NASA ADVISORY COUNCIL
National Aeronautics and Space Administration
Washington, DC 20546
Hon. Harrison H. Schmitt, Chairman

May 18, 2007

The Honorable Michael D. Griffin
Administrator
National Aeronautics and Space Administration
Washington, DC 20546

Dear Dr. Griffin:

The NASA Advisory Council met on April 19, 2007 at the Hilton Cocoa Beach, Florida. Prior to the meeting, members toured Kennedy Space Center and used Center facilities to hold fact-finding meetings. Bill Parsons and his staff should be commended for their hospitality and hard work on behalf of the Council.

The central deliberations during the meeting involved the recommendations from the Workshop on Science Associated with the Lunar Exploration Architecture, held February 27 to March 2, 2007 in Tempe, Arizona, and chaired by Brad Jolliff. Thirty-five recommendations, attached, resulted from the week's discussions at the Tempe Conference and subsequent consideration by the Science Committee and the full Council. The Council spent over three hours in public session making final inputs to these recommendations.

The Council feels strongly that the attached recommendations should receive serious consideration. In addition, the following three high-level messages developed by the Outreach committee are specifically brought to your attention:

- The Moon is witness to 4.5 billion years of Solar System history and human exploration of that body will contribute greatly to discovering the origin and evolution of the Earth and of life.
- The Moon is a unique location from which to gather, analyze and fuse information about the ever-changing nature of the Earth, Sun, and Universe.
- The Moon is a fundamental stepping-stone to the human exploration of Mars and the rest of the Solar System.

The following supporting documents also are attached to provide the full context of the major recommendations and the deliberations of the Tempe Conference:

1) Synthesis Report – The final summary work product from the Tempe Workshop, produced following the Tempe Conference by a Synthesis Team composed of members of the Council Science Subcommittees.
2) Individual Subcommittee Reports – Workshop reports from the five Council Science Subcommittees and summarized in the Synthesis Report.
3) Outreach Committee Presentation –This presentation, developed under the leadership of Dean G.L. Kulcinski, is a useful summary of messages from the Tempe Conference that could be delivered to scientists and public concerning lunar science.

If there are any questions on these recommendations, please contact me.

Best Regards,
SIGNED (18 MAY 2007)

Harrison H. Schmitt
Chairman

Enclosures

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-1

Committee Name:	Science
Relevant Subcommittees*:	APS, ESS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Scientific input to landing sites and other operational decisions

Short description of the Recommendation
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.

Major reasons for the 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).
- Pre- and post-landing robotic exploration opportunities and missions.
- Options to mix human and robotic exploration.
- Surface science experiments and operations at the human outpost.
- Surface science experiments and operations during human sorties.
    - Mission and exploration planning
    - Critical items in space hardware design, including:
        - delivery of science experiments to the lunar surface;
        - returned payload constraints;
        - download of science (samples, data, observations, imagery) from the lunar surface;
        - orbiting module science requirements (e.g., SIM-bay);
        - crew orbiting science operational requirements (e.g. windows);
        - mission control science support requirements during operations.
- Of critical importance will be post-mission evaluations of on-going sample and data 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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-2

Committee Name:	Science
Relevant Subcommittees:	APS, ESS, HPS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Evaluation and Prioritization of Science Activities

Short description of the Recommendation
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.

Information and prioritizations developed by the Council pertaining to lunar science opportunities should enter into this SMD process in the same manner as do other SMD pre-planning activities, as well as be available to the Administrator for his ultimate consideration of resulting SMD and ESMD plans.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-3

Committee Name:	Science
Relevant Subcommittees*:	APS, ESS, HPS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

<u>Short title of the Recommendation</u>
Architecture should enable highest priority science

<u>Short description of the Recommendation</u>
The architecture should enable the highest priority science activities as long as this is not cost-prohibitive and does not compromise other key objectives.

<u>Major reasons for the Recommendation</u>
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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-4

Committee Name: Science

Relevant Subcommittees*: APS, ESS, HPS, PPS and PSS

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

<u>Short title of the Recommendation</u>
Regular reviews of Lunar Exploration Architecture decisions

<u>Short description of the Recommendation</u>
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.

<u>Major reasons for the Recommendation</u>
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. These assessments are not intended to supercede the decadal survey process, but should be considered as input to the next NRC Decadal Survey and to NASA Science Roadmaps as well as to the on-going NASA planning process related to the Vision for Space Exploration.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-5

Committee Name:	Science
Relevant Subcommittees*:	APS, HPS, and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
CEV-SIM Bay

Short description of the Recommendation
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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-6

Committee Name:	Science
Relevant Subcommittees*:	APS, ESS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Comparison study for potential non-polar Outpost sites

Short description of the Recommendation
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
This recommendation addresses the perception that the lunar architecture is “locking in” to a polar site, even though the polar site has been stated to be “notional” and a “point of departure” for further evaluation. NASA has stated that combined consideration of six overarching exploration themes and the top objectives led to the selection of a polar site for the notional Outpost. Furthermore, the Lunar Architecture Team conducted a detailed assessment of the capability to meet objectives at the notional site.

However, a similar, 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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-7

Committee Name:	Science
Relevant Subcommittees*:	PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Options for human and robotic sortie missions

Short description of the Recommendation
Keep open the possibility of sortie missions (human or robotic) prior to establishment of the Outpost site.

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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-8

Committee Name:	Science
Relevant Subcommittees*:	HPS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Return payload capabilities

Short description of the Recommendation
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
Achievement of many of the highly ranked science objectives (Planetary Science and Planetary Protection, and possibly Biomedical), as well as engineering objectives, requires the 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, the 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 300kg, 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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-9

Committee Name: Science

Relevant Subcommittees*: HPS, PPS and PSS

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Sample collection, documentation, containment, and curation

Short description of the Recommendation
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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-10

Committee Name:	Science
Relevant Subcommittees*:	APS, ESS, HPS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Roles and capabilities of astronauts

Short description of the Recommendation
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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-11

Committee Name:	Science
Relevant Subcommittees*:	APS, ESS, HPS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

<u>Short title of the Recommendation</u>
Astronaut exploration training

<u>Short description of the Recommendation</u>
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.

<u>Major reasons for the Recommendation</u>
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.

This recommendation has a strong feed forward to human exploration of Mars.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-12

Committee Name:	Science
Relevant Subcommittees*:	APS, ESS, HPS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Improved EVA suits

Short description of the Recommendation
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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-13

Committee Name:	Science
Relevant Subcommittees*:	PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Integration of orbital data sets

Short description of the Recommendation
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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-14

Committee Name:	Science
Relevant Subcommittees*:	APS, ESS, HPS, PPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Electromagnetic and charged dust environment

Short description of the Recommendation
Instruments and procedures should be developed and used to understand the in-situ electromagnetic and charged-dust environment at a potential Outpost 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.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-15

Committee Name:	Science
Relevant Subcommittees:	HPS and PSS
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Investigation of time-stratigraphic layers within lunar regolith

Short description of the Recommendation
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.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Crosscutting Recommendation
Tracking Number: S-07-C-16

Committee Name: Science

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Options for large-area lunar-surface emplacement

Short description of the Recommendation
There should be an assessment of the mobility or emplacement capabilities needed to deploy high-priority science experiments such as dipole antennae, retro-reflector/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.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Astrophysics Recommendation
Tracking Number: S-07-APS-1

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Far-side meter-wavelength radio environment

Short description of the Recommendation
Appropriate steps should be taken throughout architecture planning to ensure that a 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 and that the architecture would enable eventual deployment of such a facility.

Major reasons for the Recommendation
The principal advantage offered by the Moon as an observatory platform for Astrophysics is the radio-quiet environment of the lunar far side and the potential to emplace a, low frequency (meter-wave) radio telescope. Because of shielding from terrestrial (continuous) and solar (half time) radio emissions and lack of a lunar ionosphere, a far-side observatory offers the potential for extremely sensitive probes of cosmic evolution of the Universe. If 21-cm radiation from hydrogen, emitted early during the formation of structure in the universe, can be detected, this red-shifted signal would provide a unique and sensitive probe of cosmic evolution.

The maintenance of a radio-quiet environment need only be implemented over the frequency range of interest (~10-250 MHz). The expected strength of these signals from the early universe are orders of magnitude below the strength of typical human-generated transmissions, solar radio emissions, and natural terrestrial radio emissions. Thus, the most sensitive observations of these red-shifted 21-cm hydrogen signals only will be obtained in a location that is shielded from interfering signals. Implementation of this recommendation, of course, must take into consideration any prohibitive cost implications.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Astrophysics Recommendation
Tracking Number: S-07-APS-2

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Options for science operations in free space

Short description of the Recommendation
Trade studies should be conducted (including independent cost analysis) to investigate ways in which the exploration architecture can be enabling for astrophysics science through human and robotic operations.

Major reasons for the Recommendation
Several kinds of observatories once considered to be advantageous for deployment on the lunar surface are now considered to be scientifically more flexible and more capable if operated in free space. However, consideration of various operational and cost advantages that might come with the integration of observatories with on-going outpost operations and logistics could potentially balance or off-set the apparent advantages offered by free space. Trade studies are needed to fully investigate the potential trade-offs in this trade space. These studies should include deployment and servicing capabilities for experiments and instruments, including maintenance, refurbishment, and upgrade opportunities that might be integrated with other operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Astrophysics Recommendation
Tracking Number: S-07-APS-3

Committee Name: Science

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Use of Constellation heavy lift capability for Astrophysics payloads

Short description of the Recommendation
A study should be conducted to determine the feasibility of future use of the Constellation Program's heavy lift capability (Ares V) to deliver large Astrophysics payloads to space

Major reasons for the Recommendation
Future major astrophysics and other science missions in space can be enabled by the capabilities of the proposed Ares V heavy-launch vehicle, specifically the mass and volume that can be delivered to priority locations throughout the Earth-Moon system. Access to heavy lift capabilities afforded by the Ares spacecraft is viewed as enabling for potentially revolutionary future astrophysics (and other) missions in space.

Potential assessment and trade studies to more fully understand how Ares V can enable multiple goals in space include: (1) detailed designs and performance estimates, including options for fairings for alternative payloads (e.g., height, width, aspect ratio); (2) cost estimates, potential schedules, and required milestones; (3) operation of the Ares V with other plausible systems available during the same time period, such as the Orion or Ares I vehicles; and (4) recommendations for professional outreach to inform the science communities about the performance capabilities of these vehicles.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Earth Science Recommendation
Tracking Number: S-07-ESS-1

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Earth Science from the Moon

Short description of the Recommendation
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.

Major reasons for the Recommendation
High-priority science objectives can be achieved by Earth observations from a stable and serviceable platform to address a range of Earth Science issues including, but not limited to:

- global, continuous full-spectrum views of the Earth,
- detection and analysis of time-dependent atmospheric composition (global mapping of emissions, long range transport of pollution plumes, greenhouse gases sources and sinks),
- ecosystem monitoring,
- changes in the polar caps and other aspects of the cryosphere,
- vertical structure of the Earth's atmosphere,
- full-spectrum signature of a life-bearing planet.

A lunar platform also allows the Sun-Earth system to be observed instantaneously and continuously, providing data on the Earth's radiation balance and the influence of solar variability on climate.

An observatory located on the lunar surface would allow for growth and serviceability over time. A facility at the lunar outpost could also serve as a communications bridge across satellite platforms in other orbits (e.g., LEO, GEO, GPS), providing for synergistic operation and fusion of data from Earth-observing assets.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Earth Science Recommendation
Tracking Number: S-07-ESS-2

Committee Name: Science

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Earth view from the Outpost

Short description of the Recommendation
The 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 (see ESS-1).

Major reasons for the Recommendation
The Earth-facing side of the Moon provides a unique observation point with the potential for full-disc and full-spectrum, long-term observation of Earth's changing surface and atmosphere from a stable and serviceable platform. The notional South-Pole Outpost site at Shackleton Crater rim does not afford a full-disc view of the Earth; however, locations within the region such as Mt. Malapert might be suitable. Deployment of an observatory to such a site would require regional mobility.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Heliophysics Recommendation
Tracking Number: S-07-HPS-1

Committee Name*:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Develop predictive capability for space weather

Short description of the Recommendation
Early in the human exploration program, space-weather predictive capabilities should be developed to enable safe, sustained operations on the Moon (see S-07-HPS-2).

Major reasons for the Recommendation
One of the key objectives for Heliophysics is to "safeguard the journey" through monitoring, understanding, and predicting solar activity. The Moon is immersed in a magnetized plasma environment. Interaction of the magnetic fields of the Earth, Sun, and locally, the Moon regulate the local environment of the Moon and thus, the particle radiation (protons, electrons, neutrons) environment experienced by astronauts. Additionally, the neutron and non-ionizing radiation (x-rays and gamma rays) from the Sun are of concern for long-term human operations on the Moon.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Heliophysics Recommendation
Tracking Number: S-07-HPS-2

Committee Name*:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

<u>Short title of the Recommendation</u>
Real-time space weather monitoring

<u>Short description of the Recommendation</u>
Locate real-time space weather monitoring measurements as close to solar sources as feasible.

<u>Major reasons for the Recommendation</u>
The technology needed to establish an infrastructure to monitor space weather over timescales of days, hours, and minutes exists. Simple full-Sun sensors can provide valuable intensity and location information about the x-ray flux and on particle acceleration in the low corona that can be used to warn astronauts of impending radiation hazards.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Heliophysics Recommendation
Tracking Number: S-07-HPS-3

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Provide capability for 'drop-off' Satellites

Short description of the Recommendation
Several of the high priority Heliophysics objectives can best be achieved from lunar orbit. Consideration should be given to deployment of relevant sensors as drop-off satellites (see recommendation S-07-C-5, CEV-SIM Bay).

Major reasons for the Recommendation
Satellites delivered to lunar orbit can address objectives such as (1) studying the dynamics of the Earth's magnetotail as it is transited by the Moon or (2) studying the effect of the Moon on the surrounding plasma environment and incident solar wind both in and out of the Earth's magnetotail.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Heliophysics Recommendation
Tracking Number: S-07-HPS-4

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Improved measurements of solar wind composition and flux

Short description of the Recommendation
Improved measurements should be accomplished on the lunar surface of solar wind composition and fluxes, the composition and fluxes of interplanetary and interstellar grains, and high-energy x-rays and gamma rays.

Major reasons for the Recommendation
The solar wind composition was investigated during Apollo and has recently been measured by the Genesis spacecraft, but with less than complete success. Lunar observations would complete the necessary reservoir of samples for 21st century science. The flux and composition of the interplanetary and inter-stellar grains bombarding the lunar surface are important measurements to both the Heliophysics and the Astrophysics communities. They, along with solar and galactic particle and non-ionizing radiation, are fundamental means of implanting solar volatiles, maintaining the lunar atmosphere, and modifying the micro-meteor-gardened lunar soil.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Protection Recommendation
Tracking Number: S-07-PPS-1

Committee Name*: Science

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Contamination control technologies

Short description of the Recommendation
Contamination control technologies should be developed to the extent feasible before human missions are sent to Mars (more specific recommendations follow in S-07-PPS 2-6).

Major reasons for the Recommendation
The Moon is an excellent test bed for developing technologies that will be required to permit human exploration of protected planetary bodies. Lunar missions can facilitate development and testing of equipment and technologies designed to limit human-associated contamination. Many processes and technologies required for planetary exploration are likely to produce organic and biological contaminants that are regulated by Planetary Protection policy. Because organic and biological contamination of the Moon is not restricted, technologies that will be required for exploration of protected locations can be tested and optimized without costly limitations. Necessary technologies will need designs that minimize contamination include pressurized habitats and spacesuits as well as robotic and human-associated mobile equipment used for exploration or in situ resource utilization (ISRU). Such technologies and procedures, to the extent they are feasible, are needed before humans can travel to Mars or other protected Solar System bodies.

* Recommendation also relevant to engineering design and/or operations.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Protection Recommendation
Tracking Number: S-07-PPS-2

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Equipment for planetary protection assays

Short description of the Recommendation
Technologies and experimental equipment to perform planetary protection assays should be investigated for relevance to human exploration requirements and considered for inclusion in up-mass to the lunar Outpost.

Major reasons for the Recommendation
Technologies and instruments, which include robotic sample collection and sensitive, rapid assay methods using field-portable equipment, have been developed for robotic exploration and have been adapted to interface with humans, either with the assistance of a robot or through direct operation while wearing a space suit. Such instruments have been operated successfully in remote locations on Earth such as Svalbard Island and Antarctica. In planning the lunar outpost, it will be important to include sufficient allotments for up-mass for equipment that facilitates testing of planetary protection technologies and potential allotments of down-mass for even more sensitive, Earth-based testing of specially protected samples.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Protection Recommendation
Tracking Number: S-07-PPS-3

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Back contamination of sample containers

Short description of the Recommendation
Containment technologies for preventing contamination of lunar samples (by mission-associated contaminants) or containers (by lunar dust or other materials) should be considered as an objective for testing contamination prevention designs for sample containers to be used in Mars exploration.

Major reasons for the Recommendation
The Moon, with its significant concentration of extremely fine dust and solar wind volatiles, provides an excellent test bed for developing and testing technologies for containment of collected samples, to prevent both forward contamination of the sampling site, and back contamination of the habitats, return vehicles, and laboratories in which the sample containers are to be opened.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Protection Recommendation
Tracking Number: S-07-PPS-4

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
In-situ investigation of lunar sites for biologically derived or other compounds

Short description of the Recommendation
In-situ investigation of lunar sites using highly sensitive instruments designed to search for introduced, biologically derived, or other organic compounds should be given high priority.

Major reasons for the Recommendation
Exploration of the Moon has produced and will produce biological and organic contamination at the sites where human and/or robotic exploration takes place. Operations on the Moon are not constrained by Planetary Protection restrictions, which makes the Moon an optimal location to establish the magnitude of contamination associated with human exploration and exploration systems. Previous lunar exploration efforts, including both robotic missions and the manned missions of the Apollo program, have left behind artifacts on the Moon that are known to contain organic and microbial contaminants. These locations are ideal for testing planetary protection technologies and procedures to detect biological or organic contamination. Studies will be needed to determine lunar systems competency, containment, and leakage as well as the ability of evolving requirements to affect designs for Mars suits, landers, habitats, and other requirements. In addition, it is important to understand the potential for contamination of putative lunar ice or other volatile deposits with non-organically clean spacecraft and effluents.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Protection Recommendation
Tracking Number: S-07-PPS-5

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Planetary Protection protocols

Short description of the Recommendation
Make use of the opportunity of lunar exploration to develop planetary protection protocols that will be needed for exploration of Mars.

Major reasons for the Recommendation
Exploration of the Moon affords a unique opportunity to test planetary protection protocols in a challenging space environment, known to be sterile but not restricted by planetary protection policy. Such tests should be done to the extent that will be required for future human missions to Solar System bodies receiving more than Category I protection. [1]

[1] A Category I mission has no Planetary Protection restrictions, because the target location has been determined not to need protection. According to NPR 8020.12C, a Category I mission goes to a place that is "not of direct interest for understanding the process of chemical evolution, or where exploration will not be jeopardized by terrestrial contamination. No protection of such planets is warranted and no requirements are imposed."

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Protection Recommendation
Tracking Number: S-07-PPS-6

Committee Name: Science

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Advanced life-support systems

Short description of the Recommendation
The International Space Station and the facilities on the Moon should be used as test beds for advanced life-support systems for Mars exploration.

Major reasons for the Recommendation
As will be required on Mars, there should be a move towards development of sustainable, high efficiency, closed-loop systems, systems supplied by local resources, as well as a comprehensive effort to qualitatively and quantitatively assess their effectiveness. These demonstrations should begin on the ISS as soon as practicable and continue at the lunar outpost. Support should be provided to integrate exploration requirements into existing ISS life-support system deployments.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Science Recommendation
Tracking Number: S-07-PSS-1

Committee Name: Science

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Moon as a recorder of the impact history of the Inner Solar System and early Solar System dynamics

Short description of the Recommendation
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 our 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.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Science Recommendation
Tracking Number: S-07-PSS-2

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Geophysical network on the lunar surface

Short description of the Recommendation
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, a 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.

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.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Science Recommendation
Tracking Number: S-07-PSS-3

Committee Name:	Science
Workshop General Chair:	Bradley Jolliff
Date of Public Deliberation:	April 19, 2007
Date of Transmission:	May 18, 2007

Short title of the Recommendation
Mobility on the lunar surface

Short description of the Recommendation
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 (10-20km) 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 has feed forward to Mars exploration.

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Planetary Science Recommendation
Tracking Number: S-07-PSS-4

Committee Name: Science

Workshop General Chair: Bradley Jolliff

Date of Public Deliberation: April 19, 2007

Date of Transmission: May 18, 2007

Short title of the Recommendation
Technology development needs

Short description of the Recommendation
A lunar instrument and technology development program is needed to provide focused technological development for applications on the lunar surface.

Major reasons for the Recommendation
Technological developments are needed to achieve several of the highest-ranked scientific objectives are listed below. Such technologies need not be lunar-specific but can feed forward to Mars (and beyond) and include, but are not limited to, 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 (e.g., hand-held laser Raman spectrometer, x-ray fluorescence spectrometer).
- 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.

NASA Advisory Council Workshop on “Science Associated with the Lunar Exploration Architecture”

February 27 - March 2
2007

Tempe, Arizona

- Pre-Decisional –

18 May 2007

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FOREWORD

From February 27 through March 2, The NASA Advisory Council Science Committee conducted the "Workshop on Science Associated with the Lunar Exploration Architecture" at the Fiesta Inn Resort in Tempe, Arizona. The Workshop was planned and timed to feed into ongoing efforts by NASA's Lunar Architecture Team (LAT) to develop an exploration architecture for the return of humans to the Moon by 2020 in accordance with the Vision for Space Exploration and the NASA Authorization Act of 2005. The goals of the workshop were (1) to ensure that NASA's exploration strategy, architecture, and hardware development enable the best and appropriately integrated science activities in association with the return of humans to the Moon and subsequent exploration of Mars; (2) bring diverse constituencies together to hear, discuss, and assess science activities and priorities for science enabled by the exploration architecture; and (3) identify needed science programs and technology developments.

The workshop was a key part of the Council's obligation to advise the NASA Administrator on science associated with the Vision for Space Exploration while, in parallel, making its findings directly available to NASA's Exploration Systems Mission Directorate (ESMD) and Science Mission Directorate (SMD). The agenda was planned to cover exploration science, lunar science, lunar-based science, and science otherwise enabled by the emerging exploration architecture. Specific science objectives were discussed and priorities assessed as initial guidance for the return-to-the-Moon program planning. The workshop deliberations and the ensuing assessments from the science subcommittees are intended to enable the Council to make recommendations to the Administrator relative to the exploration strategy and architecture being developed by NASA. The workshop served as a major venue for the Science Community to provide input through the Council and Science Subcommittee representatives. In addition to the Council Science Committee and Subcommittee representatives, approximately 75 topical experts were invited to the workshop to make presentations and to assist with assessment of science objectives and priorities. An ad-hoc Outreach Committee was established to consider the key messages to be communicated to the Science Community and to the Public regarding the workshop outcome. The workshop was also open to the Science Community and the Public. Some 250 attendees were present at the beginning of the Workshop.

The workshop was organized by a committee consisting of representatives from each of the Science Subcommittees of the Council working with the subcommittee executive secretaries and representatives from SMD and ESMD at NASA Headquarters. The workshop was organized primarily according to subcommittee disciplines. Following an opening plenary with presentations by NASA officials and Science Community representatives to set the context, the workshop proceeded with breakout sessions designed to address the science objectives appropriate to each of the subcommittees as well as several cross-cutting themes. Subcommittees worked from objective lists developed by the Lunar Architecture Team from April to December 2006. Assessment of priorities and recommendations stemming from that effort are detailed in this report and its appendices. Members of the Lunar Architecture Team as well as program managers and others from NASA Headquarters participated in each of the breakout sessions. Scientists considered potential constraints imposed by the Exploration Architecture and provided results of assessments directly to members of the Lunar Architecture Team as well as to the Workshop Synthesis Committee representatives. This report by the Synthesis Committee summarizes and formalizes those assessments for consideration by the Council's Science Committee and the full Council.

Logistics for the workshop were supported by SMD, ESMD, and the NASA Advisory Council. On behalf of the Science Organizing Committee and the participants of the workshop, gratitude is expressed to NASA for its support of this activity. Contributions from the many participants of the Workshop are likewise gratefully acknowledged. As with the Falmouth Conference of 1965, which served to define and assess science objectives prior to the Apollo Program, preceded and followed by other conferences, this report is not a final or complete document on the subject. Instead, it is the beginning of a fruitful partnership and process through which the Science Community can have input to NASA's Exploration Architecture and implementation of the Vision for Space Exploration.

Bradley L. Jolliff, Workshop General Chair

ORGANIZING COMMITTEE

Bradley L. Jolliff (Chair)	Council Science Committee, Washington University, St. Louis
Clive R. Neal (Vice Chair)	LEAG Chair, University of Notre Dame

Astrophysics

Heidi Hammel	Space Science Institute
John C. Mather	Goddard Space Flight Center
Eric P. Smith	NASA SMD, Executive Secretary

Earth Science

Michael Ramsey	University of Pittsburgh
Kamal Sarabandi	University of Michigan
Bernard Minster	University of California San Diego
Lucia S. Tsaoussi	NASA SMD, Executive Secretary

Heliophysics

James Spann	Marshall Space Flight Center
David S. McKay	Johnson Space Center
Barbara Giles	NASA SMD, Executive Secretary

Planetary Protection

Nancy Ann Budden	Naval Postgraduate School
Andrew Steele	Carnegie Institute of Washington
Catharine A. Conley	NASA SMD, Executive Secretary

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Gerald L. Kulcinski	Chair, Human Capital Committee, University of Wisconsin-Madison; Outreach Committee Chair for the workshop

NASA Headquarters

Michael J. Wargo	NASA ESMD Lead and ESMD Lunar Exploration Scientist
Lisa D. May	NASA SMD Lead
Marc Allen	NASA SMD
Marian Norris	NASA SMD

The Workshop Synthesis Committee includes most of the members of the Organizing Committee listed above with the addition of Dr. Paul Hertz, NASA SMD.

Executive Summary and Key Assessments

The overall objective of the Workshop was to provide input from the scientific community through the NASA Advisory Council to the NASA Administrator regarding science associated with the return-to-the-Moon phase of the Vision for Space Exploration. Findings developed during the "Workshop on Science Associated with the Lunar Exploration Architecture" are intended to form a basis for Council recommendations regarding planning and implementation of NASA's Lunar Exploration Architecture and related science programs. Through attendance of their representatives, workshop considerations and findings became immediately available to the two Mission Directorates.

The workshop brought together diverse groups of space scientists with others who represented NASA Science Mission Directorate programs, science program managers, Exploration Systems Mission Directorate personnel, and Lunar Architecture Team members involved in planning lunar exploration. Breakout sessions were organized mainly along science discipline lines and focused on:

(1) defining the key objectives of science associated with, or enabled by, lunar exploration;
(2) discussing implementation to achieve the objectives;
(3) establishing overall science priorities within disciplines;
(4) prioritizing objectives within the framework of the emerging lunar architecture, in particular, those relevant to a polar outpost.

The participants in the workshop had access to a variety of previously released studies in the context of their discussions. Studies that were referred to included, but were not limited to the Report on the Scientific Context for the Exploration of the Moon (Space Studies Board), the Astrophysics Enabled by the Return to the Moon Workshop (Space Telescope Science Institute), the Earth Science Decadal Survey (Space Studies Board), and the lunar exploration White Paper of the Field Exploration and Analysis Team (FEAT).

Findings and key assessments

Each of the subcommittees effectively identified the highest priority science activities that could be accomplished or enabled by the lunar exploration architecture and by the specific notional architecture that has been proposed, i.e., a lunar polar outpost. They also identified the highest priority science activities for a lunar outpost as well as the general priorities for all science objectives for each subcommittee discipline. Some of the key findings are summarized in the following sections; however, the reader is encouraged to consider each of the discipline workshop reports (appendices 1–5) in their entirety. Only a brief summary is given here. A premise of the report (and of the workshop deliberations) is that the architecture will be based on an outpost concept. Assessments are made with respect to the notional polar outpost location, but attendees understood that a polar location and the sequence of missions to establish such an outpost are not set in stone at this time.

Astrophysics. The principal advantage offered by the Moon as an observatory platform for Astrophysics is the radio-quiet environment of the lunar far side and the potential to place low frequency (meter-wave) radio telescopes there. Because of shielding from terrestrial (continuous) and solar (half time) radio emissions and lack of a lunar ionosphere, a far-side observatory offers the potential for extremely sensitive probes of cosmic evolution of the Universe. If 21-cm radiation from hydrogen, emitted early during the formation of structure in the universe, can be detected, this highly red-shifted 21-cm signal would provide a unique and sensitive probe of cosmic evolution, including the formation of the first structure in the Universe and the first luminous objects. Appropriate steps must be taken throughout the architecture planning to ensure that a sufficiently radio-quiet environment can be maintained on the lunar far side and that infrastructure is planned to enable eventual deployment of such a facility.

Some of the observatories envisioned by the astrophysics community for deployment beyond Earth would optimally be placed in free space. Future Exploration program assets may enable or enhance deployment of such observatories. Others may be advantageously placed on the lunar surface, including low-frequency radio observatories, retroreflectors, and small, competitively selected “payloads of opportunity.” As the Exploration program evolves, NASA should sponsor studies to investigate ways in which the Exploration architecture can be enabling for astrophysics missions identified in science-community planning processes. The Astrophysics community should consider these potential enabling capabilities as it conceives programs to yield the highest priority science within the available resources.

Earth Science. The Earth Science community is the one for which the Lunar Exploration Architecture has the most critical implications owing to the potential siting of an outpost at a location that has a limiting view of Earth. Earth observations, which arguably have the most immediate societal relevance of all of NASA’s science enterprises, require a vantage point from which the whole Earth is in constant or nearly constant view. The Earth-facing side of the Moon provides a unique observation point with the potential for full-disc and full-spectrum, long-term observation of Earth’s changing surface and atmosphere from a stable and serviceable platform. If a polar outpost site were to be chosen, then to realize this potential, the architecture should include provisions for mobility to permit access to a suitable location such as the slopes of an Earth-facing massif such as Mount Malapert, near the lunar South Pole.

Given suitable viewing geometry, a dedicated Earth Observatory at or on the Moon would allow for global, continuous full-spectrum views of the Earth to address a range of Earth Science issues. Such issues include detection and analysis of time-dependent atmospheric composition (global mapping of emissions, long range transport of pollution plumes, greenhouse gases sources and sinks), ecosystem monitoring, observation of changes in the polar caps and other aspects of the cryosphere, and vertical structure of the Earth’s atmosphere. A lunar platform also allows the Sun-Earth system to be observed simultaneously, providing data on the Earth’s radiation balance and the influence of solar variability on climate. An observatory sited on the lunar surface would allow for growth and serviceability over time. A facility at the lunar outpost could also serve as a communications bridge across satellite platforms in other orbits (e.g., LEO, GEO, GPS), providing for synergistic operation and fusion of results of Earth-observing assets.

Heliophysics. Heliophysics science is unique among the science disciplines in that it directly addresses one of the major hazards of space-faring explorers, i.e., the solar radiation environment. Many of the Heliophysics observations and science objectives therefore fall into the category of ‘enabling’ for exploration in that they are necessary for safe and sustained operations on the Moon. The Moon is also seen as a recorder of past solar activity that is available for the reading in much the same way as ancient ice cores on Earth provide a record of atmospheric composition and activity as well as overall climate change. Heliophysics shares with Earth Science the objective of studying and monitoring interactions of the Sun and its fields with Earth's atmosphere and fields. Ultimately, such observations have great impact for society in terms of anticipating short-range hazards to space and satellite operations as well as understanding long-term responses of Earth's fields and atmosphere to the Sun's radiation and plasma environment.

Of the listed LAT objectives for Heliophysics, 13 were considered to be high-priority science. Five of these relate to understanding the lunar environment and several should be done prior to sustained human activity. Of special concern is understanding the electromagnetic and charged dust environment at a potential outpost or other lunar site. Several of the high-priority objectives are best accomplished from orbit and could be deployed as "drop-off" satellites. Real-time space weather monitoring would not be done on the Moon; monitoring measurements must be located as close to the solar source as is feasible. Lunar surface operations should include, as a high priority, sampling of the surface regolith and regolith strata within the context of well understood stratigraphy, such as within volcanic flow sequences, in order to investigate the nature and history of solar emissions and galactic cosmic rays. Although trenching could be done at a polar outpost site, access to a surface with inter-layered regolith and ancient, datable lava flows would be particularly significant. Improved measurements of the solar wind composition and the flux and composition of interplanetary and interstellar grains bombarding the lunar surface, and imaging of high energy x-rays and gamma-rays can also be accomplished on the lunar surface.

Planetary Science. Planetary Science seeks to understand the origin of the Solar System, the diversity of its planets and moons, and the factors involved in the origin and sustainability of life on Earth and perhaps on other planets and moons. For Planetary Science, the Moon is the keystone recorder of early solar-system processes, especially those pertaining to the Earth-Moon system and other terrestrial planets. The most important processes on the early Earth that shaped the environment in which life originated are recorded on the surface of the Moon in a uniquely accessible way.

