Response of The MITRE Corporation to the OSTP RFI on Cislunar Science and Technology

July 20, 2022

For additional information about this response, please contact:
Duane Blackburn
Center for Data-Driven Policy
The MITRE Corporation
7596 Colshire Drive
McLean, VA 22102-7539

policy@mitre.org
(434) 964-5023

<<This page is intentionally blank.>>

About MITRE

MITRE is a not-for-profit company that works in the public interest to tackle difficult problems that challenge the safety, stability, security, and well-being of our nation. We operate multiple federally funded research and development centers (FFRDCs); participate in public-private partnerships across national security and civilian agency missions; and maintain an independent technology research program in areas such as artificial intelligence, intuitive data science, quantum information science, health informatics, policy and economic expertise, trustworthy autonomy, cyber threat sharing, and cyber resilience. MITRE's 9,000-plus employees work in the public interest to solve problems for a safer world, with scientific integrity being fundamental to our existence. We are prohibited from lobbying, do not develop or sell products, have no owners or shareholders, and do not compete with industry. Our multidisciplinary teams (including engineers, scientists, data analysts, organizational change specialists, policy professionals, and more) are thus free to dig into problems from all angles, with no political or commercial pressures to influence our decision-making, technical findings, or policy recommendations.

Introduction

Cislunar space is at the forefront of current activities in the space domain, specifically amongst commercial companies. To enable application of R&D in cislunar space that will help advance a robust, cooperative, and sustainable ecosystem, it is important that the U.S. government maintain (if not enhance) its existing collaboration with the broader space community and ensure that coordination and collaborative decision making amongst agencies continues to be fostered. In addition, the U.S. and like-minded nations must establish sufficient guidelines and regulations in scope of building upon the Artemis Accords. The need to develop standards and guidelines for use of the Moon's resources for sustainment needs to be addressed before implementation of an ecosystem begins.

Answering this RFI's open-ended questions required first developing some assumptions that provide a clearer vision of the proposed future state and working environment:

- Throughout this document, it is assumed that cislunar space is defined as the space from geostationary orbit out to 500,000 km past the Moon (therefore encompassing the lunar surface).
- It is assumed that the Artemis Accords (or replacements) will be accepted as the source of best practices and responsible norms of behavior for the broader international community.
- Government-funded sustained human presence in the cislunar region will begin within 10 years (including lunar bases), and that there will be a level of commercial human presence when company business models justify the expenditures in human resources and capital.
- There will be a level of military use of cislunar space and lunar bases that could hamper or otherwise interfere with scientific and commercial exploration. The regulations

surrounding the use of cislunar space for military purposes will also have been addressed prior to establishing a sustained ecosystem in the cislunar environment.

Questions Posed in the RFI

1. What research and development should the U.S. government prioritize to help advance a robust, cooperative, and sustainable ecosystem in cislunar space in the next 10 years? And over the next 50 years?

The return to the Moon by the U.S. government has entered an unprecedented era, and landing on the Moon is no longer a NASA-only endeavor. Indeed, the involvement of commercial companies is not new and is expanding rapidly, while the international community is actively supporting the development of sustained human presence on the Moon. In the next 10 years, important milestones must be achieved to help advance a robust, cooperative, and sustainable ecosystem in cislunar space.

There will be increased traffic to/from and around the Moon, and there is currently no framework in place to manage such traffic as is done on Earth. NASA's mission control will not be scalable to accommodate the anticipated quantity of human and robotic spacecraft in the cislunar region. There already has been a close approach between India's Chandrayaan-2 orbiter and NASA's Lunar Reconnaissance Orbiter[1] that resulted in India performing a collision avoidance maneuver. Therefore, Space Situational Awareness (SSA) and Space Traffic Coordination (STC) efforts, currently limited to Earth orbits, should be expanded to cislunar space, which would be a step towards avoiding a similar congestion situation that is experienced in Low Earth Orbit and Geostationary Orbit. This will require development of adequate in-space and/or lunar surface sensors, efforts which have already begun but need to be prioritized and further developed.

There is also an urgent need for communication and Positioning, Navigation and Timing (PNT) in the cislunar region. NASA's LunaNet architecture, which is bicentric (Earth and Moon), is a necessary endeavor, but requires further research and development to be deployable. Moreover, an interim system might be required as the first of the Artemis missions, Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), has already launched[2], and more experiments are planned in the near future. Current government initiatives[3,4] could be further developed and leveraged to fill this gap until LunaNet can be implemented.

---

[1] Chandrayaan-2 Orbiter (CH2O) performs an evasive manoeuvre to mitigate a critically close approach with LRO. 2021. Indian Space Research Organization, https://www.isro.gov.in/update/15-nov-2021/chandrayaan-2-orbiter-ch2o-performs-evasive-manoeuvre-to-mitigate-critically. Last accessed July 18, 2022.

