NASA Human Spaceflight Architecture Team
Cis-Lunar Analysis

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ABSTRACT

The Cis-Lunar Destination Team of NASA's Human Spaceflight Architecture Team (HAT) has been performing analyses of a number of cis-lunar locations to inform architecture development, transportation and destination elements definition, and operations. The cis-lunar domain is defined as that area of deep space under the gravitation influence of the earth-moon system, including a set of orbital locations (low earth orbit [LEO], geosynchronous earth orbit [GEO], highly elliptical orbits [HEO]); earth-moon libration or "Lagrange" points (EML1 through EML5, and in particular, EML1 and EML2), and low lunar orbit (LLO). We developed a set of cis-lunar mission concepts defined by mission duration, pre-deployment, type of mission, and location, to develop mission concepts and the associated activities, capabilities, and architecture implications. To date, we have produced two destination operations concepts based on present human space exploration architectural considerations. We have recently begun defining mission activities that could be conducted within an EM L1 or EM L2 facility. This paper will review details of this work.

1. INTRODUCTION

NASA's Human Spaceflight Architecture Team (HAT) has defined four destination teams: (1) Cis-Lunar (also termed the Servicing and Deployment Working Group or SDWG), (2) Lunar, (3) Near-Earth Asteroids, and (4) Mars. For the purposes of these analyses, the cis-lunar domain is defined as that area of deep space under the gravitation influence of the earth-moon system, including a set of orbital locations (low earth orbit [LEO], geosynchronous earth orbit [GEO], highly elliptical orbits [HEO]); earth-moon libration or "Lagrange" points (EML1 through EML5, and in particular, EML1 and EML2), and low lunar orbit (LLO).

The HAT Destination Teams are chartered to develop destination activities and operations concepts -- or "destination design reference missions" -- for all potential destinations of human space exploration. The destination activities and operational concepts are intended to inform (a) architecture development, (b) transportation and destination element design, including new elements, (c) more detailed operations concepts and design reference missions, and (d) campaigns, which combine multiple missions and destinations into near- and long-term sequences. In this paper we will describe work performed to date by the HAT Cis-Lunar Destination Team, with a primary focus on a Cis-lunar Mission Tree, Operations Concepts, and Issues and Implications as they are understood in the present programmatic and technical context in which HAT operates.

2. CIS-LUNAR MISSION TREE

A mission possibility space can often be a large and complex theoretical space. Cis-lunar space offers numerous locations and types of missions and the mission space has also been relatively unexplored (e.g., compared to human missions to the moon or Mars). We developed a mission tree to enumerate the possibilities and serve much like a decision tree or a trade tree. The mission tree helped us understand the plausible mission possibilities and forced us to think carefully about key mission drivers. In defining this mission space, our primary mission drivers were: (a) mission duration, (b) whether assets were pre-deployed or not, (c) mission type, and (d) location within cis-lunar space.

The "duration" parameter was based on the present projections for the Orion Multi-Purpose Crew Vehicle (MPCV) habitation period of approximately 21 days for a crew of four, beyond which additional habitation resources would be needed. We contemplated additional time period distinctions; however, given the high-level nature of this mission tree and our belief that the 21-day MPCV habitation distinction was sufficient to capture key mission profiles, we used the simple binary approach of either (a) less than or equal to 21 days (where the MPCV would serve as the crew habitat, providing the necessary pressurized volume) or (b) greater than 21 days (where additional pressurized volume would be required). The second parameter, "pre-deployment," referred to whether or not assets would be pre-deployed to the mission location prior to crew arrival and would, therefore, be available for crew use during the mission. This was an important distinction, because the MPCV has limited cargo upmass carrying capability with a crew of four, especially to the cis-lunar locations under consideration, thereby significantly limiting the assets in support of the mission. The third parameter, "mission type," characterized missions as (1) servicing missions, (2) deployment/assembly missions, and (3) human exploration research and technology development missions, where science was considered to be part of both deployment/assembly and exploration research and development. Last, the fourth critical mission space parameter was the specific location within cis-lunar space, which could be significantly affected by the capabilities of the transportation elements and delta v requirements; for the purposes of this cis-lunar mission space analysis, these locations included LEO (including the International Space Station (ISS)), GEO, HEO, EML1/L2 and LLO.

