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CISLUNAR STEWARDSHIP: PLANNING FOR SUSTAINABILITY AND INTERNATIONAL COOPERATION

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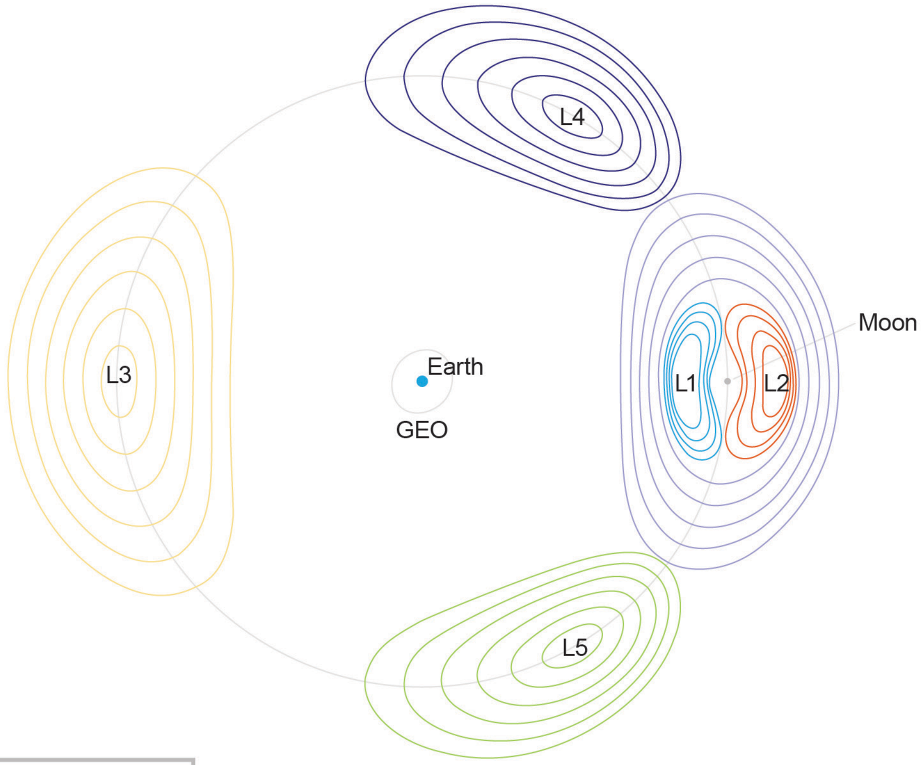
Summary

Space operations are expanding beyond the geosynchronous Earth orbit (GEO) to other parts of the Earth-moon system. As this trend continues, space operators will find preferred orbits and seek to leverage points of relative gravitational stability. These locations can enable lower-energy transits or provide useful parking places for various types of facilities (e.g., fueling depots, storage sites, and way stations with access to the lunar poles). As cislunar activity grows, a policy framework should be developed to promote the sustainability of operations in these locations. Motivated by lessons learned in space operations thus far, this paper discusses the need to extend best practices for debris mitigation (preventing its accumulation) to cislunar space lest we create a space debris mess in this valuable regime. Additionally, current international policy prevents spacefaring nations from removing space debris left by other actors. Significant policy adjustments are needed if debris remediation (removal of nonfunctional and potentially dangerous objects from useful orbits) is to become an effective complement to debris mitigation in cases where mitigation is not completely effective. Beyond the extension of current practices, significant future work remains in characterizing new orbital environments, monitoring their evolving use, and determining appropriate sustainability practices.

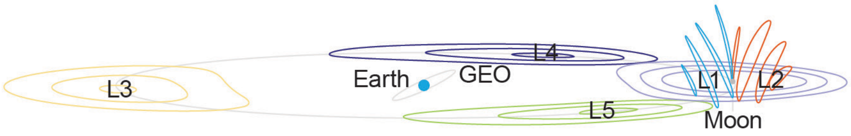
Why is Cislunar Space Important?

