such hazard. Scientific and engineering investigations should be specifically targeted to the particular nature of the lunar dust environment and the issues of critical systems and human operations.
- Safety concerns, operational planning, the reliability of equipment and experiment designs, and long-term engineering design solutions to adverse effects warrant investigation of the in-situ properties of dust and the lunar regolith early during renewed human activity on the Moon.

S-07-C-15, Investigation of time-stratigraphic layers within lunar regolith

- To maximize use of the Moon as a recorder of past solar activity, lunar surface operations should include precise, documented sampling of the surface regolith and regolith strata as a high priority, within the context of the overall geologic setting at the Outpost or other sites.

Major reasons for the Recommendation

- The impact generated strata of the lunar regolith carries a record of the history of solar energetic particles, interstellar dust, galactic cosmic rays, and the motion of the heliosphere through the galaxy. As part of any surface operations and in conjunction with use of regolith for in-situ resource utilization, precise sampling and documentation of surface regolith and buried regolith layers will be needed to investigate this record.

S-07-C-16, Options for large-area lunar-surface emplacement

- There should be an assessment of the mobility or emplacement capabilities needed to deploy high-priority science experiments such as dipole antennae, retroreflectors/ transponders, and geophysical instruments or packages across broad areas of the far and near sides of the Moon as well as globally in the case of a variety of geophysical instruments.

Major reasons for the Recommendation

- Many key science objectives require access to large areas (tens to thousands of km in extent) on the lunar surface. For example, a far-side facility designed to conduct radio astronomy requires a significant amount of collecting area on the lunar far side (tens of km^2). Tests of theories of gravity require widely dispersed laser retroreflectors, transponders, or both on the near side of the Moon.
- Geophysical instruments such as seismometers and heat-flow probes need wide, global dispersal in a variety of geologic terrains.

Astrophysics

APS-1. Far-side meter-wavelength radio environment

Recommendation: Appropriate steps should be taken throughout architecture planning to ensure that a <u>radio-quiet environment can be maintained on the lunar far side at a site suitable for deployment of a low frequency, meter wavelength (~10-250 MHz) radio observatory</u> and that the architecture would enable eventual deployment of such a facility.

APS-2. Options for science operations in free space

APS-3. Use of Constellation heavy lift capability for Astrophysics payloads

Earth Science

ESS-1. Earth Science from the Moon

The lunar architecture should be enabling for continuous or near-continuous observations of the Earth from an Outpost site as part of a balanced and complementary program of Earth observation from other vantage points, including near-Earth orbital platforms.

ESS-2. Earth view from the Outpost

Architecture should include provisions for mobility to access a suitable location, such as the slope of an Earth-facing terrain feature, which provides a full-disc vantage point if an outpost site is chosen that does not afford a full-disc view of Earth.

ESS-2a. Earth Observation from the Earth-Moon L1 point (added 7/19/07)

Heliophysics

HPS-1. Develop predictive capabilities for space weather

HPS-2. Real-time space weather monitoring

HPS-3. Provide capability for ‘drop-off’ satellites

HPS-4. Improved measurements of solar wind composition and flux

Planetary Protection

PPS-1. Contamination control technologies

PPS-2. Equipment for planetary protection assays

PPS-3. Back contamination of sample containers

PPS-4. In-situ investigation of lunar sites for biologically derived or other compounds

PPS-5. Planetary Protection Protocols

PPS-6. Advanced life-support systems

Planetary Science

PSS-1. Moon as a recorder of the impact history of the inner Solar System and early Solar System dynamics

The lunar architecture should be enabling for understanding the record of impacts in the Solar System with <u>access to and sampling of many impact basins and craters on the Moon and return of samples to Earth for age dating</u>.

PSS-2. Geophysical network on the lunar surface

The lunar architecture should include plans to place a long-lived geophysical measurement station at every lunar landing site, including an outpost site.

PSS-3. Mobility on the lunar surface

…options should be defined for local (up to 50 km), regional (up to 500 km), and global access from an outpost location.

PSS-4. Technology development needs

Key Issues

- Outpost site selection with respect to science objectives.
- Robotic precursors for science and for exploration preparation.
- Role of Sortie missions.
- Mobility to access science objectives locally and regionally from the Outpost.
- Global access.
- Integration of exploration and science activities.
  - Taking care that certain activities do not preclude others (exosphere, dust, contamination, radio environment).

Next steps

- Science Community must continue to follow up with active involvement in exploration & science objectives.
  - NRC Decadal Surveys
  - LEAG ‘goals and objectives’
  - NASA Advisory Council (Sci Comm & subcommittees)
- Precursor exploration to Outpost
  - Ensure optimal Outpost site selection.

