Findings of the Lunar Exploration Analysis Group Special Analysis Team on an Earth-Moon L2 Research Facility

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LEAG Earth-Moon L2 SAT - General Findings

- An Earth-Moon Lagrangian point location (either E-M L1 or L2) provides a venue for a number of research operations that cannot be done at ISS
  - The low latency (2-way 400 milliseconds) for communication to the lunar surface enhances our ability to conduct investigations and deployment/construction activities that require more direct operational control of robotic assets than is possible with latency periods ≥2-3 seconds
  - The radiation environment will enable a number of life sciences experiments that will be critical to decision making for long-duration human missions outside cis-lunar space that cannot be conducted at a facility within the influence of the Earth's magnetosphere, such as ISS

- However, the SAT Team did not find any research area that could be used to justify a Lagrangian point facility on the basis of research alone

- This report lays out a subset of investigations that can be done at E-M L2 or L1 that were selected from a larger body of relevant scientific research
  - There are many investigations that were considered, but those that received a low priority for E-M L1/L2 implementation were not included in this report

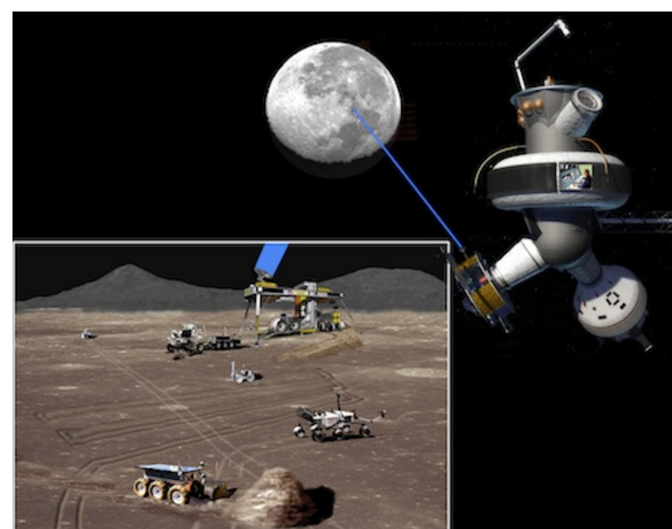
- The membership of this SAT, of necessity, did not include a broad representation by many of the investigators conducting both Life or Microgravity sciences research
  - Consequently, it is important that NASA vet the results of this work to a broader community prior to making decisions on the development of an E-M L2/L1 research facility

LEAG Earth-Moon L2 SAT - General Findings

- All of the ideas expressed in this report require a lead time in development before they can be included in a large program, including the facility
  - In particular, the science community needs to be involved in planning and requirements development
- The use of ISS-derived payload hardware, hardware designs or hardware standards for the E-M L2/L1 research facility is a good idea, as it takes advantage of existing capabilities such as International Standard Payload Rack and Middeck-locker-based experiment hardware
  - However, it is not clear that the Orion spacecraft will accommodate these hardware designs
    - This includes both pressurized and externally attached payloads
  - Without an integration of L1/L2 facility concepts and the planned Orion transportation architecture, there may be serious mismatches in payload accommodation that may require expensive new developments
  - In addition, it was noted that ISS-heritage hardware was designed for exposure to the LEO environment, which may prove to be inadequate for locations outside of the Earth's magnetic field
  - The SAT suggests strongly that integration of design concepts be undertaken to take advantage of technology developments conducted for Shuttle and ISS, and to confirm that ISS components will be safe in the E-M L1/L2 environment
- The EM-Lagrangian points are not appropriate locations for processing or analysis on geological samples returned from the Moon
  - The high priority sample science recommended by this report requires the precision and accuracy that is only available in terrestrial laboratories
  - Scientific integrity of the sample is the first priority for sample science, and processing in an L2 facility represents an unnecessary intermediate-step contamination risk for samples that are going to be returned to a terrestrial laboratory
  - However, if there is a mismatch between sample return mass to an L-facility and the capability of Orion to return these samples in one batch, it may be possible to stow unopened sample return containers at an L-facility prior to Earth return