A polar outpost will provide access to one of the major, unexplored and unsampled regions of the Moon, i.e., the poles, adding significantly to knowledge gained through exploration of the central near side by Apollo. A southern polar site also would be on the rim and would potentially provide access to associated materials of the huge and ancient South Pole-Aitken Basin, the earliest and largest impact basin that has been identified on the Moon, and a key to deciphering the early heavy bombardment history of the Moon and Earth. Many other of the Planetary Science objectives can be addressed at an outpost, but most require access to multiple locations around the entire Moon. Mobility – both short range near the outpost and long range, away from the outpost – is highlighted as a key asset to accomplish high-priority science. Robotic missions, both before and during human return to the Moon, are also considered appropriate to accomplish some of the highest priority science, primarily to access far-distant sites on the Moon, particularly from the outpost site. Development of technologies and strategies to deploy and maintain a geophysical network for a long duration, with broader implications for planetary exploration in general, is among the highest priorities.

As with Apollo, one of the legacies of the return of humans to the Moon will be the return of carefully selected, collected, and documented geologic sample materials – rocks and regolith – to Earth for study in terrestrial laboratories. Strategies, technologies, and operational techniques to maximize the mass and vertical and lateral diversity of returned lunar samples, as well as detailed documentation of their locations and associations, as developed during Apollo, must be modernized and new protocols developed and implemented. Crew composition, crew training, and documentation efficiency are critical components of success relative to returned samples. As part of the developing lunar exploration architecture, plans for geological and geophysical field training need to be established as an essential component in the preparation of astronaut crews for future missions to the Moon. The Orion Crew Exploration Vehicle (CEV) should have a capability similar to the Apollo science instrument module (SIM) to facilitate scientific measurements and the deployment of payloads from lunar orbit, a capability also important to Heliophysics. Lastly, continuous scientific input should be an integral component of the decision-making process for landing site targets for a lunar outpost or any lunar mission.

Planetary Protection. Operations on the Moon are not constrained by current Planetary Protection restrictions. This makes the Moon an optimal location to establish the magnitude of forward 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 occur. Tests such as the prevention of back contamination of sample containers by the extremely fine-grained lunar dust can serve as a surrogate objective for preventing such contamination of sample containers planned for use on Mars. Technologies and experimental equipment to perform Planetary Protection assays will need to be included in up-mass to the lunar science laboratory and crews will need to be trained in operation of equipment.

The Lunar environment may have some aspects needing protection (e.g., polar volatiles). Planetary Protection science objectives with high priority include: future in-situ investigations of locations on the Moon by highly sensitive instruments designed to search for biologically derived or other organic compounds, which will provide valuable “ground truth” data on in-situ contamination of samples; study of lunar space-suit competency, containment, and leakage, and the ability of evolving suit requirements to affect Mars suits, habitat designs and requirements; and understanding possible contamination of lunar ices with non-organically-clean spacecraft.

Cross cutting Issues

Trade studies should consider options for outpost and observatory siting. This issue is especially important for Earth observations, but also plays a role in Heliophysics objectives and Planetary Science objectives. Clearly, access to solar power has contributed to the decision to select a polar location for the notional architecture. However, options and trade studies for outpost locations at other latitudes are needed.

The 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 need to be clearly defined and supported. Much experience exists through Apollo, Skylab, Shuttle, Hubble Servicing, and International Space Station EVA’s to understand the roles of astronauts in the various elements of the architecture. For full mission success, many of the science objectives will necessarily require, for example, involvement of a Scientist Astronaut as an integral part of the science experiment or as a field geologist.

Science activities enabled by lunar exploration should continue to be evaluated and prioritized within the science community by the decadal survey and science roadmapping processes. Lunar science assessments formulated at the workshop 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. The NASA Science Mission Directorate has a well-validated process for establishing science priorities within their resource allocations. Once complete, information pertaining to the lunar science opportunities should enter into this process in the same manner as other SMD pre-planning Activities.

Implementation of the Vision for Space Exploration should be planned to accommodate capabilities that will enable the highest priority science, at least to the extent that other major objectives are not compromised. Because science missions are competed and not set forth in a specific programmatic way, the exploration architecture should be designed to enable the kinds of activities that are listed as being of potentially high scientific priority, even though some of these activities may never actually be done. This approach proved to be highly advantageous and flexible during Apollo.

Regular reviews (e.g., through the NASA Advisory Council structure) of major LAT decisions that may influence the science productivity of the Lunar Architecture should be conducted. Future evaluations of science objectives must assess the cost effectiveness of lunar outpost implementations versus implementations that utilize robotic/unmanned missions around the Moon or elsewhere.

Outreach

The Outreach Committee was integrated with subcommittee breakout groups throughout most of the workshop, but convened toward the end of the workshop to articulate the main messages of the workshop to the Scientific Community and to the Public. These are as follows:

(1) The Moon is witness to 4.5 billion years of Solar System history. Human exploration of the Moon will contribute greatly to discovering the origins of the Earth and of humanity.

(2) The Moon is a unique location from which to observe and analyze the ever changing nature of the Earth, Sun, and Universe.

(3) The Moon is a fundamental stepping stone to the human exploration of Mars and the rest of the Solar System.

The Outreach Committee also formulated messages relative to each of the subcommittee disciplines. These messages are listed in the body of the main report.

Concluding Statement

As with any new phase of space exploration, the scientific possibilities associated with the return-to-the-Moon exploration architecture are numerous and exciting. In this case, the human element brings a unique set of capabilities, and the global exploration strategy associated with the Vision for Space Exploration offers the potential to extend the possibilities considerably. This intent of the Tempe Workshop was to provide a clear assessment of the science priorities for activities enabled by the exploration plans and architecture. At the workshop, the science community began this process, and substantial progress was made, especially through interactions between individuals and groups that represent the US stakeholders in space science and exploration. We hope to continue this process as development of the exploration architecture progresses in coming years, leading to the return of human spaceflight to the Moon and preparation for the journey beyond.

Introduction and Overview of the Workshop

The NASA Advisory Council Workshop on Science Associated with the Lunar Exploration Architecture was held Feb. 27 through March 2, 2007, at the Fiesta Inn Resort in Tempe, Arizona. The Workshop was planned to bring together the Science Subcommittees, representing the various space science disciplines within NASA, representatives from the Science and Exploration Systems Mission Directorates (SMD, ESMD), the Lunar Architecture Team (LAT), and members of the Space Science Community at large to discuss science activities associated with or enabled by the emerging exploration architecture. The workshop is part of an ongoing effort to advise NASA on the exploration architecture associated with the Vision for Space Exploration.

One of the goals of the workshop was to bring together the diverse constituencies for science activities associated with the Vision for Space Exploration (VSE) and human return to the Moon. The first day of the workshop provided an overview of the activities and science objectives being considered as part of this new exploration program so that all participants could gain a sense of the diversity potential activities and began the process of assessing the various activities in terms of priorities, architecture capabilities and requirements, and phasing. The workshop opened with a plenary session during which NASA officials, including the Administrator, Dr. Michael Griffin, laid out plans for implementing the VSE. These plans include NASA's Global Exploration Strategy and specific efforts to delineate a notional lunar exploration architecture. Details of the notional architecture are given in a subsequent section as context for the subcommittee assessments of science activities and objectives. Development of the exploration architecture and constraints imposed by the architecture are not necessarily - or even mostly - driven by science considerations. The key issues for the science community are to determine the highest priority science activities that could be accomplished within the constraints of the exploration architecture. Of course, it is also desired wherever possible and wherever warranted to suggest changes to the architecture that would accommodate or enable high-priority science activities without compromising other key objectives.

Lunar science priorities are also under study by the National Research Council (NRC) and results from the interim report on the Scientific Context for Exploration of the Moon were presented during the opening plenary session. The NRC's recently released Earth Science Decadal Survey was also available, however, this Decadal Survey does not address Earth science possibilities enabled by lunar exploration. Each of the subcommittees, including Astrophysics, Earth Science, Heliophysics, Planetary Protection, and Planetary Science, presented an overview of the topics to be addressed during the workshop. The full agenda is included as Appendix 6 of this document.

One of the specific goals of the workshop was to have the science community, through the subcommittees, invited experts, and other participants, provide assessments and prioritization of science objectives that had been previously identified and grouped according to discipline by the LAT. The process of identifying potential objectives began in April 2006 at ESMD's Lunar Exploration Workshop and continued through December 2006 with a series of reviews and assessments by various organizations, including the Council subcommittees, the NRC lunar science study, and various Special Action Teams organized by the Lunar Exploration Analysis Group (LEAG). Independently, the Field Exploration and Analysis Team (FEAT), organized through the efforts of the Universities of Texas, Wyoming, and Arizona State, provided attendees with a detailed lunar field exploration White Paper and sponsored a pre-workshop geological-methods field trip. At the Tempe Workshop, the subcommittees provided assessments with respect to prioritization, phasing, needed technology developments and other issues, on the final list of science objectives. These important assessments are included in this report as Appendices 1-5. The final assessments of each of the subcommittees were briefed at the closing plenary session on March 2.

A key element of the workshop was the activity of the Outreach Committee. This committee was given the charge to determine how best to communicate the results of the workshop to the broader Science Community and to the Public. The Committee included members from each of the science subcommittees as well as outreach specialists. The Committee prepared a set of high-level highlights for science activities discussed by each of the subcommittees, which are detailed in a subsequent section.

The workshop was purposely designed to be an open meeting that anyone with an interest was free to attend. This was by design part of the effort to ensure that the Science Community has input to the development of the exploration architecture, which is to the mutual benefit of Exploration and Science. The plenary sessions of the workshop were broadcast over the internet using WebEx technology. Finally, in addition to this report, individual presentations made during the Workshop and White Papers submitted to the workshop (for oral or poster presentation and print only) have been placed on a public-access internet web site hosted by the Lunar and Planetary Institute, Houston, Texas http://www.lpi.usra.edu/meetings/LEA/.

The Vision for Space Exploration and the Role of Science

The Vision for Space Exploration as set forth by the President in 2004, and the role of science within the Vision, were articulated in the opening plenary by NASA Administrator, Dr. Michael Griffin, and by Deputy Associate Administrator for Science, Dr. Colleen Hartman, respectively. The President's and the Congress's mandate to extend NASA's human exploration beyond low-Earth orbit, beginning with the establishment of a sustained presence on the Moon, was expressed very clearly.

Such exploration endeavors, however, require multinational efforts if they are to be affordable and of maximum global impact, and this requirement forms a basis for the lunar-outpost approach for this next phase of human exploration. Specifically, NASA plans to provide the key infrastructure elements and core capabilities, including transportation and communication systems, but will welcome international and commercial proposals to augment other aspects of the exploration program, such as mobility, habitats, robotic capabilities, and science activities. Current budget levels and projections may constrain some important elements such as robotic precursor missions to be minimal, but such areas are ripe for augmentation of core capabilities by international partners or through science-focus missions by means of established programs. If critical components of the architecture are not forthcoming from international sources, such as mobility and habitats, it was made clear that NASA will seek funding to provide them.

The model that has been described for the lunar outpost concept has a useful analog in the historical exploration of Antarctica and the establishment of research outposts such as the Base at McMurdo. Legal aspects of lunar activity would be constrained by the Outer Space Treaty of 1967, portions of which were influenced by the Antarctic Treaty Regime. In such an endeavor, the role of science, while not the only ingredient, is a key ingredient. Not only are good science opportunities enabled by this architecture, but science is also enabling for exploration. Heliophysics, for example, provides an understanding of and predictive capabilities for space weather, including potentially deadly solar radiation events. Planetary Science includes the identification of hazards as well as the delineation of lunar resources and approaches to utilize them.

"Science in the space exploration vision is both enabling and enabled."
-- President's Commission on Implementation of US Space Exploration Policy

An expressed concern among some scientists across disciplines relates to the role of science activities enabled by the human exploration program and identified as compelling by the science community. Specifically, will such science activities have a greater or lesser priority than other space-science activities previously planned. The answer to this question was clearly stated that NASA will continue to use community-based processes such as decadal surveys and science roadmaps, as well as the Council's activities, to ensure that science investigations enabled by exploration are effective, relevant, and of the highest science quality.

For Exploration, the Moon is a stepping stone – a proving ground for eventual expansion of human activities to Mars. Humans must learn to live and work in space, off Earth and beyond low-Earth orbit. The Moon is where humans will first accomplish these goals.

The Global Exploration Strategy

Beginning in April 2006, NASA held a workshop to begin the process of defining exploration objectives across a wide range of themes. The workshop included representatives from the science community, commercial sector, and international representation, including all of the International Space Station partners. A strategy was developed to respond to two key issues, namely, (1) why are we going back to the Moon, and (2) what do we hope to accomplish when we get there. Six overarching exploration themes were identified in response to the first question, as follows:

- Human civilization
- Scientific knowledge
- Exploration preparation
- Global partnerships
- Economic expansion
- Public engagement

In answer to the second question, 180 specific lunar exploration objectives were defined that fall within the six exploration themes. Over 1000 people from around the world and experts of 14 space agencies have commented on and contributed to the themes and objectives. The "global" approach means inclusion of all stakeholders in the strategy development process in order to understand the interests of international partners, academia, the industrial and commercial sectors, and private US citizens. The "global" approach ensures a strong foundation for further discussion and cooperation, recognizing that this next phase of human exploration must have broad support, including international partnerships. In the long term, this exploration approach includes the Moon and Mars, and expansion to destinations beyond Mars. The initial focus, however, is on the human exploration of the Moon.

As part of developing the global exploration strategy, NASA identified 40 objectives of particular interest. These objectives include activities associated with preparing for human missions to Mars and other destinations, providing the capabilities to support scientific investigations; activities that would enable an extended/sustained human presence on the Moon, such as demonstrating the use of in-situ resources and measuring lunar phenomena, analyzing lunar resources and characterizing their possible use; activities that would enable international participation; and activities that would engage, inspire, and help educate the public.

To move from an exploration strategy to an exploration design required development of a notional architecture that takes into account budget and technology constraints, and that achieves national goals while maximizing response to the six exploration themes. Such a notional architecture permits assessment of how well the specific objectives might be met. From consideration of the broad set of themes and the specific objectives, NASA determined that an outpost rather than a set of sortie missions would enable a sustained human presence on the Moon that meets the priorities of the Vision for Space Exploration.

Although the lunar exploration architecture includes a wide variety of activities, ranging from the transportation and communication infrastructure to habitat development and on-surface exploration activities, a key aspect of the approach to developing the architecture was to identify those areas in which NASA would take the lead and those areas that would be well suited to commercial or international involvement, or that would have primarily a science focus. Key areas for NASA development include, but are not limited to, space transportation (including the Orion crew exploration vehicle, the Ares I and Ares V rockets, and the Lunar Surface Access Module), initial communications and navigation capabilities, the development of a suit for extravehicular activity on the lunar surface, providing a closed-loop life support system, and obtaining knowledge about the effects of the lunar environment on humans. Development of habitat elements and surface activities including in-situ resource utilization, scientific experiments, and on-surface mobility are examples of areas for which the involvement of the commercial, international, and scientific communities could augment the exploration infrastructure.

NASA’s approach to sustaining a human presence on the Moon is based on a "go-as-we-can-afford-to-pay” approach that would enable humans to return to the Moon no later than 2020. Through the combined exploration activities, NASA intends to extend operational experience in the hostile extraterrestrial planetary environment and to develop experiments and demonstrations to characterize the planetary environment. Operations at the outpost are planned to include demonstration of the feasibility of in-situ resource utilization and will provide opportunities for scientific investigation, economic expansion, education, and international participation, all of which will help to prepare the way for the human exploration of Mars.

The Lunar Exploration Architecture

The notional lunar architecture presented at the Tempe workshop was that of the south polar outpost, as first described at the December 2006 Exploration Conference held in Houston, Texas. This architecture follows from NASA’s human exploration objectives and national priorities, coupled with the global exploration strategy, described in the previous section. The polar outpost scenario follows from consideration of five key questions.

(1) What are the US priorities and phasing for what will be achieved at the Moon?

(2) How do priorities drive important decisions? Key decisions include whether to design to an outpost or to engage in a series of sortie missions, where to locate the landing site(s), and how much flexibility to incorporate to address other US priorities or far-term interests.

(3) What infrastructure is required to support priorities? Considerations include schedule vs. flight rate and cost vs. available budget.

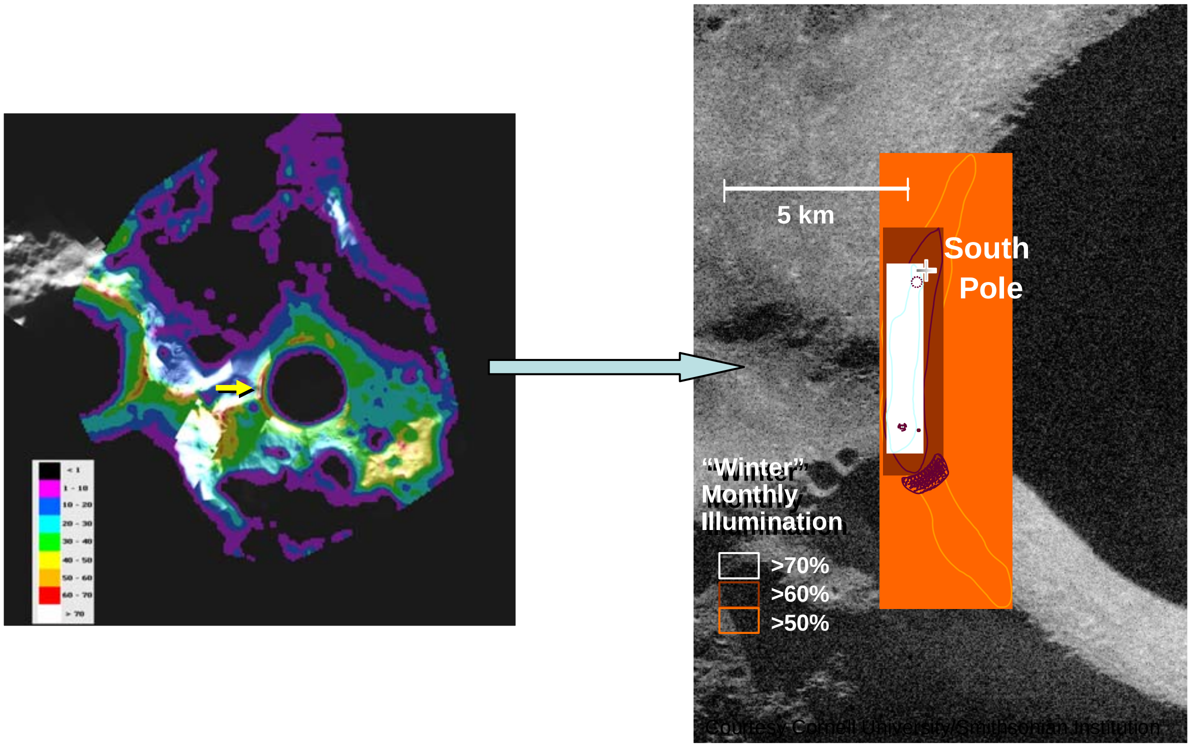
(4) What will NASA plan on developing, for example, critical-path hardware to achieve primary objectives while allowing for parallel developments from commercial and/or international communities?

(5) What level of limiting resources will allow for optimum realizable capability? Such resources are enabled by the basic NASA transportation architecture, including down-mass and up-mass at the Moon and power generation at the outpost.

Consideration of three of the exploration themes drove the architecture development to an *outpost.* These are Exploration Preparation, Human Civilization, and Economic Expansion. The outpost concept is thought to better enable global partnerships and allow development and maturation of In-Situ Resource Utilization (ISRU) efforts. According to LAT assessments, the outpost concept should result in the quickest path toward other destinations. Moreover, many science objectives can be satisfied at an outpost.

The decision to select a *polar* location for the notional outpost site (see figure) stems from several lines of argument. In terms of safety, a polar location provides good opportunities to return and the opportunity to abort to surface from orbit. The polar location permits a relatively low-energy return to Earth. A high percentage of sunlight allows the use of solar power and shortens the time required to sustain outpost operations through the lunar night. Initially, this access to plentiful power potentially makes a polar site more cost effective than one at lower latitudes that requires other sources of power. The polar site permits access to regolith with enhanced hydrogen concentrations and possibly water-ice (as well as other needed volatile elements) in permanently shadowed craters. Oxygen is as abundant in the lunar soil there as it is everywhere on the Moon. A polar site is flexible in that it allows incremental buildup using solar power, enhanced surface daylight operations, one communication asset (with backup), and more opportunities to launch. As a location on the Moon that is far removed from previous landing sites and well known areas, a polar site offers an element of exploration excitement and a unique environment of proximity to cold, dark craters.

Clearly, a key driver of the polar locations is access to solar power. The south polar site at the rim of Shackleton crater (see figure above) has a zone of 70% illumination during the middle of southern winter and better during southern summer. This site is within several kilometers of areas of permanent shadow within Shackleton crater. The Moon's north pole has three areas that experience 100% sunlight during northern summer and two zones that are proximal to craters in permanent shadow. Detailed mapping and imaging by the polar-orbiting Lunar Reconnaissance Orbiter, scheduled for launch in 2008, will better define the areas at the poles that are subject to constant or near-constant illumination.



Above: South polar region showing sunlight during southern winter (maximum darkness). **Right:** Possible location of an outpost on the rim of Shackleton Crater.

Although a polar site is considered for the notional architecture, the transportation infrastructure and the lunar-lander design are intended to enable human sortie missions to any location on the Moon, including the top ten sites identified by the 2005 ESAS Report[1]. Options exist within the architecture to trade crew for science payloads, including sample-return mass. For the outpost architecture, the point-of-departure design envisages landing missions beginning in 2020 at 6-month intervals that will incrementally build up outpost infrastructure and capabilities, including habitation modules, solar power collection and storage units, surface mobility and other logistics equipment, and ISRU modules. The ability to fly human sorties and cargo missions with the human lander will be preserved. The initial power architecture will be solar with the potential augmentation of nuclear power at a later time. Robotic missions will be used to characterize critical environmental parameters and lunar resources and to test technical capabilities as needed. The ability to fly robotic missions from the outpost or from Earth will be a possible augmentation.

NASA’s implementation philosophy is that the US will build the transportation infrastructure, the initial communication & navigation systems, and initial surface mobility capability. The architecture is open; NASA will welcome external development or augmentation of lunar surface infrastructure. The US will perform early demonstrations to encourage subsequent development

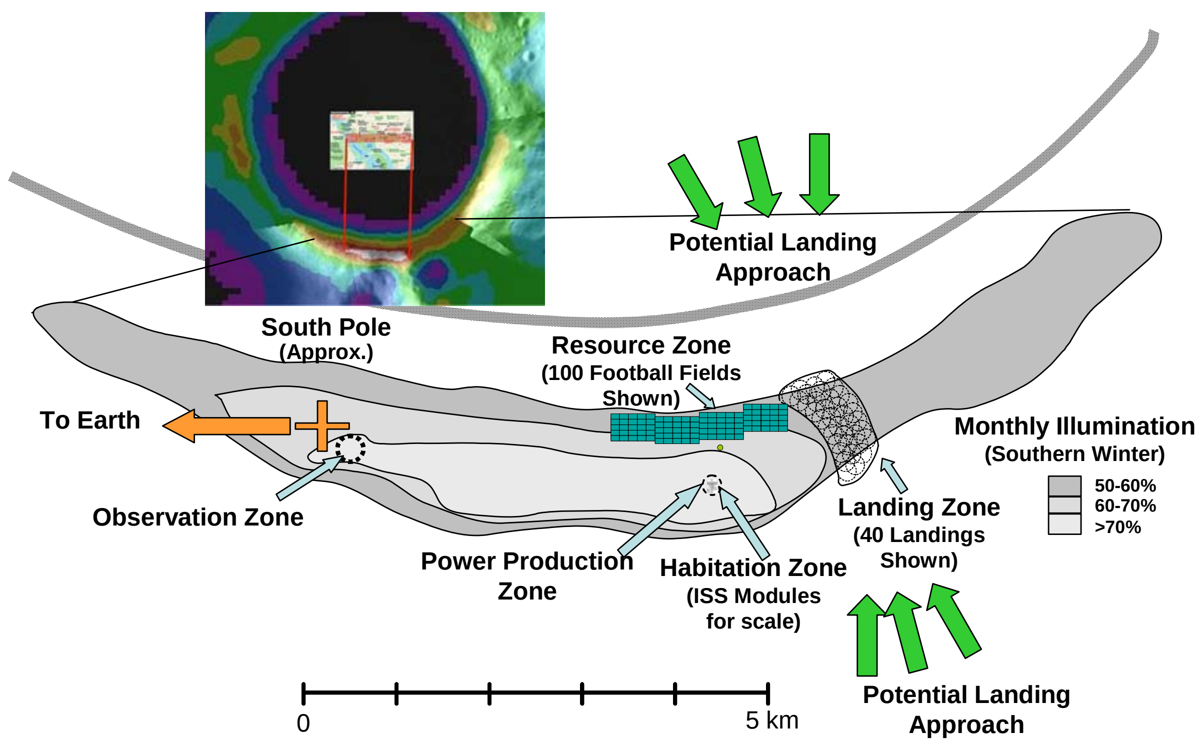
[1] ***NASA’s Exploration System Architecture Study*** (ESAS), Final Report, NASA TM-2005-214062, Nov. 2005

and will welcome external cooperation and parallel development of capabilities initially developed by NASA.

Desired capabilities at the outpost include a mature transportation system, a closed loop habitat, long duration human missions beyond LEO, surface EVA and mobility, autonomous operations, advanced robotic missions, minimal reliance on Earth via in-situ fabrication and resource utilization, and enhanced commercial and international partnerships.

The architecture envisages follow-on to outpost construction to possibly include human exploration of other lunar sites via sorties, expanded lunar outpost site operations, and expanded lunar outpost activities through commercial and/or international partnerships. Some of the exploration objectives for the outpost include, for example, developing and validating tools, technologies, and systems that excavate lunar material, characterizing radiation bombardment on the lunar surface and subsurface, understanding the effects of the integrated lunar environment on human performance, and providing position, navigation, and timing capabilities to support lunar operations, eventually evolving to support operations at Mars.

The lunar exploration architecture as articulated at the Tempe workshop was intended to be viewed as a point of departure. Subsequent activities of the lunar exploration architecture development include updating the objectives that drive the architecture, coordinating lunar exploration plans with interested communities, finding opportunities to collaborate, refining campaign and architecture concepts, and refining hardware concepts for the different elements of the architecture. Following the initial phase of lunar architecture development, a similar effort will be un-



Notional activity zones at an outpost site located on the rim of Shackleton crater at the South Pole.

dertaken to develop a Mars reference mission. The expressed intent throughout the process is to continue to engage academia, the private sector, and other stakeholders in defining a sustainable program of exploration.

Assessment of Potential Science Activities

Part of the development of the lunar architecture involved an assessment of science activities, conducted by the Science Capability Focus Element (SCFE) of the Lunar Architecture Team. The results of this assessment, conducted in 2006, were briefed at the Tempe Workshop by Dr. Laurie Leshin, Director of Sciences and Exploration, NASA GSFC and co-lead of the Science Capability Focus Element. This assessment involved a distillation of all the science-related objectives into a set of 45 objectives that fall within the disciplines represented by the main divisions within the Science Mission Directorate. Each objective was "deconstructed" to define needed capabilities and time-phasing issues. Each of these objectives was mapped to the lunar exploration architecture for "goodness of fit" and the resulting assessment was used to show what science can be relatively easily accommodated as well as what changes might need to be incorporated to accomplish additional science goals.

The matrix of science objectives was a focal point of the Tempe Workshop and participants were asked to evaluate the objectives in terms of their science priorities and how they would map to the lunar exploration architecture. Each of the Science subcommittees had previously seen and commented on the objectives, but the workshop was specifically tasked to present and discuss the related science issues and provide assessments of priorities for the potential science activities associated with these objectives.

Assumptions pertaining to capabilities for this assessment included the following:

A polar outpost-based architecture – all missions in this phase would go to (or near) the outpost site (except for any orbital capability);

Four crew, 7-14 day stay initially, followed by longer missions;

Some capability to fly robotic missions, especially before humans arrive;

Some moderate mobility for the crew from the outpost site during the short-stay missions -- ~10-20 km away from the site;

~500 kg of payload down-mass for science experiments/tools on crewed missions;

~100 kg sample return capability on crewed missions, including sample containers.

In the original assessment done by the SCFE, the following rating criteria were used:

Green – objective can be substantially accomplished by 2025 within the current architecture assuming the priority and funding are allocated.

Orange – objective will very likely take longer than the 2025 time horizon to accomplish, but could be accomplished in an outpost-based architecture.

Yellow – some part of the objective can be accomplished within the current architecture by 2025.

Pink – the objective can be accomplished with a combination of outpost-based science and robotic sorties.

Red – the objective can really only be accomplished through addition of human sorties, selection of a different site for the outpost, or addition of some other capability, such as long-range mobility, to the current architecture.

The initial overall assessment by the SCFE was positive and indicated that a polar outpost site would accommodate a large number of the science objectives, with over 50% potentially falling within the green rating. Science priorities for the objectives were not factored into the initial assessment; all objectives were treated with equal rank. Providing the priorities for specific objectives was requested of the Council and its Science Subcommittees to be accomplished at the Tempe Workshop. The findings of the workshop (next section) reflect the efforts of the workshop participants to consider the listed science activities, evaluate priorities, and assess the implementation of activities to address the objectives within the notional architecture.

Workshop participants recognized that the notional architecture was intended to be a point of departure and that results of the workshop would be used, along with other inputs, such as the NRC study on the Scientific Context for Exploration of the Moon, to further refine or revise the notional architecture and to help determine the optimal time phasing and relationships of the various possible activities. The assessments and findings of the Science Subcommittees are summarized in the next section and placed within the overall context of the exploration architecture as presented at the workshop. These assessments include discussion of issues of how the potential science activities might or might not fit within the exploration architecture, including how some of the activities might be enabled by the transportation infrastructure (Constellation) as well as outpost-specific issues. The full reports of findings and assessments are provided as appendices to this report.

Findings of the Workshop

Astrophysics

Four science goals were identified that are widely believed to pose intriguing astrophysical challenges for the next two decades, and to encompass the breadth of current astrophysics research. These are:

1. What is the nature of the dark energy that is propelling the cosmic expansion to accelerate?

2. Are there habitable extrasolar planets and, in particular, is there extraterrestrial life?

3. Which astronomical objects and which physical processes were involved in the “first light” in (and the re-ionization of) the universe?

4. How did galaxies and the large-scale structure of the “cosmic web” form?

The participants in the Tempe workshop agreed with these scientific goals, and adopted them as a framework within which to evaluate the objectives crafted by the Lunar Architecture Team.

Astrophysical opportunities within the Lunar Architecture worth pursuing

Meter-wavelength radio telescopes on the lunar far side would have exciting applications in cosmology, extra-solar planet characterization, and the physics in the nuclei of active galaxies. Concepts for such telescopes have a reasonable science and technology expansibility from small precursors to eventually large facilities. Also, in that field, good synergies exist between heliophysics and astrophysics. A similar access to the lunar near side would be desirable for deployment of a widely-dispersed retroreflector/transponder network to obtain increased accuracy for tests of general relativity. Smaller "payloads of opportunity" can provide interesting and competitive science. These smaller payloads, which should be competitively selected, do not necessarily do science of the highest (decadal survey) priority but still do good science that meshes well with the Lunar Architecture.

Enabling Capabilities for Astrophysics

Radio-quiet (RFI) environment and infrastructure on the lunar far side, or near the Shackleton site, for a meter-wavelength radio observatory. The far side of the Moon, because of its continuous shielding from terrestrial radio emissions and part-time shielding of solar radio emissions and lack of a lunar ionosphere, offers the potential for extremely sensitive probes of cosmic evolution of the Universe. During at least a portion of the process of the formation of structure in the universe, the dominant baryonic component, hydrogen, should have emitted 21-cm radiation. If this radiation can be detected, this (highly) red-shifted 21-cm signal will provide a unique and sensitive probe of cosmic evolution, including the formation of the first structure in the Universe and the first luminous objects. The most sensitive observations of these red-shifted 21-cm hydrogen signals will be obtained in a location on the lunar far side that is shielded from interfering signals.

Large launch vehicles capabilities. The Ares launch system offers a capability that could revolutionize astrophysics (and other sciences) by enabling entirely new classes of missions that will achieve priority observations. Current estimates for the launch mass and faring volume could enable: (1) a 6- to 8-meter class monolithic UV/Visible/IR observatory; (2) a 5-meter cube (130,000 kg) gamma ray water calorimeter; (3) a 4-meter-class x-ray observatory; (4) a 15- to 20-meter-class far-IR/sub-mm observatory; (5) a 25- to 30-meter-class segmented UV/Visible/IR observatory; (6) a 150-meter-class radio/microwave/terahertz antenna; or (7) constellations of formation-flying spacecraft.

Capability for secondary payload of small or medium science instruments. The architecture should include the capability for secondary payloads on both the Ares launch vehicles and the Orion space vehicles. These capabilities could include features such as an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring on the launch vehicles that could carry secondary payloads for deployment in near-lunar space, or the ESPA ring could form the structure for a secondary spacecraft like LCROSS (Lunar CRater Observation and Sensing Satellite) that would be deployed after the primary payload has been separated. Capabilities might also include secondary payloads for on-spacecraft autonomous instruments that do not require deployment. The Orion service module should also have the ability to carry secondary payloads that could be deployed in lunar orbit, and a payload bay that could accommodate remote sensing and in-situ experiments with the necessary thermal, mechanical, power and data handling interface.