Between now and mid-century, some basic assumptions about the state of space operations are reasonable. Geosynchronous Earth orbit (GEO) will continue to be valuable and actively used. The number of operational satellites, especially in low and medium Earth orbits (LEO and MEO), will increase. Space operators will become more numerous and more diverse. Orbital debris will continue to be a significant concern. Most relevant for purposes of this paper, a greater variety of cislunar orbits will be used for an assortment of space applications, including communications, navigation, space domain awareness, scientific remote sensing, and human exploration.

> ***There may be aggregation of space structures into industrial parks at locations deemed valuable…***

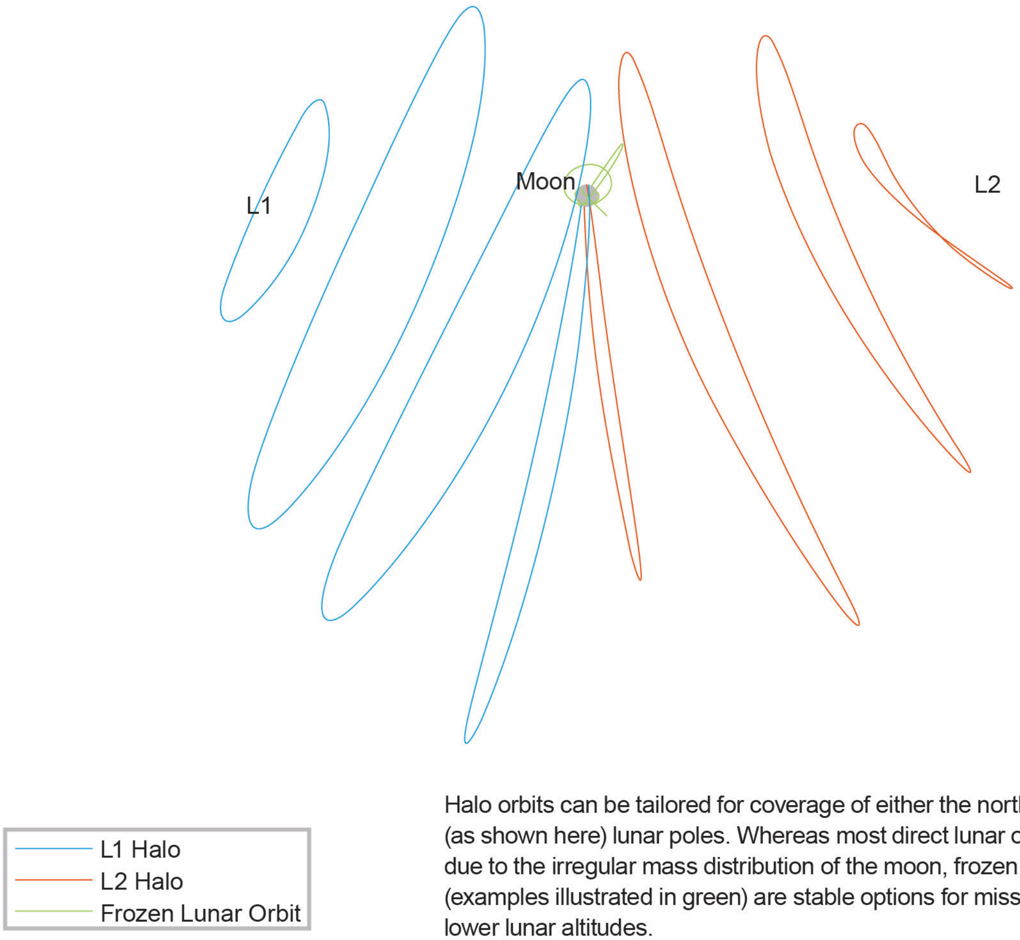


These orbits reside in the plane of the moon's orbit around Earth and are depicted in an Earth-moon rotating frame. The blue orbits about L1 and the orange orbits about L2 stay on the near and far sides of the moon, respectively, while never actually encircling the moon. The orbits about L3 are centered at a point opposite the moon. L4 and L5 orbits lead and trail, respectively, the position of the moon in its orbit.



Halo orbits (examples shown here in blue and orange about L1 and L2, respectively) exhibit motion above and below the moon's orbit plane, which enables visibility to the lunar poles. L2 halo orbits offer a unique location for a communication relay, with continuous visibility to both Earth and the far side of the moon.

