Exploring the Moon in the 21st Century:
Themes, Goals, Investigations, and Priorities, 2009

Theme 2: Use the Moon to Prepare for Future Missions to Mars and Other Destinations

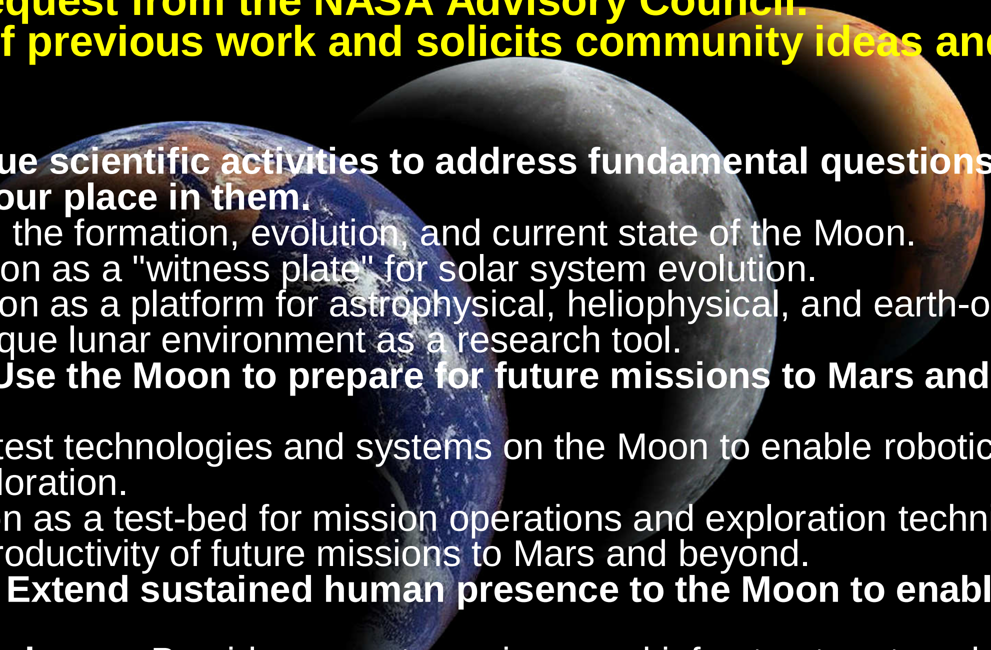
A Community Effort – Coordinated by the Lunar Exploration Analysis Group

Jeff Volosin
jeffvolosin@verizon.net

Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations and Priorities 2009

A Community Effort Coordinated by the Lunar Exploration Analysis Group

- **Goal: Coordinate the development of a community based Lunar Exploration Roadmap for NASA based on a request from the NASA Advisory Council.**
- **Approach: Builds off of previous work and solicits community ideas and priorities.**



Theme Areas:

- Science (Sci) Theme: **Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them.**
  - **Goal Sci-A:** Understand the formation, evolution, and current state of the Moon.
  - **Goal Sci-B:** Use the Moon as a "witness plate" for solar system evolution.
  - **Goal Sci-C**: Use the Moon as a platform for astrophysical, heliophysical, and earth-observing studies.
  - **Goal Sci-D**: Use the unique lunar environment as a research tool.
- Feed Forward (FF) Theme: **Use the Moon to prepare for future missions to Mars and other destinations.**
  - Goal FF-A: Identify and test technologies and systems on the Moon to enable robotic and human solar system science and exploration.
  - Goal FF-B: Use the Moon as a test-bed for mission operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond.
- Sustainability (Sust) Theme: **Extend sustained human presence to the Moon to enable eventual settlement.**
  - **Goal Sust-A: Expand Science**: Provide support, services, and infrastructure to enhance and enable new science to the Moon, on the Moon, and from the Moon (crossover with Theme 1).
  - **Goal Sust-B: Expand Human Exploration**: Expand in-space and surface transportation capabilities beyond initial NASA transportation architecture to discover and reach new territories (crossover with Themes 1 and 2).
  - **Goal Sust-C: Enhance Security:** Protect and benefit Earth, and guarantee peace and safety both for settlers and for the home planet.
  - **Goal Sust-D: Commercial on ramps** (Enable space economic activity to benefit Earth and lunar settlement and to enable NASA to explore beyond the Moon).
  - **Goal Sust-E:** Sustaining human presence on the Moon.