The Case for Lunar Surface Telerobotic Control from EM Lagrange Points

- E-M L2 allows ≈400 ms 2-way comm latency, which is 6x better than from Earth (2.6 sec), allows operational telepresence and gives 24/7 control authority over much of a lunar hemisphere
- The E-M L2 location benefits from continuous communication link with Earth, and near-continuous solar illumination for power
- Exercising robotic assets at E-M L2 allows:
  - Practice with a control strategy that is highly extensible to other potential destinations (e.g. for Mars, NEOs)
  - Provides fine dexterity and visual perception that is better than with space-suited humans
  - Requires only limited crew vehicle hardware (e.g. no extra docking ports or EVA capabilities, Block 0 capability)
  - Makes construction of science instruments and emplacement of science stations, such as farside lunar telescopes or environmental monitoring stations, more feasible



Possible Early Orbital Communications Asset Deployment during 2017 Opportunity

- Small satellite in a halo orbit around EM L2
  - Could be deployed during the planned 2017 Orion un-crewed L2 mission
    - Designed to fit within the payload constraints of the Orion vehicle
    - Small bus with low-power (electric) propulsion suitable for station keeping
    - Solar array to provide power to run proposed instrument packages
  - Simple payload
    - A communication package – establish high bandwidth communications from Lunar far side to the Earth
      - Sets the stage for Lunar far side exploration from L2 facility and/or Earth
    - An environmental package - provide continuous measurements of ionizing radiation, micrometeorite flux, and potentially other factors in the vicinity of EM L2
    - A televideo package - provide live, streaming, high-definition video from an EM L2 halo orbit perspective
      - Designed primarily for education and public outreach purposes and would frequently be targeted at Earth to provide whole-hemisphere views
- Concept employs existing technologies
  - Builds on the HEOMD capability-driven exploration strategies
  - Demonstrates America's intent to pursue deep space exploration
  - Enables early telerobotic scientific investigations of the far side of the Moon, including the strategically important South Pole-Aitkin Basin
  - Serves as a dramatic tool for education and public outreach in support of NASA's earth and space science activities
- Deployment schedule should be phased with long-term program planning

LEAG Earth-Moon L2 SAT Research Areas - Lunar Geosciences

- Lunar Geosciences includes sample return, drilling/coring, operating exploratory rovers and environmental monitoring of the lunar farside, as well as remote sensing from the L2 vantage point
- There are a number of locations on the lunar farside that have surface geology that is either critical to our understanding of the geologic history of the Earth-Moon system, or has unique rock types that are rare on the lunar surface and need to be sampled and studied
    - Many of these locations may not be high priorities for early human missions, but nonetheless are important locations to sample in order to address important research priorities as defined by the 2013 Planetary Science Decadal Survey, National Research Council, NASA Advisory Council and the LEAG Roadmap, including:
        - Geologic sample return from the South Pole-Aitkin Basin is among the highest priority activities for solar system science established by both the 2003 and 2013 Planetary Decadal Surveys as well as the National Research Council Scientific Context for Exploration of the Moon report. The mission's high priority stems from its role in addressing multiple science objectives, including understanding the interior of the Moon and impact history of the solar system.
            - Acquiring geochronologic data for the SPA Basin, considered the oldest large impact basin one the Moon, has a high priority for the lunar geoscience community and would be critical to addressing Science Goal 1b in the National Research Council Scientific Context for Exploration of the Moon report
        - Acquiring samples of farside volcanic areas with multiple compositions and sampling the diversity of farside rock units will be critical to addressing Science Goals 2d, 3a, 3b, 3d, and 5a-d in the National Research Council Scientific Context for Exploration of the Moon report
        - Obtaining direct measurements of the composition and ages of the Moon's lower crust and mantle (Planetary Science Decadal)
        - Elucidate the sources of thorium and other heat-producing elements in order to understand lunar differentiation and thermal evolution (Planetary Science Decadal)
        - Evaluation of the distribution and character of volatile species on the farside (especially SPA Basin) will support Science Goals A-3-D and A-4-D of the LEAG Roadmap