Illustration of several types of cislunar orbits: halo and Lyapunov orbits about the five Lagrange points; distant retrograde orbits.



Halo orbits can be tailored for coverage of either the northern or southern (as shown here) lunar poles. Whereas most direct lunar orbits are unstable due to the irregular mass distribution of the moon, frozen lunar orbits (examples illustrated in green) are stable options for missions that require lower lunar altitudes.

Illustration of example L1 and L2 halo orbits and frozen lunar orbits.

In addition to today's familiar applications, the cislunar environment of tomorrow may host some combination of the following:

- Next-generation multi-purpose orbiting platforms for use as labs, manufacturing facilities, and habitats
- Propellant storage depots
- Research outposts on the moon
- Extraction, processing, and use of extraterrestrial resources
- Training and support for deep space missions

Efforts to stimulate a space economy could result in sophisticated structures in various orbits designed to take advantage of the unique characteristics of the space environment, such as microgravity, vacuum, high-intensity solar exposure, and isolation from Earth, to produce useful knowledge and products. There may be aggregation of space structures into industrial parks at locations deemed valuable for their proximity to space resources, relatively stable gravitational points ("Lagrange" or "libration" points), or other attributes.

These activities all have the potential to be realized in less than a human lifetime. The scope and complexity of these developments may challenge spacefaring actors to be good stewards of this emerging enterprise and preserve it for the generations to come.

Lessons from Space Operations to Date

Spaceflight experience in orbits nearer to Earth offers both positive and negative lessons that can help to avoid unsustainable practices in cislunar space. As space activities ramped up in the 1960s and 1970s, no policy framework governed debris mitigation and disposal in the most frequently used orbits. In GEO, for example, many spacecraft were disposed in orbits that continue to cross the operational orbit. These defunct satellites impose a permanent burden of monitoring and tracking for safe operation, and they are prone to breakups and collisions that yield numerous untrackable debris pieces.

Since those early decades, several methods of spacecraft disposal have been used to mitigate debris. At the completion of a mission, a spacecraft could be:

- **Placed into a long-term storage orbit**. The most common example of this is relocation of expired satellites from the GEO belt to higher (super-synchronous) disposal orbits.

- **Sent into Earth's atmosphere for reentry**. Satellites in LEO can gradually reenter on their own due to orbital decay caused by atmospheric drag. If properly equipped and fueled, they can be commanded to reenter using onboard propulsion systems. For any vehicles that are intended for destructive reentry, the U.S. government's Orbital Debris Mitigation Standard Practices (ODMSP) impose a threshold on the allowable likelihood of pieces surviving to Earth's surface causing human casualties.

- **Actively removed**. An owner/operator may retrieve a spacecraft and remove it from orbit. Spacecraft components may be salvaged or recycled. To date, this has been done very rarely and only for demonstration purposes. Operational employment of active debris remediation faces many technical, economic, and legal hurdles. For example, the current regulatory framework does not allow any actor other than the original owner or launching state to remove an object from orbit.

Today's U.S. orbital debris mitigation standards are the result of a gradual evolution that began with NASA and the Department of Defense (DOD) in the 1990s. The standards originally were built around four objectives:

1. Control of debris released during normal operations

2. Minimizing debris generated by accidental explosions during and after mission operations

3. Selection of safe flight profiles and operational configurations to limit the probability of creating debris by collisions

4. Post-mission disposal of space structures to minimize impact on future space operations[1]

Once established in December 2000, the U.S. guidelines proved influential on global best practices. The U.S. government proposed the guidelines to the international community through NASA's participation in the Inter-Agency Space Debris Coordination Committee (IADC), an organization founded in 1993 that currently includes the world's most active civil space agencies. The IADC published its own version of the guidelines in

2002.[2] The essential elements are the same as the U.S. version, plus it contains additional background information, definitions, and some technical details. The IADC presented this version to the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS), which deliberated on it for five years before issuing its own version,[3] which was endorsed by the U.N. General Assembly a few months later.[4] Once again, the COPUOS version retained the same essential elements. The U.N. document states that nonoperational space objects "should be disposed of in orbits that avoid their long-term presence" in the heavily populated LEO or GEO regimes. (Other orbital regimes are not mentioned.) Note that the process from U.S. outreach to U.N. endorsement took seven years even though there is broad agreement about the need to mitigate orbital debris. Plans to establish or change international laws and norms must factor in long lead-times, even for issues that appear noncontroversial.