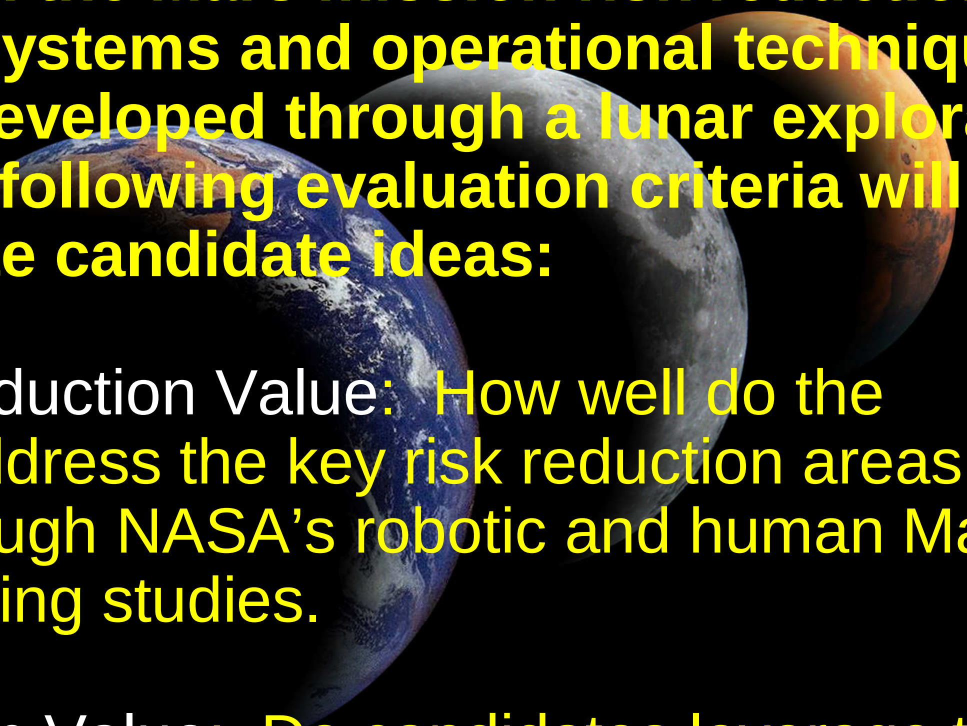
Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations and Priorities 2009

A Community Effort Coordinated by the Lunar Exploration Analysis Group

Data Collection Descriptors:

- **Roadmap Timing: Investigations and objectives defined in terms of implementation timing:**
  - **Short**: Robotic Precursors and up to the second human landing
  - **Mid**: Initial Outpost build-up to and including stays of <30 days
  - **Long**: Outpost established, stays of > 30 days
- **Prioritization Criteria:**
  - **Low Priority**: Would be good to do, but is not essential for habitat/exploration development; Would only give an incremental advance to our scientific knowledge; and/or Could be conducted more efficiently elsewhere.
  - **Medium Priority**: Falls in between Low and High Priority Could be enabled with sufficient infrastructure investment.
  - **High Priority**: Is essential to do in order to make progress in habitat/exploration development; Would facilitate a fundamental advance in our scientific knowledge; Is facilitated by or should be facilitated by the Lunar Architecture; and/or is best done on the lunar surface.