In-space Operations. Very large aperture systems and spatial interferometers will be necessary to achieve many of the highest-priority astrophysics goals. Such systems must operate at various locations in free space throughout the Earth-Moon system, such as libration points, and high-Earth and geosynchronous orbits. Capabilities to support these high-value systems will eventually become essential (e.g., assembly, service, repair, refuel). Such capabilities may be achieved by augmentations to NASA's Exploration Architecture, which will be operational during the same timeframe. Examples of enabling capabilities include robotic or telerobotic systems, advanced in-space EVA from Orion, and capable transportation, including the Ares system.

Large area lunar access - Autonomous and/or human-assisted mobility. Several high-priority astrophysics programs are uniquely enabled by access to large areas of the lunar surface. Two such concepts are: (1) a large-area radio observatory located sufficiently far from human radio interference, and (2) a widely-dispersed retroreflector/transponder network to obtain increased accuracy for tests of general relativity. Both of these experiments/facilities could eventually require access to sites located hundreds to thousands of kilometers from a lunar base. Deployment of the assets potentially could be done either autonomously or via sortie missions by astronauts.

<u>Evaluations and/or Trade Studies to achieve Astrophysics Goals</u>

Function of humans on lunar surface. Although opportunities have been identified for astrophysics from lunar surface instruments that offer important science, these opportunities are either for small, largely self-contained packages, or for facilities (e.g., long-wavelength radio interferometers, lunar-ranging targets) that do not require precision alignment or positioning. Because it may be possible that general maintenance and servicing of such instrumentation may be uniquely enabled by hands-on access, a detailed assessment of the specific functionality of humans with respect to these opportunities should be done. This assessment can evaluate the viability of implementation plans for these opportunities that are entirely autonomous (or perhaps telerobotic), and to what extent such plans might compromise or enhance the performance of these facilities.

Options for large-area lunar-surface emplacement. Two astrophysical observations require access to a large fraction of the lunar surface. First, a facility designed to observe the highly red-shifted hydrogen 21-cm line from the distant Universe requires a significant amount of collecting area on the lunar far side. Current telescope designs envision a large number of individual elements (e.g., dipole antennas) that would need to be emplaced over this area. Second, sensitive tests of theories of gravity require laser retroreflectors, transponders, or both on the Moon. Optimal locations of these retroreflectors or transponders require wide spacing over the lunar surface at a variety of latitudes on the near side. An assessment is required of the manner in which these elements (dipole antennae or retroreflector/transponders) would be emplaced and how their emplacement sites can be integrated with the long-term objectives of the Planetary and Earth Sciences for global or complete near-side access.

Options for operations in free space. Capable operations in free space appear critical to achieve major goals for science, industry, and national security. Assessments and trade studies are necessary to understand more fully how these operations may enable multiple national priorities and to provide a reliable basis for the design of elements of the Lunar Architecture. The assessment elements may include: (1) the function in space of astronauts and robotic partners; (2) technology investment strategies; (3) options for coordinated development with industry, other government agencies, and international partners; (4) design options for block changes to the Orion/Ares 1/5 systems; (5) cost estimates for possible augmentations to the Exploration Architecture; (6) cost trades related to lunar based astrophysics observatories integrated into outpost activities vs. stand alone, independent space-based observatories; and (7) traceability of in-space systems to major national goals.

Strategies to maximize the potential for a meter-wave radio observatory. The expected signal strength from highly red-shifted hydrogen is quite small (~10 mK), requiring dynamic ranges of at least 1 part in 10,000, and the signal is expected to be spread over a significant frequency range, e.g., 10-200 MHz. To achieve such dynamic ranges and spectral access, a lunar telescope must be shielded from terrestrial, solar, lunar outpost, and other human-generated radio emissions. This requirement dictates a far-side location; however, even on the far side, multiple options exist to both realize the telescope and preserve the radio frequency environment. Examples of potential trade-offs include: (1) the degree of shielding and location on the far side, specifically with respect to how distant a long-wavelength observatory can be from a human outpost if relevant noise is being generated there; and (2) the design of the communications infrastructure so as to maintain the radio frequency environment, particularly at low frequencies.

Capabilities of the Ares system. Future major missions in space, both for science and national security, can be enabled by the capabilities of the proposed Ares V heavy-launch vehicle, specifically the mass and volume that can be delivered to priority locations throughout the Earth-Moon system. Assessment and trade studies are needed to more fully understand how Ares V can enable multiple goals in space and the science community must be informed about the performance capabilities of these vehicles.

Other findings. Astrophysics supports regular reviews (e.g., through the NASA Advisory Council structure) of major LAT decisions that may influence the science productivity of the Lunar Architecture. The VSE should be planned so as include (and not to preclude) capabilities that will enable astrophysics activities. Any lunar-enabled science can and should be evaluated and prioritized within the community by the decadal survey process. SMD funds are already committed to activities of the highest priority ranking in the Decadal Surveys. Assessments from the workshop should not be considered to replace or supercede the decadal survey process, although it is recognized that budgetary and operational considerations influence NASA's ability to implement specific objectives.

Earth Science

The goal of NASA Earth Science research is to observe, understand, and model the Earth system to monitor its processes and discover the way changes occur, to enable accurate prediction of these changes, and to understand the consequences for life on Earth. The data currently used for this research is collected by an array of low Earth orbiting (LEO) and geostationary (GEO) satellite-based instruments. During the Workshop, there were two overarching questions addressed by the Earth Science Subcommittee (ESS) and interested members of the community:

(1) What unique and/or complementary set of observations of the Earth can be made from the Moon that would significantly enhance data from LEO or GEO satellites?

(2) Could those measurements be made from the notional lunar South Pole outpost on the rim of Shackleton Crater and if not, from where could they be made?

A lunar Earth Observatory would offer a unique, stable, serviceable platform for global, continuous, full-spectrum views of the Earth to address a range of Earth-science issues over time, as well as provide instrument synergy among multiple LEO and GEO satellites for cooperative operations and enhanced calibration and science. The proposed outpost location, while only offering limited views of the Earth, could still be useful initially for Earth science and instrument testing in the early stages of lunar exploration. However, a longer-term phased approach is desired, where the future observatory would be located away from the outpost in order to provide the desired continuous Earth views and collect time-dependent data of atmospheric composition, ecosystem heath, and hazard monitoring. These data could be collected from a location further northward, at a higher elevation near the outpost, from a location further southward, or in orbit at the Cislunar Lagrange Point (L1). The ESS also adopted the criterion of *unacceptable* if the Earth was in view less than 50% of the time; *acceptable* if the Earth was in view more than 50% of the time; and *desirable* if the Earth was viewable more than 90% of the time.

The benefits of Earth observing from the lunar surface include a very stable platform that would be both accessible and serviceable, allowing a broader suite of instruments to be deployed and upgraded for Earth monitoring over a long time scale. The rotation of Earth as seen from the Moon, would provide unprecedented and valuable temporal views of transient phenomena such as natural hazards, pollution, and climate. Furthermore, the Earth's orbital precession would allow observations of the polar regions (one pole at a time, in summer), which is not possible with GEO satellites. This dynamic observing opportunity was illustrated qualitatively by descriptions made by the Lunar Module Pilot during Apollo 17's three-day trip to the Moon in 1972.

The potential for simultaneous measurements of the Sun and Earth from the Moon is another example of a set of observations that would allow a better understanding of the processes and interactions that determine the composition of the Earth's whole atmosphere including the connections to solar activity. Such measurements would also map atmospheric species concentrations (greenhouse gases, aerosols, ozone) and provide real-time space weather data for predictive modeling of the space environment.

The concept of a lunar-based Earth Observatory is highly compelling, but it must planned so as to maximize the science return while not distracting from critically needed Earth science observations from other platforms. Certain Earth science observations can only be made well from LEO (e.g., high spatial resolution imaging, lidar, etc.) and these datasets should not be abandoned in the planning and implementation of a possible lunar-based Earth Observatory.

To achieve the maximum return on Earth Science from the Moon and to best integrate with the final lunar architecture, the ESS recommends a phased approach to instrumentation, beginning with relatively simple instruments deployed either at the surface by humans or into an L1 orbit, and extending to more complex instruments requiring significant infrastructure. A detailed assessment of this phasing concept is presented in the Earth Science workshop report in Appendix 2.

The following key points were made with respect to Earth Science and the Exploration Architecture.

1) There are worthwhile and important Earth Science opportunities enabled from a lunar outpost. Large telescopes are not needed; good science can be obtained with ~ 0.3 m telescopes.

2) Implementation of the VSE should be planned so as to accommodate capabilities that will enable Earth Science. Earth Science observations will become increasingly critical in the coming decades to record climate change and to monitor and forecast natural hazards and potential disasters. Furthermore, there is great societal value to seeing Earth and its fragile atmosphere in the vastness of space. However, without significant mobility, Earth observing science is limited at the notional Shackleton outpost location. Cost-effective alternatives to this location should be considered.

3) Trade studies should consider options for outpost and observatory siting. Engineering studies should be conducted to determine the best strategy for maximizing the Earth observation potential. The study of possible locations should include sortie locations within easy reach of the lunar outpost such as a lower-elevation site with a clear view of Earth or a site at higher elevation and with Earth-facing slopes (e.g., Mt. Malapert) in regional proximity to the outpost. Both would possibly require new logistical and infrastructure considerations for the current lunar architecture.

4) Studies are needed to model sensor designs and data quality needed to address the Earth Science objectives from lunar platforms. More precise and formalized engineering studies must be carried out in order to constrain both the common architecture desired in a future Earth Observatory as well as specific sensor designs.

5) Options for operations in free space. Because of the limited options and cost associated with a lunar surface Earth Observatory, an option would be to place instruments at the Cislunar (L1) point in order to provide full-Earth views and achieve the major Earth Science goals. Assessments and trade studies are needed to understand how these operations might be enabled within the Lunar Architecture as well as to understand the cost trades related to lunar based observatories integrated into outpost activities vs. stand alone, independent space-based observatories.

6) Any science enabled by the lunar exploration should be evaluated and prioritized within the Earth Science community by the Decadal Survey process. However, it is recognized that the recent Earth Science Decadal Survey was conducted without consideration of the future (lunar) exploration architecture. In the near term, continued activity within the NASA Advisory structure will be required to fill this gap.

7) Further involvement of the Earth Science community in planning for science enabled by the lunar exploration architecture is needed. The ESS should organize and plan an *Earth Sci-*

ence from the Moon workshop comparable to the recent workshop on “Astrophysics enabled by a Return to the Moon.”

Public Outreach. The human response to seeing Earth from space is significant. Images from the Apollo, Mariner 10, Voyager, Galileo, and MESSENGER missions have provided a global view of the home planet that can not be seen from LEO. It is important to expand beyond the remarkable but only occasional photograph of the entire Earth to a more systematic and synoptic set of measurements that can only be realized and enabled by the Vision for Space Exploration. The lunar exploration architecture will disable a key opportunity in terms of public perception, outreach, and support if an outpost location is chosen with little or no opportunity to perform quantitative Earth observations and science.

Heliophysics

From presentations and discussion at the workshop, it was apparent that the exploration architecture potentially available by NASA’s return to the Moon presents interesting and exciting new opportunities to extend scientific progress in Heliophysics areas in ways that have not been previously available or considered.

Since the inception of the space program with Explorer 1 and continuing through to the present space weather missions, scientists in the Heliophysics community have worked to develop a detailed understanding of the connected Sun-Earth-Moon system. The Moon is immersed in a plasma environment – the local cosmos – that is “magnetized.” These fields play an essential role in organizing the space environment and have significant influence on the terrestrial environment as well. It is the twisting and folding of the various interacting magnetic fields – of the Earth, of the Sun, and locally, of the Moon itself – that regulate the local environment of the Moon and thus, the environment experienced by astronaut explorers. By working to understand this environment and ultimately to predict the variations likely to occur from day to day, and region to region, the efficiency, safety and productivity of future lunar robotic and manned missions can be significantly enhanced.

The Heliophysics science topics related to lunar exploration are grouped in four themes: (1) Heliophysics Science of the Moon – investigating fundamental space plasma processes using the Moon and its environment as a natural laboratory, (2) Space Weather; Safeguarding the Journey – understanding the drivers and dominant mechanisms of the lunar radiation and plasma-dust environment that affect the health and productivity of human and robotic explorers, (3) The Moon as a Historical Record – seeking knowledge of the history and evolution of the Sun and Solar System as captured in the lunar soil, (4) The Moon as a Heliophysics Science Platform – exploring possibilities of establishing remote sensing capability on the lunar surface to probe Geospace, the Sun and the Heliosphere.

Several issues that apply across Heliophysics science objectives are as follows:

1) For several Heliophysics science opportunities, drop-off satellites or early robotic operations are optimal for deployment and thus, the availability and capabilities of an Apollo-like Scientific Instrument Module (SIM) bay is of great importance.

2) Lunar science assessments formulated at this workshop are deemed to be valuable input to the next NRC Decadal Survey for Solar and Space Physics and NASA Heliophysics Science Roadmap. The NASA Science Mission Directorate has a well-validated process for establishing science priorities within their resource allocations. Once complete, the lunar science opportunities information should enter into this process in the same manner as other SMD Pre-Planning Activities.

3) Future evaluations of these science objectives must assess the cost effectiveness of these lunar site implementations versus more independent implementations that use robotic/unmanned missions around the Moon or elsewhere.

4) For full mission success, many of these science objectives will necessarily require involvement of a Scientist Astronaut as an integral part of the science experiment.

Heliophysics Science Objectives given a high priority include the following:

- Study the dynamics of the magnetotail as it crosses the Moon's orbit to learn about the development and transport of plasmoids.

- Study the impact of the Moon on the surrounding plasma environment and incident solar wind to better understand the magnetotail.

- Characterize the lunar atmosphere to understand its natural state. Of major importance, is the electromagnetic and charged dust environment and interaction with the variable space environment.

- Map the surface electromagnetic field of the Moon to understand the operational environment of the Moon.

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

- Monitor space weather in real time to determine and mitigate risks to lunar operations. Utilize the coordinated, distributed, simultaneous measurements by the heliospheric great observatory for predictive models of space radiation at the Moon.

- Monitor lunar environmental variables in real time to determine and mitigate risks to lunar operations. Use real-time observations on the Moon to determine the potential and duration of radiation hazards, the electrodynamic plasma environment, and effects of dust dynamics and adhesion.

- Understand the nature and history of solar emissions and galactic cosmic rays through studies of lunar regolith and regolith stratigraphy.

- Perform meter-wave radio astronomy observations of the Sun to improve understanding of space weather.

- Analyze the composition of the solar wind to improve understanding of the composition and processes of the Sun. Composition and flux of interplanetary / interstellar grains should also be considered.

- Image the interaction of the ionosphere and magnetosphere to understand space weather in the regions of space where most commercial and military space operations occur.

- Perform high-energy and optical observations of the Sun to improve understanding of the physical processes of the Sun.

- Analyze the Sun's role in climate change to gain a better overall understanding of climate.

Not all of these objectives would necessarily be best achieved by an observatory at a polar outpost. For example, for real-time space-weather monitoring, upstream monitoring measurements must be located between the Sun and Earth and as close to the solar source as is feasible. Some of these objectives require multiple observation locations, and some require or are benefited by collocation with human operations. Some require a view of the Earth and some require maximum exposure to sunlight and solar wind. Detailed assessments are given for each of these objectives in Appendix 3.

Planetary Protection

The Planetary Protection Subcommittee (PPS) of the Science Committee of the NASA Advisory Council is charged with providing advice on planetary protection policy and mission categorization to NASA and the Planetary Protection Officer, in accordance with guidelines of Article IX of the 1967 Outer Space Treaty. At the Tempe Workshop, the goal of the PPS was to ensure that planetary protection requirements for preventing biological and organic contamination of Solar System bodies will be considered to the greatest extent possible during the development of technologies and procedures to enable human exploration of the Solar System, for which a return to the Moon is the first step.

By NASA policy, missions to the Moon are currently considered Category I, which means that operations on the Moon are not constrained by planetary protection restrictions on biological and organic contamination. The Moon is considered to be a sterile and organically clean environment, which makes it an optimal location to evaluate the magnitude and range of biological contamination associated with human exploration, as well as to develop technologies designed to mitigate contamination resulting from human presence. A better understanding of organic and biological contamination resulting from past or planned human activities on the Moon will facilitate development and testing of equipment and technologies designed to limit human-associated contamination during exploration of more distant planetary bodies, including Mars, to which Planetary Protection restrictions are applied.

Planetary Protection, Key Findings

During the workshop, two key issues were considered essential to address during exploration of the Moon in order to prepare for future missions to Mars. A third concern, specific to the Moon, is that exploration of scientifically interesting polar regions on the Moon does increase the possibility of contamination that might interfere with future scientific discovery. Key findings are listed here:

1) Exploration of the Moon has produced and will produce biological and organic contamination at the sites where human and/or robotic exploration takes place. Operations on the Moon are not constrained by Planetary Protection restrictions, which makes the Moon an optimal location to establish the magnitude of contamination associated with human exploration. Previous lunar exploration efforts, including both robotic missions and the manned missions of the Apollo program, have left behind artifacts on the Moon that are known to contain organic and microbial contaminants. These locations are ideal for testing planetary protection technologies and procedures to detect biological or organic contamination. In addition, the Moon is an excellent testbed for developing and testing technologies for containment of collected samples, to prevent both forward contamination of the sampling site, and backward contamination of the habitat, return vehicle, and laboratory in which the sample containers are to be opened.

2) The Moon is an excellent testbed for developing technologies that will be required to permit human exploration of protected planetary bodies. The lunar return can facilitate development and testing of equipment and technologies designed to limit human-associated contamination. Many processes and technologies required for planetary exploration are likely to produce organic and biological contaminants that are regulated by Planetary Protection policy. Because organic and biological contamination of the Moon is not restricted, technologies that will be required for exploration of protected locations can be tested and optimized without costly limitations. Necessary technologies that will need optimization to minimize contamination include pressurized habitats and spacesuits as well as robotic and human-associated mobile equipment used for exploration or in-situ resource utilization (ISRU). Such technologies and procedures are absolutely required before humans can be permitted to travel to Mars or other protected Solar System bodies.

3) Lunar volatiles in polar deposits are susceptible to organic contamination during exploration, and future investigation may indicate that these regions contain materials of interest for scientific research. These regions of the Moon, though currently considered Category I, may become protected at a greater level pending future policy discussions.

Planetary Protection Objective Assessments

The two main science objectives considered by the PPS were (1) evaluate astrobiology protocols and measurement technologies that will be used to test for life on other planets, and (2) evaluate planetary protection protocols to develop the next generation planetary protection policy. Both of these objectives can be accomplished at an outpost location and within the notional lunar exploration architecture. These two objectives were subdivided to highlight or to expand specific components or activities, and these were each assigned priorities as follows:

High Priority:

Perform in-situ investigations of a variety of locations on the Moon by highly sensitive instruments designed to search for biologically derived organic compounds to assess the contamination of the Moon by lunar spacecraft and astronauts.

Understand possible contamination of lunar ices with non-organically-clean spacecraft. Evaluate and develop technologies to reduce possible contamination of lunar ices to address both mission-science and resource contamination concerns.

Use the Moon and lunar transit / orbits as a testbed for planetary protection procedures and technologies involved with implementing human Mars mission requirements prior to planning human Mars missions.

Medium Priority:

Perform chemical and microbiological studies on the effects of terrestrial contamination and microbial survival, both during lunar robotic and human missions (dedicated experiments and "natural" experiments in a variety of lunar environments/depths, etc.) and during the Apollo missions (study Apollo sites).

Develop technologies for effective containment of samples collected by humans to feed forward into designs that will help prevent forward and backward contamination during Mars missions.

Low Priority:

Use the lunar surface as a Mars analog site, to test proposed life detection systems in a sterile environment that are designed to go to Mars.

Enabling Technologies

Technology development is needed to ensure that life support and habitat technologies developed for the Moon can be used for later human missions to other Solar System bodies that have more stringent planetary protection requirements. Technologies and instruments developed for robotic spacecraft exploration and adapted for human interface, either with the assistance of a robot or through direct operation while wearing a space suit, include sample collection and sensitive, rapid assay methods using field-portable equipment. These should be reinvestigated for relevance to human exploration requirements. Commercial off-the-shelf technologies, however, are not rated for space-flight, and necessary modifications may require re-engineering to accommodate human-rated space-flight requirements such as low outgassing from construction materials and radiation-resistant electronics. The Moon can well be used as a testbed of advanced life-support systems for Mars exploration, emphasizing sustainable high efficiency closed-loop systems and comprehensive efforts to assess their effectiveness.

Planetary Protection Issues

The near-term focus on exploration of the Moon affords a unique opportunity for testing planetary protection protocols in a challenging space environment, known to be sterile but not restricted by planetary protection policy. Every effort should be made to take advantage of this opportunity, to ensure that planetary protection protocols are established to the extent that will be required for future human missions to Solar System bodies receiving more than Category I protection.

A separate, follow-on meeting to explore opportunities in biological sciences in partial gravity and at a pressurized Lunar Outpost is suggested. Such a meeting will continue and expand the recent effort that brought together Planetary Protection experts, astrobiologists, life-support specialists, and engineers to discuss human exploration of space

Substantial proportions of lunar dust are submicron-sized and could pose a significant health hazard. Current efforts to use data from Apollo and terrestrial dust exposure studies should be strongly encouraged to better understand exposure times, particle distributions, particle morphology, chemistry, and reactivity that may a pose health risks.

Planetary Protection technologies to reduce contamination from human missions must be supported if human missions to Mars are to be planned and implemented with appropriate planetary protection protocols.

Effective communication with the public about planetary protection goals and requirements is key to garnering and retaining public support for both robotic and human missions to other planetary bodies.

Planetary Science

The Planetary Sciences Subcommittee grouped science objectives under 5 broad science themes, as follows:

> (1) Investigation of the geological evolution of the Moon and other terrestrial bodies, including origin of the Earth-Moon system.
>
> (2) Improved knowledge of impact processes and impact history of the inner Solar System.
>
> (3) Characterization of regolith and mechanisms of regolith formation and evolution.
>
> (4) Study of endogenous and exogenous volatiles on the Moon and other planetary bodies.
>
> (5) Development and implementation of sample documentation and return technologies and protocols.

Within the context of these five science themes, 16 specific science objectives were ranked, as follows, (in approximate order of priority, but see Appendix 5 for specific priority rankings):

Determine the internal structure and dynamics of the Moon to constrain the origin, composition, and structure of the Moon and other planetary bodies. (mGEO-1) Achieving this objective requires emplacement of a seismic network with long-lived power supply for seismometers and multiple (3 or 4), widely separated sites. This objective cannot be addressed entirely 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, importantly, it would represent a start toward establishing a long-duration global seismic/geophysical network. This objective is one that would benefit from collaboration with international partners who might have landed missions to other lunar locations and could emplace additional network nodes.

Characterize impact flux over the Moon's geologic history, to understand early Solar System history. (mGEO-7) This objective requires the return of geologic samples for precise age dating by isotopic methods. Long-range surface mobility and/or access to multiple crater locations (e.g., via sorties) from many locations is needed to obtain the range of samples required to determine adequately the impact flux. If the outpost was located 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 to determine ages of superimposed younger basins. Access to South Pole-Aitken basin requires a far-side, southern hemisphere site.

Determine the composition and evolution of the lunar crust and mantle to constrain the origin and evolution of the Moon and other planetary bodies. (mGEO-2) Achieving this objective requires targeted sample returns from multiple locations; however, some progress can be made by intensive study of one site as well as by documentation and return of rock and regolith samples collected 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.

Study the lunar regolith to understand the nature and history of solar emissions, galactic cosmic rays, and the local interstellar medium. (mGEO-9) Activities needed to accomplish this objective include drilling and/or trenching of the lunar regolith. Extensive regolith excavation at a single site could address this objective by identifying layers deposited by specific impact events; however, such activities would be best done where inter-layered volcanic deposits provide an age record. Extensive ISRU processing could aid this scientific activity.

Characterize the lunar geophysical state variables to constrain the origin, composition, and structure of the Moon and other planetary bodies. (mGEO-3) These variables include the gravitational potential field, heat flow, lunar rotational fluctuations, lunar tides and deformation, and the present and historic magnetic fields. Little progress can be made on this objective from a single site, with the exception of temporal heat flow and magnetic measurements, which should span the lifetime of the outpost. The utility of a single heat-flow measurement depends on the complexity of the geological setting of the site.

Characterize the crustal geology of the Moon via the regolith to identify the range of geological materials present. (mGEO-5) This approach is less effective than going to diverse terrains on the Moon to sample the crust, but significant progress can be made at one site. A polar location represents a previously unsampled terrane. Regolith samples and rock fragments in the regolith complement any collection of large-rock samples. Regolith sampling could be conducted robotically.

Characterize the impact process, especially for large basins, on the Moon and other planetary bodies to understand this complex process. (mGEO-6) Significant progress can be made at a single site by studying a number of impact craters in detail; however, local to regional surface mobility for astronauts is needed. Achieving this objective requires orbital and sample data, including geological and geophysical field studies and return of key samples to Earth.

Characterize lunar volatiles and their source to determine their origin and to reveal the nature of impactors on the Moon. (mGEO-12) The analysis of volatiles in the lunar exosphere and in/near polar cold traps are well enabled by a polar outpost location. In terms of phasing, this activity should be done early in the human exploration program.

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. (mGEO-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.

Investigate meteorite impacts on the Moon to understand early Earth history and origin of life. (mGEO-8) This objective is aimed at finding Earth or other extralunar materials ejected from large impacts on Earth or by collisions involving other objects that later fell to the Moon. This objective requires access to multiple impact craters and regolith samples. It is well addressed at a single outpost site where large amounts of regolith can be processed and techniques employed to search for key indicator minerals or chemical compositions that would indicate the origin of the impactor.

Determine lunar regolith properties to understand the surface geology and environment of the Moon and other airless bodies. (mGEO-10) Achieving this objective involves extensive study of regolith, including excavation, sampling, and geophysical studies. This objective can be achieved at an outpost site. The investigation would go far beyond what is known from Apollo cores and active seismic measurements, and could involve in-situ measurements of many geotechnical and other regolith properties. Such investigations would be enabling for exploration.

Characterize the lunar regolith to understand the space weathering process in different crustal environments. (mGEO-11) This requires local surface mobility, trenching, sample documentation, collection, and return of samples to Earth. It can be done well at a single site with detailed investigation of regolith at different proximal locations and with different degrees of surface exposure.

Characterize transport of lunar volatiles to understand the processes of polar volatile deposit origin and evolution. (mGEO-13) This objective is best approached through global access (range of latitudes and locations). Much of this objective, however, can be achieved at a polar outpost site through access to permanently shaded craters and regolith near to and at a range of distances from the pole.

Characterize volatiles and other materials to understand their potential for lunar resource utilization. (mGEO-14) Ground truth/in-situ characterization of deposits located from orbital data can lead to accurately targeted locations on the Moon. This should be done during the robotic precursor phase to identify the best outpost location. Doing this activity from a polar outpost location instead of during the precursor phase will adequately characterize the deposits at the site, but would be too late to influence the optimal outpost location. This should be considered an exploration-enabling objective/activity.

Two of the objectives relate to implementation activities and are ranked along with the other science objectives with high priority:

Provide curatorial facilities and technologies to ensure contamination control for lunar samples. (mGEO-15) This objective can be well achieved at an outpost location. Potential polar volatile deposits would provide a test case for extremely environmentally sensitive sample documentation, collection, transfer, and processing.

Provide sample analysis instruments and protocols on the Moon to analyze lunar samples before returning them to Earth. (mGEO-16) This objective can be achieved at an outpost and could prove useful to enable adequate sample return in the event of return-mass limitations. Instrumentation can be used by astronauts to aid in documentation and selection of geologic samples.

Planetary Science recommendations

Geophysical Networks. Achievement of several of the highest-ranked lunar science objectives requires the deployment of long-lived geophysical monitoring networks. Precursory technology investments are needed, e.g., development of a long-lived power source and a deployment strategy for stations that are part of such networks. 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.

Sample Return. Achievement of several of the highest-ranked scientific objectives requires the development of a strategy to maximize the mass and diversity of returned lunar samples. The PSS views the 100 kg total return payload mass allocation in the current exploration architecture for geological sample return as far too low to support the top science objectives. The PSS requests that that CAPTEM be asked to undertake a study of this issue with specific recommendations for sample return specifications to be completed as soon as possible. The PSS recommends that NASA establish a well-defined protocol for the collection, documentation, return, and curation of lunar samples of various types and purpose in order to maximize scientific return while protecting the integrity of the lunar samples.

Astronaut Training. As part of the developing lunar exploration architecture, extensive geological, geochemical, and geophysical field training should be established as an essential component in the preparation of astronaut crews and the associated support community for future missions to the Moon. Training should involve experts and experience from the non-NASA community as well as NASA personnel of significant background and 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 of the next generation of lunar explorers. Crews for future lunar missions should include astronauts with professional field exploration experience. Research is needed to determine how robots can best be used to assist humans in activities associated with the lunar architecture.

Mobility. To maximize scientific return within the current exploration architecture, options should be defined and developed for local (~50 km), regional (up to 500 km), and global access from an outpost location. It is important that access to scientifically high-priority sites not be compromised by mobility limitations, both for outpost and sortie missions.

Robotic Missions. Robotic missions are highly desirable to carry out many of the highest-priority lunar-science objectives. Robotic precursor missions beyond LRO are important for both basic and exploration science (e.g., determining seismicity in proposed outpost locations and defining the nature of the cold-trap volatile deposits). To achieve the highest-ranked lunar science objectives, continued robotic sortie missions will be needed, before and after human presence is established.

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

Landing Site and Other Operational Decisions. Scientific input should be an integral component of the decision-making process for landing site targets and exploration planning and execution for a lunar outpost or any lunar mission.

Integration of Data Sets. Lunar data sets from all past missions, LRO, and future international missions should be geodetically controlled and accurately registered to a common format to create cartographic products that will enable landing-site characterization, descent and landed operations, and resource identification and utilization through a variety of data fusion techniques.

Technology Developments. A lunar instrument and technology development program is needed to achieve several of the highest-ranked scientific objectives, for example, exploration and sample documentation aids, long-lived 1-10 W power supplies; deployment of networks from orbit (e.g., from the CEV-SIM bay); sampling in permanently shadowed regions; development of robotically deployable heat-flow probes.

Sustained Scientific Input to Lunar Exploration Planning. Regular reviews of the major decisions that will influence the science outcome and legacy of lunar exploration should be carried out by the Council and its science subcommittees, and their findings and recommendations transmitted to NASA. Topics for such reviews should include:

- Options for full access to the Moon (low, mid, and high latitudes; nearside and farside; polar).
- Pre- and post-landing robotic exploration opportunities and missions.
- Options to mix human and robotic exploration.

- Surface science experiments and operations at the human outpost.
- Surface science experiments and operations during human sorties.
- Mission planning
- Critical items in space hardware design, including:
    - delivery of science experiments to the lunar surface;
    - returned payload constraints- upload of science (samples, data) from the lunar surface;
    - orbiting module science requirements (e.g., SIM bay);
    - crew orbiting science operational requirements (e.g., portholes).
    - mission Control science requirements during operations.

Outreach Message and Highlights of the Workshop

During the Workshop, the Outreach Committee formulated messages relative to each of the sub-committee disciplines, both for the science community and the Public. These messages provide an excellent summary of the scientific possibilities associated with or enabled by the return to the Moon and are given in the following paragraphs.

For **Astrophysics**, key messages for the science community are: (1) the return to the Moon will enable progress in astrophysics through the associated infrastructure. Some important astrophysical observations, as well as a few smaller experiments, can be uniquely carried out from the lunar surface and in lunar orbit. Potentially important observations include long-wavelength radio observations from the far side of the Moon, lunar laser ranging observations for fundamental physics, and characterization of Earth and dust in the Solar System as they apply to extra-solar planet research. (2) Astronauts can carry relatively small astronomy experiments with them to the Moon. These packages can accomplish a wide range of science from understanding how gravity really works to using the full view of our own Earth in understanding how to search for signs of life on other worlds. (3) The rockets that will take us back to the moon give astronomers the heavy lifting they need to put bigger and better telescopes in space. Among other things, these telescopes will look for earth-like planets beyond our solar system, investigate the environment around black holes, and probe the dark energy that makes up most of our Universe.

Public-oriented messages are: (1) The far-side of the Moon provides a radio quiet zone that enables astronomers to look back in time and find out when the first stars were born. (2) Astronauts can carry relatively small astronomy experiments with them to the Moon. These packages can accomplish a wide range of science from understanding how gravity really works to using the full view of our own Earth in understanding how to search for signs of life on other worlds. (3) The rockets that will take us back to the Moon give astronomers the heavy lifting they need to put bigger and better telescopes in space. Among other things, these telescopes will look for Earth-like planets beyond our Solar System, investigate the environment around black holes, and probe the dark energy that makes up most of our Universe.

For **Earth Science**, key messages are: (1) A lunar observatory provides a unique, stable, and serviceable platform for global, continuous full-spectrum observation of the Earth to address a range of Earth science issues over the long-term. (2) Synergy of current (LEO, GEO, GPS) assets with lunar instrumentation will insure the collection of the widest array of information from a lunar base. (3) There are numerous atmospheric profiling opportunities from visible (stars) to microwave (GPS) to VHF (communications).