The U.N. Working Group on Long-Term Sustainability of Outer Space Activities under COPUOS undertook related sustainability issues. Its multi-year work plan approved in 2011 sought to identify best practices in a variety of areas designed to keep space accessible and usable for all nations.[5] Its guidelines on space debris and space operations largely mirrored the U.N. Space Debris Mitigation Guidelines and suggested practices in data sharing. No guidelines were proposed for space debris removal.[6]

In November 2019, the U.S. government updated its debris mitigation guidelines,[7] as directed by Space Policy Directive-3.[8] The update, which replaces the original December 2000 guidance, makes clarifications and adds specificity to orbit descriptions and collision probability estimates. A greater variety of orbits between LEO and GEO are addressed, as well as new satellite disposal options. The new guidelines specify a goal of 90 percent success for post-mission disposal and encourage even higher success rates for large constellations. There is also acknowledgment of emerging activities, such as various types of proximity operations. All these changes are important steps to better stewardship of orbital space, but none of them specifically address activities beyond GEO and its graveyard orbit.

Space domain awareness (SDA) beyond GEO stretches an already challenged capability.

The process of developing, promoting, and institutionalizing debris mitigation best practices took the better part of a decade, and effective implementation is an ongoing process. This implies that planning for expansion to the full cislunar environment should begin now, so space operators are ready to employ best practices for debris mitigation and remediation as activity beyond GEO grows and diversifies.

What Will Be Different in Cislunar Operations?

The operational environment in the cislunar region is different than that found in LEO, GEO, or other regions where humans have operated spacecraft, so we must be cautious in extrapolating our experience. Just as GEO has a slower speed and longer orbital path from that found in LEO, the cislunar environment is different from either of these. Sunlight is essentially perpetual, with rare passages through Earth's or the moon's shadow. The radiation environment is more intense than LEO, since cislunar orbits are largely outside of Earth's magnetic bubble. The volume of cislunar space is vastly larger and distances from Earth-based sensors much farther, so the tracking of objects is much more difficult. Similarly, the relative speed of an encounter with a neighboring cislunar object will be different than in other orbit regimes. We must adapt our expectations and our best practices for this new environment.

For many cislunar orbits, orbit periods can be measured in days, and the volume of space traversed is larger than the congested LEO regime near Earth. Collision risk from debris depends on the density of the debris and the frequency of encounters with the debris. Therefore, the collision risk with other cislunar spacecraft may be relatively small in many cases. However, we should learn from the early missions to GEO with respect to disposal practices. Early GEO satellites often were disposed in place, leaving the orbital inclination to drift, which has resulted in twice daily passages of the GEO belt to this day, decades after their retirement. Had the ODMSP and other nations' similar practices been in place in the 1960s, far fewer wayward dead satellites would transit the highly valuable GEO belt today. Foresight can prevent similar disposal regrets for important cislunar orbits.

High above Earth, but still in the Earth-moon system, the combination of Earth and moon gravity yields orbits whose behavior differs substantially from objects directly orbiting Earth. Many of these orbits are unstable, and small changes in initial conditions can lead to widely varied resulting trajectories. Some of the unstable orbits (e.g., halo orbits) are slow to diverge, such that actively controlled objects can efficiently maintain an orbit that enables specific mission applications. Still other orbits (e.g., distant retrograde orbits) can enable objects—even without active control—to persist in a stable orbit for decades to centuries. Many of the particularly useful orbits exist about the five Lagrange points, or points of gravitational equilibrium. Their natural mission utility will attract increasing use, and the complex dynamical behavior motivates a rigorous approach to traffic management, including debris mitigation and remediation.