Backup Charts

S-07-PSS-1, Moon as a recorder of the impact history of the Inner Solar System and early Solar System dynamics

- The lunar architecture should be enabling for understanding the record of impacts in the Solar System with access to and sampling of many large impact basins and craters on the Moon and return of samples to Earth for age dating.

Major reasons for the Recommendation

- The Moon holds a detailed record of the impact history and flux for the inner Solar System and potentially of early solar-system dynamics. Precise age-dating methods needed to advance understanding of the impact record requires careful, targeted sampling of large impact basins and craters, and return of samples to Earth.
- Field exploration and careful sample documentation will be required to access the most promising samples to meet this high-priority science objective.

S-07-PSS-2, Geophysical network on the lunar surface

- The Lunar Architecture should include plans to place a long-lived geophysical measurement station at every lunar landing site of a sufficiently capable human or robotic lander, including an outpost site.

  - Such packages should contain a seismometer, a heat-flow probe, magnetometer, and possibly an optical retroreflector.

  - Efforts should be made to coordinate with international partners on the emplacement and standardization of geophysical stations at landing sites established by other partner space agencies.

S-07-PSS-2, Geophysical network on the lunar surface, cont.

Major reasons for the Recommendation

- Geophysical networks are needed to accomplish exploration and high-priority science and operational objectives such as investigating the lunar interior and understanding the lunar surface seismic environment. A deployment strategy is needed for stations that are part of such networks.
- Such networks need not be limited to geophysical instruments, but could also include mass spectrometers for exosphere measurements and other instruments.
- Such networks need to be long-lived (>6 years to encompass one lunar tidal cycle and >10 years to survive until other stations come on line) which requires the development of a power source that can function over such long duration.
- Networks could be built up in partnership with other space agencies provided that a framework for compatible timing and data standards is established. The tradeoff between station lifetime and the timeframe for network deployment should be fully explored.

S-07-PSS-3, Mobility on the lunar surface

- To maximize scientific return within the current lunar exploration architecture, systems and operational options should be defined for local (up to 50 km), regional (up to 500 km), and global access from an outpost location.

Major reasons for the Recommendation

- It is important that access to scientifically high-priority sites not be compromised by mobility limitations, both for outpost and sortie missions.
- The outpost architecture will allow the goals of many more of the science objectives to be achieved as long as sites other than those in the immediate vicinity (10-20 km) of the habitat are accessible.
- Long-range local to regional mobility could be achieved by robotic operation of rovers. Global access could possibly be achieved by ultimately refueling and reactivating lunar landers to achieve global access. This option feeds-forward to Mars exploration.

S-07-PSS-4, Technology development needs

- A lunar instrument and technology development program is needed to provide focused technological development for applications on the lunar surface.

Technological developments needed to achieve the highest-ranked scientific objectives are listed below. Such technologies need not be lunar-specific but can feed forward to Mars and include the following:

- Imaging, ranging, position determination and other aides to field exploration and sample documentation.
- Long-lived (6-year life-time minimum) power supplies, especially in the 1-10 W range.
- Interfacing of human and robotic field exploration capabilities.
- Hard vs. soft landing options (capabilities) for deploying instrument packages from orbit to establish network stations.
- Development of robotically deployable heat-flow probes.
- Analytical capabilities in the field – efficient sample documentation and analysis by astronauts on EVAs and by robotic field assistants.
- Field exploration equipment development and systems integration for lunar fieldwork.
- Automated instrumentation/equipment deployment capabilities.
- Automated (robotic) sample return.
- Technologies to sample, document samples, and make measurements in permanently shadowed environments.
- Integration of scientific equipment and systems with surface mobility systems, including rovers, flyers and space suits.

Synthesis Committee

Workshop Chair	Brad Jolliff	Washington Univ., St. Louis
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	John Mather	Goddard Space Flight Center
Earth Science	Michael Ramsey	Univ. Pittsburgh
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NAC	Harrison Schmitt	Ex-officio (NAC Chairman)
NASA	Mike Wargo	ESMD, Lunar Program Scientist
NASA	Paul Hertz	SMD