Theme 2: Use the Moon to Prepare for Future Missions to Mars and Other Destinations



- **Goal: Establish the Mars mission risk reduction technologies, systems and operational techniques that could be developed through a lunar exploration program – The following evaluation criteria will be used to evaluate candidate ideas:**
  - Mars Risk Reduction Value: How well do the candidates address the key risk reduction areas identified through NASA's robotic and human Mars mission planning studies.
  - Lunar Platform Value: Do candidates leverage the unique attributes of a lunar program to achieve success – or – would other platforms be more effective from a technical/cost perspective.

Theme 2: Use the Moon to prepare for future missions to Mars and other destinations.

Hardware

Goal 2A: Identify and test technologies and systems on the Moon to enable robotic and human solar system science and exploration.

Objective 2A-1: regenerative life support
Objective 2A-2: crew health systems
Objective 2A-3: surface mobility
Objective 2A-4: in-situ resource utilization
Objective 2A-5: power systems
Objective 2A-6: autonomous landing
Objective 2A-7: structures and habitation
Objective 2A-8: communication
Objective 2A-9: crew protection

Operations

Goal 2B: Use the Moon as a test-bed for missions operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond.

Objective 2B-1: autonomous crew operations
Objective 2B-2: crew / robotic interaction

Goal 2A: Identify and test technologies on the Moon to enable robotic and human solar system science and exploration

- The focus of Mars enabling technology research is on surface systems development.
- While the Moon and Mars have different gravities and drastically different environments and soil properties, both are still hostile environments that require similar functional capabilities for humans to explore and live off Earth.
- On the other hand, for many Mars systems, the Earth can serve as a more cost effective analog for evaluating technologies, components, subsystems and integrated systems.
- At the component and subsystem level, many Mars technologies have gravity dependent components that perform functions such as phase separation or 2-phase flow control. It is unclear whether the gravity field of the Moon or Earth is a better analog for evaluating these technologies. Preliminary research will be required at the flow-rates and capillary diameters that are being considered for component designs to evaluate the best testing ground for these components.
- At the integrated system level, the risk reduction value of actually deploying Mars-prototype integrated systems on the Moon for evaluation may provide additional value that testing on Earth can not. But, again, additional preliminary research should be done to see if the value associated with this approach outweighs the associated costs when compared against performing these integrated tests on Earth.

Goal 2A: Identify and test technologies on the Moon to enable robotic and human solar system science and exploration

The Moon can serve as a test bed for technologies that will enable sustained human exploration of Mars and beyond.

- Regenerative life support
- Crew health systems
- Surface mobility
- In-situ resource utilization
- Power systems
- Autonomous landing
- Structures and habitation
- Communication
- Crew protection

Objective 2A-1: Develop surface life support systems to reduce risks associated with long duration Martian surface stay times

General Requirements:

- Evaluate technologies required to achieve life support closure of >90% (TBD) which will be required to support Mars surface systems operations.
- Evaluate technologies required to reduce surface system life support IMLEO by 25% (TBD) and Total System Volume by 25% (TBD) over current ISS technologies.
- Evaluate technologies that reduce crew interaction requirements by 50% (TBD) over ISS baseline systems
- Evaluate life support technologies that leverage partial gravity environments to increase efficiencies and reduce IMLEO over ISS baseline systems.
- Evaluate life support technologies that leverage in-situ resources in areas that have applicability to Mars surface operations
- Perform extended operational evaluation of an integrated 90% (TBD) closure surface life support system to simulate Mars surface stay periods of >500 days

Objective 2A-1: Develop surface life support systems to reduce risks associated with long duration Martian surface stay times

