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THE ROLE OF CIS-LUNAR SPACE IN FUTURE GLOBAL SPACE EXPLORATION

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Cis-lunar space offers affordable near-term opportunities to help pave the way for future global human exploration of deep space, acting as a bridge between present missions and future deep space missions. While missions in cis-lunar space have value unto themselves, they can also play an important role in enabling and reducing risk for future human missions to the Moon, Near-Earth Asteroids (NEAs), Mars, and other deep space destinations. The Cis-Lunar Destination Team of NASA's Human Spaceflight Architecture Team (HAT) has been analyzing cis-lunar destination activities and developing notional missions (or "destination Design Reference Missions" [DRMs]) for cis-lunar locations to inform roadmap and architecture development, transportation and destination elements definition, operations, and strategic knowledge gaps.

The cis-lunar domain is defined as that area of deep space under the gravitational influence of the earth-moon system. This includes a set of earth-centered orbital locations in low earth orbit (LEO), geosynchronous earth orbit (GEO), highly elliptical and high earth orbits (HEO), earth-moon libration or “Lagrange” points (E-ML1 through E-ML5, and in particular, E-ML1 and E-ML2), and low lunar orbit (LLO). To help explore this large possibility space, we developed a set of high level cis-lunar mission concepts in the form of a large mission tree, defined primarily by mission duration, pre-deployment, type of mission, and location. The mission tree has provided an overall analytical context and has helped in developing more detailed design reference missions that are then intended to inform capabilities, operations, and architectures.

With the mission tree as context, we will describe two destination DRMs to LEO and GEO, based on present human space exploration architectural considerations, as well as our recent work on defining mission activities that could be conducted with an EML1 or EML2 facility, the latter of which will be an emphasis of this paper, motivated in part by recent interest expressed at the Global Exploration Roadmap Stakeholder meeting. This paper will also explore the links between this HAT Cis-Lunar Destination Team analysis and the recently released ISECG Global Exploration Roadmap and other potential international considerations, such as preventing harmful interference to radio astronomy observations in the shielded zone of the moon.

I. INTRODUCTION

Cis-lunar space offers affordable near-term opportunities to help pave the way for future global human exploration of deep space and may serve as a bridge between present near-earth missions and future deep space missions. NASA's Human Spaceflight Architecture Team (HAT) recently created a set of “destination teams” to focus analysis of activities during crewed missions in multiple deep space locations. These destination teams address missions to (1) earth’s moon, (2) cis-lunar space, (3) near-earth asteroids (NEAs), and (4) Mars and Mars’ moons.

The HAT “Cis-Lunar Destination Team” was chartered to perform a number of analyses of potential missions and activities, to provide a foundation for understanding how cis-lunar locations in near-earth deep space could support future human space exploration missions to more distant locations. For purposes of these analyses, the team defined cis-lunar space as *that area of deep space under the gravitational influence of the Earth-Moon system*. Therefore, missions within the following locations

were considered: (1) a set of earth-centric orbital locations (low earth orbit/LEO, medium earth orbit/MEO, geosynchronous earth orbit/GEO, and high-earth orbit or highly elliptical orbits/HEO); (2) the five earth-moon libration or Lagrange points, E-M L1 through E-M L5; and (3) low-lunar orbit (LLO) (lunar surface mission analyses were conducted by HAT's Lunar Destination Team). Note that missions within "Sun-Earth space" were not considered in these analyses, as they are beyond the earth-moon system; however, it was recognized that there are methods by which to move between "sun-earth space" and "earth-moon space" and possible missions that would exploit this connectivity were considered, such as transporting an observatory from S-E L2 to a point in earth-moon space for crew rendezvous for servicing and repair. An overview graphic depicting Earth-Moon cis-lunar space is given in Figure 1.

To understand how cis-lunar locations could fit within a broader strategy of human exploration of deep space, the HAT cis-lunar team performed the following types of analyses:

- Developed a number of notional crew + robot mission concepts (or "design reference missions"/DRMs) for cis-lunar locations
- Defined crew habitation requirements during cis-lunar missions
- Identified mission support payload delivery requirements and concepts
- Analyzed robotic capabilities and functionality in support of crew during cis-lunar missions
- Evaluated automated rendezvous, docking, capture, and berthing operations that may be required during cis-lunar missions
- Identified technologies and capabilities required to support cis-lunar missions
- Analyzed potential crewed and uncrewed activities that could be performed in cis-lunar space, especially with regard to exploration and science activities that may be conducted within an Earth-Moon L1/L2 crew-tended facility.

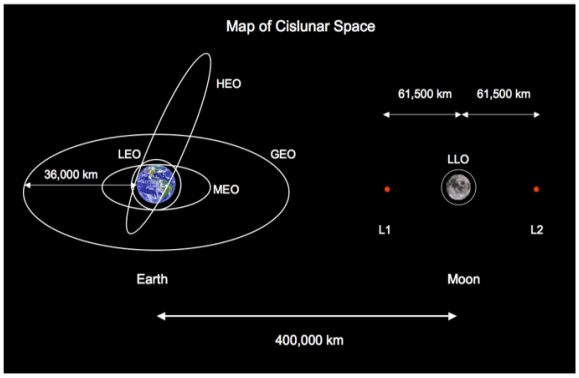

Figure 1. Cis-lunar space. (Dr. Paul Spudis/LPI)

II. POTENTIAL CIS-LUNAR MISSIONS: THE CIS-LUNAR "MISSION TREE"

To explore the range of possible cis-lunar missions that would be enabled using the space transportation system presently in development (the Space Launch System/SLS and the Multipurpose Crew Vehicle/MPCV), we constructed a "mission tree" using four driving criteria:

(1) Duration
(2) Pre-Deployed Assets
(3) Mission Type
(4) Location

The cis-lunar mission space is shown in Figure 2 with the four evaluation criteria and representative examples of potential missions.