One of the more important considerations (as noted in the tree in Figure 1) is whether mission assets are pre-deployed on a separate launch in advance of crew arrival at the destination. Pre-deployment is important for missions less than 21 days as well as missions greater than 21 days, but it is more important for the latter. For example, assuming a 105 metric ton (mt) Space Launch System (SLS) capability to LEO, for missions less than 21 days that do not have pre-deployed assets (i.e., all mission support assets are launched with the crew in a single launch), it is possible to bring extra payload (beyond the MPCV and Cryogenic Propulsion Stage [CPS]) ranging from three to 10 mt, depending on the destination (as shown in Figure 1); this holds for cis-lunar destinations other than GEO, for which the present architecture does not close (that is, the "extra payload possible" is effectively 0 mt). For missions greater than 21 days, additional habitation resources are required, so any extra payload mass would likely be taken by those additional habitation resources, making any extra payload beyond that effectively 0 mt. However, if assets are pre-deployed with an additional launch, much more mission-support payload can be delivered to the destination.

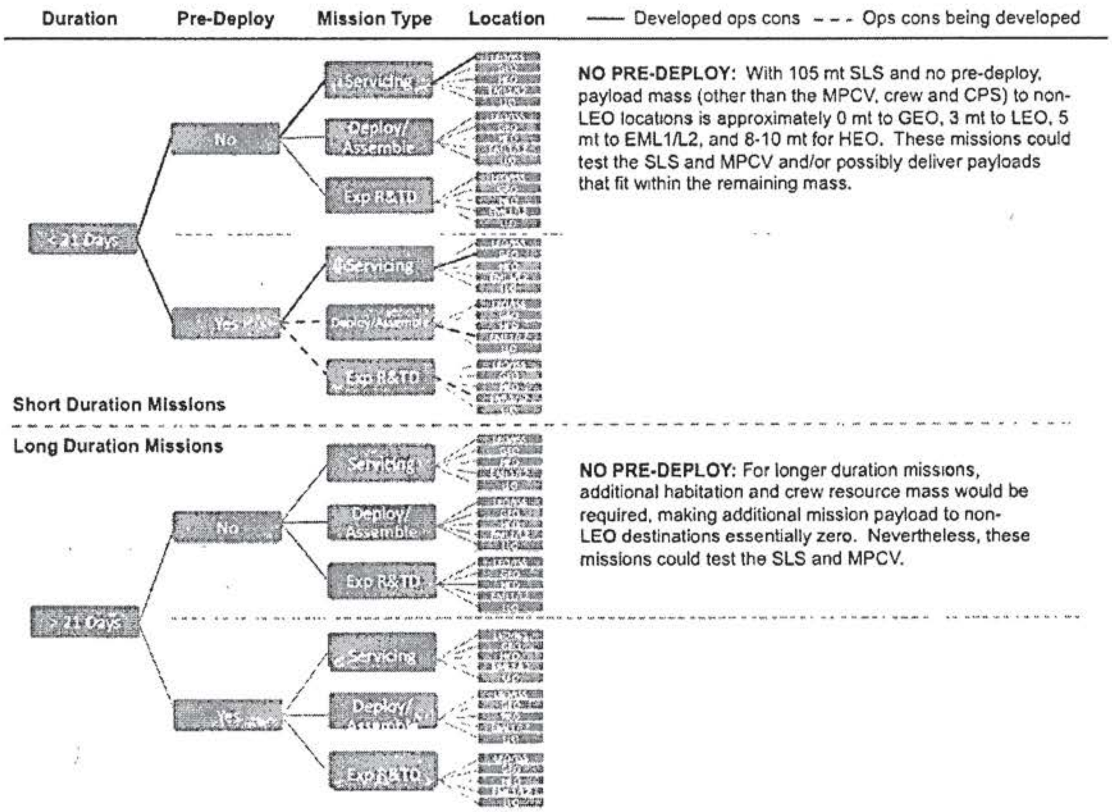

Figure 1. Cis-lunar mission tree with duration, payload pre-deployment, mission type, and cis-lunar location parameters.

3. OPERATIONS CONCEPTS

One of the primary activities of the HAT destinations teams is to produce notional missions or operations concepts that emphasize activities at the destination. The two operations concepts we have developed to date have been (1) a generic asset servicing mission conducted in LEO and (2) a generic asset servicing mission conducted in GEO. We have begun work on a third operations concept, a mission to the EML1/L2 system (where the transit between EML1 an EML2 can be done with low delta v).