- **Investigation 1:** Evaluate air revitalization technologies in areas such as carbon dioxide reduction to increase loop closure over ISS baseline and in areas such as trace contaminant control where reduction in IMLEO need to be increased over ISS baseline. Also, evaluate technologies where partial gravity environments can be leveraged to design systems with lower IMLEO requirements versus ISS baseline systems (Timing: Mid)
- **Investigation 2:** Evaluate water management and recovery technologies that reduce IMLEO requirements over the ISS baseline. Also, evaluate technologies where partial gravity environments can be leveraged to design systems with lower IMLEO requirements versus ISS baseline systems. (Timing: Mid)
- **Investigation 3:** Test waste management technologies to recover resources from manufactured and packaging waste, as well as human waste (Timing: Mid)
- **Investigation 4:** Test bioregenerative technologies to support waste water processing, air revitalization and food production (Timing: Mid)
- **Investigation 5:** Perform long-duration testing of an integrated surface life support system to simulate Mars surface stay times exceeding 500 days. (Timing: Mid/Long)
- **Investigation 6:** Evaluate environmental monitoring technologies for gas and liquid consumables to ensure quality over long duration missions. Specifically address technologies where partial gravity can be used to improve performance over the ISS baseline. (Timing: Mid)
- **Investigations 7**: Evaluate fire detection and suppression strategies for partial-g environments. Specifically address technologies where partial gravity can be used to improve performance over the ISS baseline. (Timing: Mid)

- **NOTE:** For all of these technology evaluation projects, preliminary research should be done to evaluate whether the Moon or the Earth has the key attributes for evaluating Mars systems. Particularly when it comes to technologies with gravity sensitivities, it may turn out that the Earth is a more cost effective analog for Mars surface technology testing.
- **NOTE**: The priority for technology evaluation should be on those technologies that can greatly reduce IMLEO and loop-closure. These technologies will be enabling for Mars missions.

Objective 2A-2: Develop Crew Health Systems That Enable Safe, Long Duration, Surface Stays

- Low-gravity, dust, radiation, and isolation will have combined or integrated effects on human biology at all levels and human psychology during long-duration exploration missions on planetary surfaces

- **Investigation 1:** Test countermeasure technologies that will assure human performance remains at an acceptable standard (Timing: Mid)
- NOTE: This research should be tied back to fundamental research on biological and physiological effects of partial lunar environment (e.g., partial gravity, oxygen concentration, reduced pressure) over long periods to inform countermeasure requirements (Timing: Early/Mid)
- **Investigation 2:** Test medical diagnosis and treatment technologies to allow well-patient care in addition to the treatment of illnesses/injuries on a planetary surface
- NOTE: includes effective in-site and remote health care applications as well as IVA and EVA health care (Timing: Mid)
- **Investigation 3:** Test long-term food storage technologies to ensure lasting nutritional value of foods stored for extended periods of time on a planetary surface (Timing: Mid)
- **Investigation 4**: Perform psychological health research on impact of extreme isolations for periods of >500 days (Timing: Mid/Long)

- **NOTE:** For all of these technology evaluation projects, preliminary research should be done to evaluate whether the Moon or the Earth has the key attributes for evaluating Mars systems. Specifically, variable gravity research should be done that determines if humans in Mars gravity will or will not exhibit the same issues as seen in microgravity regarding bone loss, muscle atrophy, immune system changes, etc. – and – whether the impact of Mars gravity on humans will be more similar to the impact of Earth's gravity or that of the Moon.
- **NOTE**: The priority for crew health system technology evaluation should be on those technologies that can enable surface stay times in partial gravity of >500.

Objective 2A-3: Develop surface mobility capabilities that allow human crews to efficiently and safely explore the surfaces of the Moon and Mars

- Extensive extravehicular activity (EVA) will be needed for crews to work on and explore planetary surfaces
- Major surface features on the Moon and Mars, prime targets for intensive investigations, are on the order on many 10's to several 100's km apart, and capabilities beyond those used during Apollo will be needed to traverse these great distances

Things that would contribute to preparing for Mars (IN PRIORITY ORDER)

- **Investigation 1:** Test surface mobility systems with the following attributes:
- RANGE: traverse distances of at least several 100s km away from a landing or outpost site,
- DURATION: surface exploration sorties lasting up to several weeks
- TERRAIN: Capability to access both steep (defined by slopes of >XX degree inclines) and rough terrain
- TIME: Use time on the surface as efficiently as possible, so as to maximize the fraction used for science exploration. Optimize Autonomy
- (Timing: Long)

