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LUNAR EXPLORATION ANALYSIS GROUP

http://www.lpi.usra.edu/leag/

To:
Douglas Cooke, Associate Administrator ESMD
William Gerstenmaier, Associate Administrator SOMD
Edward Weiler, Associate Administrator SMD
Robert Braun, NASA Chief Technologist
Waleed Abdalati, NASA Chief Scientist

On June 16-17, 2011, a group of lunar scientists and engineers from many different backgrounds (**Appendix 1**) met at the Lunar and Planetary Institute in Houston, Texas, to develop a robotic implementation strategy for the Lunar Exploration Roadmap [hereafter the "Roadmap"] developed by the Lunar Exploration Analysis Group (LEAG; see http://www.lpi.usra.edu/leag/). The Lunar Destination co-leads (Rob Mueller and John Connolly) of NASA's Human Spaceflight Architecture Team (HAT) also participated. The objectives of this meeting were twofold:

1) Evaluate the Roadmap against the current Planetary Sciences Division Decadal Survey: *Vision and Voyages for Planetary Science in the Decade 2013-2022* (hereafter the "Decadal"); and
2) Devise an enabling robotic precursor campaign that would implement the Roadmap in a sustainable way.

This document emphasizes the latter objective.

The group evaluated the high priority items within Roadmap as they formulated the implementation strategy described below. This implementation strategy was developed in the context of the recent "Decadal" and the current Joint Robotic Precursor Activity (JRPA). The strategy focuses on the "early" stage of the Roadmap (robotic precursors and up to the second human landing, which means stays of ≤1 lunar day). This strategy was assembled with the recognition of a tight federal budget and that planning for a robotic precursor must consider budgetary constraints from the beginning. The robust implementation strategy outlined here could be viewed as a framework to begin the discussion.

In conducting this study, we used the current version of the Roadmap, the relevant LEAG specific action team (e.g., EXPO-SAT 2009 report commissioned by ESMD) and Community Forum 2009, and the 2010 Town Hall reports (also available on the LEAG web site), the RLEP-2 mission study, and the Exploration Systems Architecture Study (ESAS) Final Report published in 2005.

This analysis assumes that we are returning to the Moon to:

- Demonstrate innovative technologies and operations that will enable us to efficiently operate in and venture beyond cislunar space;
- Expand our economic sphere of influence to cislunar space and the Moon;
- Enable solar system exploration and science;
- Enable a permanent continuous human presence to learn to live away from Earth;
- Enable NASA to move beyond the Moon.

We focused on the science and technology aspects of finding, extracting, refining, and eventually using lunar resources (specifically, the volatile elements recently discovered to be abundant at the lunar poles). Technology developments required for this strategy will be strategic inasmuch as they will not only enable future lunar exploration, but also exploration of destinations beyond the Moon using lunar resources (**Table 1**). The incremental approach described below reduces risk and cost, enhances sustainability, enables the "feed-forward to other destinations" strategy outlined in the Roadmap, and the focus on lunar resources promotes commercial and international partnerships (**Table 2**). This campaign involves science, exploration, commerce, and technology developments and also responds directly to the lunar objectives outlined in the "Decadal" Survey (**Table 2**).

Phase I: Lunar Resource Prospecting. Building upon the results of the LRO/LCROSS and Chandrayaan-1, Lunar Prospector, and Clementine, as well as the recent discoveries from the Apollo samples, the most important science and exploration goal is surface prospecting for lunar resources to provide ground truth for orbital observations and estimate the potential for reducing payloads launched from Earth required for Solar System exploration. In this phase, mobile explorers are the required next missions to explore polar regions (volatiles) and non-polar regions (e.g., mature Ti-rich soil for solar wind implanted H, pyroclastic deposits for indigenous volatiles, etc.). These prospectors will incrementally address science, exploration, technology, commercial and public outreach objectives by:

- Defining the composition, form, and extent of the resource;
- Characterizing the environment in which the resources are found;
- Defining the accessibility/extractability of the resources;
- Quantifying the geotechnical properties of the lunar regolith in the areas where resources are found;
- Being able to traverse several kilometers and sample and determine lateral and vertical distribution on meter scales;
- Identifying resource-rich sites for targeting future missions.