The *Duration* parameter ($\leq$ 21 days, > 21 days) was driven by habitation and crew support considerations regarding the MPCV, which is capable of supporting four crewmembers for a maximum of 21 days. Additional crew accommodations and support would be required for cis-lunar missions with durations greater than 21 days

The *Pre-Deployed Assets* parameter addressed the need for hardware (e.g., tools, airlock, instruments, systems) to support the crew when conducting the mission. When transporting four crew in the MPCV to cis-lunar locations, the 105 t SLS has limited additional cargo carrying capacity to cis-lunar locations (e.g., approximately 0 t to GEO and 5 t to E-M L1/L2); therefore, methods for "pre-deploying" assets needed for the mission were considered. Note that "pre-deployed" refers to assets that could be delivered to the cis-lunar destination prior to crew

arrival (e.g., as cargo on an EELV) or assets that are already at the cis-lunar destination (e.g., a spacecraft to be serviced).

The third driving parameter, *Mission Type*, referred to the primary objective of the mission. There were three mission types considered: (1) *Servicing* an asset (e.g., upgrading an existing spacecraft in cis-lunar space to extend its operational lifetime; preparing an existing asset for end-of-life and disposal; boosting an existing asset to a new position), (2) *Deploying and/or Assembling* an asset (e.g., a fuel depot to be emplaced in GEO; a multi-element spacecraft performing a deep space science mission), and (3) *Exploration Research & Technology Development* that could, for example, be performed within a crew-tended facility at an Earth-Moon Lagrange point (e.g., emplacing radiation measuring instrumentation, testing radiation shielding methods, evaluating high-reliability Environmental Control & Life Support/ ECLS systems).

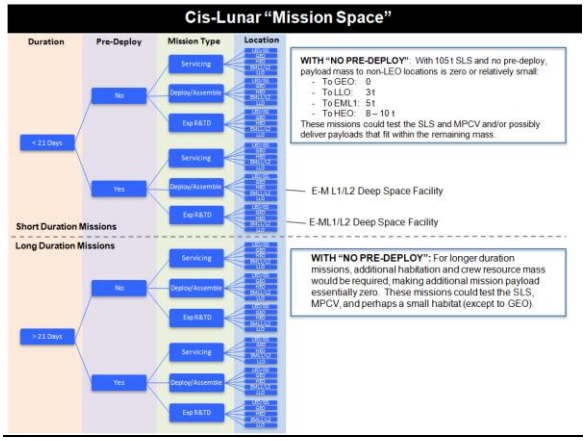

Figure 2. Cis-lunar destination mission tree.

The fourth driving parameter, *Location*, referred to the specific mission destination within cis-lunar space (i.e., LEO, GEO, HEO, E-M L1 through E-M L5, LLO).

In summary, a cis-lunar mission tree was created to identify representative missions that fall within a set of duration, asset pre-deployment, mission type, and location within cis-lunar space criteria. A subset of these representative missions was selected for further study. The duration parameter identified the need for providing crew habitation and accommodations beyond those provided by the MPCV for missions longer than 21 days. The ability to pre-deploy (or have pre-existing) assets in support of missions is an important factor, particularly for beyond-LEO destinations, because of the limited mass allocations and launch shroud volume restrictions. Missions to GEO were found to be particularly difficult, because of upmass limitations and charging issues. It was noted that a heavy-lift version of the SLS (i.e., 130 t) broadens cis-lunar space mission capture.

III. REPRESENTATIVE CIS-LUNAR DESIGN REFERENCE MISSIONS

Using the cis-lunar mission space as context, a number of *notional* Design Reference Missions (DRMs) were created across the cis-lunar destinations, durations, and mission types, to aid in understanding requirements for fielding cis-lunar missions using the emerging transportation architecture. Two of these notional missions captured as DRMs – a LEO asset servicing mission and a GEO asset servicing mission – are briefly described below.

LEO Asset Servicing Mission

A notional DRM was created for a crewed mission to service an existing asset in LEO. The purpose of the mission was to extend the life of the asset and prepare it for safe de-orbit and disposal at the end of its useful life. In addition, this mission would provide an opportunity to test the in-development transportation systems (SLS, MPCV) in an operational environment. Additional mission objectives included gaining experience with increased crew autonomous operations in preparation for the high levels of autonomy expected during deep space operations and developing an enhanced crew and robotic partnership in space operations.

The following assumptions were made with regard to the LEO asset servicing mission:

- The primary objective of the LEO DRM was to develop a notional mission using HAT architectural elements and the in-development space transportation system to service and repair a generic asset presently in LEO
- Three crew, with crew and robotic elements working cooperatively

- A single launch of the SLS with the MPCV, a "servicing platform (SP)" or "cargo hauler," and a Service Module (SM)-derived kick stage (an overview of the mission sequence is given in Figure 3)
- An SP would need to be developed and launched with the crew to be deployed on-orbit in support of the mission
- Given that there is no airlock with the MPCV, it was assumed that the SP provides the airlock for crew extravehicular activity (EVA) to service the asset and transports the cargo (e.g., tools, upgrade instruments, replacement systems) to the work site
- The kick stage inserts the launch stack into the proper orbit for rendezvous with the asset to be serviced
- After launch and reaching the proper orbit, the MPCV and SP undock, then the MPCV re-orients and docks "nose-first" to the SP, thus allowing crew access to the airlock and cargo in the SP; the MPCV is the active vehicle during rendezvous and proximity operations
- Upon rendezvous with the asset in LEO, a robotic arm on the SP is used to grapple and secure the asset in the SP for servicing (the asset requires a stabilization mechanism to enable crew and robotic servicing operations); the robotic arm may also be used to position the EV astronauts during servicing operations
- There are three two-person EVAs over the mission, with the third crew member remaining inside the MPCV, providing support to the EV astronauts
- The MPCV is operated at an internal pressure that provides short pre-breathe times to optimize EVA time
- Autonomous or "scripted" robotic arm operations are used to retrieve, transport, and stow payloads; autonomous or scripted robotic servicer operations perform such activities as removal and installation of panels, replacement of external components, and preparation of the asset for crew servicing
- The total mission duration was seven days. Representative crew and robotic servicing operations for days four through six are shown in Figure 4 as an hourly crew activity plan (robotic elements would perform additional crew-assisted and autonomous intra-vehicular (IV) and EV activities outside of the shown eight-hour crew days)
- Upon completing the servicing and repair portion of the mission, the MPCV releases the asset and backs away; complete checkout of the LEO asset is performed by ground operations
- The MPCV performs a direct entry burn; during return, the SM is jettisoned and the crew returns in the Crew Module (CM)
- The SP may be disposed of or may remain on-orbit for possible future use

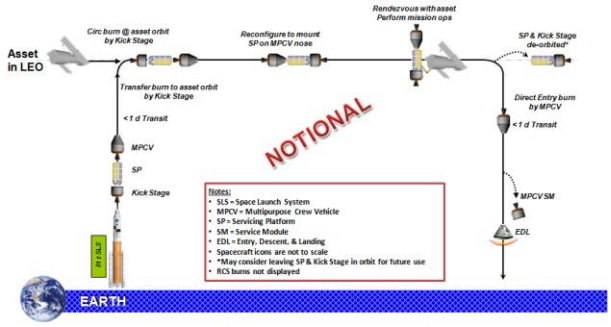

Figure 3. Transportation architecture and mission sequence for LEO asset servicing mission.