The operations concepts performed to date provide an operations flow of activities at the destination to the level of day-to-day activities, without specific details regarding how activities would be executed (i.e., a level of detail often associated with "conops" or a more tactical level of detail). These operations concepts can also be thought of as notional missions and, within HAT, have been referred to as "Destination Design Reference Missions (DRMs)," (as opposed to Transportation DRMs), although at present they do not have the level of detail and rigor often associated with DRMs

The operations concepts consist of essentially three representations: (1) a brief "bulletized" description (including such information as a mission description, elements used, transit operations, stack reconfiguration operations, rendezvous operations, crew operations, and earth-return operations), (2) a high-level day-by-day crew activities timeline, and (3) a "streetview" (a graphical representation of the ops con activities, focused primarily on what happens at the destination).

3.1 LEO Servicing Mission

To allow for more space to discuss the GEO and EML1/L2 missions, we only briefly describe the LEO servicing mission using text from our mission description.

- Assumptions: The satellite is cooperative but it did not reach the desired orbit and the solar arrays failed to fully deploy. An upgraded satellite sensor package needs to be installed, but the satellite was not designed for sensor replacement.
- Elements: The elements included are the MPCV, a Cargo Hauler, and Robotics and EVA Module (REM) which acts as an airlock and carries EVA tools, a Sensor Package upgrade and Kick Stage (or Cargo Hauler propulsive stage).
- Satellite Rendezvous: The MPCV is the active vehicle for all rendezvous maneuvers. As the reconfigured stack approaches the target satellite, the crew uses REM robotic arms to capture the satellite. The servicing activities require that the target satellite is held in a stable locked position.
- Crew Operations: The REM suit lock provides EVA access and the MPCV is operated at a pressure that provides short pre-breathe times to optimize EVA time. The EVAs are performed with two crew, with one crewmember supporting the EVA team in the MPCV at all times. Over the next three days, three EVA teams prepare the satellite for servicing, deploy stuck solar arrays, and replace the failed sensor package. On day six, the satellite is powered-up and checked out, and the orbit is corrected. On day seven, the satellite is released.
- Earth Return Operations: After releasing the satellite, the MPCV backs away.. At a safe distance from the satellite. The MPCV performs the de-orbit burn to initiate re-entry. The Cargo Hauler may remain on orbit for future use (it can be move to another location for reuse/repurposing), or it can de-orbit with the Kick Stage

3.2 GEO Servicing Mission

The GEO Servicing Mission Operations Concept: An 11-day mission to service two satellites in geosynchronous orbit. *Satellite #1* has a mechanical failure of the antenna gimbal and requires control gyro replacement and optics package upgrade, which was originally designed to allow crew EVA access. *Satellite #2* has reached the operational end-of-life with no propellant remaining. It is currently uncontrolled but still functioning and requires refueling to extend operational life on GEO.

Elements included in two launch stacks: The first launch pre-deploys the Cargo Hauler, which carries (a) the REM (including EVA tools and satellite-capture contingency tools, such as robotic arms), (b) components to be upgraded and replaced, and (c) a "Robotic Servicer." There is a Kick Stage (or Cargo Hauler propulsive stage) and also an Upper Stage that places the Cargo Hauler on a GEO Transfer Orbit (GTO). The second launch includes the MPCV with crew and the CPS.

Satellite Rendezvous: With the MPCV as the active vehicle, the stack approaches *Satellite #1* and the crew uses REM robotic arms to capture the satellite which is then held in a stable, locked position by TBD mechanism (e.g., with robotic arms with adequate stiffness or docking mechanism on REM or Cargo Hauler). A docking mechanism may need to be custom made for the satellite

Crew Operations: The REM suit lock provides EVA access and the MPCV is operated at a pressure that provides short pre-breathe times to optimize EVA time. The EVAs are performed by two crew, with one crewmember observing and supporting EVA in the MPCV at all times. As with the LEO mission, there are three EVA teams. In Figure 2 is shown part of the mission as an hourly crew activity timeline and Figure 3 shows a "streeview" chart that is intended to graphically represent the overall mission on one page.