Public-oriented messages are: (1) The view from the Moon offers a unique perspective of the full Earth, all at once, over time. (2) From an Earth Observatory on the Moon, we can take the pulse of the Earth from the Moon by monitoring long term Earth events such as, climate variability, air pollution sources and transport, natural hazards (extreme weather, volcanic plumes, hurricanes), and seasonal and long term variations in polar ice. (3) By viewing the Earth from a distance we can collect data to help us detect and study far away Earth-like planets.

For **Heliophysics**, key messages are: (1) Understanding our space environment is the first step to "Safeguarding the Journey." (2) The Moon can be used as an unique vantage point to better understand the Sun-Earth space environment –our "Home in Space." (3) The analysis of lunar regolith will provide a history of the Sun's brightness and radiation output and reveal how the Sun –Earth connection has changed through the ages. (4) The Moon is a natural laboratory for Space Physics.

The same key messages apply to the Public as for scientists. In terms of safeguarding the journey, we must recognize that outer space is a perilous ocean through which we must pass to reach the dusty shores of the Moon, then Mars. This ocean is permeated with charged particles, electromagnetic fields, and blasts of radiation from the Sun. We seek to enhance astronaut and robot productivity by forecasting and learning to mitigate resulting space weather and charged-particle impacts.

Planetary Protection is an important on-going focus of both science research and mission planning to safeguard planetary environments and exploration throughout the Solar System**.** Key messages are: (1) Based on the Outer Space Treaty, international policies, and decades of research and experience on protecting planetary bodies during exploration, lunar missions will not require special planetary protection controls. (2) Lunar exploration provides the opportunity for an integrated test bed of sophisticated technologies and methods needed to understand and control mission-associated contamination on long-duration expeditions. (3) Lessons learned on the Moon will provide essential, enabling, and comparative information such as understanding background and mission-associated organic and inorganic contaminants to ensure protection of planetary environments and humans as we explore Mars and other destinations.

Public-oriented messages are: (1) Based on international treaties, policies, and decades of research experience on protecting planetary bodies during exploration, lunar missions will not require special planetary protection controls. (2) Lunar exploration provides a good opportunity for testing technologies and methods to understand and control mission-associated contamination on long-duration expeditions. (3) Lessons learned on the Moon will provide essential information to ensure protection of planetary environments and humans as we explore Mars and other destinations.

For **Planetary Science**, key messages are: (1) The Moon is critical for accessing the early formation, differentiation, and impact history of the terrestrial planets, with implications for biotic evolution of Earth and, potentially, Mars. (2) Additional data are needed: geophysical and geochemical data to determine the composition, structure, condition, and evolution of the lunar interior; data from the lunar surface to understand the processes that have occurred during its evolution, such as the history of impact cratering and formation of regolith, and the distribution of resources; and data to inform us more about the lunar environment (conditions in cold traps, atmosphere, volatiles). (3) These new data will enable us to validate lunar science process models, understand the early history and evolution of Earth and other terrestrial planets, and prepare for human habitation of the Moon and beyond. Furthermore, the notional exploration architecture as presented (access to South Pole-Aitken Basin from the southern rim) will enable long-term lunar science in a region of high interest and can potentially address several scientific questions (e.g., crust to upper mantle access, impact processes). The scientific goals will have to be prioritized in a cohesive vision across a timeline. This long-term planning should encompass (a) robotic and robotic/human sorties to acquire distributed samples and establish the geophysical network necessary to prepare for a lunar outpost, as well as to address the fundamental science questions, and (b) samples from diverse locations on the lunar surface and subsurface to address fundamental science questions. In-situ science will optimize science output / return. The exploration and science community should actively participate in the development of human capital to fuel the pipeline of scientists and engineers.

Public-oriented messages are: (1) The Moon has a record of the early history of terrestrial planetary formation and change that is absent on other planets because they have active resurfacing processes like weathering and plate tectonics. (2) We are in a position to build on four decades of lunar science. There is much more new information to learn about our Moon and - from the Moon - about our Earth. For example, the Moon maintains a cratering history and may inform our understanding of the evolution of life on Earth and potentially elsewhere in the Solar System. (3) The lunar outpost will serve as a test-bed for science and exploration of the Moon, Mars and beyond (camp first in your own back yard!).

Concluding Statement

An outpost on the Moon will help us understand our ‘home in space’ and will provide a beginning to the next steps toward sustained human presence on another planet. An outpost on the Moon will enable many scientific observations and activities to be made to address fundamental questions in space science. Through scientific components of our exploration, we seek to understand how and why the Sun varies and what its effects are on the Earth, not just for the present, but over long periods of time as well. How do the Earth and other planets such as Mars and Venus respond to changes in the Sun’s activity and to other solar system events such as the impact of asteroids and comets? What is it about the Earth-Moon system that makes our part of the Solar System and Earth in particular perhaps uniquely habitable? What changes have occurred over time on the Moon, on Earth, and on other planets that affect the ability of life to claim a foothold and to sustain its presence? How unique is our Solar System within the Universe and how did our Solar System and Galaxy come to be as they are? Armed with a better understanding of our planetary past and our place in the universe, humanity will be richer in knowledge and better able to chart a course into the future. Scientific roles within the exploration architecture are key to charting this course and, thus, to implementation of NASA’s Vision for Space Exploration.

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Appendices: Workshop Subcommittee Reports of Findings and Program

Appendix 1. Astrophysics

Appendix 2. Earth Science

Appendix 3. Heliophysics

Appendix 4. Planetary Protection

Appendix 5. Planetary Science

Appendix 6. Workshop Program

Appendix 7. List of Acronyms used in the Report

White Paper and Presentation Archive. An electronic archive of white papers (oral, poster, and print only) and workshop presentations is maintained by the Lunar and Planetary Institute at http://www.lpi.usra.edu/meetings/LEA/

Appendix 1: Workshop Findings, Astrophysics Subcommittee

Astrophysics enabled by the Lunar Architecture: Context

In November 2006, representatives from the US astrophysics community participated a workshop entitled "Astrophysics Enabled by the Return to the Moon." The workshop was organized by the Space Telescope Science Institute (STScI), in collaboration with the Johns Hopkins University, the Association of Universities for Research in Astronomy, and NASA. The decision to hold the meeting was in direct response to the encouragement by the NASA Administrator to provide scientific input to the VSE, which envisions the return of humans to the lunar surface by 2020. The STScI workshop focused primarily on science: the broad workshop goal was to identify key questions in astrophysics, and to critically examine whether the proposed return to the Moon can—either directly or through the capabilities developed by the VSE—provide opportunities for significant progress toward answering those questions. Four science goals were identified that are widely believed to pose intriguing astrophysical challenges for the next two decades, and to encompass the breadth of current astrophysics research. These are (in no particular order):

1. What is the nature of the dark energy that is propelling the cosmic expansion to accelerate?
2. Are there habitable extrasolar planets and, in particular, is there extraterrestrial life?
3. Which astronomical objects and which physical processes were involved in the “first light” in (and the re-ionization of) the universe?
4. How did galaxies and the large-scale structure of the “cosmic web” form?

The participants in this Tempe workshop agreed with these scientific goals, and adopted them as a framework within which to evaluate the objectives crafted by the Lunar Architecture Team.

Our tasks at the Tempe workshop were to: first, confirm that the list of objectives identified by the Lunar Architecture Team (LAT) was complete and representative of the science goals outlined above, and second -- through invited presentations, posters, and general discussion -- assess the capabilities of the lunar architecture to achieve those objectives. The assessments include both intrinsic scientific value and also our best understanding of how well the objectives meshed with the architecture as we understood it. We were also asked to identify key technology developments required for implementation, and to identify needed trade studies.

Here we summarize our results. First, we present our key findings regarding astrophysics as enabled by the lunar architecture. We then list enabling technologies, along with succinct discussions of why those technologies were identified; we also identify a "Point of Contact" for each technology. After that, we list the studies relevant to the highest priority objectives. Finally, we provide a table that identifies each LAT objective, provides our assessment, discusses the primary factors that motivated the assessment, and details the specific trade studies associated with each objective.

Key Findings for Astrophysics

1. There are some worthwhile astrophysical opportunities within the Lunar Architecture.

Most promising seem to be low-frequency radio telescopes on the lunar surface, which have a reasonable science and technology expansibility from small precursors to eventually large facilities. Also, in that field there are good synergies between heliospheric physics and astrophysics. Smaller "payloads of opportunity" can also provide interesting and competitive science without deleterious effects on SMD planning or budget. These smaller payloads, which should be competitively selected, do not necessarily do science of the highest Decadal Survey priority but still do good science that meshes well with the Lunar Architecture. We recommend regular reviews through the NASA Advisory Council of major LAT decisions that may influence the science productivity of the Lunar Architecture.

2. VSE should be planned so as not to preclude – and to the extent possible, include – capabilities that will enable astrophysics.

This refers both to possible additions of capability in the future and to keeping environments in an appropriate condition for future development.

3. Any lunar-enabled science can and should be evaluated and prioritized within the community by the decadal survey process.

SMD funds are already committed to activities of the highest priority ranking in the decadal surveys. Our assessments should not be considered to—in any way—replace or supercede the decadal survey process. The assessments include, in addition to intrinsic science, the manner in which the science may mesh with the Lunar Architecture.

Detailed Assessment of LAT Astrophysics Objectives

Key for Assessments (details provided in "comments" section for each objective):
1 = high priority science and/or perceived excellent mesh with lunar architecture
2 = medium priority science and/or difficult fit with lunar architecture
3 = low priority science and/or poor fit with lunar architecture

Key for Trade Studies (details provided in the next section):
[1] Function of humans on lunar surface
[2] Options for large-area lunar-surface emplacement
[3] Options for operations in free space
[4] Strategies to maximize the potential for a low-frequency observatory
[5] Capabilities of the Ares system

Code	Our title	Assess	Comments	Studies
mA1	Low-frequency Radio	1	A low-frequency observatory on the lunar far side would open a new window below the ionospheric cutoff. Such a facility would have exciting	[1],[2],[4]

	Observations		applications in cosmology, extra-solar planet characterization, and the physics in the nuclei of active galaxies. There are good opportunities for scientific and technological expansibility, and strong synergies with some heliospheric experiments.	
mA2	*Lunar Optical Interferometer*	*3*	*Space-based telescopes will do a better job of covering the UV plane. Free space is also a cleaner and more flexible environment*	
mA3	*Detect Gravitational Waves*	*3*	*Free space is a superior environment.*	
mA4	*Large Lunar Optical Telescope*	*3*	*Transit telescopes have limited scientific usefulness. Free space is a cleaner and more flexible environment.*	
mA5	Lunar Energetic Observatory	1	1 = Low Earth Orbit mission: the Ares V would uniquely enable this. Potential successor mission to GLAST. 3 = On lunar surface: this option would require significant in-situ construction capabilities (125 tons of materials processed on surface). Alternative of using Ares V to launch detector to low earth orbit seems more attractive.	[5]; [1] for lunar surface option
mA6	*Search for exotic stable states of matter*	*3*	*There are already very strong limits from terrestrial studies. The science case was not compelling.*	
mA7	Fundamental Physics	1	The recent astrophysical evidence for an accelerating universe strengthens the case for tests of gravity. Shackleton Outpost is useful for a single deployment. We would eventually like several widely-dispersed locations.	[1]
mA8	*Near-Earth Asteroids*	*N/A*	*Sent to Planetary Science Subcommittee.*	
mA9	Site Charac-terization	1	The highest priority for site characterization would be for low-frequency radio observatory. Many astronomical applications need clean environment, and there is also good synergy with site characterization activities in the other disciplines (heliophysics, planetary protection).	[1],[2],[4]
mA10	"Piggyback" missions to surface and lunar orbit	1	1 = good fit with lunar architecture. This capability offers the potential for frequent inexpensive access to space. A science assessment would depend on the specific competitively-selected mission. There is a wide range of potential applications, including simple	[1],[5]

			retroreflectors, as well as earth-observing telescopes and inner zodiacal dust characterization (the latter two concepts have implications for extra-solar planet research).	
mA11	Large Telescope at Earth-Sun L2	1	Ares V provides a launch vehicle capable of launching an 8- to 15-m optical/UV space telescope. This capability would remove pressure for light-weighting of structures and optics. Other possible payloads include infrared, X-ray, and gamma-ray telescopes. Fairing sizes of 12 meters have been identified as useful.	[3],[5]

Enabling Capabilities for Astrophysics

Examples of capabilities that will enable astrophysics. Within each category, no prioritization is implied.

High-Priority Astrophysics, and may influence Architecture

Radio-quiet (RFI) environment and infrastructure on the lunar far side, or near Shackleton site, for low-frequency observatory (e.g., the local lunar atmosphere and electronic density goes up significantly for a month with every landing). Point of contact: Joe Lazio (NRL).

The far side of the Moon, because of its shielding from terrestrial and solar radio emissions and lack of a permanent ionosphere, offers the potential for extremely sensitive probes of cosmic evolution of the Universe. In the "hot Big Bang" cosmology, the Universe started in a dense, ionized state. As it expanded and cooled, it underwent a transition to a neutral state (this process is called recombination). After recombination, baryons began to collapse into regions of higher density, leading to the formation of stars and galaxies. Today, their radiation maintains the Universe in an ionized state. During at least a portion of this process of structure formation, the dominant baryonic component of the Universe, hydrogen, should have emitted 21-cm radiation. If this radiation can be detected, this (highly) red-shifted 21-cm signal will provide a unique and sensitive probe of cosmic evolution, including the formation of the first structure in the Universe and the first luminous objects. The implied wavelength range (wavelength > 1.5 m or frequency < 200 MHz) is a heavily-used spectral region on Earth (e.g., for FM radio). The expected strengths of the hydrogen 21-cm signals are quite small, many orders of magnitude below the strength of typical human-generated transmissions, solar radio emissions, and natural terrestrial radio emissions. Thus, the most sensitive observations of these red-shifted 21-cm hydrogen signals will be obtained in a location that is shielded from these interfering signals. The lunar far side is an excellent environment for such studies.

Large launch vehicles capabilities - VSE will include large launch vehicles like the Ares V, and the community should be part of the dialogue in crafting its capabilities or those derived from it (examples include but are not limited to volume, large mass capability, and

similar aspect ratio). The community can envision several large telescopes which could utilize this capability. Point of contact: Phil Stahl (NASA/MSFC)

The Ares launch system (i.e., Ares I and Ares V) offers a capability that could revolutionize astrophysics (and other sciences) by enabling entirely new classes of missions that will achieve priority astrophysics. Specifically, current estimates for the launch mass and faring volume could enable: (1) a 6- to 8-meter class monolithic UV/Visible/IR observatory; (2) a 5-meter cube (130,000 kg) gamma ray water calorimeter; (3) a 4-meter-class x-ray observatory; (4) a 15- to 20-meter-class far-IR/sub-mm observatory; (5) a 25- to 30-meter-class segmented UV/Visible/IR observatory; (6) a 150-meter-class radio/microwave/terahertz antenna; or (7) constellations of formation-flying spacecraft.

Capability for secondary payload of small or medium science instruments (on lunar orbiters, or for transportation to lunar surface – Ares system, CEV). Point of contact: Tupper Hyde (NASA/GSFC)

The VSE architecture should include the capability for secondary payloads on both the Ares launch vehicles and the Orion space vehicles. These capabilities could include features such as an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring on the launch vehicles that could carry secondary payloads for deployment in near-lunar space, or the ESPA ring could form the structure for a secondary spacecraft like LCROSS (Lunar CRater Observation and Sensing Satellite) that would be deployed after the primary payload has been separated. Capabilities might also include secondary payloads for on-spacecraft autonomous instruments that do not require deployment. The Orion service module should also have the ability to carry secondary payloads in an Apollo-like Scientific Instrument Module (SIM) that could be deployed in lunar orbit, and a payload bay that could accommodate remote sensing and in-situ experiments with the necessary thermal, mechanical, power and data handling interface.

In-space Operations - holds potential for assembly, servicing, and deployment (trade studies). Point of contact: Harley Thronson (NASA/GSFC)

We found that very large aperture systems and spatial interferometers will be necessary to achieve many of the highest-priority astrophysics goals; this finding was supported by presenters at this and other workshops. Such systems must operate at various locations in free space throughout the Earth-Moon system, such as libration points, and high-Earth and geosynchronous orbits. Capabilities to support these high-value systems will eventually become essential (e.g., assembly, service, repair, refuel). Such capabilities may be achieved by modest augmentations to NASA's Exploration Architecture, which will be operational during the same timeframe. Examples of enabling capabilities include robotic/telerobotics systems, advanced in-space EVA from Orion, and capable transportation, including the Ares system.

Large area lunar access - Autonomous and/or human-assisted mobility (depending on trade studies) Points of contact: Joe Lazio (NRL) & Tom Murphy (UCSD).

Several high-priority astrophysics programs are uniquely enabled by access to large areas of the lunar surface. Two concepts demonstrating this need are: a large-area radio observatory located sufficiently far from human radio interference, and a widely-dispersed retroreflector/transponder network to obtain increased accuracy for tests of general relativity. Both of these experiments/facilities could eventually require access to sites located hundreds to thousands of kilometers from a lunar base. Deployment of the assets could be done either autonomously or via astronauts.

Moderate Priority for astrophysics, may influence architecture

Minimize dust in environment of small facilities (with optics, retro-reflectors).

High priority to astrophysics but will probably not influence Architecture

Enable high-bandwidth communication.

Evaluations and/or Trade Studies to Achieve Astrophysics Goals

No prioritization is implied – numbering is for ease of reference only.

[1] Function of humans on lunar surface

Although opportunities have been identified for astrophysics from lunar surface instruments that offer important science, these opportunities are either for small, largely self-contained packages, or for facilities (e.g., long-wavelength radio interferometers, lunar-ranging targets) that do not require precision alignment or positioning. In this context, conveyance to the lunar surface is a requirement, but the need of humans for emplacement, deployment, or operations may not be. Because it may be possible that general maintenance and servicing of such instrumentation may be uniquely enabled by hands-on access, a detailed assessment of the specific functionality of humans with respect to these opportunities should be done. This assessment can evaluate the viability of implementation plans for these opportunities that are entirely autonomous (or perhaps telerobotic), and to what extent such plans might tend to compromise the performance of these facilities. More broadly and in the context of the current Exploration architecture, such an assessment could list the functional advantages by which a human agent could add value to any astrophysical installation on the lunar surface.

[2] Options for large-area lunar-surface emplacement

There are two astrophysical observations that require access to a large fraction of the lunar surface. First, a facility designed to observe the highly red-shifted hydrogen 21-cm line from the distant Universe requires a significant amount of collecting area on the lunar far side: spread over at least tens of kilometers, and potentially more. Current telescope designs envision a large number of individual elements (e.g., dipole antennas) that would need to be emplaced over this area. Second, sensitive tests of theories of gravity require laser retroreflectors, transponders, or both on the Moon. Optimal locations of these retroreflectors or transponders require wide spacing over the lunar surface at a variety of latitudes on the near side. An assessment is required of the manner or manners in which these elements (dipole antennae or retroreflector/transponders) would be emplaced across the desired area.

[3] Options for operations in free space

Capable operations in free space appear critical to achieve major goals for science, industry, and national security. Assessments and trade studies are necessary to understand more fully how these operations may enable multiple national priorities and to provide a reliable basis for the design of elements of the Lunar Architecture. The assessment elements may include: (1) the function in space of astronauts and robotic partners; (2) technology investment strategies; (3) options for coordinated development with industry, other government agencies, and international partners; (4) design options for block changes to the Orion/Ares 1/5 systems; (5) cost estimates for possible modest augmentations to the Exploration Architecture; and (6) traceability of in-space systems to major national goals.

[4] Strategies to maximize the potential for a low-frequency observatory

The expected signal strength from highly red-shifted hydrogen is quite small (~10 mK), requiring dynamic ranges of at least 1 part in 10,000. Moreover, the signal is expected to be spread over a significant frequency (wavelength) range. In order to achieve such dynamic ranges and spectral access, a lunar telescope must be shielded from terrestrial, solar, and human-generated radio emissions. Generally, this requirement dictates a far-side location. Even on the far side, though, there are multiple options to both realize the telescope and preserve the radio frequency environment. Examples of potential trade-offs include: (1) the degree of shielding and location on the far side, specifically with respect to how distant a long-wavelength observatory can be from a human outpost; (2) planning constraints for human and/or robotic sortie mission to far side exploration targets; and (3) the design of the communications infrastructure so as to maintain the radio frequency environment, particularly at low frequencies.

[5] Capabilities of the Ares system

Future major missions in space, both for science and national security, can be enabled by the capabilities of the proposed Ares 5 heavy-launch vehicle, specifically the mass and volume that can be delivered to priority locations throughout the Earth-Moon system. Assessment and trade studies to more fully understand how Ares 5 can enable multiple goals in space include: (1) detailed designs and performance estimates, including options for the fairing for alternative payloads (e.g., height, width, aspect ratio); (2) cost estimates, schedule, and milestones; (3) operation of the Ares V with other plausible systems operating during the same time period, such as the Orion or Ares I vehicles; and (4) recommendations for professional outreach to inform the science communities about the performance capabilities of these vehicles.

Authors

Heidi B. Hammel, Space Science Institute, Boulder, CO <hbh@alum.mit.edu>

John C. Mather, NASA Goddard Space Flight Center, Greenbelt, MD
<John.C.Mather@nasa.gov>

Appendix 2. Workshop Findings, Earth Science Subcommittee

Earth Science Executive Summary

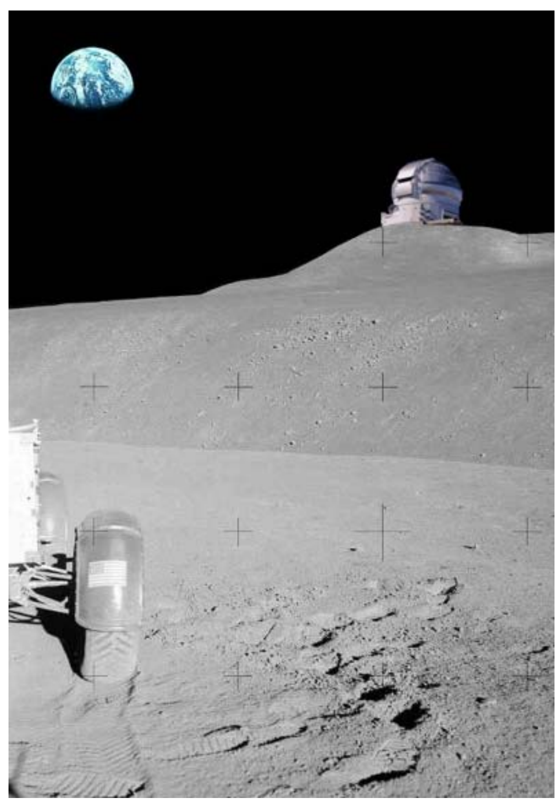
The goal of NASA Earth Science research is to understand the surface, atmospheric, and near-Earth space processes. To advance this understanding, we observe and model the Earth System to monitor its processes and discover the way changes occur. In so doing, we enable accurate prediction of changes and improve our understanding of the consequences of those changes for life on Earth. Much of the data needed for this research is currently collected by an array of low Earth orbiting (LEO) and geostationary (GEO) satellite-based instruments.

During the Workshop on Science Associated with the Lunar Exploration Architecture held in Tempe, AZ there were two overarching questions addressed by the Earth Science Subcommittee (ESS) of the NASA Advisory Council and interested members of the science community:

i. What unique/complementary set of observations of the Earth can be made from the Moon that would significantly enhance data from LEO or GEO satellites?

ii. Could those measurements be made from the proposed lunar South Pole outpost on the rim of Shackleton Crater?

These questions were addressed in a diverse set of talks presented in four scientific sessions: (1) A Lunar-based Earth Observatory, (2) Solid-Earth Science, (3) Atmospheric Composition and Climate, and (4) Sun-Earth Interactions.



The ESS concluded that a lunar Earth Observatory would offer a unique, stable, and serviceable platform for global, continuous, full-spectrum views of the Earth to address a range of Earth Science issues over time, as well as provide instrument synergy among multiple LEO and GEO satellites for cooperative operations, enhanced calibration, and science. The proposed outpost location, while only offering limited views of the Earth, could still be useful initially for Earth Science and instrument testing in the early stages of lunar exploration. However, the ESS endorsed a longer-term phased approach, where the future observatory would be located away from the outpost in order to provide the desired continuous Earth views, mitigate the inevitable noise (e.g., radio, light, seismic, etc.) and dust problems associated with human activity, and thereby collect time-dependent data of atmospheric composition, ecosystem health, and hazard monitoring. This could be accomplished either from a location further northward or further to the south, one at a higher elevation near the outpost, or from orbit at the Cislunar Lagrange Point (L1). The ESS also adopted the criterion for location of *unacceptable* if the Earth was in view less than 50% of the time; *acceptable* if the Earth was in view more than 50% of the time; and *desirable* if the Earth was viewable more than 90% of the time. The final location of such an observatory should be subject to careful analysis and study (see Required Studies section). Furthermore, a consistent architecture across instruments (e.g. communication links, compatible data formats, etc.) that would enable simplified instrument integration and expansion over time is the goal. Finally, a phased growth from relatively simple instruments taken to the new outpost location to more complex instrumentation involving human or robotic sorties is recommended.

Regardless of the issues attached to the observatory location, the ESS recognized that there would be certain challenges and unique benefits by using the Moon as a remote-sensing platform from which to observe the Earth. The rotation of Earth as seen from the Moon would provide unprecedented temporal views of transient phenomena such as natural hazards, pollution, and climate. Furthermore, the Earth's orbital precession would allow observations of the polar regions (something not possible with GEO satellites). The Moon provides a stable and large platform for very unique remote-sensing instruments, such as optical telescopes and long-baseline radar interferometers, which would be both accessible and serviceable, and allow the Earth to be monitored over the long term. In addition many of lunar-based remote-sensing instruments can be more readily expanded and upgraded. However, the Moon is ~10 times further from Earth than GEO satellites, which makes acquiring data with useful spatial scales for smaller-scale processes more difficult. The Earth-Moon orbit also changes by ~ 5% through the year, making spatial resolution somewhat variable. Only limited views of the Earth would be possible depending on the time of day and day of the month/year. And finally, if instruments were located on the lunar surface, environmental factors (e.g., variable thermal conditions, those that may come from dust, etc.) would present challenges to instrument operations.

The concept of a lunar-based Earth Observatory is highly compelling, but it must be planned so as to maximize the science return while not distracting from critically needed Earth Science observations from other platforms. Certain Earth Science observations can only be made well from LEO (e.g., high spatial resolution imaging, lidar, etc.) and these datasets should not be abandoned in the planning and implementation of a possible lunar-based Earth Observatory. Furthermore, the ESS recommends that all future discussion and planning of Earth Science return from the Moon be considered in light of the recently released NRC Decadal Survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (National Academies Press, 2007). However, we also recognize that the Decadal Survey did not consider the options for observations from the Moon.

The following are the three primary concepts endorsed by the ESS and enabled by a future lunar-based Earth Observatory. The list of science objectives (Table 1) can be assessed, ranked, and placed within the overarching framework of these concepts.

1. **A dedicated Earth Observatory at or on the Moon allows for global, continuous full-spectrum views of the Earth to address a range of Earth Science issues.**

   The high temporal data frequency coupled with the ability to observe a given location for up to 12 hours enables detection and analysis of time-dependent atmospheric composition (i.e., global mapping of emissions, long range transport of pollution plumes, greenhouse gases sources and sinks). This observational geometry makes new Earth and ecosystem monitoring abilities possible (i.e., volcanic eruptions, wildland fires, health and structure of vegetation, drought and land degradation). With climate change comes the critical need to observe changes in the cryosphere (i.e., ice shelf disintegration, sea ice change, snow cover cycles). A lunar platform also allows the Sun-Earth system to be observed simultaneously, providing data on the Earth's radiation balance and solar variability influence on climate. Finally, the numerous limb occultation opportunities over wavelengths from the visible (using stars) to the microwave (using GPS signals) to VHF (using communication signals) provide additional opportunities for observing the vertical structure of the Earth's atmosphere.

2. **The observatory provides a unique, stable, serviceable platform over the long-term.**

   The location of the observatory will be critical to the amount, quality, and usefulness of the data returned. The location enabled most readily by, and with the lowest impact on, the proposed lunar architecture would be to place a series of Earth-observing instruments at the Cislunar L1 point (possibly being deployed by missions in transit to the lunar outpost location). This strategy has the benefits of: (1) being low cost (no down-mass carried to the surface and no sorties needed for surface instrument deployment); (2) being clean (no dust or thermal cycling contamination); and (3) having unobstructed Earth views (no surface location constraints). Such an approach would still allow for longer-duration instrumentation and human or robotic serviceability in order to add, upgrade, or repair instruments. Despite those potential benefits, the ESS recommends a ground-based observatory as the first choice, allowing for much more growth and serviceability over time.

3. **The observatory would serve as a communications bridge across satellite platforms in other orbits (e.g., LEO, GEO, GPS).**

   A future lunar-based Earth Observatory could also be used for enhanced calibration and science synergy with other orbital assets. For example, if a GEO/LEO satellite instrument with higher spatial resolution initially detected a thermal anomaly on a remote volcano, it could then task a targetable lunar-based IR instrument. The high temporal frequency (seconds) data from that instrument would be ideal for tracking the progression of the entire early stages of the eruption (i.e., the ash cloud migration). In the longer term, a lunar-based SAR whole-disk illuminator could also be used in conjunction with SAR receivers in LEO for surface deformation and cryosphere studies.

Overarching Earth Science Themes

The attending members of the Earth Science Subcommittee and interested/invited guests that participated in the Workshop on Science Associated with the Lunar Exploration Architecture in Tempe, AZ worked to assess the original scientific objectives in light of the Lunar Architecture

Team's (LAT) rankings, determine how these objectives/rankings would be impacted by the proposed outpost location, understand the possible science that could be accomplished from an Earth Observatory on the Moon, and adopt recommendations for the Council and the LAT. Furthermore, all lunar discussions were tempered by the recently released NRC Decadal Survey, which called for a substantial increase in both Earth Science funding and new missions in a time of shrinking budgets. The ESS also considered the objections of many in the Earth Science community to the overall concept of locating Earth observing instrumentation on the Moon. They see such a deployment as a diversion of future limited resources (made even more poignant by the recommendations put forth in the Decadal Survey) away from LEO or GEO.

However, regardless of the Decadal Survey's impact, the primary task of the subcommittee was to critically assess the original science objectives for a lunar outpost in light of the low rankings given to most of those objectives by the LAT with respect to the capability to accomplish them within the constraints of the notional polar-outpost architecture. A second and related task was to assess how Earth Science objectives could be better achieved at a location different from Shackleton Crater. Through invited presentations, posters, and general discussions, the subcommittee worked to assess the capabilities of the lunar architecture to achieve those objectives and determined both the intrinsic scientific value and our best understanding of how well the objectives meshed with the proposed architecture.

The results are summarized below in four main sections. We first present a framework of three fundamental tenets within which the subsequent detailed assessment of Earth Science objectives should be framed. We then describe a phasing strategy and the Earth Science capabilities enabled by the VSE. Following that are two sections: *Required Studies/Factors Needed to Achieve Earth Science Goals,* which describes the key research studies needed prior to further development of the lunar architecture as it relates to specific Earth Science objectives; and *Emerging Technologies for Earth Science,* which identifies new and innovative technology developments that would be important for implementation of the overarching science themes. Lastly, we summarize the public outreach that could stem from this observatory.

Detailed Assessment of Earth Science Objectives

The original list of science objectives was crafted by the ESS at the September 2006 subcommittee meeting (Table 1). We present those objectives with several new levels of assessment that were based on the expertise at the Tempe Workshop and the recommendation that a future Earth Observatory be located away from the proposed outpost site in order to maximize Earth viewing. In addition, the criteria below must be considered prior to implementation of the Science Objectives or revision of the lunar architecture.

1. **There are worthwhile and important Earth Science opportunities enabled by a lunar outpost.**

   There was an assumption by many in the Earth Science community (as well as the LAT) that Earth observations from the Moon would require very large telescopes (>> 1 m) and therefore would not be feasible. This is factually not true and several presentations were made showing the potential science return using telescopes as small as ~ 0.3 m. These relatively “modest” instruments have already been flight tested (e.g. HiRISE on the Mars Reconnaissance Orbiter), and furthermore, significant technological advances are expected in the next 10-20 years that may further reduce their size, mass, and complexity.

The viewing geometry of the Earth from the Moon will be both a benefit and a hindrance depending on the type of science observation needed. The spin and precession of the Earth enable instruments on/at the Moon to view constantly changing conditions and track objects with very high temporal frequency during the viewing intervals. However, the phases of the Earth, the variable Earth-Moon distance, and the inability to observe certain locations continuously for long periods will hinder some optical remote sensing objectives.

Three examples of fundamental science (in no particular order) made possible *only* from a lunar viewing position are (1) the collection of “whole Earth” spectral data as a calibration source for future terrestrial planet finder missions; (2) the ability to track temporally-variable atmospheric, pollution, and volcanic plumes; and (3) the rapid response to natural disasters in coordination with LEO and GEO assets.

2. **The VSE should be planned so as to accommodate capabilities that will enable Earth Science.**

   Earth Science observations will become increasingly critical in the coming decades with accelerating climate change and the need to monitor (and if possible forecast) natural disasters. Furthermore, the psychological impact of seeing our home world in the vastness of space cannot be underestimated. Therefore, we feel it absolutely critical that worthwhile Earth Science be conducted from the Moon above and beyond the occasional astronaut photograph. Without significant mobility, Earth observing science is seriously limited at the notional Shackleton outpost location; cost-effective alternatives should be considered.