In summary, a concept for a three-crew + robotic support LEO asset servicing mission was created using the SLS and MPCV as transportation elements and a servicing platform for transporting required cargo and providing airlock services. The mission concept included primary objectives, mission assumptions, transportation architecture and mission sequence, a "cargo hauler/servicing platform" concept, a high-level crew activity plan, and a "streetview-level" graphical representation of the overall mission. A graphic depiction of this mission is shown in Figure 5.

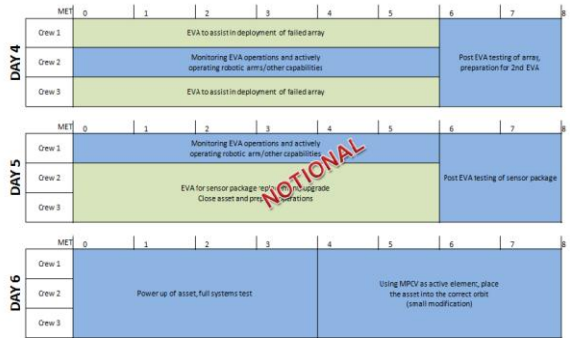

Figure 4. Representative crew activities conducted during the LEO asset servicing mission (days four through six).

Figure 5. Notional LEO asset servicing mission.

GEO Asset Servicing Mission

A second notional DRM was created for a mission to service two existing assets in GEO. The following assumptions were made with regard to this mission:

- The primary objective of the notional GEO DRM was to explore operations required to conduct a GEO satellite servicing mission with the proposed HAT architectural elements and the in-development space transportation system
- Three crew, with crew and robotic elements working cooperatively
- Two existing GEO satellites to be serviced and/or upgraded
- A method for delivering cargo and providing a platform for servicing (e.g., an SP) would need to be developed and launched to be deployed on-orbit in support of the mission
- Two launches are required to deliver crew and all supporting elements to GEO (an overview of the mission sequence for the second launch is given in Figure 6):
  - *Elements in Launch Stack #1 (Commercial Launch Vehicle):* SP or "cargo hauler" containing robotics and EVA system, tools, servicing/upgrading components, robotic servicer; kick stage (performs circularization burn to insert stack into GEO near asset #1); and upper stage (places SP in GEO Transfer Orbit [GTO] and is then placed in disposal orbit)
  - *Elements in Launch Stack #2 (SLS):* MPCV with Crew and interim Cryogenic Propulsion Stage (iCPS; transfers crew to target GEO orbit for rendezvous with mission elements and asset #1)
- After reaching the proper orbit and performing the rendezvous of launched elements, the MPCV and SP undock, then the MPCV re-orients and docks "nose-first" to the SP, thus allowing crew access to the airlock and cargo in the SP; the MPCV is the active vehicle during rendezvous and proximity operations
- The SP provides the airlock for crew EVA to service the asset and transports the cargo (e.g., tools, upgrade instruments, replacement systems) and robotic servicer to the work site
- Upon rendezvous with the first asset in GEO, a robotic arm on the SP is used to grapple and secure the asset in the SP for servicing (the asset requires a stabilization mechanism to enable crew and robotic servicing operations); the robotic arm may also be used to position the EV astronauts during servicing operations
- There are three two-person EVAs to service asset #1, with the third crew member remaining inside the MPCV, providing support to the EV astronauts
- The MPCV is operated at an internal pressure that provides short pre-breathe times to optimize EVA time
- Autonomous or "scripted" robotic arm operations are used to retrieve, transport, and

stow payloads; autonomous or scripted robotic servicer operations perform such activities as removal and installation of panels, replacement of external components, and preparation of the asset for crew servicing

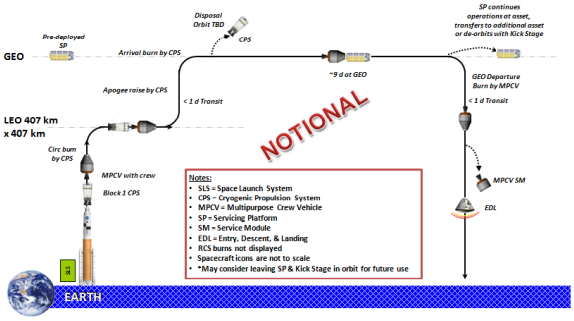

Figure 6. Transportation architecture and mission sequence for GEO asset servicing mission (SLS/MPCV/ Crew/SP launch sequence shown).

- UV light is used to neutralize internal charging build up during servicing operations
- After asset #1 servicing and checkout are complete, the asset is placed in its proper orbit by using the kick stage; the MPCV/crew/SP stack undocks and asset#1 is released
- The MPCV/crew/SP stack transfers to the vicinity of asset #2 to be serviced; upon rendezvous, the teleoperated robotic servicer docks to asset #2 and safes it for servicing
- The crew operates the robotic servicer to refuel and check out asset #2
- On completion of servicing asset #2, the asset is released
- The MPCV performs a direct entry burn; during return, the SM is jettisoned and the crew returns in the CM
- The SP may be disposed of or may remain on-orbit for possible future use
- The total mission duration was 11 days. Representative crew and robotic servicing operations for days seven through nine are shown in Figure 7 as an hourly crew activity plan (robotic elements would perform additional crew assisted and autonomous IV and EV activities outside of the shown eight-hour crew days)
- Contingency days were built into the crew activity plan

In summary, a concept for a three-crew + robotic support mission servicing two assets in GEO was created using the SLS and MPCV as transportation elements and a servicing platform for transporting required cargo (including a robotic servicer) and providing airlock services. The mission concept included primary objectives, mission assumptions, transportation architecture and mission sequence, a high-level crew activity plan, and a "streetview-level" graphical representation of the overall mission (shown in Figure 8).