Earth Return Operations: After releasing the satellite, the MPCV backs away, and when it is at a safe distance from the satellite (to not contaminate / "plume" the satellite and sensors), the MPCV performs the de-orbit burn. Following nominal procedures, the Service Module (SM) separates from the MPCV and the capsule re-enters for crew earth return. The Cargo Hauler may remain on orbit for future use (it can be move to another location for reuse/repurposing), or it can de-orbit with Kick Stage

	MET	0	1	2	3	4	5	6	7
DAY 7	Crew 1	EVA to upgrade ORU optics package with Crew 3. Use UV light to neutralize charging, close satellite and prep for operation.						Power up satellite and full systems test	
	Crew 2	Monitoring EVA operations and actively operating robotic arms/other capabilities.							
	Crew 3	EVA to upgrade ORU optics package with Crew 1. Use UV light to neutralize charging, close satellite and prep for operation.							

	MET	0	1	2	3	4	5	6	7
DAY 8	Crew 1								
	Crew 2	Using MPCV as active element, place the satellite into the correct orbit (small modification, RCS only)				Release satellite		With MPCV as active element perform first burn to transition to second satellite	
	Crew 3								

	MET	0	1	2	3	4	5	6	7
DAY 9	Crew 1								
	Crew 2	Finish transition to second satellite and perform burn to rendezvous in second satellite vicinity				Tele-operate robotic servicer to capture and safe satellite			
	Crew 3								

Figure 2. GEO Servicing Mission Hourly Timeline for Days 7-9.

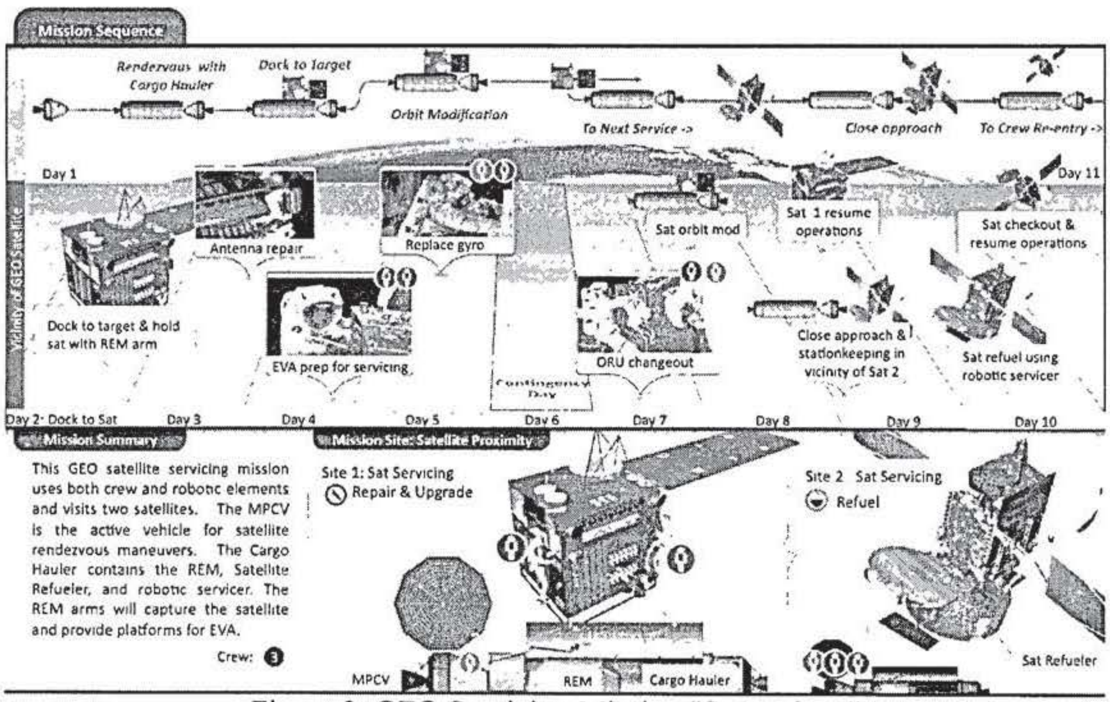

Figure 3. GEO Servicing Mission "Streetview."