Debris shed or objects discarded in cislunar orbits can meet a variety of fates, including passing near or even colliding with operational vehicles, impacting the lunar surface, and departing the Earth-moon system entirely. Achieving a desired long-term orbit in these orbital neighborhoods is challenging, particularly due to the gravitational perturbation from the sun. Therefore, researchers have begun examining the criteria that determine the behavior of objects in orbits that may see frequent use, such as the near rectilinear halo orbit planned for the Lunar Gateway.[9,10]

Space domain awareness (SDA) beyond GEO stretches an already challenged capability. Current ground-based and Earth-orbiting SDA sensors cannot provide the coverage or the sensitivity needed to robustly detect, track, and monitor spacecraft-sized objects at the lunar distance. To address these shortfalls, space-based SDA systems could be added in the Earth-moon system and their data integrated with that from ground-based systems. The limited capacity of SDA sensors for tracking cislunar objects motivates robust spacecraft disposal practices, so scarce sensor time is not redirected to monitor retired vehicles.

What Could Be Done to Advance Cislunar Stewardship?

In general, the provisions of multilateral space treaties apply to space operations anywhere. However, specific rules and recommended practices to date have been aimed at orbital regimes within the GEO arc. There is no agreement, for example, on how multiple operators will share orbits around Lagrange points. It would be an unsound practice to wait—as we did in the early space age—until the most valuable orbits become crowded before we define protected regions, devise space traffic management protocols, and establish norms for debris mitigation and disposal practices. For example, the region near the Earth-moon L1 Lagrange point is likely to emerge as a high-traffic "strait" transited by most vehicles passing between Earth and the moon. A sustainability plan for the L1 region could include traffic management among resident L1 orbit vehicles and others transiting the space.

The cislunar orbits that require sustainability plans should be informed by at least two principal factors: the utility of the orbit, which likely will correlate strongly with the future volume of traffic there, and the stability of the orbit, which governs the longevity of debris that are generated in that vicinity. Examples of orbits with high potential utility include Lyapunov and halo orbits about the five Lagrange points (including the sub-type of near rectilinear halo orbits as is planned for NASA's Lunar Gateway), distant retrograde orbits, and frozen lunar orbits. The distant retrograde orbits and frozen lunar orbits are among the most stable of these orbits. Useful orbits in the Earth-moon system should be evaluated relative to the need to establish cislunar protected regions where spacecraft operators may not dispose of their space systems.

> ***There is no agreement, for example, on how multiple operators will share orbits around Lagrange points.***

New disposal options may become available for high-orbit applications, and the traditional disposal options enumerated earlier may have new factors to consider in cislunar orbits:

- **Long-term storage orbit.** Finding suitable disposal orbits in the cislunar environment and ensuring they can be achieved is an area of ongoing study. This option necessitates detailed analysis of orbital stability over decades to centuries, in the presence of perturbative forces, in addition to determining the likelihood of a sufficiently accurate final maneuver to enter the disposal orbit.

- **Reentry into Earth's atmosphere.** This option will be common for returning crew or cargo vessels. For other vehicles operating in the lunar vicinity, atmospheric reentry may not represent an affordable option as it can be quite costly to return objects to Earth.

- **Active removal.** As noted earlier, space system operators will need to overcome a variety of technical, economic, and legal hurdles to retrieve spacecraft and remove them from orbit. If cislunar operations prompt a market for salvaged or recycled spacecraft components, this may provide incentives to overcome the hurdles. However, the vast area involved and the greater distance from Earth are likely to increase the challenges compared to active removal efforts in LEO and GEO.

- **Crash into the moon.** This option invokes planetary protection issues (i.e., preventing contamination of celestial bodies) and safety considerations for lunar surface operations planned by several countries and nongovernment entities. Most low lunar orbits are unstable, so objects left there will commonly crash into the moon unless deliberate action is taken to use an alternate disposal option.

- **Send into heliocentric escape.** Perhaps the "cleanest" option, space vehicles can be sent away from the Earth-moon system on a trajectory that rarely, if ever, returns to that neighborhood. As in the case of storage orbits, this option also requires detailed analysis of the long-term orbit behavior and the necessary accuracy for the insertion maneuver.

These spacecraft disposal options, except for crashing the object into the moon, directly parallel methods in the current U.S. ODMSP for Earth-orbiting missions. Additional study is needed to inform their effective use and relative merits for cislunar missions, but these disposal methods are broadly considered viable options in the space community.