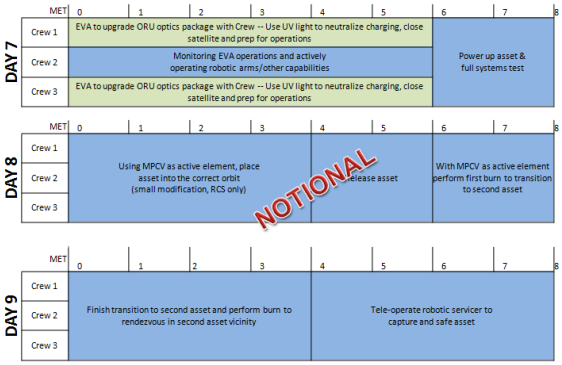

Figure 7. Representative crew activities conducted during the GEO asset servicing mission (days seven through nine).

A number of issues were identified as a result of constructing this DRM. For example, while exposure to radiation (both Galactic Cosmic Radiation/GCR and Solar Particle Events/SPEs) in GEO is similar to that in deep space, the trapped electron environment is unique to this location. The MPCV is not designed for this environment and potentially significant requirements are added to the crew vehicle, EVA suits, habitable spaces, and electronic equipment. Servicing assets requires reliable capture and stabilization capabilities. A system that provides reliable crew EVA access is required. There is significant crew autonomy and crew/robot interaction.

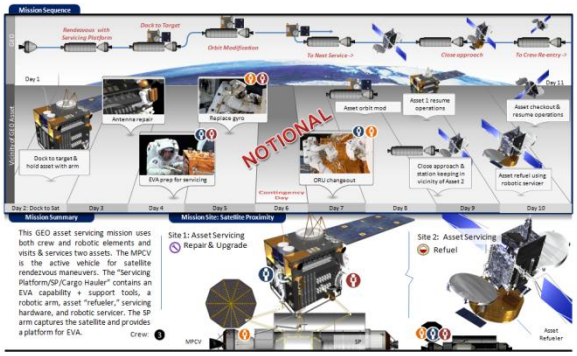

Figure 8. GEO asset servicing mission "streetview" overview.

Summary of DRMs

A number of notional DRMs were created to explore multiple aspects of potential future missions that could be conducted in cis-lunar space locations. Two of these representative DRMs – one examining a human + robots crew servicing an asset in LEO and a second examining a human + robots crew servicing multiple assets in GEO – were briefly summarized here. For each conceptual mission that we developed, a number of products were created: an overview of the transportation architecture using the in-development MPCV and SLS, a description of the mission and operations, a high-level crew activity plan over the mission days, and a "streetview" overview of the mission.

As a result of developing a number of DRMs for conceptual missions in multiple cis-lunar space locations, it was found that cis-lunar missions require a number of the following enabling technologies and capabilities:

- Reliable delivery of mass and crew to beyond-LEO locations
- Orbit modification capability
- Precision approach and Automated Rendezvous & Docking (AR&D)
- Autonomous vehicle station-keeping
- In-space cryogenic fluid transfer /refueling
- Next generation crew EVA system
- Human and robot autonomous operations
- Advanced human and robot interaction
- Next-generation space robotics & robotic servicing capability
- Cis-lunar / deep space habitation
- Assembly of large space structures beyond LEO

IV. A FACLITY AT EARTH-MOON L1/L2 AS A HUMAN SPACE EXPLORATION DESTINATION

In addition to developing a number of DRMs to explore mission operations during cis-lunar missions, a conceptual mission is presently in development that focuses on a crew-tended facility that would be positioned at the Earth-Moon L1 or L2 Lagrange points. (Note that consideration is also given to emplacing such a facility at either L1 or L2 and moving the spacecraft between the points, as may be required for operations.)

Earth-Moon L1/L2 Characteristics of Operational Interest

We began by evaluating characteristics of operational interest at E-M L1 and L2. For example,

- *E-M L1/L2 provide a near-earth deep space location beyond the Van Allen Belts* that could serve as a demonstration and test site for long-duration human space exploration missions within (relatively) easy return to earth. Vehicle systems, advanced EVA systems and operations, autonomous mission operations, crew and robot interaction, and radiation mitigation methods and capabilities could be tested and brought to operational status prior to fielding an exploration mission beyond near-earth space (e.g., to a NEA).

- *E-M L1/L2 are in "free space"* and, therefore
  - The gravity wells of earth and the moon are avoided
  - Surface environmental issues (e.g., dust) are avoided
  - There is little hazard from artificial or natural space debris
  - There is low (on the order of cm/s) station keeping propellant requirements
  - Travel between L1 and L2 is relatively easy (and has been demonstrated by NASA's recent ARTEMIS mission), and
  - There is a natural connection between earth-moon space and sun-earth space

- *E-M L1/L2 could support lunar science and exploration without the requirement to land crew on the lunar surface*
  - The lunar surface is easily reachable and accessible with minimal launch window constraints and low delta-v's
  - A facility at this location provides a stable platform for the teleoperated control of robotic assets on the lunar surface, and
  - E-M L2, in particular, provides a long-term view of the moon's farside

- *A facility at this location could support deep space science operations*
  - *F*or example, it provides full view of the earth and lunar hemispheres
  - A tight "halo orbit" could support observations within a "radio quiet zone"

Assumptions Regarding an E-M L1 / L2 Facility

Our team was given direction regarding an E-M L1/L2 facility and, during discussions, we made a number of assumptions to focus development of the DRM. These assumptions and direction are summarized below.