NASA Exploration Lunar Activities Address the Following Themes

Human Civilization

Global Partnerships

Scientific Knowledge

Economic Expansion

Exploration Preparation

Public Engagement

Scientific Knowledge is integral to Exploration Themes


Human Civilization


Global Partnerships


Scientific Knowledge


Exploration Preparation

Economic Expansion


Public Engagement

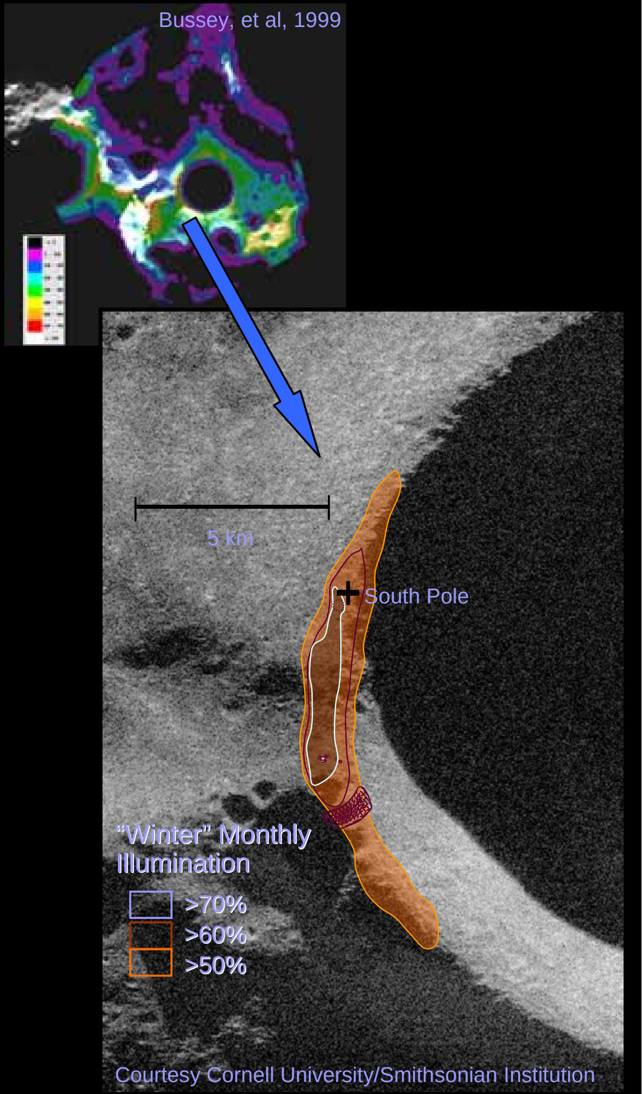
NASA's Lunar Exploration Architecture

Key elements of architecture planning:

- Outpost vs. Sortie Mode
- Location of Outpost (notional for now)
- Outpost Buildup
- Scientific and other Objectives at an Outpost

Key Decision: Sortie vs. Outpost

- Three Top Themes lead to Outpost concept:
  - "Exploration Preparation"
  - "Human Civilization"
  - "Economic Expansion"
- Better enables "Global Partnerships"
- Allows development of ISRU
- Results in quickest path toward other destinations
- Many science objectives can be satisfied at an outpost as well.