- **Investigation 2:** Test advanced space suit technologies that will allow greater mobility, dexterity, and range than the space suits used during the Apollo, Space Shuttle, and International Space Station programs. (Timing: Mid)

- **Investigation 3:** Test robotic field assistant technologies to compliment and augment the abilities of human crew members exploring or working on a planetary surface (Timing: Early/Mid)

Objective 2A-4: Develop the capability to acquire and use local resources to sustain long-term exploration and habitation of planetary surfaces

- Mars possesses abundant natural resources that could be used to supply human consumables, such as air and water, and construction materials
- Relying on earth-based supplies for extended operations on the Mars is likely neither affordable or sustainable, and achieving a certain level of self-sufficiency would also reduce the risks involved with the delivery of those supplies.

Things that would contribute to preparing for Mars (IN PRIORITY ORDER)

- **Investigation 1:** Test resource identification/characterization procedures and technologies (Timing: Early/Mid)
- **Investigation 2:** Test electrolysis technologies especially for water and carbon dioxide (Timing: Mid/Long)
- **Investigation 3:** Test technologies to produce water from frozen regoliths (Timing: Mid/Long)
- **Investigation 4:** Test phase separation technologies for handling solids, liquids, and gases (Timing: Early/Mid)
- **Investigation 5:** Test product storage technologies (Timing: Early/Mid)
- **Investigation 6:** Test technologies to produce construction materials or paved/prepared surfaces (Timing: Long)

- **NOTE:** For all of these technology evaluation projects, preliminary research should be done to evaluate whether the Moon or the Earth has the key attributes for evaluating Mars systems. Particularly when it comes to technologies with gravity sensitivities, it may turn out that the Earth is a more cost effective analog for Mars surface technology testing.

Objective 2A-5: Develop the capability to produce adequate levels of power on planetary surfaces to allow human crews to work and live productively

- Studies of initial planetary outposts have shown power levels in the several 10's of kW are needed on a continuous basis for sustained human operations
- When resource development is considered in addition to the outposts, the power levels increase to many 10's of kW, and sometimes to a few 100's of kW
- It is not practical to rely only on solar technologies for producing these high power level on the Mars surface

- **Investigation 1:** Test surface fission power system technologies capable of generating >100kW. These systems should be capable of being autonomously deployed and able to initiate/sustain power generation without human interaction. Systems for providing radiation shielding to ensure crew safety should be incorporated in the design. (Timing: Mid)
- **Investigation 2:** Test radioisotope thermal generator technologies for small remote science stations and observatories that can operate at power level >1kW. These systems should be capable of being autonomously deployed and able to initiate/sustain power generation without human interaction. Systems for providing radiation shielding to ensure crew safety should be incorporated in the design. (Timing: Early/Mid)
- **Investigation 3:** Test rechargeable energy storage technologies for fixed and mobile surface applications. (Timing: Early/Mid)

- **NOTE:** For all of these technology evaluation projects, preliminary research should be done to evaluate whether the Moon or the Earth has the key attributes for evaluating Mars systems. Particularly when it comes to technologies with gravity sensitivities, it may turn out that the Earth is a more cost effective analog for Mars surface technology testing. Priorities for lunar research should be driven by the results of this preliminary research to determine which technologies should benefit most from evaluation in the lunar environment.

Objective 2A-6: Develop the capability to autonomously land safely and accurately on the Moon and Mars

- The surfaces of the Moon and Mars are unprepared surfaces with natural hazards such as boulders, craters, and sloping terrain. Mars landings through an atmosphere are much different than lunar landings – but – there are some technologies for landing guidance that could have similarities.