LEAG Earth-Moon L2 SAT Research Areas - Lunar Geosciences

- Robotic missions could be enhanced or enabled by teleoperations from the L2 vantage point, which provides a significant improvement in latency over an Earth-based link.
    - Rovers could be operated from either an Orion cabin or the proposed L2 facility using a dedicated workstation modeled after existing medical or mining teleoperation consoles
    - The 400 millisecond 2-way latency improves teleoperation efficiency, and may simplify mission design by allowing some types of missions to be completed in one lunar day, avoiding the difficulty of designing for lunar night survival and multi-day ops
    - Low latency also improves overall teleoperation by allowing more immediate feedback to the operator, leading to less difficulty for the robot operator
    - Sample return could either be direct to Earth or to the L2 facility for stockpiling and eventual Earth return
    - Development of robotic sample return technologies maps to LER Objective Sci-A-2
- There are a number of remote sensing techniques that lend themselves to making important observations of the lunar far side, although some implementation difficulties exist
    - The ~60,000 km range from L2 to the surface means that engineering solutions must be found to increase resolution of sensors flown at L2 as, at present, most remote sensing technologies placed at L2 would not improve upon data being collected by recent lunar missions
    - Long-term, diurnal thermal inertia observations of the farside will provide data on lunar surface properties which would allow for the development of multi-layer thermal models
    - Photometric studies of the farside through complete day/night cycles will provide baseline topographic information that will improve lunar cartographic investigations and products

LEAG Earth-Moon L2 SAT Research Areas - Lunar Geosciences

- Emplacement of a Lunar Geophysical Network is a high priority science goal in both the National Research Council Scientific Context for Exploration of the Moon report and the 2013 Planetary Science Decadal Survey
  - A next-generation global lunar geophysical network, of the type envisioned by the Decadal Survey, will greatly benefit from farside stations. A communications relay at L2 would be enabling for this configuration.
  - Geophysical instruments have a variety of deployment requirements such needing to be leveled, oriented, or coupled to the subsurface. Robotic mechanisms exist and/or can be developed for deployment, but might be enhanced by telerobotic control over deployment.
  - Geophysical stations do not necessarily have to be placed in precise locations, but fine-scale site selection (within a chosen area) may be enhanced by telerobotic site scouting.

Life Science Experiments On L-2 Missions

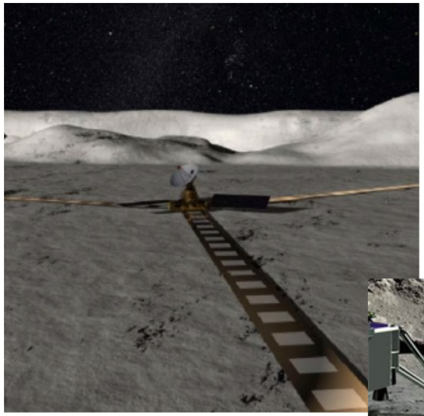
- L-2 provides a unique opportunity for life science in a very low gravity environment and the novel radiation beyond the Moon. In advance of human missions, cells and microbes can provide valuable indices of the terrestrial life response to this unique environment.
- Microbiology
  - Investigation of spacecraft flora
  - Take advantage of the rapid replication (1 generation every ≈0.5 hour)
    - Investigate the effects of microgravity and radiation on the nature and rate of mutation
    - Is radiation and/or microgravity a selective pressure leading to stable variants speciation?
    - Investigation of G-thresholds for ‘normal’ biological function using fractional G technology
- Cell biology
  - Use human cells as surrogates to understand the effect of the microgravity and radiation environments on ‘normal’ function
  - Perform generational and G studies as indicated for the microbes
  - Use engineered tissue to determine the effect on more complex systems
- Human systems (Crew Studies)
  - Operations and equipment validation
  - Behavior and performance investigations
  - Exposure to high LET radiation in a mission scenario
  - Monitor for new health issues that may be peculiar to the environment

Microgravity Physical Sciences Research at Earth-Moon L2

- The International Space Station (ISS) serves as a convenient “reference mission” for evaluating the potential for microgravity physical sciences research in a spacecraft-based laboratory at Earth-Moon L2
- The categories and sub-disciplines of microgravity physical sciences research currently being conducted on, or planned for ISS, do a good job of capturing any and all potential microgravity physical science research that would be a candidate for Earth-Moon L2
    - These sub-disciplines include: 1) combustion science, 2) materials processing, 3) fluid physics and 4) fundamental physics
- The potential and priority of any possible microgravity research physical science research at Earth-Moon L2 should only be evaluated relative to any possible advantage over ISS, i.e., there is no rationale for using Earth-Moon L2 for microgravity research if there is no substantive advantage over ISS.
- The conditions for microgravity research at Earth-Moon L2 can be anticipated to be different relative to ISS, but to an as-yet undetermined degree; these difference would apply to all three of the main categories of residual acceleration:
    - Quasi-steady acceleration: the relatively constant magnitude/direction residual acceleration existing as at any point in the spacecraft that is not at the spacecraft’s center of gravity.
    - Structurally-induced vibrations: oscillatory accelerations existing throughout the spacecraft structure and pressurized volume due to vibration modes and acoustic disturbances excited by spacecraft systems.
    - Transient acceleration disturbances: oscillatory accelerations due to short-lived forces, such as dockings and thruster firings, that dissipate out over a finite time period.
- The SAT recommends that the research community in microgravity physical sciences be polled as to the desirability of obtaining high-fidelity models of the quasi-steady microgravity environment for a nominal spacecraft at Earth-Moon L2, to determine any possible advantages for microgravity research at Earth-Moon L2 over ISS. This modeling could also be performed to a lower fidelity degree, using a spacecraft model, for the vibrational and transient microgravity environments.