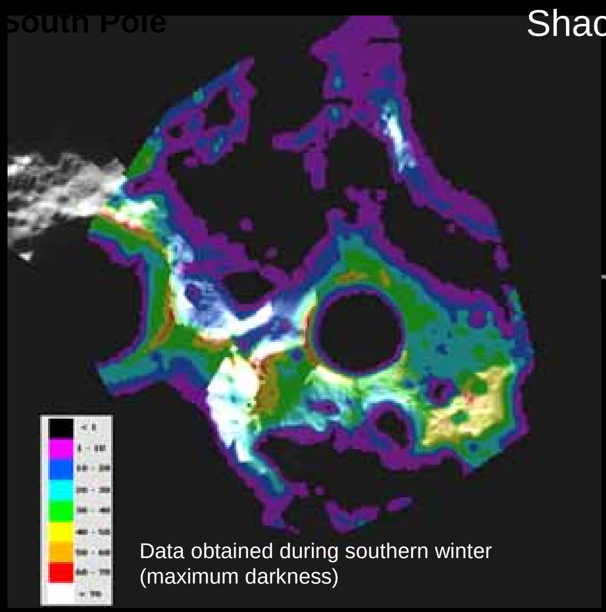

Bussey, et al, 1999

Courtesy Cornell University/Smithsonian Institution

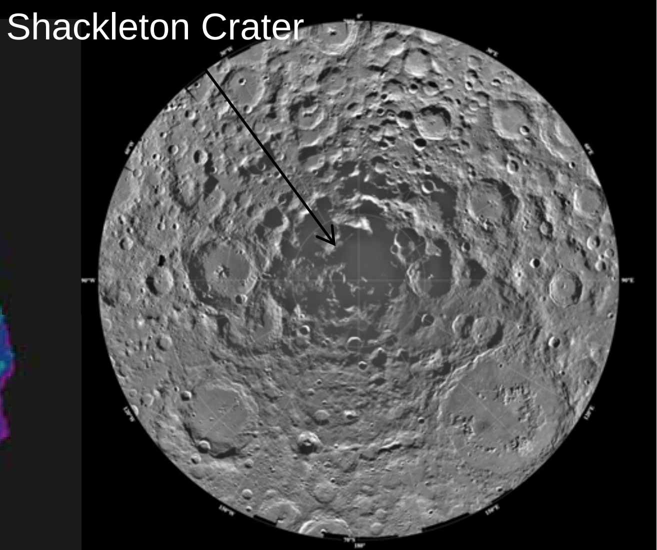
Sunlight at Poles

South Pole:

- Three areas identified with sunlight for more than 50% of lunar day
- One zone receives 70% illumination during dead of southern winter