Future iterations of the ODMSP and similar guidance documents will need to address protection of orbital regions in the space beyond GEO. Increasing cislunar activity will result in the placement of space systems in unusual orbits (by today's standards). Disposal practices for cislunar orbits would need to account for lunar planetary protection policies and specify acceptable disposal options. Space system developers will need incentives and flexibility to incorporate reliable means to achieve successful disposal.

Future operations will need to strike a balance between mitigation of debris (preventing its accumulation) and remediation (removal of nonfunctional and potentially dangerous objects from useful orbits). For the foreseeable future, mitigation will be more economical than remediation. However, perfect mitigation is not possible, and the technical and economic feasibility of remediation may improve, so both options should be explored in long-term planning.

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Enabling Remediation

In cases where debris mitigation is not sufficient, active remediation may be warranted. However, in addition to technical and economic challenges, other significant barriers to debris remediation must be addressed. These challenges include international law granting perpetual ownership of space objects to their launching states and concerns about potentially hostile actions.

Eventually, as space operations become more sophisticated and active removal becomes a practical way to remediate debris, space salvage restrictions will likely need to be revised in some manner to allow actions akin to salvage at sea.[11] Diplomats in the 1960s were not thinking about establishing a business-friendly environment for space salvage, as the primary focus was on national security concerns. That emphasis persists to a large extent today, and diplomats are not likely to emphasize space commerce unless the required technologies, plausible business cases, and political feasibility are within sight.

In the international space treaty regime, the Outer Space Treaty (OST) of 1967[12] established the Cold War's only rules governing the treatment of orbital debris. The issue was less pressing at the time, and the link to debris is indirect. Article IX, which is primarily concerned with contamination from extraterrestrial matter, is generally interpreted to be applicable to orbital debris as well, due to language that directs "appropriate international consultations" prior to engaging in activities that could cause "potentially harmful interference with activities of other States Parties." To address the sensitivities of the United States and the Soviet Union—each worried that the other would try to abscond with its satellites—the OST granted perpetual ownership of space objects to their launching state, even after the objects are deactivated and become uncontrolled junk. Although this is an obstacle to effective cleanup efforts, most active spacefaring nations (including the United States) are reluctant to suggest changes to the OST, even though Article XV permits any signatory to offer amendments.

In addition to the OST, there are three multilateral space treaties to which the United States is party: the Assistance Agreement (1968),[13] the Liability Convention (1972),[14] and the Registration Convention (1975).[15] They were designed to expand on provisions of the OST and do not directly address orbital debris or space traffic management. However, they do play a role in debris discussions and incident resolution because they deal with space object ownership, liability for damages, and public recordkeeping by parties responsible for space objects.

In a new era of greater numbers of government and private operators in space, some means to permit routine transfer of ownership and the development of an accompanying liability framework are necessary. Operators should have legal and efficient options to allow cleanup of valuable orbits through removal, with permission, of space objects left there by another party.

Advances in robotics, satellite bus design, automated rendezvous and docking, and orbital maneuvering systems, coupled with a variety of efforts to reduce launch costs, may make debris remediation practical in the next 10 to 15 years. Using the same technologies, commercial space operators have demonstrated substantial progress toward satellite servicing capabilities.[16,17] Northrop Grumman achieved a major milestone in February 2020, as its Mission Extension Vehicle-1 completed the first docking of two commercial satellites by successfully capturing the client Intelsat-901. The MEV-1 is planned to take over maneuvering for Intelsat-901 to extend the useful life of the client by five years. Adding to the complexity of the mission, the Intelsat satellite was not originally designed for docking.[18] Meanwhile, NASA conducted risk-reduction demonstrations for satellite refueling aboard the International Space Station starting in 2011[19] and in December 2016 awarded a contract for a satellite servicing demonstration spacecraft, Restore-L, to be flown in 2023.[20,21] Building on these satellite servicing developments, if satellite retrieval becomes an accepted norm, it could usher in a market for used satellites as debris remediation is accompanied by repair and refueling services.