3.3 EML1/L2 Mission

Our team has just begun working on details of an Earth-Moon Lagrange Point 1 (EML1) and Lagrange Point 2 (EML2) notional mission, showing potential activities that could be conducted at such a facility by crew when present and when the facility is uncrewed. EML1/L2 provide a deep space location beyond earth orbit and the van Allen radiation belts that can easily serve as an environment for testing, proving, and certifying technologies and capabilities required for human exploration beyond earth. There are clear differences between the two Earth-Moon Lagrange Points, the most obvious being that EML2 is located on the far side of the moon (which could possibly interfere with a "radio quiet zone"); however, the two locations can be thought of as a system, as one potential destination, since transit between the two can be done with relatively low delta-v. EML1/L2 missions have the advantage of not requiring landing on the lunar surface and, therefore, not requiring operations within the lunar "gravity well" and no requirements to deal with lunar surface environmental conditions (e.g., dust).

The initial EM L1/L2 missions consist of two launches, one to launch and position the "deep space facility" (DSF) and a second to bring the crew; given the location, both missions require a Cryogenic Propulsion Stage (CPS) to reach EML1/L2. Once the crew arrives in the MPCV, the MPCV docks with the DSF and system check-out begins, followed by activities in the categories noted below, such as technology demonstrations, human research, tele-operation of lunar surface assets, etc.

We've established a high-level preliminary "streetview" for these missions (as shown in Figure 4), as well as a list of potential activities for EML1/L2 grouped into the following categories:

- Develop and certify human spaceflight operational capabilities in deep space
- Serve as an assembly point for large space structures
- Conduct lunar support operations (e.g., via robotic transport to/from the surface, teleoperation/telepresence on the lunar far side, etc.)
- Serve as an off-Earth sample return quarantine and collection facility
- Serve as the initial node in an HSE communications and navigation infrastructure
- Serve as a deep space node for international education and public outreach
- Serve as a platform for science from the unique L1 / L2 location
- Serve as a "hub" for space-based servicing
- Serve as a transportation node / "staging location"
- Provide a platform and services for commercial vehicles and services (e.g., docking port)

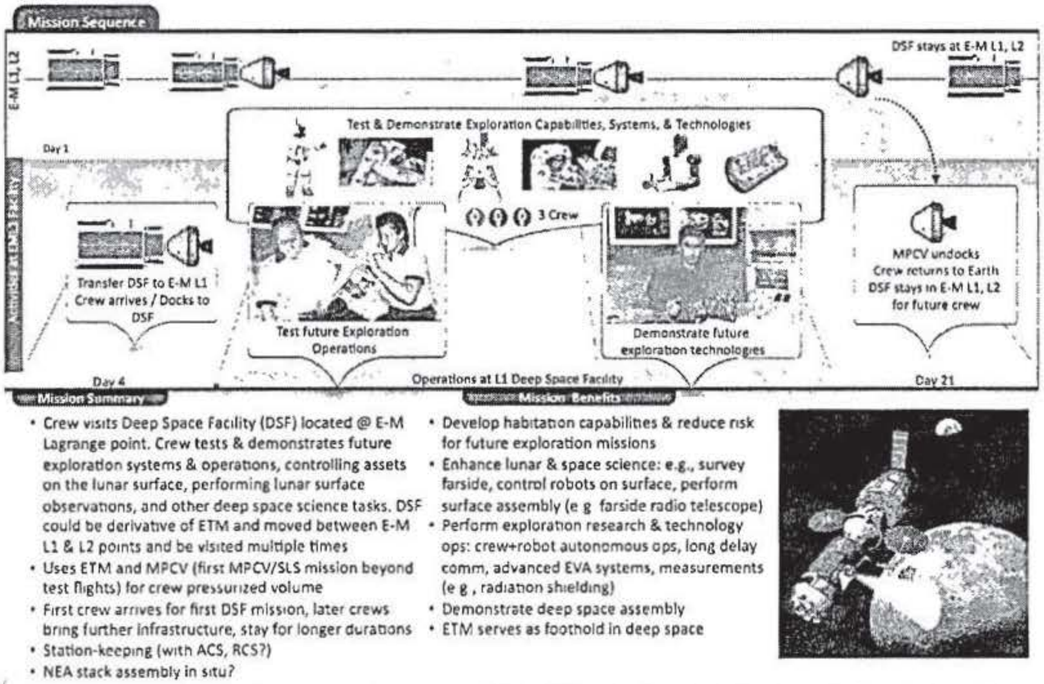

Figure 4. Preliminary Earth-Moon L1 / L2 Notional Mission "Streetview."