- Objectives of the DRM were to:
  - Establish a crew-tended facility at E-M L2 (with the capability to be repositioned to E-M L1)
  - Expand human presence beyond LEO
  - Establish a deep space communications link to earth and to the lunar farside
  - Enable long-term observation and survey of the lunar farside
  - Establish a platform for enabling scientific exploration of the moon and deep space
  - Extend MPCV capabilities beyond LEO
  - Enable long-duration testing of exploration technologies and development of exploration capabilities
- Use early configurations of the SLS, MPCV, and iCPS-1 with existing NASA and International Partner hardware systems to deliver a basic E-M L2 facility to deep space that could be incrementally expanded and supported by international and commercial launch systems and exploration payloads
- The facility would operate nominally with four crew in a "crew-tended" mode (human crew does not permanently occupy the facility)
- There is basic crew habitation and accommodations with SPE protection and GCR mitigation
- The facility would have the capability for the crew to perform EVA
- The facility operates in a (TBD) halo orbit once delivered to the E-M L2 point
- The crew, when resident, would be delivered by the MPCV, which would remain attached to the facility during the crewed mission and would be used for crew return
- The facility assumes significant robotic support (both EV and IV), working with the human crew when they are resident and maintaining/servicing the facility when the human crew is not resident
- A notional transportation architecture showing the launch and delivery of the E-M L2 facility was developed assuming the 81 t SLS and the first-generation iCPS, as shown in Figure 9.
- A notional transportation architecture showing the launch and delivery of four crewmembers using the SLS in the MPCV to the E-M L2 facility was developed and is shown in Figure 10.
- The facility supports automated rendezvous and docking of uncrewed elements

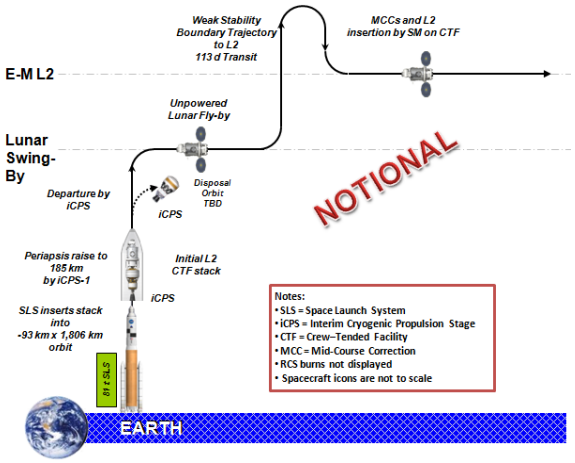

Figure 9. Transportation architecture and mission sequence for delivery of Earth-Moon L2 crew-tended facility.

- The facility, as delivered cargo, can support up to 90 days of ECLSS, with partial water recovery and logistics resupply
- No provision is made for logistics resupply in early missions; potential future logistics resupply is TBD

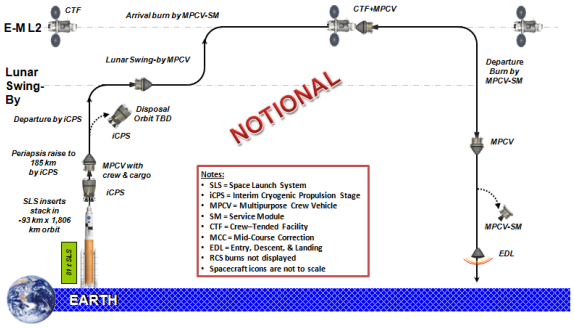

Figure 10. Transportation architecture and mission sequence for delivery of four crew to an Earth-Moon L2 crew-tended facility.

E-M L1/L2 Facility Concept

Some initial concepts were developed for an E-M L2 crew-tended facility, assuming NASA and International Partner elements. It must be noted that these concepts are very notional and were created to begin to conceptualize possibilities for such a facility. It is expected that a number of conceptual approaches to an E-M L2 facility will continue to be developed. In addition, there are a number of cis-lunar facility concepts that have been developed by a number of groups and these approaches are also under study.

One notional concept for such a facility is shown in Figure 11. This concept assumed a foundation provided by an ISS Node Structural Test Article (STA), with an attached Service Module (SM), airlock, External Payloads and Experiments Platform, and high gain antenna. Additionally, there is an unpressurized docking interface, a robotic arm, and an advanced Robonaut. In the image, the MPCV is also shown in the docked position. There may also be lunar surface robotic systems (not shown) that may be deployed and operated from the facility.

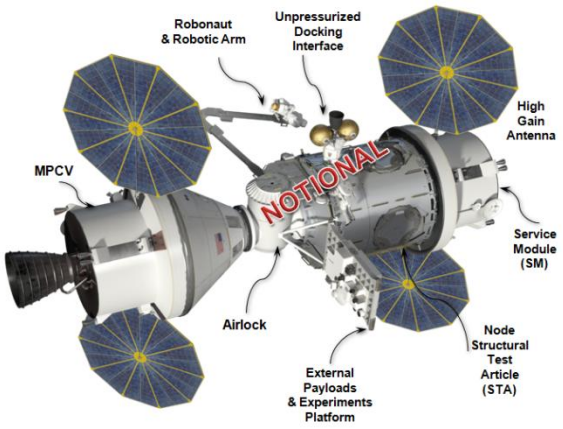

Figure 11. A notional Earth-Moon L2 crew-tended facility concept. (Goodliff, K. & Stromgren, C.)

It is assumed that inside the facility, there are basic accommodations for four crew for up to 30 days per crewed mission (while crew is not resident, the IV robotic systems maintain the facility), as well as accommodations for exploration technology demonstrations and exploration capabilities development. It is also assumed that there are internal and external areas devoted to science payloads, with basic services (e.g., power, communications) provided by the facility and some crew time devoted to science operations (e.g., sample retrieval, repositioning, instrument changeout), if required.

Representative E-M L1/L2 Facility Activities

In addition to examining transportation architectures for delivering the facility and crew and developing some notional concepts for an E-M L2 facility, the HAT Cis-lunar Destination Team began identifying categories or "domains" of activities that could be carried out within a facility at E-M L1 or L2. At this point, the team "cast a wide net," to ensure that all possible activity domains were captured; it was understood that, on further analysis, some activities would prove to be untenable or unrealistic within this environment. This activity domains analysis was conducted in preparation for future development of a concept of operations for this facility. These activity "domains" are briefly described below.