3. **Any lunar-enabled science can and should be evaluated and prioritized within the Earth Science community by the Decadal Survey process.**

   The Earth Science Directorate will need to prioritize and commit funds to activities and missions outlined in the new Decadal Survey. Our assessments should not be considered in any way to replace or supersede the decadal survey process. However, we also recognize that the recent Earth Science Decadal Survey was conducted without any consideration of future lunar assets, which would be deployed as exploration continues. The assessments below include, in addition to intrinsic science, the manner in which the science may mesh with the future Lunar Architecture.

Table 1. ESS Science Objectives and Assessment for a Lunar Based Earth Observatory

Assessment Column: *Colors/numbers synchronize with the original LAT assessment. Each number signifies a different assessment level from 1 (easily doable) to 5 (not doable at all) within the notional lunar architecture. Note that these values do not rank the objective's science potential, but rather are based on how easily the objective can be met within the proposed architecture. Three assessment levels are given:*

- *1st value:* *original LAT objective-to-architecture rating*
- *2nd value:* *modified LAT objective-to-architecture rating (reassessed by ESS)*
- *3rd value:* *modified LAT objective-to-architecture rating (enabled by an alternative Earth-viewing location)*

Science Ranking Column: *The ranking for each objective is dominated primarily by the expected science return and assumes an optimal Earth viewing location. A minor component of the ranking score is also the mission phasing timeline (Table 2) and the infrastructure required to implement the particular objective (see the "Earth Science Capabilities Enabled by the VSE" section below).*

- ***[A]*** *= highest science priority (and low impact on the current lunar architecture)*
- ***[B]*** *= high science priority (and moderate-high impact on the current lunar architecture)*
- ***[C]*** *= medium-high science priority (and high impact on the current lunar architecture)*

Code	Short Title	LAT/ESS Assessment	Comments	Science Ranking
mEO1	Monitor the Earth's Magneto-sphere	[4] / [4] / [4]	The use of ground or L1-based instruments to observe the Earth's magnetosphere to develop predictive and mitigation capabilities for magnetosphere-driven events (in conjunction with HPS). This is best-driven by HPS and without feedback from them, the original ranking was not changed.	**[B]**
mEO2	Create Topography, Altimetry, and Tomography Maps	[5] / [5] / [4]	Using SAR and multi-baseline INSAR from the lunar surface either with co-located receivers or with ones in LEO would provide high temporal resolution, full Earth deformation and topographic mapping. This is a high priority for the Earth Science community. However, the need for a near side location, possibly nuclear power, and major infrastructure has kept this objective ranked low.	**[B]**
mEO3	Characterize the Earth's Atmospheric Composition and Dynamics	[4] / [2] / [1]	A hyperspectral sensor ranging from the UV to the TIR (much like the current OMI, TES, and AIRS) coupled with the near-constant limb profiles of Earth could be used to map SO_2, O_3, CO, CH_4, NO_2, HNO_3, plumes, and sources/sinks. Full Earth views are critical, but the telescope could be as small as 30-50 cm (hence, the improved [2] / [1] ranking).	**[A]**
mEO4	Monitor the Sun-Earth System	[4] / [2] / [1]	Understand the effect of solar variability on Earth's atmospheric composition and climate. This would be uniquely enabled from an instrument at/on the lunar surface. Full Earth and Sun views are critical, but the telescope could be as small as 30-50 cm (hence, the improved [2] / [1] ranking).	**[A]**

mEO5	Determine the Earth's BRDF	[4] / [2] / [1]	Hyperspectral observations at multiple incidence, emission, and phase angles. This can provide more precise radiative balance calculations than currently available from Earth orbiting satellites for climate studies. Full Earth views are critical, but the telescope could be as small as 30-50 cm (hence, the improved [2] / [1] ranking).	**[B]**
mEO6	Measure the Earth's Ocean Color	[5] / [5] / [4]	Although 70% of the Earth's surface is covered by water and ocean observations should be numerous from the Moon, feedback thus far from the ocean community has been pessimistic. They feel that only meaningful science can be done from LEO. Therefore, we have kept this objective's ranking low, but continue to keep it in the table pending a broader examination by the ocean science community.	**[C]**
mEO7	Map the Surface Composition of the Earth	[5] / [2] / [1]	A multispectral sensor ranging from the UV to the TIR (much like MODIS) could fulfill several objectives on this list (mEO3, mEO5 and possibly mEO4, mEO12). Full Earth views are critical, but the telescope could be as small as 30-50 cm (hence, the improved [2] / [1] ranking).	**[A]**
mEO8	Measure the Historical Solar Constant	[1] / [2] / [1]	Recover information on solar variability over the past centuries through borehole thermal conductivity measurements. This could be accomplished initially with smaller boreholes at the outpost site and would be expanded as drilling technology is improved on the lunar surface and sorties are made to the nearside.	**[A]**
mEO9	Observe the Earth's Ice Surfaces Over Time	[5] / [5] / [4]	To understand how ice cover is impacted by climate change, the extent and volume must be measured. Using SAR from the lunar surface would provide high temporal resolution ice mapping covering the poles. This is a high priority for the Earth Science community. However, the need for a near side location, possibly nuclear power, and major infra-structure has kept this objective ranked low (see mEO2).	**[B]**
mEO10	Monitor Earth's "Hot Spots"	[5] / [2] / [1]	Thermally-elevated features (volcanic, fire, and anthropogenic activity) monitored with high temporal frequency (and in conjunction with LEO and GEO satellites). This instrument could be phased in from a simple radiometer to a multispectral sensor. Full Earth views are critical, but telescope could be as small as 30-50 cm (hence, the improved [2] / [1] ranking).	**[A]**

mEO11	Calibrate Earthshine	[1] / [1] / [1]	The objective is to measure true Earth albedo (and cloud amount, etc.) from the Moon and calibrate these with current and past Earth-based Earthshine measurements. This could be accomplished by using the other proposed instruments/science listed here (mEO3, mEO4, mEO5, mEO12) but does not need long term, full-Earth views (hence, the [1] / [1] ranking).	**[B]**
mEO12	Observe Lightning on the Earth	[5] / [2] / [1]	A narrow band (0.774 μm) detector with 10 km spatial resolution for detection and mapping of lightning for climatology, monitoring, and hazard mitigation (tornadoes, severe storms, etc.). Full Earth views are critical, but the telescope could be as small as 50-100 cm (hence, the improved [2] / [1] ranking).	**[A]**

In order to achieve the maximum return on the future Earth Science from the Moon and best integrate with the final lunar architecture, the ESS recommends a phased approach to instrumentation. This phasing would begin with relatively simple instruments deployed into either an L1 orbit or at the surface by humans and eventually extended to more complex instruments requiring significantly more infrastructure. We therefore have factored this expansion into the ranking column (Table 1) and urge the LAT to consider this approach during future architecture planning. In Table 2 below, short-term phasing would occur during the early years (2020-2025) of the lunar outpost. Instruments would be modest cameras/spectrometers either placed in L1 orbit or set up and tested on the lunar surface near the outpost. If the latter, Earth observations would be limited, but initial instrument testing in conjunction with some science return would still be worthwhile. Mid-term phasing (2025-2030) would involve sorties away from the outpost and begin with the establishment of the permanent Earth Observatory structure at the chosen location for optimal Earth viewing. A high scientific return is expected from this phase. Alternatively, if the observatory is to be completely orbital, this phase would see enhancements of the existing instrument complement. By the end of this phase, the Earth Observatory instrument suite (for the [A] and [B] rankings) would be complete and regular, long-term Earth observations would be underway. Finally, the long-term phasing (2030 and beyond) would include the addition of significant infrastructure and power sources – especially for active instruments, and longer term sorties to the other parts of the lunar surface. Active remote sensing such as the lunar-based SAR could come online in this phase.

Table 2. Proposed ESS Mission Phasing Timeline and Examples

Phase	Years	Comments/Examples
short-term	2020-2025	Modest instrumentation deployed either in Cislunar L1 orbit or on the surface at the outpost location. Instrument/technological/environmental testing will occur. If ground-based, very low science return is likely due to limited Earth views at the South Pole outpost location. Examples: full spectrum (UV to TIR) cameras, radiometers.

mid-term	2025-2030	More complex and longer duration instrumentation deployed either in Cislunar L1 orbit or on the surface at the permanent Observatory location. Would serve as the transition to long-term monitoring of critical Earth Science variables. New instrumentation and upgrades expected throughout. High science return expected. <u>Examples:</u> enhancements (e.g., larger foreoptics, new spectrometers, etc.) of existing complement; test drill holes (2-10 m) for thermal conductivity measurements (i.e., mEO8).
long-term	> 2030	Very complex infrastructure (nuclear power sources, deep-drilling capability) and long distance (equatorial near side) sorties required. <u>Examples:</u> microwave (SAR) illumination of entire Earth disk; LIDAR measurements (atmospheric composition, vegetation structure, ice deformation); and deep-drilling (100 m) for heat flow/solar constant.

Earth Science Capabilities Enabled by the VSE

Examples of some of the science enabled by observing the Earth from the Moon are described below. These data would complement Earth orbital observations and provide well characterized observations for long-term trends. Most importantly, the lunar platform enables new observations and new technologies not possible from LEO or GEO. The following section more fully describes the expected science returned from a lunar-based Earth Observatory and summarizes the information presented by many of the invited speakers for each of the ESS Objectives (Table 1). Within each category, no prioritization is implied.

A. Highest-Priority Earth Science that may influence Lunar Architecture planning.

Objectives which are fully or partially enabled in the short-term and are of the highest science priority include: mEO3, mEO4, mEO7, mEO8, mEO10 and mEO12.

Example 1: Rapid response time

1. **P. Christensen** (Arizona State U.) summarized the concept of a modest imager having a 0.3 m aperture with a 0.2° IFOV and a 2,048 pixel array (similar to the HiRISE Camera Mars Reconnaissance Orbiter) that would provide 0.5 km/pixel (VNIR); 1-2 km/pixel (SWIR); and 10 km/pixel (LWIR). Such an imager would only cover a 1,000 km x 1,000 km field of view during a given scan. However, if the sensor was made to be pointable, it could be integrated into a sensor web concept with LEO and GEO satellites to quickly target any given location on Earth. This instrument would be part of an initial instrument suite within the Earth Observatory, and be upgradeable over time to incorporate new technologies, operate in research mode, and provide real-time link between GEO and LEO observations.

2. **J. West** (NASA-JPL) discussed the potential of leveraging the unique advantages of the Earth-Moon (Cislunar) L1 vantage point for the placement of Earth observing satellites. This location offers continuous staring opportunities at the Earth (and back at the Moon). The advantages of the LI Earth Observatory include potentially lower cost (no down-mass to the lunar surface required), no

contamination (e.g., surface dust) potential, and unobstructed whole-Earth views. The cost of mission-specific upgrades and maintenance will need to be evaluated. This kind of orbital observatory could be implemented using small, instrumented, autonomous mini-satellites deployed by the astronauts from the crew transfer vehicle on the way to the Moon.

3. **M. Ramsey** (U. Pittsburgh) summarized the current near-real time monitoring of thermal anomalies (hot spots) using a sensor web concept between GEO satellites and higher resolution LEO instruments. That program exists in the northern Pacific region and uses moderate to low spatial resolution TIR instruments (e.g., AVHRR/GOES/MODIS) for the initial detection and triggering of high spatial resolution TIR instruments (e.g., ASTER, ETM+). The data collection is on the scale of minutes and directly applicable to real-time hazard tracking (e.g., volcanic plumes). In the future, an initial detection by LEO or GEO could trigger the lunar TIR instrument operating in the 3-12 μm region. Most importantly, that instrument could observe the volcanic eruption continuously at very high temporal resolution. For a large eruptions, the data would be unprecedented – capturing the initial stages and progress of the aerosol/gas plumes. Similar opportunities exist for observations of other disasters.

Example 2: Unique viewing geometry

1. **S. Goodman** (NASA-MSFC) presented the possibility of performing observations of lightning on Earth from the lunar surface. The detection and global monitoring of lightning has important implication for severe weather hazards, global production of NOx, and coupling with the magnetosphere. The high-speed (500 frames/sec) sensor would be centered at 0.774 μm and provide 10 km spatial resolution.
2. **J. Herman** (NASA-GSFC) introduced the concept of simultaneous measurements from the Moon of the Sun, its solar ejections, and their effects on Earth. The data would allow a better understanding of the processes and interactions that determine the composition of the Earth's whole atmosphere including the connections to solar activity. The data could also be used to map atmospheric species concentrations (greenhouse gases, aerosols, ozone) and provide real-time space weather data for predictive modeling of the space environment.

Example 3: Earth science on the Lunar surface

1. **K. Steffen** (U. Colorado) presented the potential of measuring the solar constant (TSI) on the lunar surface. The TSI is one of the most important climatic factors, which influenced the Earth's climate in the past. However, retrieving detailed measurements of the past TSI is not possible on Earth. Unlike Earth, the lunar surface is in a state of radiative equilibrium with the Sun and therefore its surface temperature is determined by TSI directly. By measuring the temperature profile in lunar boreholes, the past TSI can be recovered. The ideal site for these measurements would be near the lunar equator (large absolute flux and better resolution for TSI) and a 100 m borehole would resolve data back to 1600 AD.

B. High-Priority Earth Science that may or may not influence Lunar Architecture planning.

Objectives which are fully or partially enabled in the mid-term and are of high science priority include: mEO1, mEO5, and mEO11.

Example 1: Unique viewing geometry

1. **M. Turnbull** (STScI/Carnegie) focused on the unique viewing of the Earth from the Moon to ask are there any astrophysics projects that are uniquely enabled by the lunar platform? The ability to collect whole-Earth, full-spectrum, spatially-resolved views would provide a unique calibration dataset for future terrestrial planet finder missions. The detailed data from the Moon of the variable Earth would be important for identifying and characterizing habitable worlds around nearby stars (the spatially unresolved case).
2. **J. Mustard** (Brown U.) focused on land surface monitoring from the Moon and its unique observation conditions (changing incidence and emergence angles and the 28 day repeat of illumination conditions). In particular, the Lunar Observatory would provide an important measure of the bidirectional reflectance distribution function (BRDF). The BRDF is capable of retrieving certain properties such as ecosystem structure and its collection from the Moon would more completely sample (e.g. near 0 phase) the full BRDF for science applications. In addition, plant phenology (timing and magnitude of ecosystem processes indicated by greenness) could be measured as a function of time.
3. **N. Loeb** (NASA-LRC) compared current monitoring of the Earth's albedo from LEO satellites (e.g., CERES) to what might be possible from the Moon. Specifically, he focused on the questions of: (1) What are the climate accuracy requirements for monitoring the Earth's albedo? and (2) Can the Earthshine approach (i.e., from the Moon) satisfy these climate accuracy requirements? The detailed modeling presented initially indicates that albedo measurements of the Earth from the Moon are unlikely to achieve 0.3 Wm^{-2}/decade stability requirement needed for precise climate science. However, this measurement could still be an important validation for future LEO data and more modeling is needed before this Earth Science objective (mEO11) is abandoned.
4. **A. Ruzmaikin** (NASA-JPL) also examined the possibility of measuring the Earth's broadband albedo (0.3 to 3 μm) from the Moon for the purposes of better climate modeling. Deviations in albedo can be caused by many factors (e.g., seasons, latitude, clouds, etc.), which can propagate errors into climate models. The benefits of a lunar-based albedo measurement were found to be: homogeneous longitude sampling; high temporal (hours) and spatial resolution (10 km); observation of the polar regions; observation of the diurnal albedo cycle; and a potentially much longer lifetime than any LEO satellite can provide.

Example 2: Active remote sensing from the Moon

1. **K. Sarabandi** (U. Michigan) presented the intriguing potential of conducting large baseline synthetic aperture radar interferometry of the Earth from the Moon. The objective would be to create solid Earth, topography, altimetry, 3D

tomography, and vegetation maps. SAR images would be formed using the relative motion of the Earth with respect to Moon by having multiple antennas to form a microwave interferometer with a long baseline and extreme stability. This configuration also allows for multi-static operation in conjunction with relatively inexpensive SAR receivers in LEO. Although the implementation of this science objective would require significant infrastructure, the instrumentation would provide a whole-disk illumination of the Earth in the microwave band allowing continuous, all-weather observations of the planet.

Required Studies/Factors Needed to Achieve Earth Science Goals

Certain studies must be carried out and other factors considered in the short-term prior to any continued lunar architecture planning. The following list highlights these – no prioritization is implied (numbering is for ease of reference only).

1. **Options for lunar-surface emplacement.**

   If a future Earth Observatory is to be located on the lunar surface, engineering studies must be conducted to determine the best strategy for maximizing the Earth observation potential. The study of possible locations should include sortie locations within easy reach of the lunar outpost. These could include a lower-elevation site further north (or south) or a higher elevation site (e.g., Mt. Malapert) in closer proximity to the outpost. Both would possibly require new logistical and infrastructure considerations for the current lunar architecture. The location must at minimum meet the *acceptable* criterion (Earth observed > 50% of the time) and ideally would attain the *desirable* criterion (Earth observed > 90% of the time).

2. **Options for operations in free space.**

   Because of the limited options and cost associated with a lunar surface Earth Observatory, the second option would be to have instruments placed at the Cislunar (L1) point in order to provide full-Earth views and achieve the major goals for science. Assessments and trade studies are necessary to understand how these operations may be enabled within the Lunar Architecture. The assessment elements may include: (1) the capacity of the Orion/Ares systems to carry and deploy small satellites prior to arrival at the Moon; (2) technology, maintenance and enhancement strategies and trade-offs compared to surface-based instruments; (3) options for coordinated development with other partners; and (4) cost estimates for possible modest augmentations to the Exploration Architecture.

3. **More formal modeling of sensor design needed and data quality expected in order to address the science objectives.**

   More precise and formalized engineering studies must be carried out in order to constrain both the common architecture desired in a future Earth Observatory as well as specific sensor designs (i.e., power requirements, size, mass, orbital vs. landed). The sensor designs should consider both the Earth Science objectives (Table 1) and the proposed mission phasing (Table 2), and have detailed input from scientists working in these fields. The design criteria should (if at all possible) carry forward both space-based and surface-based options with specific trade-offs for each. For example, the complications of the lunar thermal environment and those that hypothetically may come from dust should be considered especially for larger optical telescopes. The universal architecture for a permanent lunar-based observatory must also be made in conjunction with the final lunar architecture and integrate easily.

4. **Involve the Earth Science community.**

   The ESS should organize and plan an *Earth Science from the Moon* workshop (similar to that held by the Astrophysics Subcommittee in November, 2006). This should be carried out within one year following the Tempe workshop and seek to involve a wide array of Earth scientists, engineers, the LAT, and representatives from ESD/ESMD. The current science objectives should be revisited and finalized at that time. Ideally, initial mission trade studies (see number 3 above) would have been conducted and presented at this time. Furthermore, the LAT should present the feasibility of sortie locations (ground or orbital) for the Earth Observatory (see numbers 1 and 2 above).

5. **Function of humans and instrumentation on the lunar surface.**

   Opportunities have been identified for Earth Science from lunar surface instruments that must be located away from the outpost location. In this context, conveyance to the lunar surface and deployment to the observation site is a requirement, however the need of humans for these processes may not be. If general maintenance and servicing of such instrumentation is required over time, it may be enabled by astronaut access (or perhaps telerobotic operations). Therefore, a detailed assessment of the specific functionality of humans with respect to these opportunities should be done. This assessment would evaluate the viability of the Earth Science plans for the instrument deployment opportunities and the functional advantages by which an astronaut could add value to any installation on the lunar surface.

Emerging Technologies for Lunar-Based Earth Science

During the discussion of the possible Earth Science enabled by the Lunar Architecture, several new and innovative technologies were all briefly mentioned. These were primarily focused on imaging, orbital, and power technologies and could all significantly improve the data return from the Moon. The concepts listed below should be considered in future planning and are in no particular order.

1. **Active Pixel Sensor (APS) for effective whole-Earth imaging with reduced data rate.**

   The APS is an imaging device similar to CCD. But in contrast to CCD, each APS pixel contains a photodetector and is connected to a transistor reset and readout circuit. This allows selection of the whole set of image pixels, or only a subset of pixels for readout thus focusing on interesting parts of the image with the reduced data rate. APS consumes far less power than CCD, has less image lag, and is cheaper to fabricate. The larger arrays and lower power requirements could allow the whole Earth disk to be imaged at moderately-high spatial and spectral resolutions.

2. **Spectrally resolved pixels for large imaging arrays.**

   In this CCD, which can be used for spectral imaging, each pixel is actually a microspectrometer, acting simultaneously and independently of other pixels. As a result, spectral imaging acquires a cube whose appellate signifies the two spatial dimensions of a 2D sample (x and y), and the third is the wavelength dimension. Practically, it must be combined with a monochromator that diverts light of different wavelengths onto different pixels. This CCD allows to simultaneously collect photons in a broad wavelength range, enabling to measure an entire spectrum in a very short time.

3. **Solar Electric Propulsion, Nuclear Electric Propulsion, or Solar Sail allowing for a "Pole-sitting" observatory.**

   Positioning a long-lived satellite far below the lunar south pole would require propulsion and station keeping technologies, but would serve several potential key applications. Most importantly, it would enable real-time, wide regional observation of the outpost and its surroundings, as well as simultaneous views of Sun, Earth, and Moon from different angles. It could function as a continuous communications node between the Earth and the Moon and/or between the outpost and lunar sortie missions. Depending on the instrumentation on such a satellite, it could also serve as a stable remote-sensing platform for observations of the lunar southern hemisphere. Other uses could include solar-wind monitoring and a relay for future deep-space missions.

Outreach/Public Impact

The psychological impact of seeing Earth from space should not be underestimated. Images from the Apollo and Galileo missions have provided a global view of our home planet not seen from either LEO or GEO based instruments. However, we must expand beyond the occasional photograph of the Earth to a more systematic and synoptic set of measurements that can only be realized and enabled by the VSE. We propose that it would be a serious flaw in the VSE and the proposed lunar architecture if an outpost location is chosen with little to no opportunity to perform quantitative Earth Science, which can then also be used for inspiring outreach and public impact. To highlight this concept, we include a quote from the opening statement of the former Chairman of the Committee on Science for the House of Representatives:

"The Earth Science program doesn't exist as some secondary adjunct of the exploration program…there's no reason that NASA can't robustly carry out the President's Vision for Space Exploration while conducting vital Earth Science research."

Sherwood Boehlert (R-NY)
April 28, 2005

The Earth Science members participating in the workshop were asked to craft the Public Outreach expected from our proposed Earth Observatory on the Moon. The dominant themes arose (in no particular order):

1. **The "Blue Planet Webcam"**

   In the process of collecting visible and infrared spectroscopic data for the proposed science objectives (e.g., mEO3, mEO7, mEO10, …) regular visible images of the Earth would be generated. We foresee these real-time whole Earth views to be an amazing educational resource that could be visualized in an "Google Earth" type online environment.

2. **Building the Lunar "Earth Observatory"**

   If an actual Observatory is built on the lunar surface to observe Earth, we feel the overarching imagery of an "observatory on a hill" to be very compelling. This iconic view of what an observatory is on Earth (e.g., the telescope under the white dome on the mountain) would be duplicated on the Moon in order to look back at Earth. The data collected from the instruments that comprise the Earth Observatory will be used for long-term synoptic environmental monitoring, which will become increasingly important with accelerated climate change. Furthermore, a future terrestrial planet finder mission will be able to use these data as a critical calibration source.

3. **Taking the "Pulse" of Earth from Moon**

   Related to both the first and second points above is the very reason these data would be collected: monitoring the Earth and acquiring critically-needed measurements from which to model trends in the atmosphere, lithosphere, cryosphere, hydrosphere, and biosphere. Tracking climate variability, air pollution sources and transport, natural hazards (e.g., extreme weather, volcanic plumes, hurricanes, lightning), seasonal and secular variations in polar ice, and vegetation health (e.g., spring greening) were all identified in the workshop as feasible and important data that could be collected from the Moon. Such data would be important for public consumption and useful for NASA.

Authors

Michael Ramsey, Department of Geology and Planetary Science, University of Pittsburgh, Pittsburgh, PA 15260, ramsey@ivis.eps.pitt.edu

Jean-Bernard Minster, Scripps Institution of Oceanography, University of California, IGPP (0225), La Jolla, CA 92093, jbminster@ucsd.edu

Kamal Sarabandi, EECS Department, The University of Michigan, 1301 Beal Ave., Ann Arbor, MI 48109, saraband@eecs.umich.edu

Appendix 3: Workshop Findings, Heliophysics Subcommittee

Heliophysics Science and the Moon Synthesis

Members of the NAC Heliophysics Subcommittee and interested members of the community considered at length several space science topics drawn from community input over the previous eight months by the subcommittee's Heliophysics Science and the Moon subpanel. During the deliberations it was apparent that the architecture potentially available by NASA's return to the Moon presents interesting and exciting new opportunities to extend scientific progress in ways that have not been previously available or considered. The synthesis of these deliberations, which occurred at the "Workshop on Science Associated with the Lunar Exploration Architecture" in Tempe, Arizona, is contained in this report. A separate report titled "Heliophysics Science and the Moon" is being prepared under the auspices of the Council's Heliophysics Subcommittee for release during the summer of 2007 that provides more detail on the potential solar and space physics science for lunar exploration.

Since the inception of the space program with Explorer 1 and continuing through to the present space weather missions, scientists in the Heliophysics community have worked to develop a detailed understanding of the connected Sun-Earth-Moon system. The Moon is immersed in a plasma environment – the local cosmos – that is "magnetized". These fields play an essential role in organizing the environment. It is the twisting and folding of the various interacting magnetic fields – of the Earth, of the Sun, and locally, of the Moon itself – that regulate the local environment of the Moon and thus, the environment experienced by our Explorers. By working to understand this environment and ultimately to predict the variations likely to occur from day to day, and region to region, it is widely believed that the productivity of future lunar robotic and manned missions can be significantly enhanced.

The Heliophysics science topics related to lunar exploration are grouped in four themes: (1) Heliophysics Science of the Moon – investigating fundamental space plasma processes using the Moon and its environment as a natural laboratory, (2) Space Weather; Safeguarding the Journey – understanding the drivers and dominant mechanisms of the lunar radiation and plasma-dust environment that affect the health and productivity of human and robotic explorers, (3) The Moon as a Historical Record – seeking knowledge of the history and evolution of the Sun and Solar System as captured in the lunar soil, (4) The Moon as a Heliophysics Science Platform – exploring possibilities of establishing remote sensing capability on the lunar surface to probe Geospace, the Sun and the Heliosphere.

Subcommittee Workshop Conclusions

The Heliophysics subcommittee discussed various opportunities for science related to lunar exploration. Several issues were raised during the week. Of those, the following were deemed crosscutting and/or important to Heliophysics science and the Moon.

- For several Heliophysics science opportunities, <u>drop-off satellites</u> or <u>early robotic operations</u> are optimal.
- Lunar science assessments formulated at this workshop are deemed to be <u>valuable input</u> to the next NRC Decadal Survey for Solar and Space Physics and NASA Heliophysics Science Roadmap. The NASA Science Mission Directorate (SMD) has a <u>well-validated process for establishing science priorities</u> within their resource allocations. Once complete, the lunar science opportunities

information should enter into this process in the same manner as other SMD Pre-Planning Activities.
- Future evaluations of these science objectives must assess the cost effectiveness of these lunar site implementations versus implementations that utilize robotic/unmanned missions around the Moon or elsewhere.
- For full mission success, many of these science objectives will necessarily require involvement of a Scientist Astronaut as an integral part of the science experiment.

Detailed Assessment of LAT objectives associated with Heliophysics

The subcommittee assessed of each of the objectives identified by the NASA Lunar Architecture Team (LAT) as being related to Heliophysics science. The assessment was performed according to the follow criteria:

- **High**: Science is of high value and achievable within the architecture OR the importance to lunar operations is deemed high
- **Medium**: Science is of secondary value and achievable within the architecture OR the objective is deemed important to lunar operations
- **Low**: Little or no science return OR the likelihood of achieving the objective within notional architecture is low

Full assessments for all concepts will be contained in the Heliophysics Subcommittee report on Heliophysics Science at the Moon.
The color-coded Objective-to-Architecture rating is provided in the fifth column.

Objective ID#	Title	Assess-ment	Comments	Suitability to Single Site Architecture
mHEO3	Study the dynamics of the magnetotail as it crosses the Moon's orbit to learn about the development and transport of plasmoids.	**High**	The dynamical behavior of the distant magnetotail, where a substantial fraction of the total energy coupled into the magnetosphere from the solar wind is stored, is not understood. It is different from the near-Earth, with quasi-continuous, physically different magnetic reconnection. The Moon is an unique location for studying the deep magnetotail, allowing diagnostics of the magnetic field topology and convection velocity by observations of lunar shadowing of ambient electrons.	Requires an orbital mission, perhaps as a drop-off satellite. Objective-to-architecture rating: [1]
mHEO4	Study the impact of the Moon on the surrounding plasma environment and incident solar wind to better understand the magnetotail. Study fundamental plasma physics at the fluid-kinetic interface.	**High**	The behavior of plasmas in the transition from kinetic (particle) to fluid scales is a problem of critical importance to many fields of study. The size of the lunar disk, and of regions of enhanced magnetism on the lunar surface, span the kinetic and fluid ranges of many particle species. This permits a study of fundamental physics at the kinetic/fluid interface to be made.	Requires orbital mission, perhaps as a drop off. [1]

mENVCH 7	Characterize the lunar atmosphere to understand its natural state. Of major importance, is the electromagnetic and charged dust environment and interaction with the variable space environment.	**High**	NRC interim report identifies this objective as high priority. Highly likely that electrostatic charging and dust environment will have direct impact on operational mission. Science applications are specifically targeted to the particular nature of the lunar environment and the issues of critical systems and human operations. Safety and reliability designs would require investigation before substantial human activity.	Requires both orbital mission, perhaps as a drop off, and surface lunar package, before substantial human activity. [1]
mENVCH 10	Map the surface electromagnetic field of the Moon to understand the operational environment of the Moon. Measure the lunar crustal magnetic field and understand its origins and effects.	**High**	This is a subset of complete mENVCH10 objective. The magnetic field is important for the local plasma, dust, and particle environment. This objective represents new science in unique plasma parameter regimes. It relates to the history of the Moon and an analog for Mars. Magnetic shielding may influence site selection of some exploration activities. Similar instrumentation needed for other objectives.	Orbital in initial stages (low perilune). In-situ rover studies around outpost and during sorties to supplement; selected oriented sample returns. [4]
mENVCH 4	Characterize the dust environment at several locations on the lunar surface to better understand the operational environment of the Moon.	**High**	There is a highly variable plasma environment at the orbit of the Moon due both to the changing conditions of the 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 may drive the electrostatic transport of charged lunar dust. The lunar dust-plasma is highly susceptible to space weather. Therefore, we need to observe the dust/plasma environment during range of different solar and magnetospheric activity conditions.	Consider strategic location (South Pole), as well as, or in addition to, distributed sites. [1]
mENVMON1a	Monitor space weather in real time to determine and mitigate risks to lunar operations. Utilize the coordinated, distributed, simultaneous measurements by the heliospheric great observatory for predictive models of space radiation at the Moon.	**High**	(1) Mitigating the exposure risk requires the delivery of reliable operational products, based on monitoring of hazardous radiation, to mission operators, planners and crews. It will also require a dedicated effort to generate near-real-time operational data that are supported by a fundamental understanding of the underlying physics. The infrastructure to monitor space weather over timescales of days - hours - minutes exists. This science is of high intrinsic value because developing such a predictive capability requires the solution of many long-standing problems in heliophysics. High in terms of scientific discovery potential, as well as for practical (operational) considerations. (2) This science objective will probably be achieved only partly by the time of the first lunar landings and will be improved upon continually with more capable instrumentation and higher fidelity models. Nevertheless, the accomplishments will be of high scientific value and very valuable predictive capabilities will be developed in time to support crewed lunar operations.	Not on the Moon, upstream monitoring measurements must be located on the Sun-Earth line as close to the solar source as is feasible. [5]

mENVMON1b	Monitor space weather in real time to determine and mitigate risks to lunar operations. Utilize real-time measurements on the Moon to provide redundant forecasting/now-casting of space weather.	**Medium**	Although deployment of instrumentation on the Moon for space-weather monitoring is unlikely to yield major scientific advances, even simple full sun sensors can provide valuable on-site information about the x-ray flux, and on particle acceleration in the low corona. More detailed imaging instruments can provide a redundant forecasting capability and training for the Mars outpost. These measurements provide direct input to predict the effects on the lunar dust/plasma environment.	Instrument suite can be designed to fit in the existing architecture. A major goal is learning how to run an operational system in a harsh environment. On-site operations need to be carried out by a trained scientist-astronaut at the lunar site, with a view to more independent operation during Mars missions. [5]
mENVMON2	Monitor lunar environmental variables in real time to determine and mitigate risks to lunar operations. Use real-time observations on the Moon to determine the potential and duration of radiation hazards, the electrodynamic plasma environment, and effects of dust dynamics and adhesion.	**High**	(1) Monitoring the radiation environment will require dosimetry and a solar proton telescope. It is this telescope that SMD can provide. It must measure protons from 20 to 1000 MeV. In addition to its use for assessing crew radiation exposures, it will provide scientific data for basic research in heliophysics. Further, the Moon's electrodynamic plasma and dust environment must be monitored in real-time to determine electrostatic and dust hazards. (2) The likelihood of successful operation is excellent and the likelihood of achieving science is good. (3) Important for crew safety	Implementation should be co-located with human operations [1]
mENVCH2	Characterize radiation bombardment at several locations on the lunar surface and subsurface to better understand the operational environment of the Moon.	**Medium**	(1) The only intrinsic value is the validation of transport code calculations of lunar neutron albedo. It will be helpful to validate the model predictions for the radiation environment on the lunar surface. The biggest uncertainty is thought to be the contribution of neutron albedo to the radiation dose to the crew. Low importance in terms of scientific discovery potential, but important for crew safety. (2) The likelihood of achieving this goal is very high because it relies on the use of well understood and proven detector technologies.	The objective can be completely addressed at a single site. It would have been enough to do it at only one site even if the crew were visiting multiple sites on the Moon. [1]

mGEO9	Understand the nature and history of solar emissions and galactic cosmic rays.	**High**	The lunar regolith carries a record of the history of solar energetic particles, galactic cosmic rays, and the motion of the heliosphere through the Milky Way. Shaded areas may form cold traps for volatiles. Intrinsic scientific value is high. Samples to be extracted to study lunar geology can be used. However, for dating purposes, samples should be chosen in the context of the lunar stratigraphy. Trenching is the preferred approach. The techniques required for this objective are similar to other lunar regolith survey requirements.	A comprehensive historical picture would require samples illustrating a range of dates, and limitation to a single site may limit the variety of samples available. However, the apparent ubiquity of ejecta layers on the lunar surface indicates a single site should be sufficient. [1]
mHEO1	Image the interaction of the Sun's heliosphere with the interstellar medium to enable identification and comparison of other heliospheres.	**Medium**	The heliospheric boundary can be imaged from the Moon using energetic neutral atoms, extreme ultraviolet, and soft x-ray fluxes. The study of the global structure of the heliosphere and its interaction with the local interstellar medium is of high value. However, the presence of neutral atoms in the lunar exosphere will cause a significant foreground for Energetic Neutral Atom (ENA) Imaging. Not compelling to do from the Moon.	ENA technique requires remote (satellite) perspective. Other techniques may be implemented on the lunar surface. [1]
mHEO2	Perform low-frequency radio astronomy observations of the Sun to improve our understanding of space weather.	**High**	Probe particle acceleration in the tenuous upper solar atmosphere and in interplanetary space. This is accomplished by imaging the low-frequency plasma radiation produced by the accelerated particles. An array of small radio telescopes covering spanning tens of km would provide the necessary spatial resolution. Kapton roll deployment technology may revise this assessment upward.	For full sky coverage, multiple sites would be required. [2]
mHEO5	Analyze the composition of the solar wind to improve our understanding of the composition and processes of the Sun. Composition and flux of interplanetary / interstellar grains should also be considered	**High**	(1) Solar wind composition has recently been measured by Genesis, with less than complete success due to its hard return to Earth. Lunar observations would complete the necessary reservoir of samples for 21st century science. (2) The flux and composition of the interplanetary and interstellar grains bombarding the lunar surface are important measurements to both the Heliospheric and the Astrophysical communities, and are a fundamental source of maintaining the lunar atmosphere and modifying the micrometeor-gardened lunar soil.	Observation site requires long intervals of exposure to the solar wind. [1]

mHEO6	Image the interaction of the ionosphere and magnetosphere to understand space weather in the regions of space where most commercial and military space operations occur.	**High**	Imaging of the geospace environment from the Moon has high intrinsic science value and contributes to operational space weather products. Observations from the Moon give excellent full disk coverage of the Earth unavailable from LEO and GEO orbits. Lunar surface observations of plasma distributions and flow in geospace enable comprehensive diagnostics of space weather processes.	The instrument site must maximize view of Earth. [1]
mHEO7	Perform high-energy and optical observations of the Sun to improve our understanding of the physical processes of the Sun.	**High-Energy Observatories - High;** **Optical observatories - Low**	Studies of very high energy process require imaging of high energy x-ray and gamma rays that cannot be imaged using conventional optics. However, collimators and grid shadowing techniques can provide data that can be used to form images. Grids and detectors must be extremely stable and separated by long distances, which is difficult to achieve in space. The near vacuum and seismically quiet environment of the Moon would allow the construction of an ideal hard X-ray/gamma ray observatory because stability is the primary driver of the design. While scientifically important and essential for safe lunar operations, solar optical observations are better done by a constellation of observatories in Sun-synchronous Earth orbit.	A site a few hundred meters in length in the sunlight would be sufficient. [1]
mHEO8	Analyze the Sun's role in climate change to gain a better overall understanding of climate.	**High**	The Moon is a platform from which one can measure the three fundamental components of climate (change) – the solar constant, terrestrial reflectance and Earth's thermal emission. The required technologies are mature and robust. The Moon is not considered to be the best place to measure the solar irradiance although measurements of the Earth's albedo may be. Measurements of the Earth's albedo fall within the purview of the Earth science.	The objective can be fully addressed at a single site. Long term calibration is an issue. [1]

The realm of heliophysics is the perilous ocean through which explorers, both robotic and human, must journey to reach the dusty shores of the Moon, then Mars.