4. ISSUES AND IMPLICATIONS

4.1 Transportation Architecture and Elements

Based on operations concepts we've developed so far, we anticipate that future cis-lunar missions will benefit from and directly require the following general capabilities and activities:

- Capturing "non-cooperative" satellites
- Precision approach and autonomous rendezvous and docking
- Autonomous vehicle station-keeping
- In-space cryogenic fluid transfer / refueling
- Next generation crew EVA systems
- Human and robot autonomous operations
- Advanced human and robot interaction
- Next-generation space robotics and robotic servicing
- Cis-lunar habitation
- Assembly of large space structures beyond LEO
- Some level of crew on-orbit autonomy

The MPCV and spacesuits are not presently being designed to operate in the GEO-unique charging environment. The current EVA System significantly limits the duration of crew operations in the GEO-unique environment. Presently, the architecture cannot return the crew from GEO. We expect a requirement for "hauling" and delivering cargo to specific cis-lunar locations for crew use during the missions. Therefore, the cis-lunar team has begun identifying the functionality required of such a "cargo hauler" and we have developed initial concepts for this element. In addition, the cis-lunar missions have identified a clear need for significant advancements in robotics and crew + robotics interaction and we have begun evaluating robotics capabilities and functionality required within the REM.

4.2 Global Exploration Roadmap

The first iteration of the Global Exploration Roadmap (GER) was released in September, 2011 as a product of the International Space Exploration Coordination Group (ISECG). It "reflects the international effort to define feasible and sustainable exploration pathways to the Moon, near-Earth asteroids, and Mars." The GER contains many links to mission activities being explored by the HAT Cis-Lunar Destination Team. Of significant interest for the cis-lunar domain is the "Asteroid first" scenario which calls for a Deep Space Habitat (DSH) in cis-lunar space prior to the first human asteroid mission, to demonstrate capabilities for traveling, living, and working in deep space. A potential international issue that we are investigating that is not explicitly addressed in the GER is the question of how to avoid harmful interference of the "radio quiet zone" on the lunar far side. It is also noteworthy that in the "Moon Next" scenario, "opportunities for commercial and international cis-lunar missions" are identified.

4.3 International Robotics & Servicing Working Group (RSWG)

The RSWG is an international group (managed by the Canadian Space Agency with representation from participating agencies) that focuses on identifying the requirements for advanced robotic systems to support future human space exploration missions. The cis-lunar destination team has been working with the RSWG to identify and rank/value robotic support capabilities within cis-lunar missions, to aid in identifying and guiding robotic technology development.

4.3 Summary/Lessons

- *Destination Integration / Campaigns*: The cis-lunar domain may be where the first set of future human space exploration missions occurs and it is important that they feed forward to the other HSF destinations as much as possible. More generally, this suggests the usefulness of "multi-destination" campaigns that integrate different destinations such that near and long-term objectives are incrementally addressed.
- *Strategic Knowledge Gaps*: Cis-lunar mission concepts of operations are helping to address Strategic Knowledge Gaps for other destinations, such as long duration mission challenges in a deep space environment.
- *Transportation*: For a 105 mt SLS, very large payloads can be delivered to LEO, thereby allowing single launch missions for servicing, deployment of assets, and technology development. Non-LEO crewed missions have very limited additional payload capability with a 105 mt SLS.
- *Pre-deploying assets:* Pre-deploying assets in support of non-LEO cis-lunar missions enables more robust missions.

- *Geosynchronous Earth Orbit missions:* Crewed missions within the GEO belt create significant environmental challenges that would require design changes to several elements and systems, including MPCV and suits.
- *Global Exploration Roadmap*: The GER, with additional NASA strategic goals and objectives, can serve as a useful frame of reference for developing valuable destination activities.
- *EML1/L2 Deep Space Habitat/Facility*: An EM L1 / L2 facility has the potential for a wide range of uses in support of furthering human space exploration goals, such as developing and certifying human spaceflight operational capabilities in deep space, supporting lunar surface operations, performing science, and serving as a sample return collection, analysis and quarantine facility. Lagrange points offer relatively stable locations that avoid gravity wells.
- *Commercial*: Cis-lunar missions can benefit from commercial contributions as well as potentially enable commercial interests, such as fuel depots, space communications, and tourism.

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