[2] CAPSTONE Launches to Test New Orbit for NASA's Artemis Moon Missions. 2022. National Aeronautics and Space Administration, https://www.nasa.gov/press-release/capstone-launches-to-test-new-orbit-for-nasa-s-artemis-moon-missions. Last accessed July 18, 2022.

[3] Cislunar Highway Patrol System (CHPS). 2022. Air Force Research Laboratory, https://afresearchlab.com/technology/cislunar-highway-patrol-system-chps/. Last accessed July 18, 2022.

[4] T. Hitchens. Space Force, AFRL To Demo Mobile Lunar Spy Sat. 2020. Breaking Defense, https://breakingdefense.com/2020/11/space-force-afrl-to-demo-mobile-lunar-spy-sat/. Last accessed July 18, 2022.

In addition, with NASA and its partners planning to build a lunar base and establish sustained human presence on the surface of the Moon, research is urgently needed to develop adequate equipment and health systems to ensure safety of personnel on base, to include the following:

- Development of new protective materials for spacesuits and spacecraft, designed to protect humans above the van Allen belts, is necessary as shielding from solar radiation must be provided. On Earth, humans are protected from deadly radiation (Galactic Cosmic Rays [GCR] and Solar Energetic Particles [SEP]) by the magnetosphere and the atmosphere. On the Moon, there is very little atmosphere, and even though the Earth's magnetosphere can reach that far in some locations, it does not seem to provide measurable protection at such a distance[5]. The reference for human exposure on Earth is 1 microSievert per year (µSv/yr), and the lunar surface gets as much as 1,369 µSv/yr[6, 7].
- Further research into protective materials for habitats, which is a prerequisite for sustained cislunar presence, is crucial. Regolith could provide some shielding, as well as thermal protection, although it was found that it would be more efficient when mixed with other materials, and thermal protection increases if the regolith is compressed[9]. Authors also cite lava tubes as an excellent structure to house humans, as it provides the best protection according to studies and radiation measurements (the value was found to be less than the reference value of 1 µSv/yr inside a lava tube[7, 8, 9]). Such research should be prioritized to enable meaningful advancement in protective infrastructure, which is a necessary step towards the implementation of a cislunar ecosystem.
- Dust mitigation is an important part of returning to the Moon: it is well known that lunar dust presents a hazard to astronauts. The fine grain (about 70 micrometers average grain size), electrically charged dust, can be a challenge for humans (e.g., reduced vision, difficulty breathing)[10]. Dust mitigation is of interest to NASA, as shown with the Break the Ice Lunar Challenge, where competitors were asked to excavate the icy regolith and address difficulties such as the development of technology that mitigates the hazards caused by dust, while ensuring sustainable and durable operations in orbit as well as at the surface[11]. Moreover, lunar dust can damage equipment due to its abrasive and adhesive properties[11].
- Development of space medicine and space health capabilities, including remote surgery, illness treatment/diagnosis, and emergency services, is another prerequisite for long-term presence.

---

[5] A. Case, et al. GCR access to the Moon as measured by the CRaTER instrument on LRO. 2010. Geophysical Research Letters, vol. 37, no. L19101.

[6] M. Naito, et al. Radiation Dose and its Protection in the Moon from Galactic Cosmic Rays and Solar Energetic Particles: at the Lunar Surface and in a Lava Tube. 2020. Journal of Radiological Protection, vol. 40, pp. 947-961

[7] S. Zhang, et al. First Measurements of the Radiation Dose on the Lunar Surface. 2020. Science Advances, vol. 6, no. 39.

[8] Y. Akisheva and Y. Gourinat. Utilisation of Moon Regolith for Radiation Protection and Thermal Insulation in Permanent Lunar Habitat. 2021. Applied Science, vol. 11, no. 3853.

[9] R. Miguel, et al. Mission Architectural Approach for a Short Duration Mission for a Lunar Geological Survey of the Lunar Lava Tubes and the Possibility of Helium-3 Extraction. 2021. ASCEND, Las Vegas, NV.

[10] T. Stubb, et al. Impact of dust on Lunar Exploration. 2005. Proc. "Dust in Planetary Systems", Kauai, Hawai.

[11] Break the Ice Lunar Challenge. 2021. NASA, https://breaktheicechallenge.com/wp-content/uploads/2021/01/Break-the-Ice-Challenge-Phase-1-Rules-Rev-B.pdf.