1. *Develop and certify Human Space Exploration operational capabilities in deep space*

First and foremost, a facility at E-M L1/L2 could serve as a testbed for *developing, testing, and certifying human space exploration systems* prior to fielding a crewed mission to a deep space location beyond the earth-moon system, thus extending the research and technology developed in support of human exploration beyond the environment of the International Space Station (ISS).Additionally, the facility could serve as the first "stepping stone" beyond LEO to develop *capabilities* required for deep space missions.

For example, the facility could serve as a high-fidelity test and verification environment for exploration systems, such as environmental control and life support (ECLSS) sub-systems that could contribute to increased reliability and long-duration performance. Countermeasures for mitigating the effects of long duration exposure to microgravity could be tested, extended, and verified. Technologies required for deep space missions could be operated in the L1/L2 environment prior to commissioning for beyond-earth missions. Deep space radiation effects on living systems and avionics and shielding materials and approaches could be studied.

Additionally, an E-M L1/L2 facility could provide a platform for developing and proving required space operations capabilities. High levels of crew autonomy are required for exploration missions; these operations could be extended beyond those on ISS and systems supporting crew autonomy could be used and certified in a deep space operational environment. Advanced robotics for both external EV and internal IV activities would be tested. In particular, it is expected that such an E-M L1/L2 facility would be operated in a "crew-tended" mode (such that the human crew would visit periodically and the facility would not be permanently occupied by humans, as ISS is presently operated); this crew-tended operational mode would rely heavily on robotic systems to maintain the facility without crew present.

Advanced habitation systems could be evaluated, including such factors as stowage and food preparation and stability. Crew-related areas could be investigated, such as plant growth, cell cultures in space, and crew physiological responses to the deep space environment.

While crew is present, it is expected that they would interact regularly with advanced robotic systems to conduct mission activities. An E-M L1/L2 facility would provide an operational environment for practice and refinement of such interactions; it is assumed that there would be significant crew reliance on supporting robotic systems during distant exploration missions. An E-M L1/L2 facility would also provide an operational environment for verifying and maturing long duration crew medical care operations.

The facility would provide an appropriate environment for evaluating crew psychosocial health and performance far from earth in a way not afforded by missions in LEO, especially given the higher risk associated with earth return and a much smaller view of earth from the facility window. And if it is accepted that artificial gravity methods should be considered for future exploration missions, then methods for providing such a capability could be tested at an E-M L1/L2 facility.

2. *Serve as a platform for science*

An E-M L1/L2 facility could provide significant benefits as a platform (external and internal) for conducting science investigations, particularly those that benefit from the unique near-earth deep space environment afforded by the libration points.

The international science community, including NASA and international space agencies, educational and research institutions, and other government agencies, could provide instruments, payloads, and platforms that could be attached to or be deployed from such a facility. The facility would serve as a platform and provide basic services, such as power, communications/data downlink, volume or a pressurized environment. Instrument packages could be arrayed on the facility exterior or contained in holding areas in the interior. EVA crew or a robotic arm could deploy, upgrade, change out instruments, or collect samples (such as space materials or "coupons" with microbial communities exposed to deep space over long durations).

Crew deployment would be optional and there could be occasional crew involvement on a select basis. Much of the instrumentation or test apparatus could operate passively, or could be autonomously operated or supervised from earth.

There are several domains of space, earth, and life science that could potentially be enabled by a facility at E-M L1/L2. For example, microbiological studies to assess impacts of the coupled radiation and microgravity effects, telerobotically constructing a radio telescope on the lunar farside, obtaining and returning lunar farside samples via telerobotic operations, and space weather instrument packages.

3. *Serve as location for constructing and assembling large space structures and spacecraft*

An E-M L1/L2 facility could serve as a platform for constructing or assembling many types of large space structures. Multiple pieces could be launched and delivered over time to the L1/L2 facility, which could serve as the staging location; the elements would be progressively assembled by crew and robots into a larger structure, then deployed from E-M L1/L2 to its destination when assembly is completed. It is assumed that some large-scale construction operations would require in situ crew, while others may not; in some cases, operations could be conducted autonomously (via robotics) with in situ crew oversight.

An example of a large space structure that would benefit from this type of operation is the mission stack for a crewed deep space mission, such as that to a NEA. While not necessarily astrodynamically optimal for reaching a NEA, individual elements (that would require multiple launches for delivery) could be launched and delivered via a low-thrust cargo delivery method to the E-M L1/L2 facility, where they would be captured and progressively assembled into the full stack of mission elements. Crew and robotic support could then perform end-to-end test and checkout of the entire mission stack at the L1/L2 facility. Then the integrated and certified stack could be moved (again, by low-thrust cargo delivery) to a rendezvous point (e.g., High Earth Orbit) where, upon delivery, the NEA mission crew could be launched directly to the rendezvous point, dock, transfer to the mission stack, and depart for the deep space destination.

Other large space structures include a multi-element habitat to be deployed to GEO, for example, to be visited regularly by crews conducting servicing missions. Or a fuel depot that would eventually be deployed to a location in cis-lunar space to be visited by in-space propulsion elements for refueling.

Large science structures could also benefit from this capability. An observatory could be assembled at E-M L1/L2 from multiple large elements and, when assembly is complete, be deployed to its observation location, such as Sun-Earth L2. A large-scale radio telescope could be constructed, perhaps on the lunar farside surface or in LLO, with oversight of a crew based at the L1/L2 facility and a robotic "construction crew." Free-flying large instrument platforms could be assembled and checked out at the L1/L2 facility, then deployed as co-orbiting free flyers or for solar system explorers.

4. *Conduct lunar surface operations, both in support of exploration and for lunar & planetary science*

One of the benefits of the E-M L1/L2 location is that it provides "equal energy access" to the entire lunar surface; that is, no complex maneuvers (e.g., plane changes) are required to access lunar surface locations. (However, it is recognized that the time of flight from E-M L1/L2 to the lunar surface is longer than that from LLO; for example, it requires ~1 ½ days' travel time from a libration point to the lunar surface via minimum-energy transit). Also, dynamically, the entire lunar surface is accessible from the libration points, which is not the case from LLO.