Achieving these objectives requires the ability to traverse several kilometers, sample and determine lateral and vertical distribution on meter scales, and operate (for the polar regions) in a low-temperature permanently dark environment.

Phase II: Lunar Resource Mining (LRM). Based on the Phase I results, an end-to-end resource miner feasibility demonstration would be deployed to the area with the most abundant and extractable resources. During this phase the following need to be demonstrated:

- Feedstock acquisition and handling;
- Resource extraction, refinement, transport, and storage;
- Usability of resources (e.g., fuel cell, small engine test; propellant depot test);
- Regolith handling and size sorting technologies (only for mineral-based resources);
- Operable life to give information on the longevity of systems and materials in the lunar environment;
- Dust mitigation strategies.

As in Phase I, this may require more than one mission. For example, if ice were discovered in a permanently shadowed polar crater and high H in low-latitude pyroclastic deposits, the question would then become which is more efficiently exploited.

Phase III: Lunar Resource Production. Based upon the results of Phase II, a larger-scale (i.e., more appropriate scale) continuous processing capability would be deployed to the most appropriate site. Greater quantities of resources will be produced and be used to undertake more extensive demonstrations such as life support, mobility technologies, and fuel for a robotic sample return.

An automated full-scale production capability would be established prior to the first extended human stay on the lunar surface.

This campaign will require the build-up of infrastructure at a site defined and characterized by the initial prospecting and mining phases. When complete, the production plant will enable future refuelable landers and cislunar refueling depots, in addition to providing consumables to the lunar crews. The ultimate goal of this campaign is to change the economics of human space exploration via the use of in-situ resource utilization. Flight hardware (e.g., lunar landers, Earth to moon crew modules) that is reusable and can make use of lunar resources should be developed in parallel with the campaign outlined above. The implementation of this technology represents an evolutionary shift from missions that are now 100% dependent on Earth to future missions that utilize non-terrestrial resources to enable NASA and its partners to embark on a new path of cost-effective exploration.

This analysis of the Lunar Exploration Roadmap recognizes that there is significant value leveraging the International Space Exploration Coordination Group (ISECG) cooperation strategy for international engagement and participation by identifying a core set of instruments, measurements, and capabilities that should be considered for each step in the strategy. It also finds significant additional value accrues from engagement with commercial industry involvement at the very beginning and in each phase.

Members of the LEAG Roadmapping Team are available to answer any questions you might have or provide more details as needed.

Sincerely,

Charles K. Shearer
(LEAG Chair)

Distribution:
Laurie Leshin, Deputy AA, ESMD
James Green, Director – Planetary Sciences Division
John Olson, Director, Directorate Integration Office
Paul Hertz, Chief Scientist, SMD
Chris Culbert, Chief of the Robotic Systems Technology Branch
James Adams, Deputy Director – Planetary Sciences Division
John Guidi – Deputy Director, Directorate Integration Office
Michael Hecker, Associate CIO for Architecture and Infrastructure
Charles Miller, Senior Advisor for Commercial Space, OCT

Table 1: Technology/Infrastructure Developments

- Local and Earth communications and navigation network - BAH;
- Thermal design to survive the lunar day-night cycle and polar cold traps (e.g., RLEP-2, LPRP, subsequent APL-MSFC studies);
- Power and energy storage systems;
- Dust mitigation;
- Precision landing;
- Radiation mitigation;
- Mobility (local and regional distances);
- Autonomy and Tele-operations;
- R&A Robotics and Automation;
- Develop standards for interfaces;
- Reusable, ISRU-enabled transportation systems;
- ISRU capabilities.

Table 2: LEAG Lunar Exploration Roadmap objectives enabled by this implementation strategy.