Another aspect of sustained human presence and traffic in the cislunar region is the environmental impact of such activities. From takeoff and landing to construction and mining, there needs to be research into the environmental impact of a lunar base, such as:

- Development of requirements and international standards, with a system in place to assess environmental impacts of cislunar and lunar activities. The U.S. government and like-minded countries should consider an international mechanism to require a written environmental impact statement submitted to the United Nation Office of Outer Space Affairs.
- Research and development to study the adaptation to the lunar environment of terrestrial eco-friendly mining techniques (to include extraction and processing), such as biomining[12]. For example, mining Rare Earth Elements (REEs), known to be present on the Moon[13], is associated with constraining environmental and health regulations[14]. It was indeed found that REE deposits often contain Thorium and Uranium in the ore or in the waste produced, which poses an environmental hazard. Chemicals associated with REE deposits or mining processes can also infiltrate the surrounding ecosystem, becoming a hazard to human health. The Bear Lodge Deposit in Wyoming illustrates this infiltration problem, with the content of arsenic in groundwater surrounding the mine slightly above the accepted standard of 10 parts per billion.

And finally, in the next 10 years, research and development to better enable interoperability is key to a successful presence in cislunar space, especially with the many actors currently initiating cislunar activities. Such commonality includes docking port, parts, and systems, and would ensure easy maintenance of equipment. For instance, companies are already developing gas stations in space that will require standardization to ensure that they are operational and sustainable. One such example of “gas station” is Orbit Fab’s Rapidly Attachable Fluid Transfer Interface (RAFTI™), to refuel on orbit[15], that relies on state information sharing for docking. Similar to commonality for cars that allow anyone to refuel anywhere, cislunar gas stations will need standardization, so that multiple commercial and government spacecraft can refuel at the Moon.

For longer-term needs (next 50 years), research and development for lunar surface transportation support systems, such as intelligent transportation system, should begin. There needs to be a minimum viable capability for a lunar “smart city”, which includes research on harsh environment and smart city work. For space health, research into a fulltime “space hospital” on the Moon or on a dedicated cislunar habitat will be necessary. Long term impact on human health of sustained presence on the Moon should also be investigated and fully understood. Such research has begun on the Space Station, with one astronaut staying a year while his identical

[12] The extraction of metal via the utilization of a bacteria.

[13] P. Hess and E. Parmentier. Thermal evolution of a thicker KREEP liquid layer. 2001. Journal of Geophysical Research, vol. 106, no. E11, pp. 28,028-28,032.

[14] B. V. Gosen, et al. Rare Earth Element Mineral Deposit in the United States. 2019. U.S. Geological Survey, https://pubs.usgs.gov/circ/1454/circ1454.pdf.

[15] Rapidly Attachable Fluid Transfer Interface. 2022. OrbitFab, https://www.orbitfab.com/products. Last accessed July 18, 2022.

twin brother remained on Earth to allow for comparison[16]. Not all findings could be extrapolated to cislunar space, however, and further research is necessary in this domain.

2. What key technical standards are most useful to develop in support of activities in cislunar space, and how could these standards enable and support a vibrant and sustainable cislunar ecosystem?

To support activities in cislunar space, the following standards are needed:

- Common interfaces as defined above: without standards and interoperability, maintenance of spacecraft and equipment will be extremely difficult and costly, which will not favor a sustainable cislunar ecosystem. In addition, lunar communications, monitoring, and navigation systems will require interoperability given the many stakeholders in cislunar space.
- Agreement on standards and best practices for cislunar SSA: adapt from Earth-based SSA and Global Space Traffic Coordination (GSTC). This requires a transition from a two-body system (Earth-Satellite) to a three-body system (Earth-Spacecraft-Moon).
- Standards for cislunar space traffic coordination, including returns into earth orbits, landing/takeoff at the Moon. Lessons learned and best practices can be leveraged from Air Traffic Management that oversees departures, flights, and arrivals of various commercial and government aircraft. This has proven to be effective in the National Airspace System as well as within oceanic airspace given effective coordination with other countries, and similar standards ought to be developed for cislunar space.
- Health standards for cislunar and lunar workers. Human presence in space is changing radically, and is no longer the exclusive domain of young, fit, and healthy astronauts. The permanent human presence in space will be more aligned with a diversity in age, health and skills we see on Earth. For example, there will be miners, construction and factory workers, technicians of many disciplines and full-time medical personnel. New standards must be developed to account for this major change in space workforce.
- Development of norms of responsible behavior for U.S. operators: the concept of a state safety program for U.S. commercial operations is needed.
- Standards for oversight of mission authorizations in cislunar (benefits of operator safety management systems for self-correcting actions)
- Accepted best practices and strict standards for forward and backward planetary protection. Earth must not be contaminated by cislunar space materials, and the Moon should not be contaminated by materials from Earth.
- Standards and best practices for all aspects of government and commercial nuclear power in cislunar space, including the lunar surface. Standards should address design of nuclear

[16] NASA Twins Study Confirms Preliminary Findings. 2018. National Aeronautics and Space Administration, https://www.nasa.gov/feature/nasa-twins-study-confirms-preliminary-findings. Last accessed July 18, 2022.

power sources, operation and maintenance of power sources, anomaly and accident procedures, and proper disposal of nuclear materials.

Adopting standards and best practices such as those listed above will ensure safe operations in cislunar space and provide a common framework for all nations and commercial ventures.