- Lit areas in close proximity to permanent darkness (rim of Shackleton)

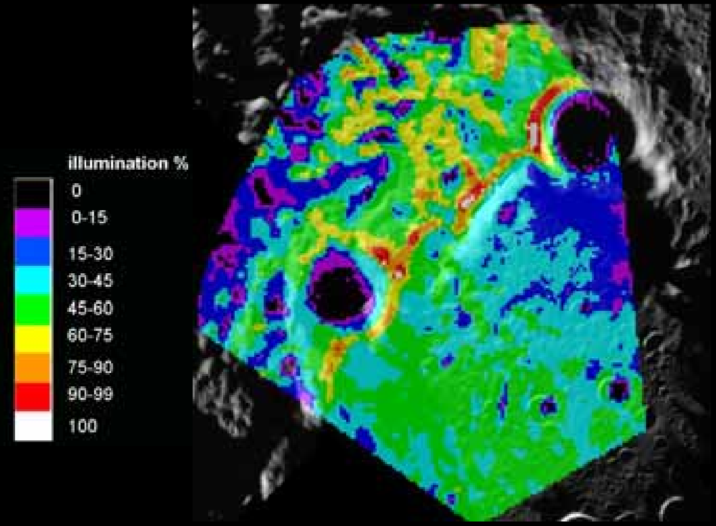


Data obtained during southern winter (maximum darkness)



North Pole:

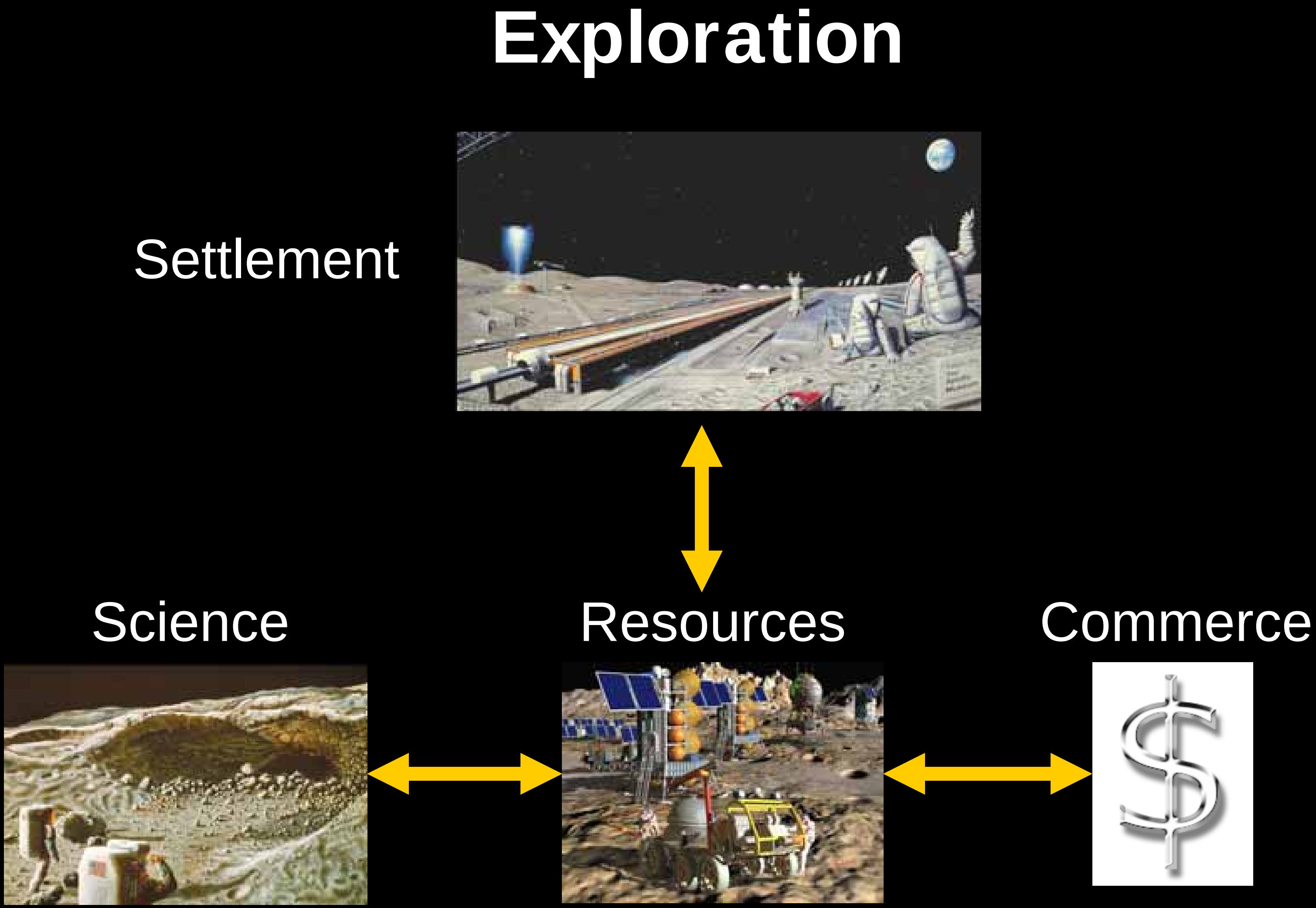
- Three areas identified with 100% sunlight
- Two zones are proximate to craters in permanent shadow
- Data taken during northern