Appendix 4: Workshop Findings, Planetary Protection Subcommittee

Context

The Planetary Protection Subcommittee (PPS) of the Science Committee of the NASA Advisory Council is charged with providing advice on Planetary Protection policy and mission categorization to NASA and the Planetary Protection Officer, in accordance with the Committee on Space Research (COSPAR) guidelines and Article IX of the 1967 Outer Space Treaty (see footnote on page A 4-6 below). At the Tempe Workshop, the goal of the PPS was to ensure that planetary protection requirements for preventing biological and organic contamination of solar system bodies will be considered to the greatest extent possible during the development of technologies and procedures to enable human exploration of the Solar System, for which a return to the Moon is the first step.

By NASA and COSPAR policy, missions to the Moon are currently considered Category I, which means that operations on the Moon are not constrained by Planetary Protection restrictions on biological and organic contamination. The Moon is considered to be a sterile and organically clean environment (with potential exceptions such as possible polar deposits of organic materials derived from impactors and sequestered in cold traps), which makes it an optimal location to evaluate the magnitude and range of biological contamination associated with human exploration, as well as to develop technologies designed to mitigate planetary contamination resulting from human presence. A better understanding of organic and biological contamination resulting from past or planned human activities on the Moon will facilitate development and testing of equipment and technologies designed to limit human-associated contamination during exploration of more distant planetary bodies, to which Planetary Protection restrictions are currently applied.

Considerable experience gleaned from the past four decades of robotic exploration, in addition to early efforts in planetary protection (then called planetary quarantine) during the Apollo program, have demonstrated that planetary protection policies and procedures must be incorporated into mission planning from the very earliest stages. Delaying planetary protection considerations to the later stages of mission design consistently leads to vastly increased costs, damaging schedule delays, and potential loss of missions. Technologies and procedures that will be used during human missions to Mars must be developed and established early in the planning process, and tested under realistic field conditions, to ensure their compliance with Planetary Protection policies. By COSPAR guidelines and NASA policy that implement international agreements of the 1967 Outer Space Treaty, missions that do not comply with Planetary Protection requirements will not be permitted to launch.

Key Findings

During the course of discussions at the workshop, two key issues were raised repeatedly that members of the PPS felt were essential to address during exploration of the Moon in order to prepare for future missions to Mars. A third concern, specific to the Moon, was also recognized, that exploration of scientifically interesting polar regions on the Moon does increase the possibility of contamination that might interfere with future scientific discovery. Key findings are listed here:

1) Exploration of the Moon has produced and will produce biological and organic contamination at the sites where human and/or robotic exploration takes place. Operations on the Moon are not constrained by Planetary Protection restrictions, which makes the Moon an optimal location to establish the magnitude of contamination associated with human exploration and effects of the lunar environment on such contamination over time. Previous lunar exploration efforts, including both robotic missions and the manned missions of the Apollo program, have left behind artifacts on the Moon that are known to contain organic and microbial contaminants. These locations are ideal for testing planetary protection technologies and procedures to detect biological or organic contamination. In addition, the Moon is an excellent test bed for developing and testing technologies for containment of collected samples, to prevent both forward contamination of the sampling site, and backward contamination of the habitat, return vehicle, and laboratory in which the sample containers are to be opened.

2) The Moon is an excellent test bed for developing technologies that may be required to permit human exploration of protected planetary bodies. The lunar return can facilitate development and testing of equipment and technologies designed to limit human-associated contamination. Many processes and technologies required for planetary exploration are likely to produce organic and biological contaminants that are regulated by Planetary Protection policy. Because organic and biological contamination of the Moon is not restricted, technologies that will be required for exploration of protected locations can be tested and optimized without costly limitations. Necessary technologies that will need optimization to minimize contamination include pressurized habitats and spacesuits as well as robotic and human-associated mobile equipment used for exploration or in-situ resource utilization (ISRU). Such technologies and procedures are expected to be required before humans can be permitted to travel to Mars or other protected solar system bodies.

3) Lunar volatiles in polar deposits are susceptible to organic contamination during exploration, and future investigations may indicate that these regions contain materials of interest for scientific research. These regions of the Moon, though currently considered Category I, may be considered for protection at a greater level pending future COSPAR policy discussions.

Detailed Assessment (objectives spreadsheet)

The spreadsheet provided to participants at the beginning of the Tempe Workshop included only two objectives considered of relevance to Planetary Protection, mOPS7 (to investigate astrobiology protocols and the search for life), and mOPS8 (to evaluate and improve planetary protection protocols). During discussion of our key findings by the PPS, the two objectives were subdivided to highlight essential components of those activities, and additional topics were also included. Both the old and the revised objectives are listed in the following spreadsheet:

Objective ID Number	Name	Summary	Value	Objective-to-architecture rating
mOPS7	Evaluate astrobiology protocols and measurement technologies that will be used to test for life on other planets.	Evaluate contamination control protocols and establish no-life baselines for scientific technologies that will be used to test for life on other planets.	Astrobiology protocols and technologies can be uniquely tested on the Moon since it is devoid of life. These technologies can be used to test for life elsewhere in the solar system. Operational tests away from the Earth provide more relevant validation of approach.	1
mOPS8	Evaluate planetary protection protocols to develop the next generation planetary protection policy.	Evaluate planetary protection protocols by first characterizing the biological effects of human activity on the lunar surface. Develop and test decontamination of astronauts and equipment returning from the Moon, to control forward and backward contamination, as precursor to human return from Mars.	Understanding the impact of human activity on the lunar surface is necessary to develop the next generation of planetary protection protocols. These protocols will help prevent forward environmental contamination of sites on the Moon and backward contamination of crew and cargo returning to Earth. After evaluating these protocols, they can be used as models for protocols for future Mars exploration missions.	1

mOPS8.1	Use the Moon and lunar transit / orbits as a test bed for PP procedures and technologies involved with implementing human Mars mission requirements prior to planning human Mars missions.	Evaluate and develop technologies to reduce organic and biological contamination produced by space suits and pressurized habitats, as well as contamination resulting from human-robotic interactions. Study lunar space suit competency, containment, and leakage issues, and the ability of evolving suit requirements to affect Mars suit / PLSS / habitat designs and requirements	Although contamination of the Moon is not restricted by COSPAR or NASA PP policy, the moon provides a sterile and organically clean environment in which to evaluate current performance of human exploration technologies, and subsequently improve contamination control as will be required for further planetary exploration in more restricted locations such as Mars.	HIGH
mOPS7.1	Perform in situ investigations of a variety of locations on the Moon by highly sensitive instruments designed to search for biologically derived organic compounds to assess the contamination of the Moon by lunar spacecraft and astronauts		Valuable “ground truth” data on in situ contamination of samples supports future Mars sample return missions (sample integrity)	HIGH

mOPS7.2	Understand possible contamination of lunar ices with non-organically-clean spacecraft. Evaluate and develop technologies to reduce possible contamination of lunar ices to address both mission-science and resource contamination concerns.			HIGH
mOPS8.2	Perform chemical and microbiological studies on the effects of terrestrial contamination and microbial survival, both during lunar robotic and human missions (dedicated experiments and “natural” experiments in a variety of lunar environments/depths, etc.) and during the Apollo missions (study Apollo sites)			MEDIUM
mOPS8.3	Develop technologies for effective containment of samples collected by humans to feed forward into designs that will help prevent forward and backward contamination during Mars missions.		Technology development for sample collection supports future Mars sample return missions (sample integrity)	MEDIUM
mOPS7.3	Use the lunar surface as a Mars Analog site, to test proposed life detection systems in a sterile environ-ment that are designed to go to Mars.	This is similar to Antarctic Analog field tests for Viking used to ensure a lack of false positives and evaluate how sensitive the system is to human contamination.	Detection at varying distances from human activity could shed light on movement of materials that could help establish the distances for “quarantine zones” around special regions.	LOW

Enabling Technologies

A number of discussions took place around the issues of technology required for planetary protection on human missions to Mars, and how exploration of the Moon could be useful in the development of such technology. Much of the required technologies have been or are being developed for the robotic space program or as commercial products, however additional work will be required to adapt available products for use during human space-flight missions. In addition, a number of technologies required for long-duration human life support are not yet mature, and will be quite costly to develop further. Considerable effort should be expended to ensure that life support and habitat technologies developed for the Moon are usable for later human missions to other solar system bodies that have more stringent planetary protection requirements. Details on three specific topics of discussion are provided below.

A substantial amount of technology relevant to planetary protection and other scientific questions has been developed by NASA through the advanced technology programs (ASTEP, ASTID, MIDP, PIDDP, etc.). Presentations given by PPS-invited speakers described several instruments developed for robotic spacecraft exploration that have been adapted to interface with humans, either with the assistance of a robot or through direct operation while wearing a space suit. Such instruments have been operated successfully in remote locations on Earth such as Svalbard Island and Antarctica. These technologies and instruments, which include robotic sample collection and sensitive, rapid assay methods using field-portable equipment, should be reinvestigated for relevance to human exploration requirements.

However, commercial off-the-shelf technologies are not rated for space-flight, and necessary modifications will require expensive retooling. For example, the LOCAD-PTS instrument that is currently being flown on the ISS required complete reengineering to accommodate man-rated space-flight requirements such as low outgassing from construction materials, radiation-resistant electronics, etc. De novo development of necessary technologies required for long-duration human space-flight missions is likely to prove at least as cost-effective as modification of existing commercially-available equipment.

The Moon should be used as a test bed of advanced life support systems for Mars exploration. There should be a move towards sustainable high efficiency closed-loop systems, as well as a comprehensive effort to qualitatively and quantitatively assess their effectiveness.

Issues

The PPS has identified several issues that would benefit from additional attention during planning of the Constellation Architecture. The near-term focus on exploration of the Moon affords a unique opportunity for testing planetary protection protocols in a challenging space environment, known to be sterile but not restricted by planetary protection policy. Every effort should be made to take advantage of this opportunity, to ensure that planetary protection protocols are established to the extent that will be required for future human missions to solar system bodies receiving more than Category I protection.

A separate, follow-on meeting to explore opportunities in biological sciences in partial gravity and at a pressurized Lunar Outpost is suggested. Such a meeting will continue and expand the effort started two years ago that brought together Planetary Protection experts, astrobiologists, life support specialists, and engineers to discuss human exploration of space. Additional meetings should address, in a systematic and detailed fashion, cross-cutting science and technologies that are both enabled by the lunar exploration program and will enable human exploration to more remote solar system bodies.

Substantial proportions of the lunar dust are submicron-sized and could pose a significant health hazard, although no adverse effects have been detected due to the limited dust exposures of the Apollo astronauts. Current efforts to use data from Apollo and terrestrial dust exposure studies should be strongly encouraged to better understand exposure times, particle distributions, particle morphology, chemistry and reactivity that may a pose a problem. Human health must be assessed routinely during exposure to planetary environments to evaluate the potential risks upon return to Earth.

A variety of equipment is available or under development that would be desirable to test on the Moon for studies relevant to human health and planetary protection and field-capable versions will certainly be completed prior to the first human return to the Moon. In planning the lunar outpost, it will be very important to include sufficient allotments for up-mass to the lunar science laboratory that facilitate testing of planetary protection technologies and experimental equipment. In addition, outpost crews will need appropriate training in operation of the equipment, and sufficient time scheduled to allow the necessary testing and experiments to be performed.

Planetary Protection technologies to reduce contamination from human missions must be supported at an appropriate budget level if human missions to Mars are to be properly planned and implemented.

Effective communication with the public about PP goals and requirements will be important to garner public support for both robotic and human missions to other planetary bodies.

Article IX of the 1967 Outer Space Treaty and COSPAR guidelines for Planetary Protection

Article IX of the Outer Space Treaty of 1967*, to which the United States is a party, states in part that "...parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose..." These basic treaty principles are not elsewhere defined in the treaty itself, but like other treaties this treaty is "the supreme law of the land" under the US Constitution (Article VI).

To ensure treaty compliance, and upon the repeated recommendations of the US National Academy of Sciences, NASA maintains a planetary protection policy to protect against biological or organic contamination that might jeopardize scientific exploration or the safety of the Earth's environment. NASA also works with COSPAR, an interdisciplinary committee of the International Council for Science that consults with the United Nations in this area, to ensure that there is an international consensus policy that can be used as the basis for planetary protection measures to be taken on international cooperative missions. In general, NASA will approve the flight of NASA-developed instruments and/or experiments on non-U.S. planetary spacecraft only if the launching organization adheres to the COSPAR-approved planetary protection policy and its requirements (As noted in NPR 8020.12C).

*("Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies" entered into force October 10, 1967. 18 U.S. Treaties and Other International Agreements at 2410-2498.)

Appendix 5: Workshop Findings of the Planetary Science Subcommittee

Presentations to the Planetary Sciences Subcommittee (PSS) breakout sessions at the Lunar Science Workshop focused on the major science themes developed by the Lunar Architecture team (LAT) and modified by the Lunar Exploration Analysis Group (LEAG). The interim report of the Space Studies Board on lunar science priorities also was considered. Discussion on Thursday afternoon included input from the PSS and input from the general audience, which fluctuated between about 65-90 participants (depending on the topic under discussion). Discussion focused on the objectives and how they would be achieved within the current lunar architecture, noting what modifications would be needed and what technology developments will need to be focused upon.

Objectives Grouped under Five Overarching Themes

The Planetary Sciences Subcommittee breakout sessions at the Lunar Science Tempe Workshop examined all 16 of the GEO-SAT objectives and grouped them under 5 broad science themes. These are given below along with the objectives that are grouped under each one.

> Investigation of the geological evolution of the Moon and other terrestrial bodies (mGEO-1, mGEO-2, mGEO-3, mGEO-5).
>
> Improved knowledge of impact processes and impact history of the inner solar system (mGEO-6, mGEO-7, mGEO-8).
>
> Characterization of regolith and mechanisms of regolith formation and evolution (mGEO-9, mGEO-10, mGEO-11, mGEO-14).
>
> Study of endogenous and exogenous volatiles on the Moon and other planetary bodies (mGEO-4, mGEO-12, mGEO-13).
>
> Development and implementation of sample documentation and return technologies and protocols (mGEO-15, mGEO-16).

On the basis of the overarching themes and subsidiary objectives, the LEAG is charged to correlate the objectives to an implementation plan. Correlation will include measurement objectives, geographic coverage, and sampling and documentation strategies. Objectives will be distinguished on the basis of major progress that can be made through the current exploration architecture.

Discussion of each of the LEAG GEO-SAT (Geoscience objectives Special Action Team) objectives as modified by the LAT

Introduction:

Science themes that were assembled by the LAT from the ESMD Lunar Exploration Workshop (April 2006) were ranked by the LEAG as the GEO-SAT for lunar-science relevance and by the Mars Exploration Program Analysis Group (MEPAG) for relevance to the exploration of Mars. During the Tempe workshop the priorities of these themes were debated and ranked. Implementation of the science was discussed in detail leading to the recommendations to NASA. Here, we list in order of the GEO-SAT / LAT objectives, the science theme, ranking, and a summary of the discussion. A table summarizing the objective assessments and rankings follows this section. Note that slight adjustments to the titles of mGEO-6, -7, -10, -12, -13, and -15 in the mGEO-SAT document have been made to clarify the science objectives.

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:
  - **<u>Two Station</u>**s: 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.
  - **<u>Three Stations</u>**: 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

seismometers will yield only approximate information at best on the locations of shallow moonquakes, and little information on crust/mantle heterogeneity.

- **<u>Four Stations</u>**: Exploring lateral heterogeneity in the lunar crust and mantle requires a minimum of four seismometers, but this depends on the distribution of the stations (to obtain global distribution of structural and seismic-velocity variations, a globally distributed array of seismic stations is required). There is no clear limit to the number of seismic stations needed to do this, but the larger the number of stations, the more detailed the result will be.
- **<u>> Four Stations</u>**: A larger number of seismometers is required to determine source depths for shallow moonquakes because a smaller spacing of stations is needed relative to that required for deep sources. What is required is to place clusters of seismometers at a number of the approximated shallow moonquake locations, as well as any proposed lunar habitat site. Such a cluster could be set up at one site using the current architecture, then at one location (at least), a cluster of three seismometers could be set up to answer some of the fine-scale questions raised above.
- **<u>General</u>**: Any network should have a broader coverage than that of the Apollo Passive Seismic Experiment (PSE) network. Many of the shortcomings of the Apollo seismic database stem from the lack of station coverage beyond the near-side center of the Moon. Thus, extending the station coverage should be the primary objective of our next lunar seismic observation. Also important is the length of observation; longer duration experiments are needed, preferably longer than the 5–8 years that the Apollo stations were operational.

- A bare-bones global network (e.g., 4 stations with much wider coverage than Apollo), set up prior to the seventh human landing, would add greatly to meeting this objective and assist in the proper planning for activities related to that landing (see above).
- Orbital geophysical data are also important, such as gravity, magnetics, and the composition and dynamics of the lunar atmosphere.
- A range of geophysical properties need to be measured over a number of years in order to achieve this objective (e.g., heat flow, magnetism, seismic events and their magnitudes, locations and travel times, and dynamics of responses).
- This objective cannot be addressed from a single site (if mobility is limited to 20 km). However, a geophysical station (seismometer, heat-flow probe(s), magnetometer, for example) should be set up at an outpost site because it would provide the following: a record of seismicity at the outpost site; some limited information about the interior; and, most importantly, it would represent the initial node of a long-duration, global seismic network.
- To ultimately fulfill this science objective, access to sites across the entire Moon is essential. If global access is available within the outpost architecture, this objective will be achievable.
- NASA is encouraged to consult with international partners to ensure that any mission to the Moon's surface deploys a common geophysical package.

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.

PSS/LEAG Score: 10
MEPAG Ranking: Medium

Discussion:

- Overlaps with mGEO1, but requires targeted sample returns from impact basins, especially the South Pole-Aitken Basin, vent crater deposits, pyroclastic deposits, central peaks of impact craters, ancient buried lava flows or "cryptomare," volcanic "red spots" – areas likely to represent compositionally evolved volcanic materials, impact crater ring exposures, far-side and polar crust and mare basalts, and unsampled near-side mare basalts (including the "youngest" basalts). As with mGEO-1, global access from an outpost could enable this objective to be achieved.
- It is unlikely that the current architecture will allow this objective to be achieved in its entirety in the near term, although important insights may be gained by sampling bedrock materials and ejecta present in the vicinity of an outpost site. However, depending on the geological setting of the specific site chosen, significant progress could be made by intensive study of the rock components present in the regolith and in crater ejecta at one site. This could be accomplished by returning significant amounts of regolith through the region surrounding the outpost (see also mGEO-5), and perhaps by using automated techniques to screen samples on the surface. Proximity to a diversity of geologic terrains is particularly important.
- Robotic missions with/without humans present will play an important part in achieving the scientific goals, especially in sampling relatively small, issue-critical sites identified from orbital data and in allowing full "global" access. Robotic missions also will play a role in deploying global network instruments. However, robotic sampling does not satisfy all sampling needs for documentation of geological context – sample context will be neglected unless robots work in unison with humans ("telepresence") to analyze or sample variable/large terranes. Even with human remote telepresence, subtle details of sample context and much of the spontaneity of follow-up observations that humans on the spot provide will be lost.
- <u>Technology development</u>: develop sample return mechanisms for (a) robotic (simple) and (b) human (complex) sampling sorties. There are some sites that can be sampled robotically and those that need human presence (or the combination of humans and robots).
- Development of technology for efficient human exploration (mobility and pressure suit systems), observation (mapping, active geophysical and geochemical sensors and geometric and geotechnical measuring systems) and sampling and sample documentation of complex sites.

mGEO-3: Characterize the lunar geophysical state variables to constrain the origin, composition, and structure of the Moon and other planetary bodies.

PSS/LEAG Score: 9
MEPAG Ranking: Medium

Discussion:

- Geophysical state variables include the lunar gravitational potential field, heat flow, lunar rotational fluctuations, lunar tides and deformation, and the present and historic magnetic fields. Geodetic information about the Moon can be used to determine global-scale geophysical characteristics that include the core and deep mantle.
- Long distance surface mobility as well as global access will enable this objective to be achieved. An analytical capability to determine geophysical/geotechnical parameters that would be useful for outpost development is desirable.
- This objective is also enabled by a combination of sample return (or collection and characterization of surface physical samples) for ground truth, and orbital measurements. Orbital measurements (e.g., magnetic measurements of Moon in free solar wind, magnetosheath, and magnetotail) are important for electromagnetic sounding and conductivity measurements to constrain the size and nature of the lunar core.
- Knowledge of the heat flow of the Moon in a global sense is needed for proper interpretation of other geophysical data. Key areas for heat-flow measurements include the 'hot spot' on the western near side in the Imbrium-Procellarum region, the interior of the far-side South Pole-Aitken basin, and a location within the feldspathic highlands away from the regions of high thorium concentration.

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.

PSS/LEAG Score: 7
MEPAG Ranking: Low

Discussion:

- Endogenous volatile deposits are not present everywhere, so surface mobility from an outpost will be an enabling capability for this objective.
- Some high priority aspects of this objective will require sample return (for example from pyroclastic deposits/cryptomare. Field-work and surface-mobility capabilities with local (~50 km), regional (up to 500 km) and global access will enable this objective to be achieved. Possibly robotic sample return. Without this capability, the objective is unlikely to be achieved because there are not substantial pyroclastic deposits known to be at the poles.
- Fieldwork will allow a better understanding of the current outgassing environment by visiting sites that are thought to be areas of active or geologically recent outgassing.

- Volatiles that are endogenous vs. exogenous need to be differentiated. Exogenous volatiles will include trapped and implanted components.

mGEO-5: Characterize the crustal geology of the Moon via the regolith to identify the range of geological materials present.

PSS/LEAG Score: 9
MEPAG Ranking: Low

Discussion:

- This is more than simply a regolith study. It requires rocks from the regolith to be sampled and returned from a variety of locales, including the farside, because a variety of samples will be needed to examine the diversity of the lunar crustal rocks. Sample return could be accomplished by human or robotic missions with significant mobility, or a combination of both. However, this objective could be initiated by a single sample of regolith (to look at the diversity of ejecta material in it), which can be obtained from anywhere, including an outpost location.
- The discussion centered around this being intimately linked with mGEO-2.
- Integration with orbital geochemical and geophysical data is vital to achieve this objective.
- Assisting in meeting this objective means routinely collecting “sortie rake samples” and "contingency" samples at various locations during exploration or landings in new regions.
- Extensive fieldwork enabled by global surface mobility along with sample characterization and documentation capabilities in the field and at an outpost are enabling for this objective.
- Robotic sortie missions could fully meet the objective in locales where human missions are unlikely to land.

mGEO-6: Characterize the impact process, especially for large basins, on the Moon and other planetary bodies to understand this complex process.

PSS/LEAG Score: 9
MEPAG Ranking: Low

Discussion:

- mGEO6 is process-oriented, but relates directly to processes active and important on the early Earth and throughout its history.
- A lunar outpost is a good place to begin addressing this objective, particularly if located on a ring of the South Pole-Aitken basin.
- Shallow geophysical studies will allow investigations of the 3D structure of craters and should be part of any study of impact processes.
- Significant progress can be made at a single site by studying a number of impact craters in detail; however, local to regional surface mobility for astronauts is needed.

- Achieving this objective requires orbital and sample data, including geological and geophysical field studies, and return of key samples to Earth.

mGEO-7: Characterize impact flux over the Moon's geologic history, to understand early solar system history.

PSS/LEAG Score: 10
MEPAG Ranking: High

Discussion:

- mGEO7 is history-oriented**,** but relates directly to the history of the Earth and the origin and evolution of life on Earth.
- Originally the objective read “Characterize impact cratering over the Moon’s…..”
- Sample return of impact melt rocks from various craters will be needed for precise age dating.
- If the outpost is located within a large basin not previously sampled, significant progress could be made. For example, South Pole-Aitken basin is a very good place to start, but would require a far-side, southern hemisphere site. A location within the South Pole-Aitken basin would provide access to sample its melt sheet (hence be able to date the event as long as the melt sheet can be identified) as well as those of superposed younger basins.
- Surface mobility is an enabling technology in order to gain access to and samples from the largest impact basins.
- Impact-melt samples will need to be returned to Earth for age dating.

mGEO-8: Investigate meteorite impacts on the Moon to understand early Earth history and origin of life.

PSS/LEAG Score: 7
MEPAG Ranking: Low

Discussion:

- mGEO8 resulted from the combination of three different, but related topics: (1) Determine timing and composition of impactors to study the impact history of the Moon. (2) Look at the cratering flux and regolith in specific lunar craters. (3) Search for material/impact ejecta from Earth and other bodies to research characteristics of the earlier impact history (i.e., Earth Meteorites).
- This is an important lunar science objective that is enabled by extensive surface mobility and fieldwork. The low PSS/LEAG score reflects the lack of confidence in finding early Earth meteorites on the Moon.

mGEO-9: Study the lunar regolith to understand the nature and history of solar emissions, galactic cosmic rays, and the local interstellar medium.

PSS/LEAG Score: 9
MEPAG Ranking: High

Discussion:
- Meeting this objective will require drilling and/or trenching of the lunar regolith, field observations, and sample return, recognizing that agitation of collected regolith will release significant amounts of solar-wind-implanted volatiles.
- This objective would be best achieved if a site can be found where fossil regolith occurs between lava flows or definable ejecta blankets so the enclosing layers can be dated and thus the age of the regolith can be constrained. Such stratigraphy may be best preserved in special environments (especially volcanic terrains) that may or may not be present near an outpost location. Extensive surface mobility would, therefore, be an enabling capability for achieving this science objective. Although the requirement for mobility is not essential to achieve some aspects of this objective, it would certainly enhance the science return.
- This objective should include a study of the megaregolith and shallow geophysical studies would be useful in defining megaregolith thickness at least at the local scale.

mGEO-10: Determine lunar regolith properties to understand the surface geology and environment of the Moon and other airless bodies.

PSS/LEAG Score: 7
MEPAG Ranking: Low

Discussion:
- This objective refers to regolith properties anywhere, including cold traps.
- These include geochemical, petrologic, and geotechnical properties. The latter will be important in understanding the transmission of seismic energy as wells and the engineering and economic aspects of construction and resource extraction.
- There was discussion of the use of a local active seismic network, including seismic tomography, near the outpost to aid in the understanding of regolith properties in this area, along with ground-penetrating radar. This type of infrastructure would be very useful in achieving the goals of this scientific objective and this is enabled by an outpost architecture.

mGEO-11: Characterize the lunar regolith to understand the space weathering process in different crustal environments.

PSS/LEAG Score: 7
MEPAG Ranking: Low

Discussion:

- In order to understand the space weathering process over time, regolith of different ages needs to be identified and sampled.
- The phrase "*in different crustal environments*" was added at the end of this objective title through consensus after discussion regarding the specific goals that this objective should encompass.
- There are two ways this objective can be achieved: (1) trenching and detailed sampling of different levels, and (2) identifying the spectrum of features at different ages (i.e., fresh features vs. degraded features (this could result in the need to sample from widely spaced sites on the Moon, although small craters of a range of ages are present at all locations.). The latter would not require trenching but would be enabled by the availability of surface mobility. Trenching and detailed sampling of different levels within the regolith could be suited to the outpost architecture if the maturity (degree of exposure to space weathering) of the regolith changes with depth.
- Detailed field observations (i.e., in-the-field, in-situ analyses by means of detailed observations and hand-held instruments) will be needed.

mGEO-12: Characterize lunar volatiles and their sources to determine their origin and to reveal the nature of impactors on the Moon.

PSS/LEAG Score: 8
MEPAG Ranking: Medium

Discussion:

- The words "*and their sources*" were added to the title of this objective (as shown above).
- This objective is aimed at understanding cold-trap volatiles (cometary, solar wind implanted, etc.) – how they were deposited, what was their source, and how they accumulated at the poles.
- In-situ cold-trap analyses may be required to fully achieve the goals of this objective – robotic technology developments for operation in extremely low temperatures are needed.
- Sample return may not preserve the integrity of the cold-trap samples unless specialized sampling and containment techniques are developed.
- Although this objective is extremely important scientifically, significant enabling technology developments will be needed to ensure this objective can be successfully achieved.

mGEO-13: Characterize transport of lunar volatiles to understand the processes of polar volatile deposit origin and evolution.