Things that would contribute to preparing for Mars

- **Investigation 1:** Test terrain-relative precision landing systems with targeting accuracy better than 100m (TBD). (Timing: Early/Mid)
- **Investigation 2:** Test hazard tolerant landing systems. (Timing: Early/Mid)
- **Investigation 3:** Test autonomous terminal hazard avoidance technologies, for those hazards that can not be tolerated. (Timing: Early/Mid)

Objective 2A-7: Develop the capability to provide or construct structures on planetary surfaces adequate for long-duration habitation by humans, and made of materials that will endure extended exposure to the deep-space environment

- Unlike the Apollo missions where the astronaut crew lived out of their lander vehicle, sustained presence on the Moon or Mars will require the use of pressurized habitats emplaced on the planetary surface
- Sustained presence on the Moon or Mars will require structural materials that can retain their integrity for extended periods of time after continuous exposure to radiation, micrometeoroids, and extreme temperatures
- **Investigation 1:** Test monolithic habitat technologies on the lunar surface. These technologies should incorporate the capability for autonomous deployment and operations without human intervention. These technologies should provide the capability to be 100% ready for crew occupancy when the initial crew arrives at the surface. (Timing: Mid/Long)
- **Investigation 2:** Test manufactured structures technologies that use construction materials made from natural lunar resources. Evaluate technologies that can reduce IMLEO while minimizing the amount of crew involvement required to generate products from available resources. (Timing: Long)

Objective 2A-8: Develop the capability for crews on the Moon or Mars to communicate with other assets on the surface, and navigate to and from those assets

- Working and living on the Moon and Mars will involve traveling long distances, over the horizon from any established facility, and likely beyond line-of-sight of any fixed communication or navigation asset at that facility

- Neither the Moon or Mars have a strong global magnetic field available for surface navigation

- **Investigation 1:** Test non-line-of-sight communications technologies on the lunar surface (Timing: Early/Mid)
- **Investigation 2:** Test technologies for navigating on the lunar surface without a strong magnetic field (Timing: Early/Mid)
- **Investigation 3:** Establish high bandwidth Earth-Moon communication links that could support public engagement activities (Timing: Early/Mid)
- **Investigation 4:** Establish time and clock capabilities to assist vehicles in cis-lunar space and surface systems in determining their relative and absolute time (Timing: Early/Mid)
- **Investigation 5:** Establish emergency position determination services to support Search and Rescue operations (Timing: Mid)

Objective 2A-9: Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards

- Due to the lack of measurable magnetic fields and the existence of thin or very tenuous atmospheres, humans working and living on the Moon and Mars will be immersed in environments with higher levels of radiation and micrometeoroid impacts than on Earth

- Other environmental hazards like dust and extreme temperatures will effect design of all planetary surface systems

- **Investigation 1:** Test radiation shielding technologies to protect astronauts on the lunar surface from galactic cosmic rays (GCR) and solar energetic particle (SEP) events (Timing: Early/Mid)
- **Investigation 2:** Test micrometeorite protection technologies to prevent damage caused by micrometeorite impacts. Leverage ISS experience to determine if additional technological advances are required to support >500 day surface stays on Mars. (Timing: Mid)
- **Investigation 3:** Test dust mitigation technologies to prevent dust from interfering with mechanical systems and causing health problems for astronaut crews (Timing: Early/Mid)
- **Investigation 4:** Test forward and backward planetary protection technologies to prepare for human and robotic operations on Mars. (Timing: Mid)
- **Investigation 5:** Establish space weather modeling, forecasting and monitoring capabilities that can be used to warn both lunar and Mars transit/surface crews of potentially hazardous solar events. The goal of these systems should be to provide as early a warning as possible of dangers. (Timing: Early/Mid)

Goal 2B: Use the Moon as a test-bed for mission operations and exploration techniques to reduce the risk and increase the productivity of future missions to Mars and beyond

- **The nearness of the Moon with respect to Earth allows for opportunities in testing of surface mission operations and exploration techniques without the concern that help from Earth or the ability of the crew to return safely is more than a year away.**
- **The Moon will serve as a training ground for mission operations that will enable sustained human exploration of Mars and beyond.**
  - Crew autonomy
  - Human-robotic interaction
  - Human performance