Overview of Workshop Assessments

Planetary Science

Lunar Resources



Exploration

Settlement

Science

Resources

Commerce

Overview of Workshop Assessments

Astrophysics

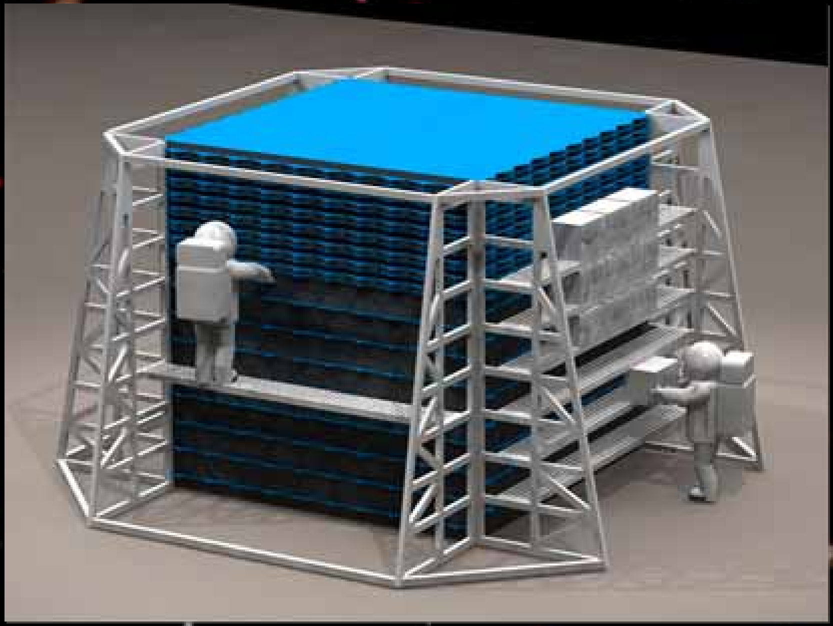
Astrophysics: High Priority Science

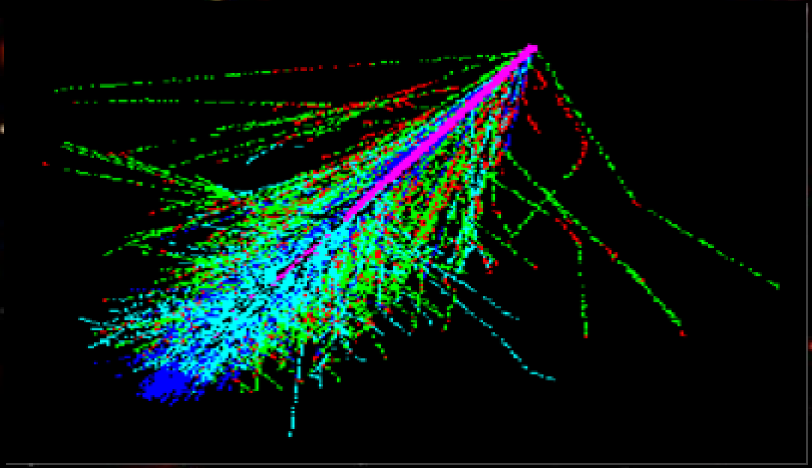
- Meter-wave Radio Observations
- Lunar Energetic Observatory
  - But better carried out in LEO with large launcher
- Fundamental Physics (laser ranging)
- Site Characterization
- “Piggyback” missions to surface and lunar orbit
- Large Telescope at Earth-Sun L2

Astrophysics: Key Findings

How are Galactic cosmic rays accelerated?