PSS/LEAG Score: 7
MEPAG Ranking: Low

Discussion:

- Goals of this objective could be achieved with orbital spectrometers or a network of surface spectrometers to monitor the exosphere at various places on the lunar surface.
- The timing of this is critical for recording the state of the lunar exosphere and volatile transport process *before* lunar missions start landing regularly and disturbing the exosphere.
- Transport of volatiles may be related to the source as well as many other variables such as, latitude, magnetospheric phase, mineral composition of the regolith, pick-up ion migration, etc.
- Volatiles, in part, will migrate from cold spot to cold spot, rather than migrating off surface although some will be entrained as solar wind pick-up ions and either lost to space or re-implanted in the regolith. Workshop participants agreed that such transport processes are important, but not well understood. Orbital mass spectrometers would be helpful, but no substitute for ground truth from a surface spectrometer network. This could be integrated with a geophysical network deployment.
- The success of this objective is enabled by having global access from an outpost location.

mGEO-14: Characterize volatiles and other materials to understand their potential for lunar resource utilization.

PSS/LEAG Score: 7
MEPAG Ranking: Low

Discussion:

- The previous title, “Characterize potential resources to understand their potential for lunar resource utilization” was changed to the title shown above.
- Any precursor missions are potentially important for carrying ISRU demonstrations, but are likely not essential to achieve the goals of this objective.
- There was no agreement on whether near-surface geophysics (e.g., ground-penetrating radar) or whether drilling and/or trenching with in-situ analysis would be the best way to characterize regolith resources.
- While sample return would yield important scientific discoveries, in-situ analyses to characterize resource potential need to be considered and developed.
- NASA and the scientific community must make the best use of orbital data sets (e.g., Clementine, Lunar Prospector, LRO, Chandrayaan (Indian mission), SELENE (Japanese mission), and Chang’e-1 (Chinese mission) to identify the locations of the sites that have

the most potential for resources as well as detectible and quantifiable surrogates (indicators) to determine the detailed distribution of resources.

- The success of this objective is enabled by having global access from an outpost location.

mGEO-15: Provide curatorial facilities and technologies to ensure contamination and environmental control for lunar samples.

PSS/LEAG Score: 10
MEPAG Ranking: Low

Discussion:

- NASA needs to take advantage of the Apollo experience and knowledge base, especially at the astromaterials sample curatorial facilities at Johnson Space Center.
- This objective is related to science decisions on what kinds of sampling techniques and sample curation/protection need to be done before samples are returned to prevent changes in properties during return trip or when opened on Earth.
- When bedrock samples are taken, mechanisms are needed to preserve knowledge of the orientation of the samples as well as full documentation of environmental variables for environmentally sensitive samples.

mGEO-16: Provide sample analysis instruments and protocols on the Moon to analyze lunar samples before returning them to Earth.

PSS/LEAG Score: 9
MEPAG Ranking: Medium

Discussion:

- Consensus was to add “and protocols” between “instruments” and “on the Moon” in order that technologies and instrumentation that facilitates better field practices (e.g., identification, sampling, documentation, and traverse planning).
- Analyses of samples before they are returned? This would allow high-grading of samples to be returned as the mass allowed to be brought back appears to be limited. However, this should not imply that ALL samples collected need to be analyzed prior to return to Earth and the difficulties in making judgments on analyses that can only be done on Earth should not be underestimated.
- Any analysis at the outpost requires careful protocol development to ensure the integrity of the samples.
- Protocols need to be developed (or refined) for sample collection.
- This has been deferred to CAPTEM for detailed study.

Table of Objective Assessments and Rankings

Table 1: PSS Objectives summary

Objective Number	Objective Description	LEAG/PSS ranking (1-10) 10: highest priority	MEPAG low-high feed fwd to Mars	implementation considerations	rating for 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 ofsuperimposed 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.
mGEO-9	Study the lunar regolith to understand the nature and history of solar emissions, galactic cosmic rays, and the local interstellar medium	9	high	drilling/trenching of the lunar regolith; best done where interlayered volcanics provide age record	3	Extensive regolith excavation at a single site could address this objective by identifying layers deposited by specific impact events. Extensive ISRU processing could aid this search.
mGEO-10	Determine lunar regolith properties to understand the surface geology and environment of the Moon and other airless bodies	7	low	extensive study of regolith, including excavation, sampling, & geophysical studies	1	This objective can be achieved well at an outpost site. Investigation would go far beyond what is known from Apollo cores and active seismic measurements, and could involve in situ measurements of many geotechnical and other regolith properties. Enabling for exploration.
mGEO-11	Characterize the lunar regolith to understand the space weathering process in different crustal environments	7	low	local surface mobility; trenching; sample documentation, collection, and return to Earth	1	Can be done well at a single site with detailed investigation of regolith at different locations and with different degrees of surface exposure.
mGEO-12	Characterize lunar volatiles and their source to determine their origin and to reveal the nature of impactors on the Moon	8	medium	in-situ analysis of volatile deposits; operation in extremely low temperatures	1	Analysis of volatiles in the lunar exosphere and in and near polar cold traps are well enabled by a polar outpost location. Needs to be done early in the human exploration program.
mGEO-13	Characterize transport of lunar volatiles to understand the processes of polar volatile deposit origin and evolution	7	low	global access (range of latitudes & locations) desired	2	Much of this objective can be achieved at a polar outpost site through access to permanently shaded craters and regolith near to and at a range of distances from the pole.
mGEO-14	Characterize volatiles and other materials to understand their potential for lunar resource utilization	7	low	linked to ISRU; exploration enabling; needs to be phased early; access to specific sites widely separated around Moon	4	Ground truth/in-situ characterization of deposits located from orbital data can lead to accurately targeted locations on the Moon. Should be done during the robotic precursor phase to identify the best outpost location. Doing this from a polar outpost location instead of during the precursor phase will characterize the deposits at the site, but this is too late to influence optimal outpost location, thus ranked a "4."
mGEO-15	Provide curatorial facilities and technologies to ensure contamination control for lunar samples	10	low	development of sample documentation, collection, environmental and orientation controls needed	1	Objective can be well achieved at an outpost location; potential polar volatile deposits provide test case for extremely environmentally sensitive sample documentation, collection, transfer, and processing.
mGEO-16	Provide sample analysis instruments and protocols on the Moon to analyze lunar samples before returning them to Earth	9	medium	none	1	Objective can be well achieved at an outpost location.

Recommendations

Geophysical Networks

Achievement of several of the highest-ranked lunar science objectives requires the deployment of long-lived geophysical monitoring networks. Precursory technology investments are needed, e.g., development of a long-lived power source and a deployment strategy for stations that are part of such networks. 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.

Background Information: Geophysical networks (i.e., networks of packages containing, for example, a seismometer, heat-flow probe(s), and a magnetometer) are highly ranked in the interim NRC report and from community input as provided by the LEAG. Such networks need not be limited to geophysical instruments, but also include mass spectrometers for exosphere monitoring. However, such networks need to be long-lived (>6 years, which encompasses one lunar tidal cycle) and requires the development of a power source that can achieve this and survive the lunar night.

Sample Return

Achievement of several of the highest-ranked scientific objectives requires the development of a strategy to maximize the mass and diversity of returned lunar samples. The PSS views the 100 kg total return payload mass allocation (including containers) in the current exploration architecture for geological sample return as far too low to support the top science objectives. The PSS requests that CAPTEM be asked to undertake a study of this issue with specific recommendations for sample-return specifications to be made by May 1, 2007. The PSS recommends that NASA establish a well-defined protocol for the collection, documentation, return, and curation of lunar samples of various types and purpose in order to maximize scientific return while protecting the integrity of the lunar samples.

Background Information: Collection and return to Earth of lunar samples is vital for science. Sample return has been achieved by the Apollo and Luna missions and the protocols that worked during that time should be enhanced; those that did not work need to be revisited so that the lessons learned from Apollo are incorporated into an overall sample strategy. Finally, integration of new field exploration technology will need to incorporated into this strategy. Technology development in terms of vacuum seals, drive tube extraction, and remote robotic sample return (i.e., direct to Earth without involving the outpost) is a necessity for a number of types of sample investigation. The input from CAPTEM regarding the return sample mass allocation will be important for achieving the science objectives described above.

Astronaut Training

As part of the developing lunar exploration architecture, the PSS recommends that extensive geological, geochemical and geophysical field training be established as an essential component in the preparation of astronaut crews and the associated support community for future missions to the Moon. Training should involve experts and experience from the non-NASA community as well as NASA personnel of significant background and 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 of the next generation of lunar explorers. Crews for future lunar missions should include astronauts with professional field exploration experience. Research and training or operational simulations are needed to determine how robots can best be used to assist humans in activities associated with the lunar exploration architecture; this has a feed forward to human exploration of Mars.

Mobility

To maximize scientific return within the current exploration architecture, options should be defined and developed for local (~50 km), regional (up to 500 km), and global access from an outpost location. It is important that access to scientifically high-priority sites not be compromised by mobility limitations, both for outpost and sortie missions.

<u>Background Information</u>: 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 (1-2 km) of the habitat are accessible. Options for local (~50 km), regional (up to 500 km), and global access from an outpost location should be explored and presented to the Council for review.

Robotic Missions

Robotic missions are highly desirable to carry out many of the highest-priority lunar science objectives. In addition, workshop participants agreed that robotic precursor missions beyond LRO are important for both basic and exploration science (e.g., determining seismicity in proposed outpost locations and defining the nature of the cold-trap volatile deposits). To fully achieve the highest-ranked lunar-science objectives, continued robotic sortie missions will be needed, before and after human presence is established.

<u>Background Information</u>: The overall lack of science associated with lunar missions for a 10-year period of time severely affects future generations of planetary scientists in the following ways. First, “passing the baton” between the Apollo generation and the new generation will not occur in the manner it should – lessons learned from Apollo will have been forgotten. Second, the outstanding young planetary scientists will not have the detailed knowledge of lunar science that has been establish by and since Apollo when we finally return to the Moon near the end of the next decade.

CEV – SIM Bay

The PSS recommends that the Crew Exploration Vehicle (CEV) have a capability similar to the Apollo science instrument module (SIM) to facilitate scientific measurements and the deployment of payloads from lunar orbit.

Background Information: The CEV SIM Bay could be used to deploy network stations on the lunar surface (see above) and make a wide variety of orbital geochemical, geophysical, mineralogical, photographic, and structural measurements that are critical to the outlined science objectives.

Landing Site and Other Operational Decisions

Scientific input should be an integral component of the decision-making process for landing site targets and exploration planning and execution for a lunar outpost or any lunar mission.

Integration of Data Sets

Lunar data sets from all past missions, LRO, and future international missions should be geodetically controlled and accurately registered to create cartographic products that will enable landing site characterization, descent and landed operations, and resource identification and utilization through a variety of data fusion techniques.

Background Information: This recommendation grew out of the discussion of how to integrate the various data sets that will be returned from the Moon in the next 5-8 years as well as those previously collected.

Planetary Astronomy

Topics such as using the Moon or lunar orbital platforms to search for near-Earth objects and characterizing zodiacal dust should be integrated further into lunar exploration science planning.

Background Information: The area of planetary astronomy largely fell between the PSS and APS at this Workshop, because the PSS focused on lunar science and the ASS focused primarily on astronomical targets outside the Solar System.

Technology Developments

A lunar instrument and technology development program is needed to achieve several of the highest-ranked scientific objectives (e.g., exploration and sample documentation aids, long-lived 1-10 W power supplies; deployment of networks from orbit; sampling in permanently shadowed regions; development of robotically deployable heat-flow probes).

Background Information: Important technological developments in order to enable vital exploration science. Such technologies will not be lunar-specific but will feed forward to Mars (and beyond). The specific technology development needs that were highlighted at the Tempe Workshop are listed below:

Technology Development Needs

- 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 studies.

- Hard vs. soft landing options (capabilities) for deploying instrument packages from orbit to set up networks.
- 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 (e.g., hand-held laser Raman spectrometer, x-ray fluorescence spectrometer, etc.).
- 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.

Sustained Scientific Input to Lunar Exploration Planning

Regular reviews of the major decisions that will influence the science outcome and legacy of lunar exploration should be carried out by the Council and its science subcommittees, and their findings and recommendations transmitted to the Council. Topics for such reviews should include:

- Options for full access to the Moon (low, mid, and high latitudes; nearside and farside; polar).
- Pre- and post-landing robotic exploration opportunities and missions.
- Options to mix human and robotic exploration.
- Surface science experiments and operations at the human outpost.
- Surface science experiments and operations during human sorties.
- Mission planning
- Critical items in space hardware design, including:
  - delivery of science experiments to the lunar surface;
  - returned payload constraints
    - upload of science (samples, data) from the lunar surface;
  - orbiting module science requirements (e.g., SIM bay);
  - crew orbiting science operational requirements (e.g., portholes).
  - mission Control science requirements during operations.

Appendix 6

NASA Advisory Council
Workshop on Science Associated with the Lunar Exploration Architecture
Detailed Program
February 27 - March 2, 2007

Tuesday, February 27, 2007

	Opening Plenary, Galleria Ballroom **Overflow room: Encantada**	
8:00 a.m.	Opening remarks	B. Jolliff and H. Schmitt
8:15 a.m.	The Vision for Space Exploration	M. Griffin
8:45 a.m.	SMD: Science associated with the VSE	C. Hartman
9:00 a.m.	NRC Interim Report on the Scientific Context for Exploration of the Moon	C. Pieters G. Paulikas
9:30 a.m.	******************** BREAK********************	
9:50 a.m.	ESMD General welcome & introduction	S. Horowitz
10:00 a.m.	Introduction of Global Exploration Strategy and Lunar Architecture Team	D. Cooke
10:10 a.m.	Global Exploration Strategy (including international and commercial components)	J. Volosin
10:50 a.m.	Overview and Status of the Lunar Exploration Architecture Team Activity	D. Cooke
11:00 a.m.	Science within the Lunar Architecture	L. Leshin
11:30 a.m.	LEAG TOP-SAT: Summary of Results and Science Objectives	J. Taylor
12:15 p.m.	******************** LUNCH********************	
	Subcommittee science discussion overviews (each SC gives a 20 min overview)	
1:30 p.m.	Astrophysics Overview	D. Spergel
1:50 p.m.	Heliophysics Overview	J. Spann, H. Spence
2:10 p.m.	Planetary Protection Overview	J. Rummel
2:30 p.m.	Planetary Science Overview	C. Shearer
2:50 p.m.	Earth Science Overview The Lunar Earth Observatory Concept	M. Ramsey P. Christensen
3:10 p.m.	******************** BREAK********************	
3:30 p.m.	Subcommittee Breakout Sessions	

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February 27 - March 2, 2007

Tuesday, February 27, 2007
Astrophysics Subcommittee, Prescott Room

3:30 p.m.	Astrophysics Introduction: Review of STScI Meeting	**Session Chair:** D. Spergel
3:40 p.m.	Astrophysics Enabled by the Return to the Moon Report	M. Livio
4:30 p.m.	Astrophysics Theme 1: IR/Optical/UV Telescopes	
4:40 p.m.	Dirt, Gravity, and Lunar-Based Telescopes: The Value Proposition for Astronomy	D. Lester
5:30 p.m.	Adjourn	

Tuesday, February 27, 2007
Earth Science Subcommittee, Palo Verde Room

	Breakout Session 1 - NRC Decadal Survey Review	
3:30 p.m.	Earth Science Decadal Survey	M. Freilich
4:30 p.m.	ESD Road Mapping Process	B. Cramer
5:30 p.m.	Adjourn	

Tuesday, February 27, 2007
Heliophysics Subcommittee, Payson Room

3:30 p.m.	**Breakout Session 1 - Heliophysics Science of the Moon**	**Session Chair:** J. Spann
3:40 p.m.	Lunar Electromagnetic/Plasma Environment	B. Lin
4:10 p.m	Determining Lunar Crustal Magnetic Fields and their Origin	J. Halekas
4:40 p.m.	The Lunar Wake as a Unique Plasma Physics Laboratory	B. Farrell, to be presented by J. Halekas
5:30 p.m.	Adjourn	

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Tuesday, February 27, 2007
Planetary Protection Subcommittee, Galleria Ballroom

3:30 – 5:30 p.m.	**Breakout Session 1 - Organic/Microbial Analyses + Experiments**	**Moderator:** M. Voytek & C. Conley
	Theme 1: Overview of life detection methods and challenges	A. Steele
	Theme 2: Organic measurements on the lunar surface: 'Natural' and planned experiments	J. Dworkin
	Theme 3: The Urey Experiment with Planetary Protection Applications	J. Bada
	Theme 4: Organics in the Apollo Lunar Samples	C. Allen, J. Lindsay
5:30 p.m.	Adjourn	

Tuesday, February 27, 2007
Planetary Science Subcommittee, Encantada Ballroom

	Breakout Session 1 - Key Science Problems I	**Moderators:** J. Head / J. Taylor
3:30 – 5:30 p.m.	Theme 1: Impact history of the inner solar system	D. Kring, T. Swindle
	Theme 2: Exosphere	A. Stern (by telephone)
	Theme 3: Nature, Origin and evolution of volatile polar deposits	D. Lawrence, B. Bussey
	Theme 4: Indigenous lunar volatiles	M. Rutherford
5:30 p.m.	Adjourn	

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Wednesday, February 28, 2007
8:00 a.m. Posters can be placed on display, Galleria Ballroom

Wednesday, February 28, 2007
APS, Prescott Room

8:30	**Breakout Session 2(a) - Astrophysics Theme 2: Talk, Radio**	**Session Chair:** J. Mather
8:50 a.m.	The 21cm Background: A Low-Frequency Probe of the High-Redshift Universe	J. Hewitt
9:30 a.m.	Peering through the Dark Ages with a Low Frequency Telescope on the Moon	J. Burns
9:50 a.m.	Radio Wavelength Observatories and the Exploration Architecture	J. Lazio
10:15 a.m.	******************** BREAK********************	
10:30 a.m.	**Breakout Session 2(b) - Astrophysics Theme 1: High Energy Astrophysics**	**Session Chair:** K. Flanagan
10:40 a.m.	High Energy Gamma-Ray and Cosmic-Ray Astrophysics on the Moon	R. Binns
12:00 noon	******************** LUNCH ********************	

Wednesday, February 28, 2007
ESS, Palo Verde Room

	Breakout Session 2(a) –Earth Science Decadal Survey Discussion	
8:30 a.m.	ESS Decadal Review Discussion: Which activities could map to a future lunar Earth Observatory? Earth Science Decadal Survey	All
10:00 a.m.	******************** BREAK********************	
	Breakout Session 2(b) - A Lunar-Based Earth Observatory	**Session Chair:** M. Ramsey
10:15 a.m.	Introduction	M. Ramsey
10:30 a.m.	A Lunar Earth Observatory	P. Hamill
10:50 a.m.	Dual-use Earth Science and Lunar Exploration missions	T. Freeman
11:10 a.m.	Science Observations from the Earth-Moon L1 Point	J. West
11:30 a.m.	Panel Discussion/Q&A (Ramsey, Freeman, Hamill, Christensen, West)	All
12:00 noon	******************** LUNCH********************	

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Wednesday, February 28, 2007
HPS, Payson Room

8:30 a.m.	**Breakout Session 2(a) - Space Weather, Safeguarding the Journey**	**Session Chair:** N. Schwadron
8:30 a.m.	Characterizing the Near Lunar Plasma Environment	T. Stubbs
9:00 a.m.	Dusty plasma issues on the lunar surface: Existing observations and required future measurements	M. Horanyi
9:30 a.m.	Space Weather Imaging from the Moon	D. Hassler
10:00 a.m.	******************** BREAK********************	
10:15 a.m.	**Breakout Session 2(b) - Space Weather, Safeguarding the Journey**	**Session Chair:** N. Schwadron
10:30 a.m	Space Weather impacts on robotic and human productivity	J. Mazur
11:00 a.m	Characterize radiation bombardment	J. Adams
11:30 a.m	Systems on the lunar surface to support of Space Weather	J. Davila
12:00 noon	******************** LUNCH ********************	

Wednesday, February 28, 2007
Joint PSS-PPS, Encantada Ballroom

8:30 a.m.	**Breakout Session 2 - Key Science Problems II**	**Moderators:** C. Neal / C. Shearer
.	Theme 1: Differentiation History of the Terrestrial Planets as recorded on the Moon	L. Borg
	Theme 2: Structure and Evolution of the Lunar Interior	B. Banerdt, L. Hood
	Theme 3: Origin and Evolution of the Earth-Moon System	K. Righter (C. Shearer presenter)
10:15 a.m.	******************** BREAK********************	
10:30 a.m.	Theme 4: Evolution of the Lunar Crust	B. Jolliff, L. Nyquist
	Theme 5: Science associated with Resource Identification and Development	J. Taylor, M. Duke
	Theme 6: Surface Processes On Airless Planetary Bodies	L. Taylor
12:00 noon	******************** LUNCH ********************	

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Wednesday, February 28, 2007
APS, Prescott Room

1:30 p.m.	**Astrophysics Theme 3: Fundamental Physics and Astronomy**	**Session Chair:** C. Hogan
1:40 p.m.	Fundamental Physics from Lunar Ranging	T. Murphy
2:20 p.m.	ALIVE: An Autonomous Lunar Investigation of the Variable Earth	M. Turnbull
2:50 p.m.	Science and Astrobiology from the Moon or near Moon.	N. Woolf
3:00 p.m.	******************** BREAK********************	
3:30 p.m.	**Astrophysics Theme 4: Astrophysics Quodlibet**	**Session Chair:** M. Cherry
3:40 p.m.	Enabling Astrophysics at the Moon	Y. Pendleton
3:50 p.m.	A Large Optical/UV Serviceable Space Telescope	M. Postman
3:00 p.m.	Large Optics in Space	P. Stahl
2 min/ea	Poster previews	poster presenters

Wednesday, February 28, 2007
ESS, Palo Verde Room

	Breakout Session 3(a) - Land Imaging and Solid Earth Science	
1:30 p.m.	Introduction	B. Minster
1:40 p.m.	Visible/Near-Infrared Remote Sensing of Earth From the Moon	J. Johnson
2:00 p.m.	Land Surface Monitoring from the Moon	J. Mustard
2:20 p.m.	Thermal Infrared Data from the Moon: Hazards and Hot-Spots	M. Ramsey
2:40 p.m.	Lunar-based Large Baseline Synthetic Aperture Radar Interferometry of Earth	K. Sarabandi
3:00 p.m.	Panel Discussion/Questions &Answers (Minster, Johnson, Mustard, Ramsey, Sarabandi)	All
3:15 pm	******************** BREAK ********************	
	Breakout Session 3(b) - Atmospheric Composition and Climate	
3:30 p.m.	Introduction	D. Jacob

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3:40 p.m.	Lunar Observations of Changes in the Earth's Albedo (LOCEA)	A. Ruzmaikin
4:00 p.m.	Observations of Lightning on Earth from the Lunar Surface	S. Goodman
4:20 p.m.	Variability in Global Top-of-Atmosphere Shortwave Radiation	N. Loeb
4:40 p.m.	Panel Discussion/Questions & Answers (Jacob, Herman, Goodman, Loeb, Ruzmaikin)	All
5:30 p.m.	******************** ADJOURN********************	

Wednesday, February 28, 2007
HPS, Payson Room

1:30 p.m.	**Breakout Session 3(a): The Moon as a Historical Record**	**Session Chair:** S. Suess
1:40 p.m.	Composition of the Solar Wind	S. Suess
2:00 p.m.	History of the Sun and Cosmic Radiation	K. Marti
2:20 p.m.	History of the Local Interstellar Medium - Cancelled	D. McKay
2:40 p.m.	History of Inner Solar System According to Lunar Cold Traps	D. Crider
3:00 p.m.	******************** BREAK********************	
3:30 p.m.	**Breakout Session 3(b): The Moon as a Heliophysics Science Platform**	**Session Chair:** A. Christensen
4:00 p.m.	Ionosphere/Magnetosphere imaging	D. Gallagher
4:30 p.m.	The Moon as a base for Solar Observations	G. Emslie
5:00 p.m.	Solar Observations associated with the Return to the Moon	A. Title
5:30 p.m.	******************** ADJOURN********************	

Wednesday, February 28, 2007
Joint PSS-PPS, Encantada Ballroom

	Breakout Session 3a - Implementation of Key Science into Lunar Exploration	**Moderators:** C. Shearer
1:30 p.m.	Theme 1: Important Scientific Sites on the Moon	J. Head
.	Theme 2: Lunar Architecture's Plans to provide Access to Science Sites - Cancelled	discussion

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	Theme 3: Geophysical Networks	C. Neal
	Theme 4: Importance of Sample Science and Sample Return	C. Shearer
	Sampling the SPA Basin: Some considerations based on the Apollo experience	P. Spudis
	Theme 5: The Need for Integrating Planetary Protection Science and Technology	M. Race
3:15 pm	******************** BREAK ********************	
	Breakout Session 3a - "Implementation of key science into the exploration of the Moon and Mars"	**Moderators:** N. Budden / L. Borg
3:30 p.m.	Theme 1: Human Surface Science	H. Schmitt
.	Theme 2: Human-Robotic Combined Activities in Accomplishing Science	P. Spudis
	Theme 3: Linkages between the Moon and Mars	D. Beaty
	Theme 4: EVA Suit Competency for Science: Capabilities and Contamination	D. Eppler, J. Lindsay
	Theme 5: The AMASE Effort and Planetary Exploration	A. Steele
5:30 p.m.	******************** ADJOURN ********************	

Wednesday, February 28, 2007
Outreach, Ponderosa

3:40--5:30 p.m.	Outreach I	G. Kulcinski
4:00 p.m.	Lunar Exploration Outreach Program	K. Erickson
4:45 p.m.	Lunar Reconnaissance Orbiter Outreach	S. Stockman
5:30 p.m.	******************** ADJOURN ********************	

Wednesday, February 28, 2007
Poster session, Galleria Ballroom

6:00 p.m.	Poster session open
	Cash bar, light snacks
8:00 p.m.	Poster session closes, posters must be removed

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Thursday, March 1, 2007
Plenary Session, Galleria Ballroom

8:15 a.m.	Introduction to Cross-cutting Topics, Thursday Agenda	B. Jolliff

Thursday, March 1, 2007
Exploration Science (Environment, Resources, Poles), Encantada

	Breakout Session 4 - "Exploration Science"	**Moderators:** M. Duke / A. Steele
9:00 a.m.	Theme 1: ISRU Program Overview, including Timing	W. Larson
	Theme 2: Effects of ISRU on the Lunar Environment	R. Vondrak
	Theme 3: Space Weather	N. Schwadron
10:15 a.m.	******************** BREAK********************	
	Theme 4: Physical / Chemical Properties and Potential Toxicity of Lunar Dust	L. Taylor
	Theme 5: Lunar Planetary Protection Testbeds and Life Support for Mars exploration	J. Rummel
	Theme 6: Astrobiology and Lunar Exploration	A. Anbar
12:00 noon	******************** LUNCH ********************	

Thursday, March 1, 2007
Sun-Earth Interactions, Payson

	Breakout Session 4 – Sun-Earth Interactions	**Moderators:** A. Christensen / K. Steffen
9:00 a.m.	Sun's Role in Climate Change	P. Goode
9:20 a.m.	A Possibility to Recover the Past Solar Constant (TSI) with the Moon	K. Steffen
9:40 a.m.	Imaging the Sun from the Moon	E. Deluca
10:15 a.m.	******************** BREAK********************	
10:30 a.m.	Lunar JANUS Mission: An Exploration of the Earth and Sun	J. Herman
10:50 a.m.	Imaging the Earth from the Moon	M. Turnbull
11:10 a.m.	Imaging Earth from the Moon	L. Paxton

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	Panel Discussion, summarize key points	All
12:00 noon	******************** LUNCH********************	

Thursday, March 1, 2007
Lunar Dust Science, Palo Verde

	Breakout Session 4 – Lunar Dust Science	**Moderator:** D. Winterhalter
9:00 a.m.	Introduction to Lunar Dust Science and Overview of the NESC Dust Workshop	D. Winterhalter
9:15 a.m.	Everything You Ever Wanted to Know about Lunar Dust	L. Taylor
9:35 a.m.	Interaction of Dust and Plasma on the Moon and Exosphere	T. Stubbs
9:55 a.m.	Measuring and Modeling the Plasma Environment	Z. Sternovsky
10:15 a.m.	******************** BREAK********************	
10:30 a.m.	Dust Analysis at the Moon	Y. Pendleton
10:50 a.m.	Microwave Magnetic Properties of Dust and Its implication for Geophysics and Cohesion	X. Yu
11:10 a.m.	Lunar Dust Distributions from Solar Infrared Absorption Measurements with a Fourier Transform Spectrometer	M. Abbas
11:30 a.m.	Autonomous Lunar Dust Observer for the Systematic Study of natural and Anthropogenic Dust Phenomena on Airless Bodies	C. Grund
	Panel Discussion, summarize key points – All	
12:00 noon	******************** LUNCH********************	

Thursday, March 1, 2007
Science potentially enabled, but not within initial scope, Prescott

	Breakout Session 4 – Science potentially enabled, but not within initial scope	**Moderator:** J. Mather
9:00 a.m.	Heliophysics low frequency radio astronomy	J. Kasper
9:20 a.m.	Synergies between Solar and Celestial Radio Astronomy"	J. Hewitt
9:50 a.m.	In-Space capabilities fostered by the return to the Moon	H. Thronson
10:15 a.m.	******************** BREAK********************	
10:30 a.m.	Costing Space and Lunar missions	D. Ebbets
10:50 a.m.	Enabling large space optics: SAFIR human and robotic development	T. Espero

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Panel Discussion, summarize key points – All

12:00 noon ******************** LUNCH********************

Thursday, March 1, 2007
Outreach, Ponderosa

9:00 a.m. - 12:00 noon **Outreach II** **Session Chair:** G. Kulcinski

Thursday, March 1, 2007
Plenary Session, Galleria Ballroom – Cancelled (time given to final Subcommittee breakouts)

1:30 p.m.	Reports of Special Topics Breakouts	B. Jolliff
1:35 p.m.	Exploration Science	L. Taylor / A. Steele
1:50 p.m.	Sun-Earth Interactions	A. Christensen / K. Steffen
2:05 p.m.	Lunar Dust Science	D. Winterhalter
2:20 p.m.	Science Potentially Enabled, but not within Initial Scope	J. Mather
2:35 p.m.	Outreach	G. Kulcinski
2:50 p.m.	Introduction to Prioritizing the Science Objective Lists	B. Jolliff
3:00 p.m.	******************** BREAK********************	
3:30 – 5:30 p.m.	**Subcommittee Breakouts, Session 5**	

Each of the Subcommittees will be asked to revisit the "Science Objectives Decomposition" matrix for their specific expertise and to use the remaining afternoon breakout sessions to prioritize the objectives and to provide any additional comments or recommendations regarding the listed objectives and implementation issues. This is also the time for subcommittees to prepare a summary of findings and recommendations for the closing plenary session on Friday morning.

Thursday Afternoon Breakout Session Locations:

Astrophysics Subcommittee, Prescott

Earth Science Subcommittee, Palo Verde

Heliophysics Subcommittee, Payson

Planetary Protection Subcommittee, Galleria

Planetary Science Subcommittee, Encantada

Outreach Committee, Ponderosa

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Friday, March 2, 2007

	Closing Plenary, Galleria Ballroom	
8:30 a.m.	Closing Plenary, Reports of Subcommittees, Lunar Architecture Team Remarks	B. Jolliff
8:40 a.m.	APS findings, recommendations	J. Mather
9:00 a.m.	ESS findings, recommendations	M. Ramsey
9:20 a.m.	HPS findings, recommendations	R. Torbert
9:50 a.m.	PPS findings, recommendations	J. Rummel
10:15 a.m.	******************** BREAK********************	
10:30 a.m.	PSS findings, recommendations	S. Solomon
10:50 a.m.	Outreach Committee	G. Kulcinski
11:10 a.m.	Lunar Architecture Team Remarks	L. Leshin/LAT
11:30 a.m.	Conclude Workshop	B. Jolliff / H. Schmitt
12:00 noon	******************** LUNCH********************	
1:30 p.m.	**Synthesis Group – Payson Room**	
	Synthesis committee reconvene	B. Jolliff / C. Neal
	Determine organization & format of final report	
	Synthesis committee writing assignments	
	Plan timeline for completion, review, and delivery of final product to NAC	
	Discuss Workshop Summary Report for EOS (AGU Newsletter)	N. Budden
	LEAG: Future activity related to the Lunar Exploration Architecture	C. Neal
4:00 p.m.	Adjourn	

Appendix 7: List of Acronyms

APS – Astrophysics Subcommittee
CEV – Crew Exploration Vehicle
COSPAR – Committee on Space Research
ESAS – Exploration Systems Architecture Study
ESMD – Exploration Systems Mission Directorate
ESPA – Evolved Expendable Launch Vehicle Secondary Payload Adapter
ESS – Earth Science Subcommittee
EVA – Extra-Vehicular Activity
FEAT – Field Exploration and Analysis Team
GEO – Geostationary Earth Orbit
GPS – Global Positioning system
GSFC – Goddard Space Flight Center
HPS – Heliophysics Subcommittee
ISRU – In-Situ Resource Utilization
LAT – Lunar Architecture Team
LCROSS – Lunar CRater Observation and Sensing Satellite
LEAG – Lunar Exploration Analysis Group
LEO – Low Earth Orbit
LSAM – Lunar Surface Access Module
NRC – National Research Council
PLSS – Portable Life Support Systems
PPS – Planetary Protection Subcommittee
PSS – Planetary Science Subcommittee
RFI – Radio Frequency Interference
SCFE – Science Capability Focus Element
SIM – Science Instrument Module
SMD – Science Mission Directorate
VHF – Very High Frequency
VSE – Vision for Space Exploration

Outreach Committee

Lunar Science Workshop

Tempe, AZ

Feb. 27-March 2, 2007

Members of the Outreach Committee

Name	Location	NASA Area
Allen, Jaclyn	NASA-JSC	Planetary Protection
Collins, Eileen	Astronaut-JSC	Earth Sciences
Fortson, Lucy	Adler Planetarium	Astrophysics
Hauck, Rick	Astronaut-USN (Ret.)	Earth Sciences
Hynek, Brian	Univ. Colorado	Planetary Sciences
Klug, Sherri	Arizona State Univ.	Planetary Sciences
Kulcinski, Gerald	Univ. Wisconsin	Heliophysics
Milgram, Jim	Stanford Univ.	Astrophysics
Shipp, Stephanie	LPI	Planetary Sciences
Slavin, Jim	NASA-GSFC	Heliophysics

Format for Outreach Committee Report

- 1) Top 3 messages from the Workshop to the general public and scientific community.
- 2) Top 3 messages to the general public for each of the 5 thrust areas.
- 3) Top 3 messages to the scientific community for each of the 5 thrust areas.