An L1/L2 facility could support a number of lunar-focused activities. Instrument packages and/or lunar robotics/rovers could be deployed from the facility to LLO or to the lunar surface. Once on the surface, rovers could be operated from the facility because of the very low latencies in communications afforded by the facility's position. This would be particularly relevant with regard to robotically collecting samples from the lunar farside and then delivering them to the L1/L2 facility for eventual return to earth with the crew. In addition, crews at the L1/L2 facility could oversee robotic construction of a radio observatory on the lunar farside or the construction of a distributed lunar geophysics

network. Crew could also oversee the delivery, deployment, and operation of a prototype In-Situ Resource Utilization (ISRU) facility on the lunar surface, as well as, perhaps, construction in support of a possible human lunar return, if this exploration path were pursued.

A libration point facility could also serve as a "way station" for assets on the way to LLO or to the lunar surface, launched from earth on a low-thrust trajectory. Elements, such as a surface communications system, supplies cache, or fuel depot, could be aggregated over time and then deployed from the L1/L2 facility under a controlled sequential deployment. An L1/L2 facility could also serve as a "lunar safe haven" in the event of an abort from the lunar surface, if future missions return humans to the moon.

5. *Serve as a deep space node for international education and public outreach and media*

An E-M L1/L2 facility could have strategically placed internal and external cameras providing live web streaming essentially 365/24/7. Children in classrooms on earth could reposition cameras for earth and deep space views, they could interact with the facility robots, and they could control lunar surface rovers (with cameras) through the facility communications system. It is assumed that the facility would be created through international partnerships and, once emplaced in deep space, it could support global educational programs in a number of ways. Live streams from deep space could be provided daily to the international media.

Additionally, the facility -- when crewed by humans or by robots -- could share space exploration with people on earth, providing a way to include the global community (and stakeholders) in the experience. In this way, the E-M L1/L2 facility would serve as a "foothold" in deep space and a stepping stone to human exploration, allowing all to share in humanity's first steps off-earth into deep space.

6. *Serve as an initial node in a Human Space Exploration communications and navigation infrastructure*

An E-M L1/L2 facility could serve as a communications / navigation relay that could interact with the existing space communications system and could grow, as needed, to support future deep space mission. It could create or extend the planned communications / navigation / tracking network for deep space to support future human exploration missions.

Such an asset would, in particular, provide lunar farside communications access. The potential interference with a lunar farside "radio quiet zone" would need to be addressed.

7. *Serve as a sample return receiving facility*

An E-ML1/L2 facility could serve as a point to receive samples returned from a number of destinations, such as the moon, NEAs, and Phobos/Deimos. Given downmass return restrictions, larger sample amounts could be aggregated, packaged, and held at the cis-lunar facility for an "opportunistic" return to earth with the crew or via an automated return system. Under some circumstances, consideration may be given to providing some basic sample analysis capability on the facility to enable high-grading of returned samples. Planetary protection considerations would have to be addressed on a case-by-case basis and would depend largely on the planetary protection category of the samples in question. For example, certain samples might have planetary protection requirements that could not be met by the receiving facility.

8. *Serve as a "hub" for space-based servicing*

Observatories based in Sun-Earth space, particularly those at the Sun-Earth L2 Lagrange point (e.g., James Webb Space Telescope), could be moved to the E-M L1/L2 location, where they could be serviced and upgraded by robotic systems and crew, then re-deployed back to their primary viewing location in Sun-Earth space. Crew and robotic systems could service large space structures, such as fuel depots. In addition, robotic servicing systems could be based at an E-M L1/L2 facility, to be deployed to other locations (e.g., GEO) to service, upgrade, and extend the operational lifetimes of existing systems. If required, the E-M L1/L2 facility could be temporarily moved to another location in deep space (e.g., HEO) to rendezvous with an asset for the purpose of servicing or upgrading.

9. *Serve as a transportation node (e.g., docking port) or staging location for commercial and international vehicles and services*

It is noted that the E-M L1/L2 locations are not likely to become "universal" departure points to other deep space and solar system locations. However, a facility in the L1/L2 location could serve as a node for spacecraft to other locations, if deemed a reasonable departure point for the particular mission. Robotic servicers could be based at the facility or nearby and their operation could be overseen by crew based at the facility.

Robotic spacecraft on the "interplanetary superhighway" often transit through E-M Lagrange points. Crew or robotic systems at the L1/L2 facility could check out and/or service spacecraft prior to deployment to their target destination. Multiple spacecraft elements could be launched separately to the facility using low-thrust propulsion systems, then aggregated and integrated at the facility prior to deployment on their primary mission.

It is not always required that human crew be present for these activities – robotic systems could operate autonomously, to some degree, or operations could be controlled from a remote site. The L1/L2 facility could also provide ports for docking international and commercial space-based vehicles performing a number of services in near-earth deep space.

Summary of an E-M L1/L2 Facility DRM

Development of a DRM addressing a possible exploration facility emplaced at E-M L1 or L2 (or both) has recently begun and was briefly described. Characteristics of operational interest at this deep space location were examined and a set of assumptions regarding such a mission was defined. A basic transportation architecture analysis was performed, addressing delivery of the facility to its deep space location and delivery and returning crew from the facility. Some concepts for an E-M L1/L2 facility were created and one such facility concept was briefly described. An analysis of potential crew and robotic activities at the facility identified eight possible domains, from conducting human space exploration technology demonstrations and capabilities development, to performing science, serving as an international node for education, building large space structures, and performing space-based asset servicing. It is planned that analysis of an E-M L1/L2 facility will continue.

V. RELATIONSHIP BETWEEN THE HAT CIS-LUNAR ANALYSES AND THE INTERNATIONAL SPACE EXPLORATION COORDINATION GROUP (ISECG) CONCEPTS

The 14 national space agencies participating in the International Space Exploration Coordination Group (ISECG) have developed and published a set of guiding principles that articulates their vision for cooperative and coordinated human and robotic exploration of space. The ISECG released the first version of the *Global Exploration Roadmap* (GER) in September 2011 (see Figure 12). In this document, a common long-range exploration strategy was introduced.

The path begins with a near-term focus that includes LEO missions and utilization of the ISS in preparation for future human exploration missions. Following from this, two paths or "scenarios" were defined that describe a sequence of possible missions through LEO, the moon, cis-lunar space and NEAs, perhaps leading eventually to Mars.