A calorimeter to study intermediate-energy ($E \sim 10^6$ GeV/particle) cosmic rays





Would use ~150 tons of layered regolith: but Ares V can launch 125 tons to low Earth orbit, without risk and cost to astronauts

Could also be done in LEO

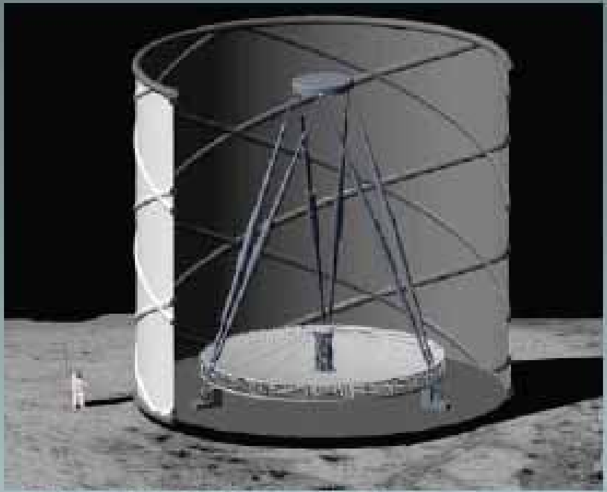
Astrophysics: Possible Activities

Possible niche: making use of lunar gravity…
Study Galaxy evolution with liquid mirror deep-field observations

Very large aperture with a rotationally shaped liquid mirror. (Angel et al.)

NEED gravity to make it work.

Need to protect against dust.



Liquid Mirror Telescope for the Moon

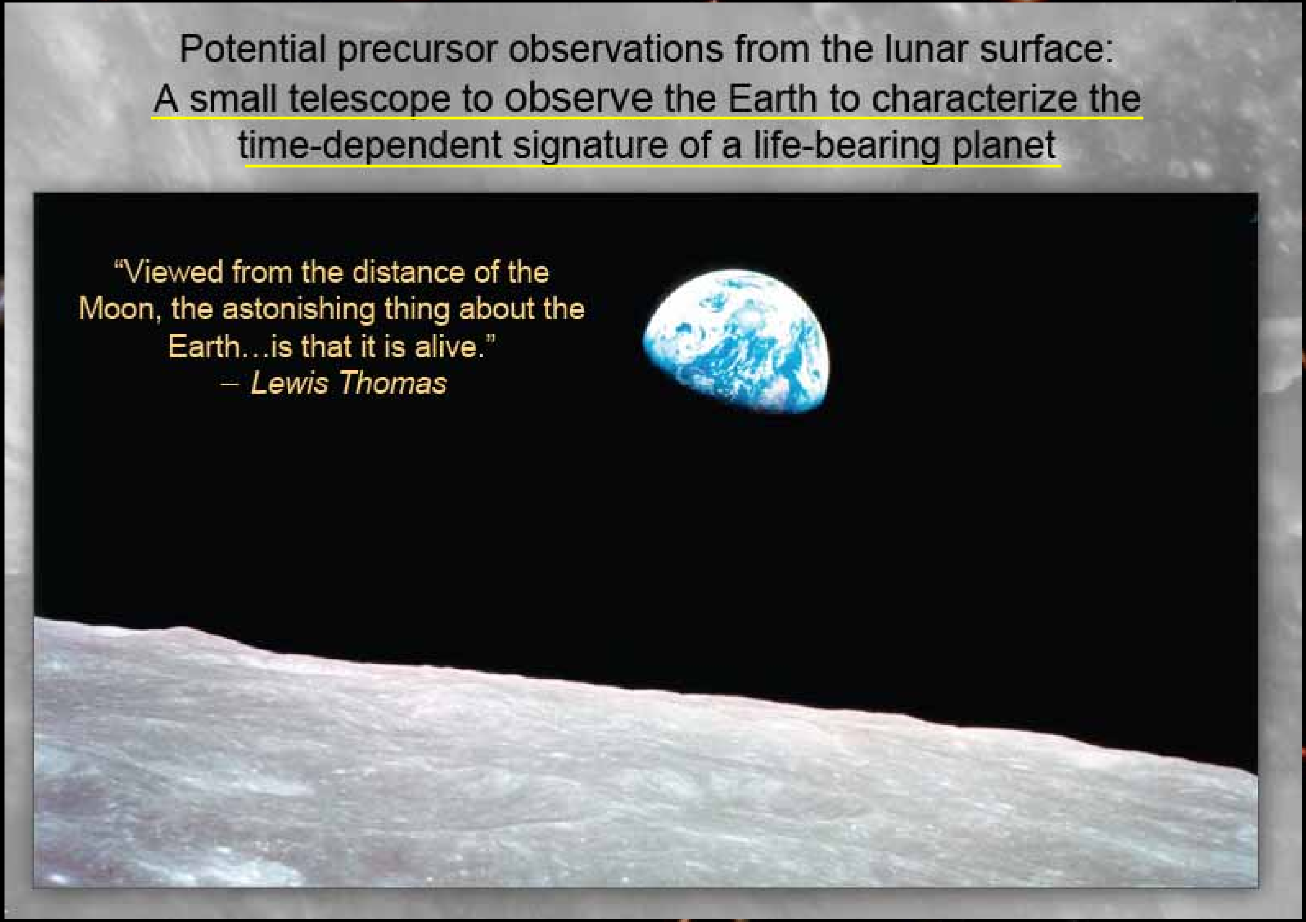
Technical feasibility? Cost??