OBJECTIVE	DESCRIPTION
	Science
Sci-A-2	Development and implementation of sample return technologies and protocols
Sci-A-3	Characterize the environment & processes in lunar polar regions and exosphere
Sci-A-4	Understand the dynamical evolution and space weathering of the regolith
Aci-A-6	Understand volcanic processes
Sci-A-8	Determine the stratigraphy, structure, and geological history of the Moon
Sci-B-2	Regolith as a recorder of extra-lunar processes
Sci-C-2	Heliophysical Investigations using the Moon
Sci-D-5	Obtain experimental data to anchor multiphase flow models in partial gravity environment
Sci-D-6	Study interfacial flow to anchor theoretical/numerical models
Sci-D-7	Study behavior of granular media in the lunar environment
Sci-D-8	Investigate precipitation behavior in supercritical water in partial gravity environment
Sci-D-9	Investigate the production of oxygen from lunar regolith in lunar gravity
Sci-D-10	Investigate the behavior of liquid-phase sintering under lunar gravity
Sci-D-11	Study and assess effects on materials of long-duration exposure to the lunar environment
Sci-D-22	Monitor real-time environmental variables affecting safe operations
	Feed Forward
FF-A-4	Develop the capability to acquire and use local resources to sustain long-term exploration and habitation of planetary surfaces
FF-A-5	Develop the capability to produce adequate levels of power on planetary surfaces to allow human crews to work and live productively
FF-A-6	Develop the capability to autonomously land safely and accurately on Mars
FF-A-7	Develop the capability to provide or construct structures on planetary surfaces
FF-A-8	Develop the capability for crews on Mars to communicate with other assets on the surface, and navigate to and from those assets
FF-A-9	Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards
FF-B-1	Develop the capability for autonomous crew operations on the Moon and Mars
FF-B-2	Develop the capability for productive & efficient human-robotic interaction in planetary surface exploration
FF-B-3	Establish an administrative structure & cost effective surface systems to facilitate strong international cooperation
FF-C-1	Ability to operate on a geologic surface
FF-C-2	Develop the capability for autonomous crew operations
FF-C-3	Development and implementation of sample return technologies and protocols
FF-C-5	Regolith as a recorder of Solar-System processes
FF-C-6	Develop the capability for human crews to operate safely on planetary surfaces
FF-C-7	Develop the capability for productive & efficient human-robotic interaction in the exploration of planetary surfaces
FF-C-9	Establish an administrative structure and cost effective surface systems to facilitate strong international cooperation
FF-C-10	Develop the capability to acquire and use local resources to sustain long-term exploration crews
FF-C-11	Establishment of in-situ resource utilization systems
	Sustainability
Sust-A-1	Establish policies and implementation of comprehensive, coordinated governmental and intergovernmental action to foster space commerce
Sust-A-2	Preparation for Commerce I: Conduct a comprehensive resource and market assessment of commercial support for scientific and exploration activities on the Moon
Sust-A-3	Preparation for Commerce II: Conduct small-scale demonstrations of potentially commercial lunar support services for scientific and exploration activities on the Moon
Sust-A-4	Transition to Commerce I: Conduct pilot-plant scale demonstrations of potentially commercial lunar support services for scientific and exploration activities on the Moon
Sust-B-1	Implementation of comprehensive, coordinated integration of diverse scientific and exploration activities to maximize complementary operations and minimize operational and environmental conflicts
Sust-B-3	Development of surface power and energy storage systems
Sust-B-4	Establishment of sustainable transportation between Earth and the lunar surface
Sust-B-5	Deployment of Robotic Facilities for Science and Exploration Operations
Sust-B-7	Establishment of sustainable human transportation between lunar sites
Sust-B-9	Establishment of in-situ production of life-support, power system reagents, propellants and related resources

Appendix 1: List of LEAG Lunar Exploration Roadmap Workshop attendees.

Dallas Bienhoff	Boeing Corporation
Dean Eppler	NASA Johnson Space Center
John Gruener	NASA Johnson Space Center
Robert Kelso	NASA Johnson Space Center
Kurt Klaus	Boeing Corporation
David Kring	Lunar & Planetary Institute
Steve Mackwell	Lunar & Planetary Institute
Clive Neal	University of Notre Dame
Jeff Plescia	Johns Hopkins University Applied Physics Laboratory
Gerald Sanders	NASA Johnson Space Center
Greg Schmidt	NASA Lunar Science Institute
Charles Shearer	University of New Mexico
Paul Spudis	Lunar & Planetary Institute
Ex Officio	
John Connolly	NASA Johnson Space Center, lunar destination co-lead
Edward Grayzeck	NASA HQ
Robert Mueller	NASA Kennedy Space Center, lunar destination co-lead
Michael Wargo	NASA HQ