LEAG Earth-Moon L2 SAT Research Areas - Astronomy

- The lunar farside is unique at radio wavelengths, and a highly enabling site for radio astronomy
  - A quiet zone on the farside (QZM) has been verified by sensors and allows outstanding radiosensitivity
    - A small radio telescope can be placed at EM L2, but would not have the sensitivity or spatial resolution to address the important science problems that a lunar surface QZM telescope can
    - At EM L2, only a small fraction of the time is actually spent shadowed from the Earth
  - The lack of a significant lunar ionosphere allows outstanding radio spatial resolution, as well as transparency
  - The Moon provides a convenient ground plane that gives dipole radio interferometers better directionality
  - Important science is served by radio arrays with lengths of 30-100 m, which may be impractical in free space
  - Different sizes and topologies address different radio science questions, which provides for a natural facility upgrade path
    - Even a small, 3-arm, 30m scale antenna could offer near term science
  - The radio science potential cannot be achieved with current telescopes (also, at high-z, with the future MWA, SKA)
  - A credible radio telescope architecture is rollable polyimide (e.g. Kapton) sheets with imprinted antennae
    - This rolled architecture is well suited to telerobotic deployment from EM L2
    - Early deployment could exercise capabilities for much larger telescopes
    - The telescope will observe 21cm HI at high-z of the epoch of first stars and galaxies and trace interactions that produce coronal mass ejections in the Sun
  - Telerobotic control architecture could be shared with lunar science tasks



LEAG Earth-Moon L2 SAT Research Areas
SmallSat Engineering Development

- The Earth-Moon unstable Lagrange points (L1 and L2) are ideal locations for launching low-thrust spacecraft (e.g., ion propulsion or solar sail)
  - Normally, a low-thrust spacecraft launched into LEO takes a long time and uses valuable propellant spiraling out of the Earth's gravity well
  - Only a small delta-V is required to either escape the Earth-Moon system onto interplanetary trajectories or to initiate gravitational assist maneuvers, utilizing the Earth or the Moon to achieve high-inclination solar orbits
- Delivery to a Lagrange point will enable more ambitious exploration missions
- Assumes the ability to be carried on existing external attach points on Orion

LEAG Earth-Moon L2 SAT
Systems Engineering/Hardware Design Issues

- Critical areas that need to be considered for an E-M L2 Facility payload operations:
  - Microgravity levels desired
    - This needs to be requirements driven within a given discipline, and coordinated between disciplines to avoid interference issues
  - Interference issues between different research disciplines
  - Increment duration for research activities, including research “throughput”
  - Upmass/downmass capability of the Orion
  - Data rates, transmission paths and required communications infrastructure from an Earth-Moon L2 location
  - Analytical facilities for samples generated by internal research activities
  - External contamination issues for optics, solar arrays, radiators and external payloads
  - Research accommodation designs, including interfaces with the Orion vehicle
- Human crew accommodations, including:
  - Life support system and crew living requirements
  - Facility de-manning requirements
  - Stowage, resupply and trash capabilities
  - Radiation and MMOD protection for crew and avionics
  - Suit lock/hardware lock requirements
  - Visiting vehicle requirements, including docking accommodations