Priority science drivers for deep small-field operation?

Trade against (pointable!) large telescopes in free-space.

Astrophysics:
A small mission to the lunar surface

What does a life-bearing planet look like?



Potential precursor observations from the lunar surface:

A small telescope to observe the Earth to characterize the time-dependent signature of a life-bearing planet

“Viewed from the distance of the Moon, the astonishing thing about the Earth…is that it is alive.”
– *Lewis Thomas*

Overview of Workshop Assessments

Earth Science

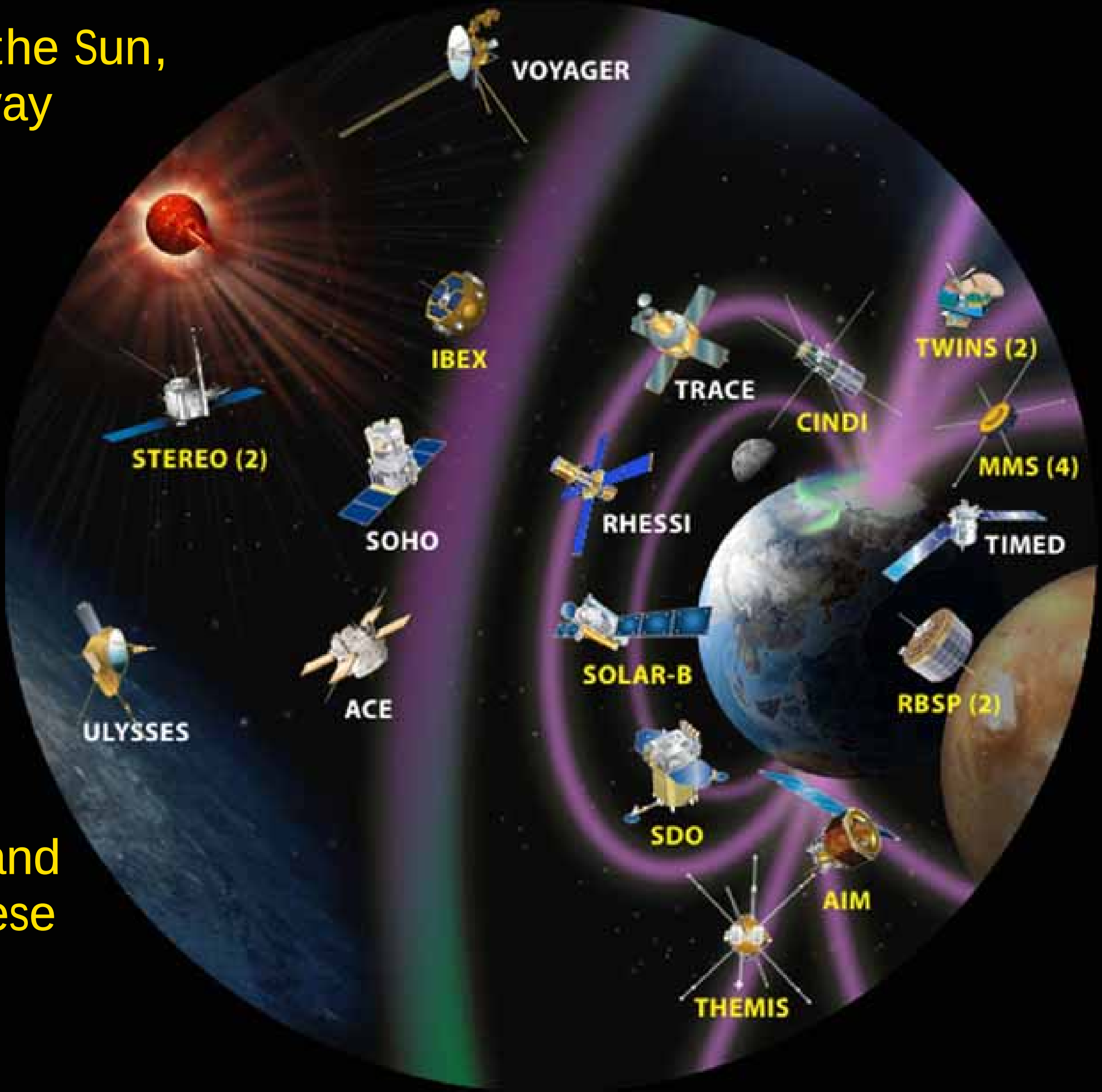
Overview of Workshop Assessments

Heliophysics

The Moon is influenced by the Sun, a main-sequence star midway through its stellar life.

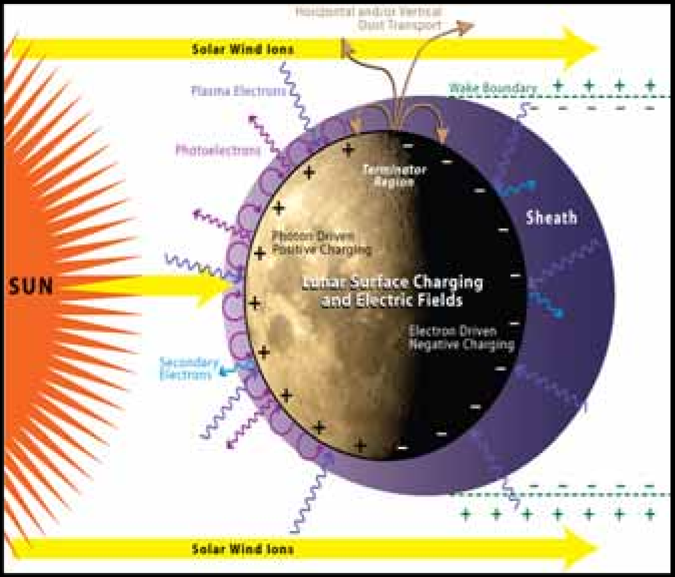
We see the Sun, Earth, and Moon as a single, interconnected system.

Heliophysics seeks to understand how and why the Sun varies, how the Earth and Moon responds, and how human activities in these environments are affected.



These science activities are considered to be fundamentally useful to the goals of the Vision for Exploration.

Space Weather, Safeguarding the Journey



Interaction of dust and plasma on the surface of the Moon and in the exosphere

mENVCH4 - Characterize the dust environment at several locations on the lunar surface to better understand the operational environment of the Moon.

Relative Assessment: High

Green

Comments: There is a highly variable plasma environment at the orbit of the Moon due to changing conditions of impinging solar wind and traversals of the magnetosphere. The moon can enter the hot and tenuous plasma sheet in the Earth's magnetotail, causing increased electrostatic potentials. The resulting surface charging can drive electrostatic transport of charged lunar dust. Lunar dust-plasma is highly susceptible to space weather. We need to observe the dust/plasma environment during range of different solar and magnetospheric activity conditions.

Suitability of Single Site Architecture: Consider strategic location (South Pole), as well as, or in addition to, distributed sites.

Overview of Workshop Assessments

Planetary Protection

Inputs to Lunar Architecture Objectives Matrix

GOAL 1) Use of the Moon and lunar transit / orbits as test beds for Planetary Protection procedures and technologies involved with implementing human Mars mission requirements, prior to Mars missions

- Valuable “ground truth” data on *in situ* contamination of samples supports future Mars sample return missions (sample integrity)

GOAL 2) Prepare for human exploration of Mars through the use of new technologies on the Moon

Planetary Protection Points and Issues

- Operations on the Moon are not constrained by current Planetary Protection restrictions
  - This makes the Moon an optimal location to establish the magnitude of contamination associated with human exploration
  - The lunar return can facilitate development and testing of equipment and technologies designed to limit human-associated contamination.

- Contamination control technologies for Planetary Protection must be developed before human missions to Mars can be permitted.