With proximity operations and satellite servicing becoming mainstream space activities, a space traffic management system will need to adopt safety of flight rules analogous to those in the air and maritime domains. Future rules and guidelines should enable and promote sharing of flight plans among operators and mechanisms for cooperative conjunction analysis and collision avoidance.

> ***Operators should have legal and efficient options to allow cleanup of valuable orbits through removal of space objects left there by another party.***

In addition to the limitations on salvage in international law, another concern that must be overcome is that rendezvous and proximity operations look like (and could double as) anti-satellite (ASAT) missions. Potential objectors to widespread use of proximity operations will need to be convinced that the benefits outweigh the risks.

Differentiating between benign and potentially nefarious rendezvous and proximity operations becomes even more difficult for many cislunar orbits due to diminished space domain awareness capabilities and longer distances. Therefore, guidelines for proximity operations should aim not only to improve safety and interoperability, but also to provide a framework for identifying bad actors who pose a potential threat to other operators. Guidelines could be developed through collaboration of government and industry stakeholders and then be reflected in licenses issued by government regulators to organizations involved in cislunar operations. In the United States, this has begun with the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), an industry-led initiative that currently has 35-member companies and initial seed funding from the Defense Advanced Research Projects Agency (DARPA). CONFERS aims to research, develop, and publish nonbinding, consensus-driven standards for a wide variety of orbital operations.[22]

The resulting U.S. guidelines could be offered up as a model in international forums such as COPUOS or as an addendum to a future space code of conduct. This would be a multi-year process, as was the case with the debris mitigation guidelines, but, if successful, the effort could prove its value in promoting growth in cislunar space activities, reducing the debris threat, and easing tensions regarding potentially threatening behavior in space.

To ease concerns about nascent ASAT capabilities, prospective U.S. proximity operations guidelines, at a minimum, could include a prohibition against interference with nonhostile satellites that have not been offered up for salvage. Other key provisions could include:

- Prior public notification of launch or orbital maneuvers to initiate satellite servicing and retrieval missions.
- Prior notification to satellite owners of operations near their space assets (e.g., within 10 km).
- Immediate alert of any servicing or retrieval mission that does not go as planned and may create a hazard for others (e.g., by generating debris).

Conclusion

As more nations become spacefarers and cislunar traffic increases, established and emerging players should employ lessons learned from operations in LEO and GEO to be better caretakers of the expanded orbital neighborhood. The space lanes throughout the cislunar region would benefit from the conscientious care of the global community in a coordinated effort to ensure safe operations in the best interests of all parties. Responsibility for coordination of the effort may reside with existing international organizations but could also be assisted by an international business collective similar to the Space Data Association, which has proven that critical operational issues affecting both government and nongovernment sectors can be addressed through cooperation among competitor-colleagues.

The following steps will be necessary to establish a cislunar sustainability paradigm:

- Extend space domain awareness capabilities to cover future operating orbits in the Earth-moon system.
- Continue analyses of the complex cislunar orbit dynamics to determine effective methods of spacecraft disposal and define the valuable regions that merit careful protection.
- Formulate space traffic management protocols, along with debris mitigation and disposal practices.
- Address the present ownership and transparency obstacles to space salvage in current international law with the intent of enabling active removal of discarded objects.

For the foreseeable future, debris mitigation will be more economical than debris remediation, but the balance between the two approaches will continue to evolve. With this in mind, it is noteworthy that Space Policy Directive-3 states "standard practices should be updated to address current and future space operating environments."[23] Although intended as a reference to the original ODMSP, this statement should remain an axiom of space operations from this point onward.

Now is the time to develop practical and broadly applicable debris mitigation and remediation practices for cislunar orbits. Today, these orbits are in near-pristine condition, and their future usability must be ensured.

Acknowledgment

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[21] NASA Satellite Servicing Projects Division (SSPD) Restore-L webpage (https://sspd.gsfc.nasa.gov/restore-L.html). For fiscal year 2020, Congress appropriated $227.2 million for Restore-L and the Space Infrastructure Dexterous Robot (SPIDER), with no less than $180 million of that amount reserved for Restore-L.

[22] CONFERS website (https://www.satelliteconfers.org/).

[23] SPD-3 (ref 6), Sec. 5, a. iii.