Overall Messages to Scientific Community and the Public From the Lunar Science Workshop

1) The Moon is witness to 4.5 billion years of Solar System history-*human exploration of the Moon will contribute greatly to discovering the origins of the Earth and ourselves.*

2) The Moon is a unique location from which to observe and analyze the ever changing nature of the Earth, Sun, and Universe.

3) The Moon is a fundamental stepping stone to the human exploration of Mars and the rest of the Solar System.

Messages to General Public

Earth Sciences

1) “Blue Planet Webcam”: The view from the Moon offers a unique perspective of the full earth, all at once, over time

2) From an Earth Observatory on the Moon, we can take the pulse of the Earth from the Moon by monitoring long term Earth events such as,
   - climate variability
   - air pollution sources and transport
   - natural hazards (extreme weather, volcanic plumes, hurricanes)
   - polar ice seasonal and long term variations

3) By viewing the earth from a distance we can collect data to help us to detect and study far away earth-like planets.

Messages to Scientific Community

Earth Sciences

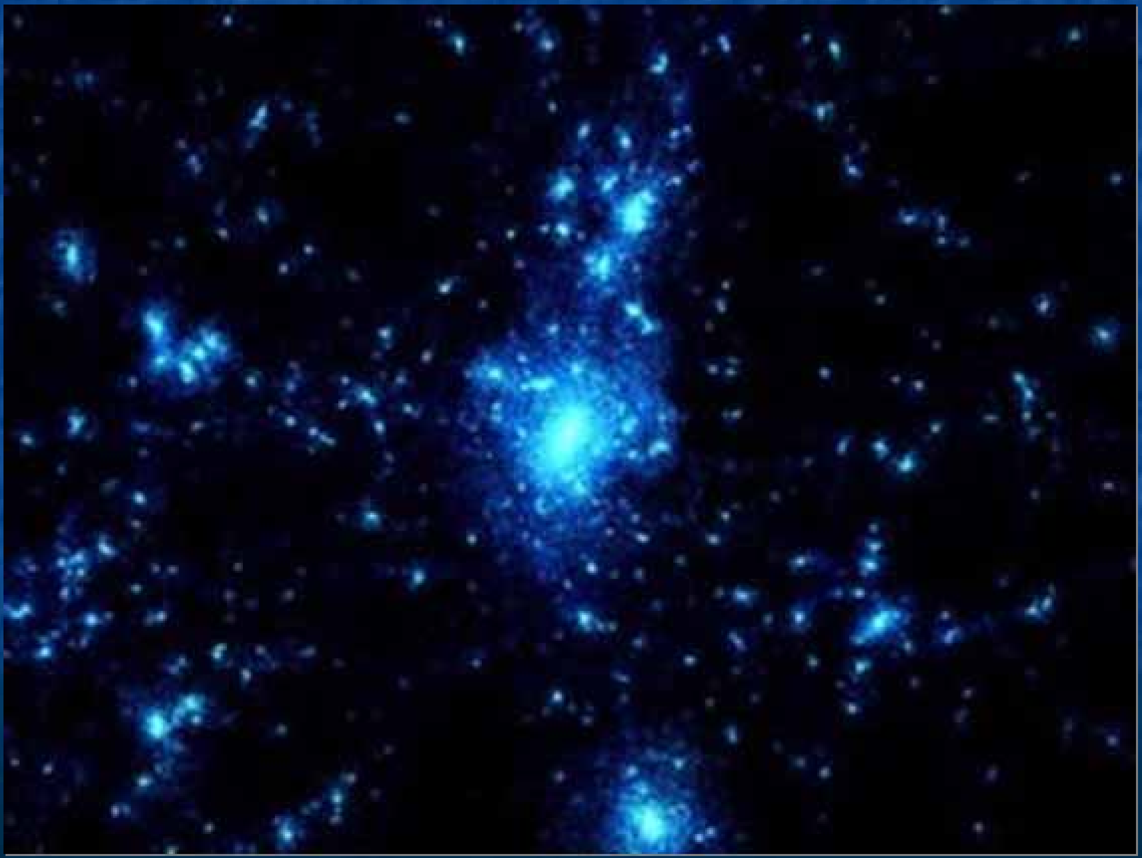
1) A lunar observatory provides a unique, stable, serviceable platform for global, continuous full-spectrum view of the Earth to address a range of Earth science issues over the long-term

2) Synergy of current (LEO, GEO, GPS) assets with lunar instrumentation will insure the collection of the widest array of information from a lunar base

3) There are numerous atmospheric profiling opportunities from visible (stars) to microwave (GPS) to VHF (communications)

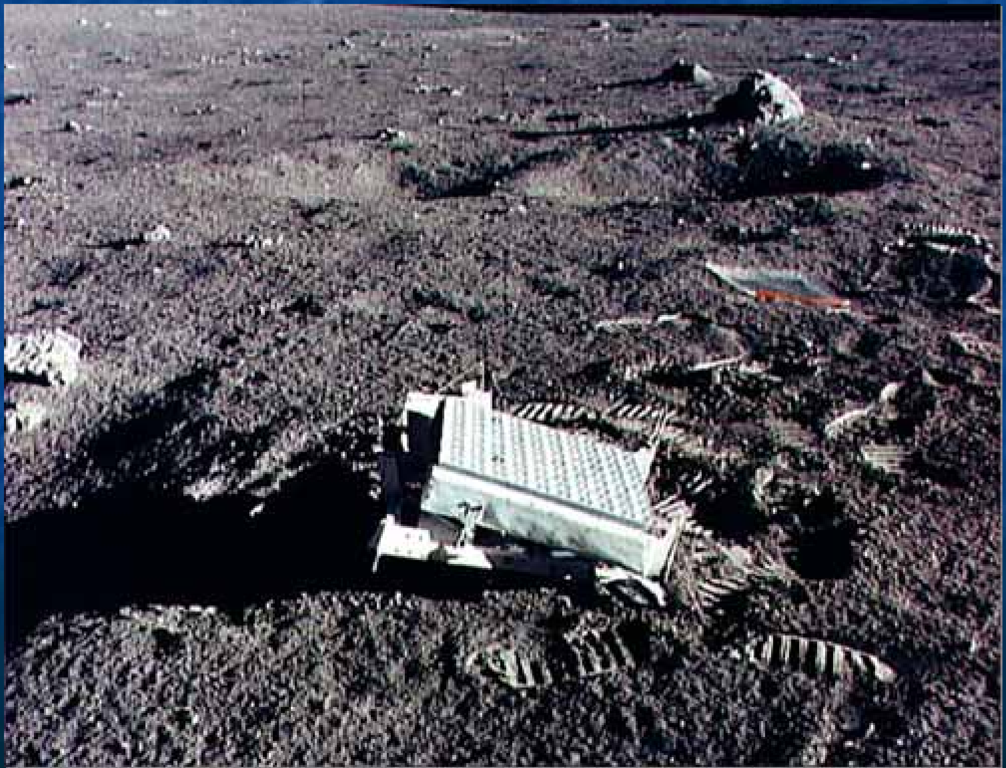
Key Astrophysics Messages for Public

- 1. The far-side of the moon provides a radio quiet zone that enables astronomers to look back in time and find out when the first stars were born.



Key Astrophysics Messages for Public

- 2. Astronauts can carry relatively small astronomy experiments with them to the moon. These packages can accomplish a wide range of science from understanding how gravity really works to using the full view of our own Earth in understanding how to search for signs of life on other worlds.



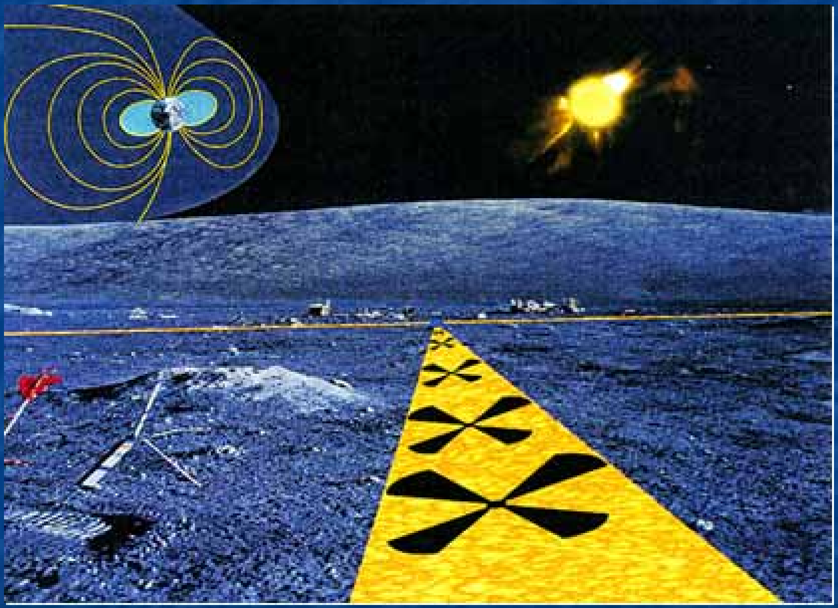
Key Astrophysics Messages for Public

- 3. The rockets that will take us back to the moon give astronomers the heavy lifting they need to put bigger and better telescopes in space. Among other things, these telescopes will look for earth-like planets beyond our solar system, investigate the environment around black holes, and probe the dark energy that makes up most of our Universe.

Key Astrophysics Messages to Scientists

1. The return to the Moon will enable progress in astrophysics through the associated infrastructure. Some important astrophysical observations, as well as a few smaller experiments, can be uniquely carried out from the lunar surface and in lunar orbit.

- **Long-wavelength radio observations from the far-side of the moon**
- **Lunar laser ranging observations for fundamental physics**
- **Characterization of Earth and dust in the solar system as they apply to extra-solar planet research**

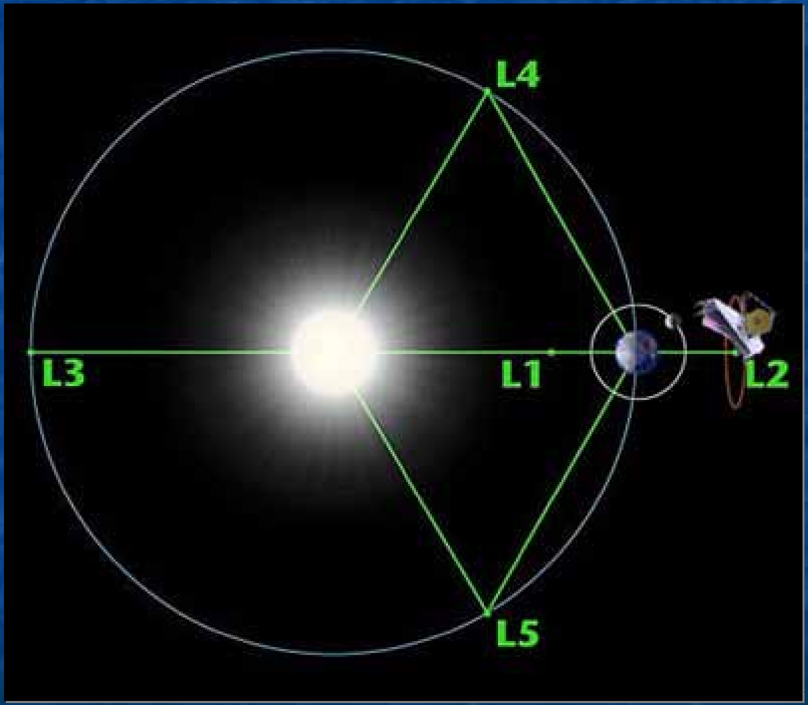


- **Other "science of opportunity" missions competitively selected**

Key Astrophysics Messages to Scientists

- 2. Observations from free space (in particular Lagrange points) enabled by the lunar architecture offer the most promise for broad areas of astrophysics.

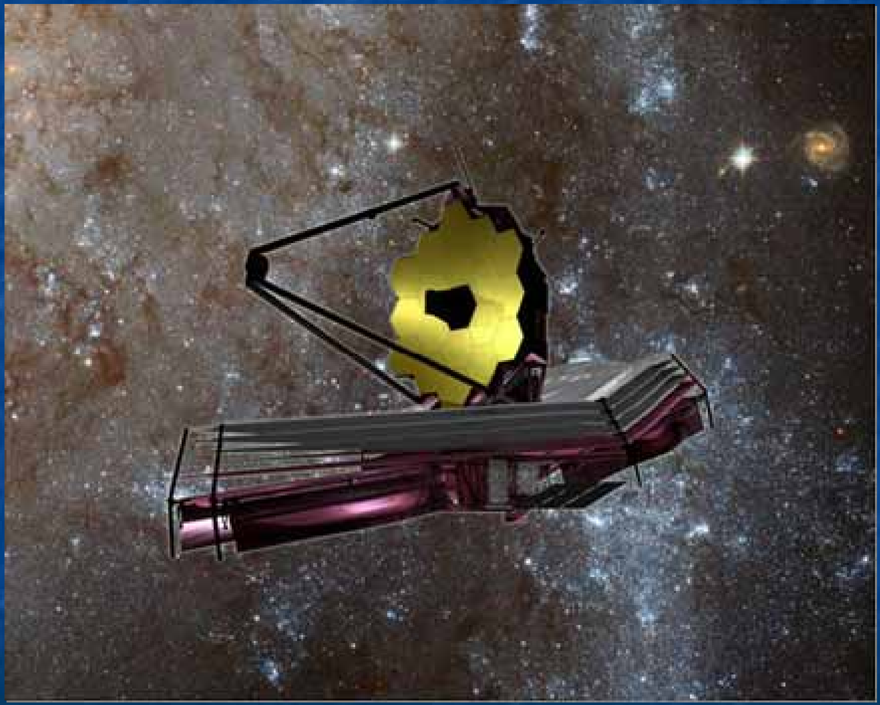
- **High-sensitivity energetic particle observations including a gamma-ray imager**
- **Single-Aperture Far-InfraRed Observatory (SAFIR)**
- **Exo-planet detection observatories**
- **Other "Great Observatory" class missions**



Sun-Earth Lagrange points (not to scale)

Key Astrophysics Messages to Scientists

- 3. The Vision for Space Exploration should be planned so as not to preclude — and to the extent possible to include — capabilities that will enable astrophysics from free space.



- Capabilities of great interest include:
  - Large fairings
  - Advanced telerobotics
  - EVA capabilities
  - High-bandwidth communication
  - A low-cost transportation system (e.g. between Lagrange points)

Messages to the General Public
Planetary Protection

1) Based on international treaties, policies, and decades of research experience on protecting planetary bodies during exploration, lunar missions *will not* require special planetary protection controls.

2) Lunar exploration provides a good opportunity for testing technologies and methods to understand and control mission-associated contamination on long-duration expeditions

3) Lessons learned on the Moon will provide essential information to ensure protection of planetary environments and humans as we explore Mars and other destinations.

Messages to the Scientific Community

Planetary Protection

<u>Preamble:</u>

Planetary Protection is an important on-going focus of both science research and mission planning to safeguard planetary environments and exploration throughout the solar system.

Messages to Scientific Community
Planetary Protection

• Based on the Outer Space Treaty, international policies, and decades of research and experience on protecting planetary bodies during exploration, lunar missions *will not* require special planetary protection controls.

•Lunar exploration provides the opportunity for an integrated test bed of sophisticated technologies and methods needed to understand and control mission-associated contamination on long-duration expeditions.

• Lessons learned on the Moon will provide essential, enabling, and comparative information to ensure protection of planetary environments and humans as we explore Mars and other destinations. (e.g., understanding background and mission-associated organic and inorganic contaminants, dusts, and microbes from the outpost).

Messages to General Public

Planetary Science

1) The Moon has a record of the early history of terrestrial planetary formation and change that is absent on other planets because they have active resurfacing processes like weathering and plate tectonics.

2) We are in a position to build on four decades of lunar science. There is much more new information to learn about our Moon and - from the Moon - about our Earth. For example, the Moon maintains a cratering history and may inform our understanding of the evolution of life on Earth and potentially elsewhere in the Solar System.

3) The lunar outpost will serve as a test-bed for science and exploration of the Moon, Mars and beyond (camp first in your own back yard!).

Messages to Scientific Community

Planetary Science

1) The Moon is critical for accessing the early formation, differentiation, and impact history of the terrestrial planets – and biotic evolution of Earth and Mars.

2) Additional data are needed:

-Geophysical and geochemical data to determine the composition, structure, condition, and evolution of the lunar interior

-Data from the lunar surface to understand the processes that have occurred during its evolution, such as the history of impact cratering and formation of regolith, and the distribution of resources

-Data to inform us more about the lunar environment (conditions in cold traps, atmosphere, volatiles).

3) These new data will enable us to validate lunar science process models, understand the early history and evolution of Earth and other terrestrial planets, and prepare for human habitation of the Moon and beyond.

Messages to Scientific Community

Planetary Science Access

1) The architecture as presented (South Pole-Aitken Basin access from the southernmost rim region) will enable long-term lunar science in a region of high interest and will address several scientific questions (e.g., crust to upper mantle access, impact processes).

2) The scientific goals will have to be prioritized in a cohesive vision across a timeline. This long-term planning will need to encompass:

- Robotic and robotic/human sorties to acquire distributed samples and establish the geophysical network necessary to prepare for a lunar outpost, as well as to address the fundamental science questions.
- Samples from diverse locations on the lunar surface and subsurface to address fundamental science questions. In-situ science will optimize science output / return.

3) The community needs to actively participate in the development of human capital to fuel the pipeline of scientists and engineers.

Heliophysics Science at the Moon

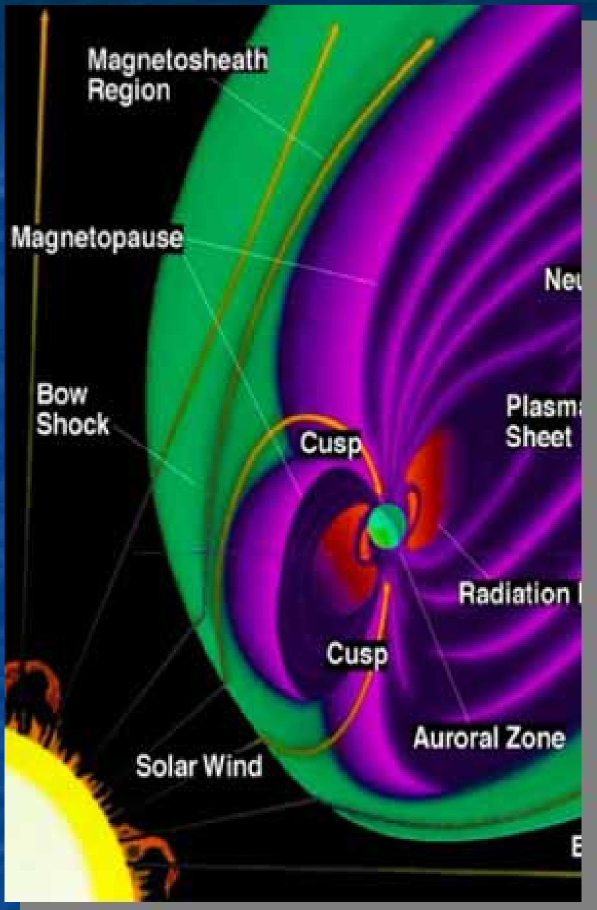
Top 3 messages for both the general public and scientists:

1) **Understanding our space environment is the first step to "Safeguarding the Journey".**

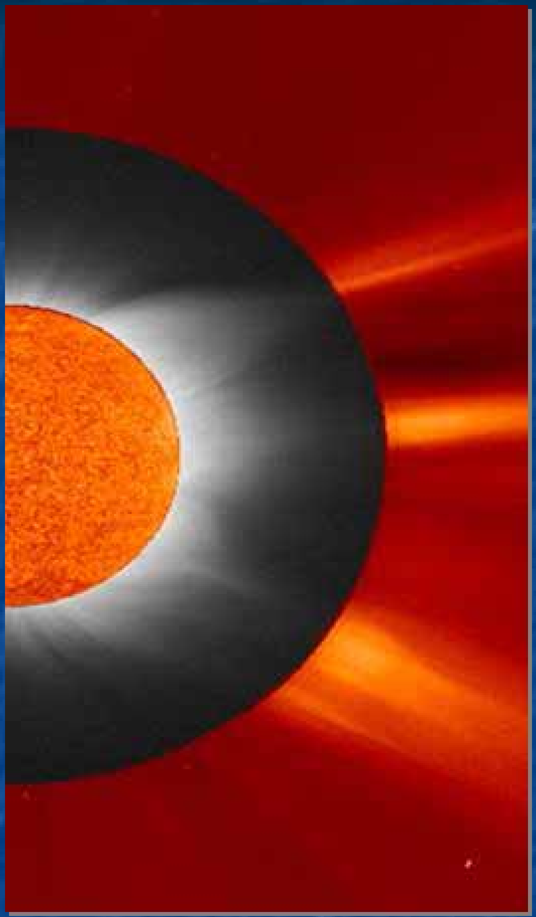
2) **The Moon can be used as an unique vantage point to better understand the Sun-Earth space environment - our "Home in Space".**

3) **The analysis of lunar regolith will provide a history of the Sun's brightness and radiation output and reveal how the Sun - Earth connection has changed through the ages.**

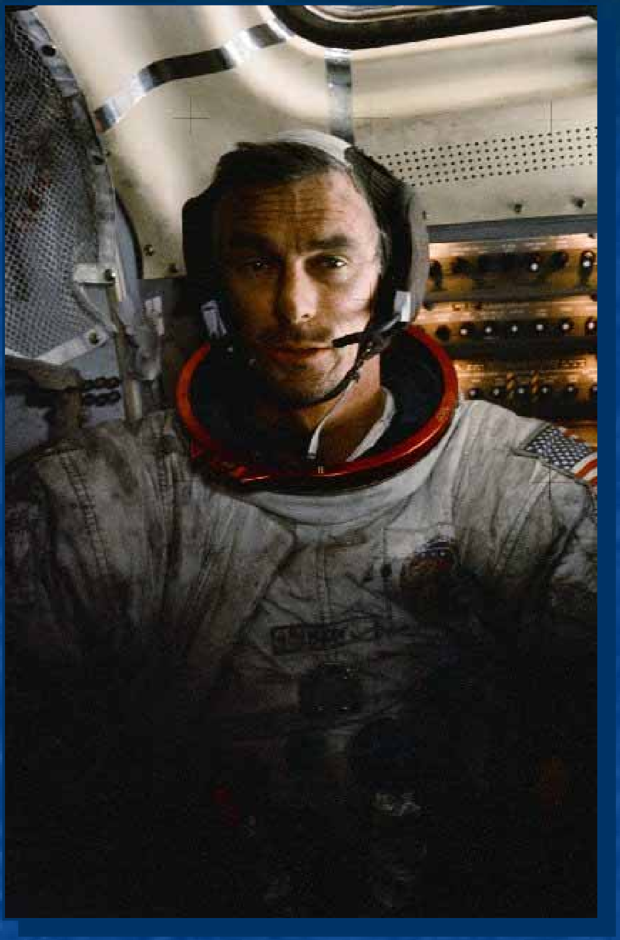
Space Weather: Safeguarding the Journey



Outer space is a perilous ocean through which we must pass to reach the dusty shores of the Moon, then Mars

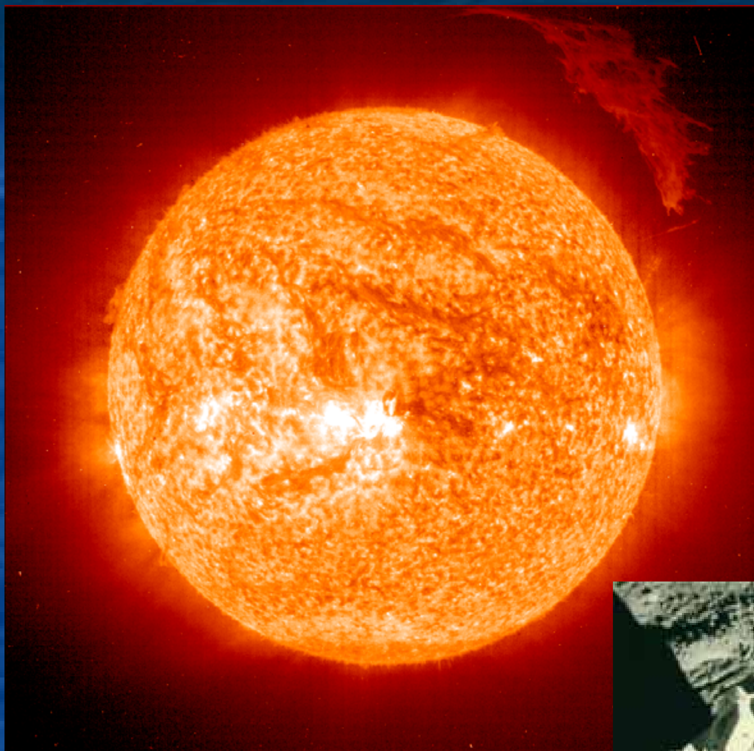


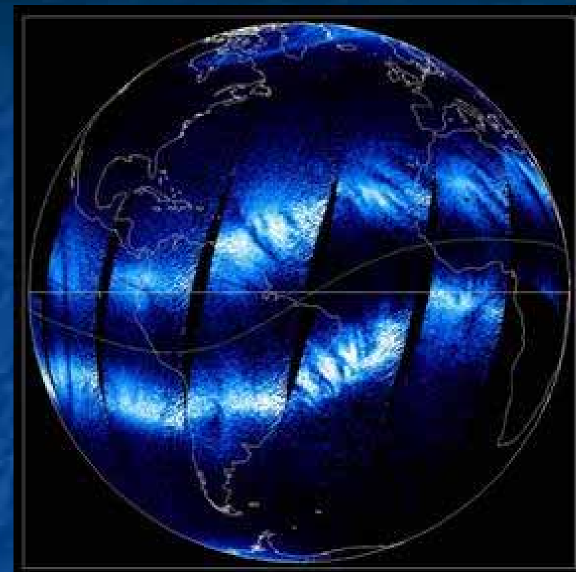
This ocean is permeated with charged particles, electromagnetic fields and blasts of radiation from the sun.

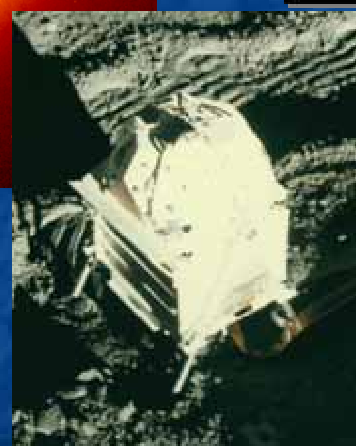


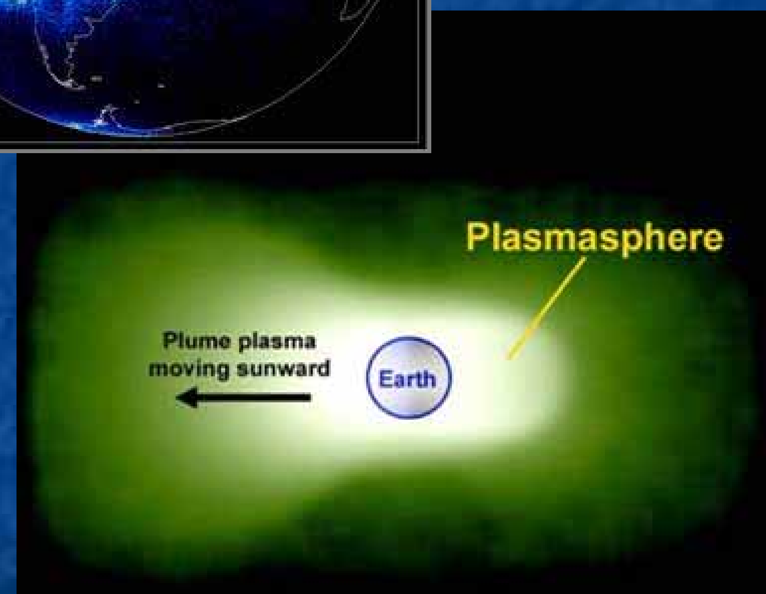
We seek to enhance astronaut and robot productivity by forecasting and learning to mitigate resulting space weather and charged dust impacts.

Bases on the Moon Help Us Understand our Home in Space







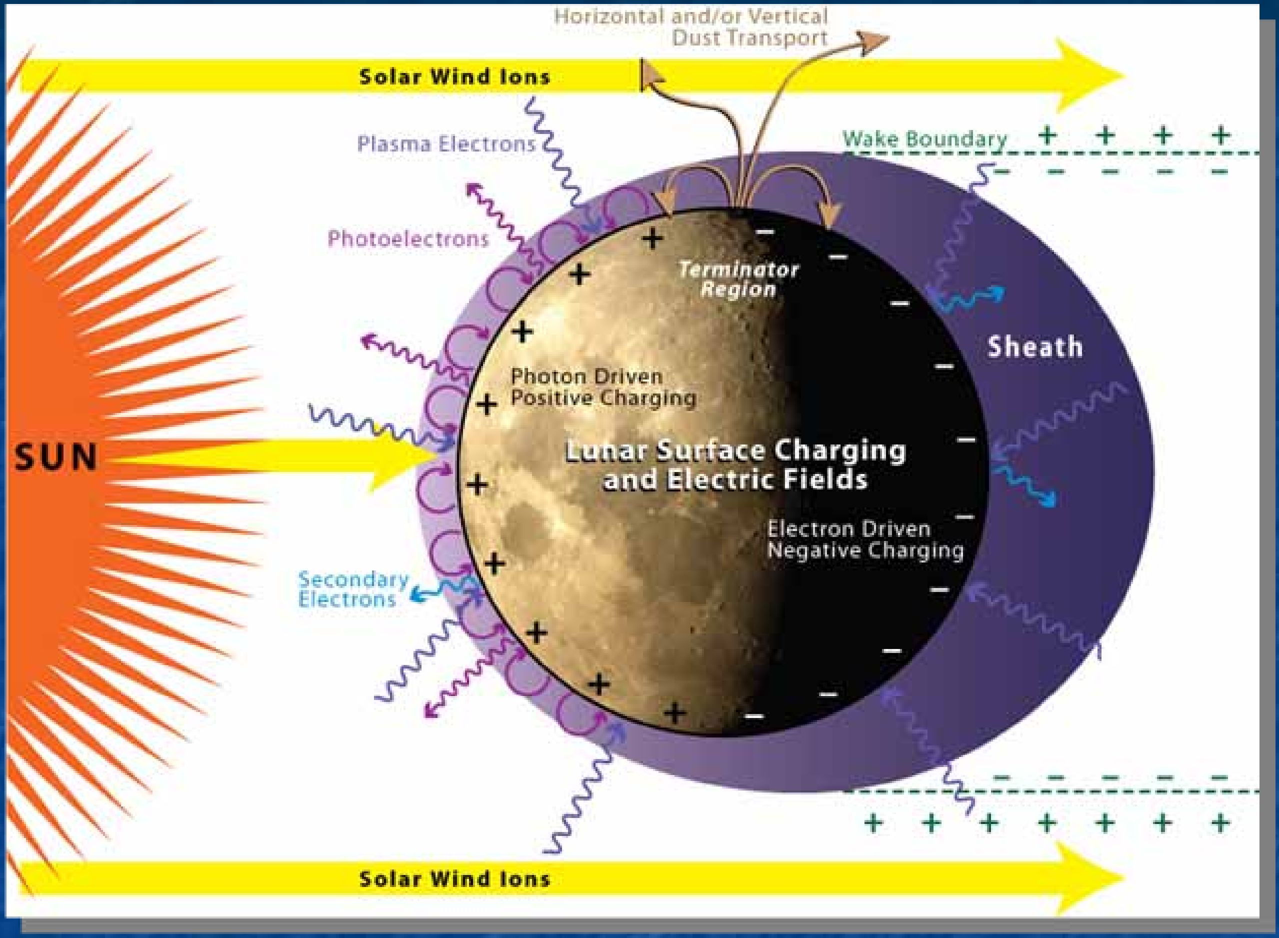


How and why does the Sun vary?

How do Earth and other planetary systems respond?

What are the effects on Humanity?

The Moon is a Natural Laboratory for Space Physics



Electromagnetic interactions with the solar wind and Earth's magnetotail

Lunar magnetic and electric fields

Plasma and dust environment at lunar surface