LEAG Earth-Moon L2 SAT Research Areas Summary and Prioritization

Research Discipline	Investigations	Facility Required	Earliest Possible Mission Date	Is Research Enhanced, Enabled or Required at L2?	Science Priority
Geology of the Moon	Robotic Geologic Investigation and Sampling at Farside Targets of Interest, such as SPA Basin or permanently shadowed craters	Either Orion or L2 Facility	2021; requires human crew as well as development of robotic rover and sample return capability to either L2 or Earth (breakout discussion of SPA vs. Permanently shadowed regions)	Enhanced	High
	Robotic Deploy of Remote Geophysical Monitoring Stations	Either Orion or L2 Facility	2021; needs farside comm capability (see Ops Capability row)	Enhanced	High
	Remote sensing using thermal inertia and long-term photometric studies	L2 Facility	Post 2021; requires facility to be in place	Enhanced	Medium
Life Sciences	Coupled effects of radiation and gravity on microbial life and cells outside the Earth's magnetosphere	L2 Facility	Post 2021; requires facility to be in place	Enabled	High
Astronomy	Construction of Farside Radio Astronomy Facility	L2 Facility	2021 deploy is engineering proof of concept; requires significantly larger follow-on capability to do cutting edge science	Enhanced	High
Small Satellite Engineering Development	Develop the capability for launch & recovery of small spacecraft using high I_{sp}, low thrust engines to go to multiple targets out of cis-lunar space	L2 Facility	Post 2021; requires facility to be in place	Enabled	Medium
Ops Capability	Emplacement of a long-lived commsat at L2 at earliest opportunity	Orion	2017; early robotic missions enabled on the farside	Enabled	High

Backup Slides

LEAG Earth-Moon L2 SAT - Approach

- This activity will be a critical part of the assessments on the feasibility of committing to an Earth-Moon L2 mission
- In addition to identifying potential research investigations, this team must make a careful assessment of the engineering requirements implications associated with implementing the different research areas
  - For instance, a science mission to return samples from the lunar farside to a human-operated spacecraft at an L2 location will have a host of second tier requirements that will affect spacecraft and system design
    - ✓ Rendezvous and proximity operations between both spacecraft
    - ✓ Grappling and docking the sample return spacecraft
    - ✓ Retrieval of sample containers
    - ✓ Sample management, including cleaning and stowage of sample containers
- None of these constraints and requirements should exclude a particular research area from our consideration
  - However, if they are ignored, they can lead to significant problems in the future, including expenditure of significant funds to correct deficiencies late in the hardware development cycle
- Our discussions should also include whether Earth-Moon L2 is the only location where this can be done, or can existing platforms, e.g., ISS, be utilized immediately
  - In particular, we need to distinguish between opportunistic science that can be done because we are already there, and “facility-class” science that must be done at L2 in a specific facility
- Lastly, we need to consider whether we need to operate in a crew transfer vehicle (whatever config/name this happens to have) or within a dedicated facility that remains at a Lagrangian Point

LEAG Earth-Moon L2 SAT - Deliverables

- Specific deliverables shall include:
  - A list of the science and exploration investigations using the unique location/environment of Earth-Moon L2 that can best performed from an L2 facility, including a definition of the facility that is best suited for a given research area
  - A list of the science, resource, technology and exploration investigations the lunar surface that can best performed from an Earth-Moon L2 facility
  - A list of the engineering implications and potential interference issues for the investigations identified
  - A prioritized list of L2 investigations that can be accomplished on 2014, 2017 and 2021 Orion-SLS test flights

LEAG Earth-Moon L2 SAT Agenda

9 February 2012

0800-0830	Meet, greet, review charter, agenda and expected outcome
0830-1000	Discussion of Earth-Moon L2 mission plans – John Connolly
1000-1015	Break
1015-1200	Discussion of potential research opportunities – Group
1200-1315	Lunch
1315-1430	Continue discussion of potential research opportunities and finalize the list – Group
1430-1645	Discussion of engineering requirements and constraints to research implementation compile list of requirements and constraints – Group
1645-1700	Review day's activities
1800	Group dinner

10 February 2012

0800-1030	Discussion of potential conflicts between research disciplines
1030-1200	Finalize products
1200	Adjourn

LEAG Earth-Moon L2 SAT - Proposed Research Prioritization Approach

- We will go with “High-Medium-Low” as our priority labels
- Our first tier should be based on known programmatic needs (do we need this information to proceed with development of downstream programs such as lunar surface operations, Mars missions, etc.?)
- Our second tier should consider whether a particular research area we define is already being done, or can be done on ISS
    - For instance, the ISTAR Program is well along at defining exploration tests that can be done at ISS
    - If something can be done at ISS, it should be done there, and not wait for an L2 mission/facility
- Our third tier consideration should be what vehicle we can do this work on
    - A research area that can be tackled on a crew transfer vehicle should have a higher priority, at least in the near term, than an area that has to be done in an L2 facility
    - Also, as per the charter, research payloads that could fly on a 2017 mission are already almost too late for development, so any high priority research to be done then should be identified for initial pre-Phase A funding in the FY13 budget