Objective 2B-1: Develop the capability for autonomous crew operations on the Moon and Mars

- The great distances between the Earth and Mars, and the associated time delays in communication make real time control of mission operations from Earth difficult
- While the Apollo missions to the moon were scripted minute by minute, long-duration missions on the Moon and Mars will need to be more goal oriented on a weekly or monthly basis
- Crews on the surface of the Moon or Mars should be able to plan and adjust their work and exploration schedule based on discoveries made in the field, or the lack of progress made on current investigations or operations
- **Investigation 1:** Test integrated system health management techniques to autonomously monitor system performance and remedy repairs to underperforming systems with little or no crew intervention
- **Investigation 2:** Test crew-centered planning and scheduling techniques to allow exploration crews tactical control of their workload
- **Investigation 3:** Test automated sampling documentation techniques to allow crews to quickly document all steps involved in the acquisition and curation of geologic samples on the Moon or Mars
- **Investigation 4:** Test the execution of mission operations with extravehicular activities (EVA) and intravehicular activities (IVA) without the control from Earth
- **Investigation 5**: Conduct a Mars surface mission simulation on the Moon. Simulation should address the degree of autonomy and self sufficiency that will be expected for Mars surface missions. The simulation should last >500 days without logistics resupply.

Objective 2B-2: Develop the capability for productive and efficient human-robotic interaction in the exploration of planetary surfaces

- Robotic explorers can be used to augment and compliment the explorations of human crews, thus making more efficient use of astronaut time for complex tasks that require human cognitive skills and dexterity

- **Investigation 1:** Test teleoperation techniques to allow human crews on the lunar or martian surface to control and direct robotic explorers

- **Investigation 2:** Test robot interface techniques that will allow human crews on the lunar or martian surface to operate a multitude of different types of robots with a single computer interface

- **Investigation 3:** Test field geology tools/instrumentation that can enable significant in-situ field analysis of geological samples. Establish methods for achieving the best accuracy/precision, diversity (results confirmable by alternate methods), minimize power/mass/volume requirements, maximize reliability, calibration (positive and negative control standards). Test field instrumentation capable of determining differences in samples based on subtle chemical and mineralogical differences in rocks and soils, sampling tools that can penetrate and sample deep enough into rocks to get below the chemically altered outer layer.

- **Investigation 4**: Test field geology research techniques, including: Analysis Adaptability (not limited by prior hypothesis)

Other Mars Mission Enabling Objectives that Can Be Supported Through a Lunar Exploration Program

- **Objective:** Establish a set of export control laws and regulations that will enhance effective global cooperation on lunar activities
- **Objective:** Establish standards and common interface designs to enable interoperability of systems developed by a global community
- **Objective:** Establish a global partnership framework to enable all interested parties to participate in exploration activities.
- ***Investigation 1:*** Initiate global participation in a robust robotic lunar exploration program
- **Investigation 2:** Initiate global participation in the early planning stages for human lunar exploration to establish a process for engaging a global community in the development process. This process should enable varied levels of participation based on the capabilities, experience, goals and funding availability of each participating nation.
- **Objective:** Develop cost effective surface systems that can be developed in a relatively short period of time (the ISS development timeline/cost of 30 years and ~$100B will not be acceptable for Mars mission surface habitation development)
- ***Investigation 1:*** Address the core lessons learned from ISS development to determine what changes are required to enable lunar surface systems development to be completed in XX% (TBD) less time and XX% (TBD) less dollars/kg versus the ISS baseline for large habitable space systems.

Summary

- LEAG SAT Continues to work at soliciting community inputs to further refine the inputs and priorities for each of the Lunar Exploration theme areas.
- Inputs are welcome from MEPAG members – please send ideas directly to Jeff Volosin – jeffvolosin@verizon.net and I will make sure they are folded into the discussion.