The two scenarios are:

1) *"Asteroid Next" Scenario:* The focus of this scenario is human exploration of NEAs as the next destination. It includes LEO missions, ISS utilization, crewed flights to an Exploration Test Module (ETM) in cis-lunar space, crewed visits to a Deep Space Habitat (DSH), robotic precursor visits to NEAs, followed by human missions to NEAs, then future human & robotic exploration missions, perhaps to Mars.
2) *"Moon Next" Scenario:* The focus of this scenario is human exploration of the moon as the next exploration destination. It includes LEO missions, ISS utilization, crewed flights to an Exploration Test Module (ETM) in cis-lunar space, Human Lunar Return (HLR), crewed visits to a DSH in cis-lunar space, followed by human missions to NEAs, then future human & robotic exploration missions, perhaps to Mars.

In addition, the ISECG enunciated a set of eight common goals and objectives to organize and focus national agencies' efforts in supporting exploration. These ISECG common goals are:

- Search for Life
- Extend Human Presence
- Develop Exploration Technologies and Capabilities
- Perform Science to Support Human Exploration
- Stimulate Economic Expansion
- Perform Space, Earth, and Applied Science
- Engage the Public in Exploration
- Enhance Earth Safety

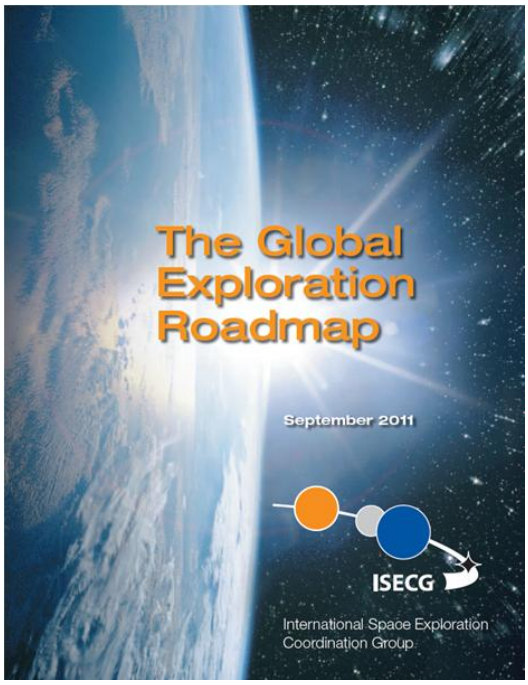

Figure 12. The International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap (GER) (September 2011).

There is a great deal of commonality between the HAT Cis-Lunar Destination Team activities and those of the ISECG-stated goals and objectives within the GER. In both the Asteroid-First and Moon-First scenarios, there is a DSH in cis-lunar space that serves to demonstrate capabilities and technologies required for future human exploration missions. In the Asteroid First scenario, in the proposed mission sequence, the DSH is identified prior to fielding the human mission to a NEA. In the Moon Next scenario, there are international and commercial opportunities for cis-lunar missions identified.

The LEO and GEO asset servicing DRMs described above provide an input into the near-term / near-Earth missions identified in the GER. And the ongoing E-M L1/L2 facility analyses can be applied directly to the DSH activities identified in the GER Scenarios. In particular, the domains of activities that could be conducted on an E-M L1/L2 facility identified within the HAT analysis may be applied directly to the ISECG common goals.

VI. FORWARD WORK

For the near future, the HAT Cis-Lunar Destination Team will continue to perform analyses in support of a conceptual E-M L1/L2 facility to enable future human and robotic space exploration. In particular, plans are to:

- Continue to analyze domains of activities that could be carried out within an E-M L1/L2 facility by crew and by robots, including the definition of potential investigations, payloads, instruments, hardware, mass/power/volume requirements, etc.
- Using the identified activities domains, develop a draft Concept of Operations for operating an E-M L1/L2 crew-tended facility
- Evaluate payload accommodations requirements
- Evaluate crew habitation requirements with the space habitation community
- Develop concepts for an E-M L1/L2 facility utilizing NASA and International Partner elements
- Evaluate how E-M L1/L2 facility missions fit within an overall long-range strategy for human space exploration, with particular focus on feed-forward from cis-lunar missions to potential future missions, such as to NEAs, HLR, and Mars
- Identify how cis-lunar missions can close Strategic Knowledge Gaps for other, future, destinations
- Continue to evaluate transportation architecture options for cis-lunar space missions
- Explore how to share information and integrate the cis-lunar mission analyses with the wider global exploration community

- Evaluate potential commercial aspects of fielding cis-lunar space missions

VII. SUMMARY & CONCLUSIONS

The HAT Cis-Lunar Destination Team was tasked with performing a number of analyses to understand the types of possible future crewed and robotic missions that could be conducted in cis-lunar space. The team developed a cis-lunar mission tree using four primary parameters -- duration, pre-deployed assets, mission type and location within cis-lunar space -- to enumerate the pool of potential cis-lunar missions. From this pool, a representative set of missions was down-selected and subjected to further, detailed analysis.

LEO and GEO asset servicing DRMs were developed, including such information products as:

- operational characteristics of these missions
- crew and robotic activities performed
- technology requirements enabling such missions
- exploration capabilities that could be developed, and
- how such missions would fit within an overall broad human space exploration strategy.

We have reported on some of those analyses in this paper.

In addition, a new DRM is presently in development, focused on understanding how a crew-tended facility emplaced at the Earth-Moon L1 or L2 Lagrange points could be used to enable future human exploration to further deep space destinations. Characteristics of operational interest at the L1 and L2 points and assumptions regarding such a mission were identified. Transportation analyses using the in-development SLS and MPCV, for delivering the facility as cargo and for transporting the crew to the facility and returning them to earth, were performed and reported herein. Further, concepts for an L1/L2 facility were developed and one such concept was discussed in this report. Domains of possible activities to be conducted at the facility were identified and examined, with representative specific investigations identified.

The relationship between the present NASA HAT work and the ISECG-created GER scenarios was discussed and future work planned to be performed by the HAT Cis-Lunar Destination Team in support of further definition of an E-M L1/L2 facility was described.

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