CENTER FOR SPACE
POLICY AND STRATEGY

SEPTEMBER 2023

PACK IT IN, PACK IT OUT: UPDATING POLICY AND STANDARDS FOR CISLUNAR SUSTAINABILITY

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Summary

A future of robust civil, military, and commercial activity in cislunar space is driving a need for updates to the global standards for spaceflight safety and disposal. Where do current policy and requirements fall short, and what can we do about it to ensure the sustainability of space beyond GEO?

Introduction

In the United States, the National Space Council has promulgated guidelines for safe and responsible space operations with the Orbital Debris Mitigation Standard Practices (ODMSP).[1] The ODMSP provide a framework for the sustainable use of space, but they were not originally envisioned for flight beyond geosynchronous orbit (GEO). The most recent update to the ODMSP occurred in 2019, but at that time NASA was the sole U.S. actor in cislunar space, and cislunar operations were not within the scope of that update. Today, in addition to NASA's own vibrant cislunar ambitions, the Department of Defense (DOD) is developing missions to the moon and cislunar space,[2] and commercial industry foresees profitable cislunar opportunities through tourism, resource extraction, and other ventures. A survey from the Center for Strategic & International Studies documented nearly fifty missions with aspirations to cislunar space by 2030.[3]

The White House released the National Cislunar Science and Technology Strategy[4] in November 2022. The strategy's purpose is to provide a vision for U.S. leadership in the responsible and sustainable utilization of cislunar space, including safe cislunar spaceflight operations. The strategy states "the U.S. government will support development of best practices related to debris mitigation, minimizing the hazard of Lunar landing ejecta, end-of-life operations, mishap reporting,

Geosynchronous Orbit (GEO): An orbit around the Earth with a period equal to the Earth's rotation, such that an object in orbit appears to remain in the same longitudinal position over Earth's surface (about 36,000 km from Earth).

Cislunar: The three-dimensional volume of space beyond Earth's geosynchronous orbit that is mainly under the gravitational influence of the Earth and/or the moon.

Lunar Impact Ejecta: Particles such as dust, sand, gravel, and rocks that are thrown from the surface of when an object strikes the moon's surface.

End-of-Life Operations: Preparing spacecraft for disposal as they reach the end of their operational lives, which may include moving to a graveyard orbit or preparing for reentry, expelling any remaining propellants, and draining stored power sources.

collision avoidance, and other events associated with safety of flight." The White House's strategy clearly signals the importance of cislunar space's sustainability, but the government's primary means of compelling sustainable behavior—the ODMSP—were composed without cislunar operations in mind. Upcoming cislunar missions must plan sustainable operations despite this ambiguity.

In anticipation of compliance challenges for civil and military missions, The Aerospace Corporation (Aerospace) undertook a cislunar-focused review of three foundational documents on space-debris mitigation, disposal, and safety of flight. These documents were the ODMSP, Air Force Instruction (AFI) 91-202,[5] which formalizes the ODMSP into requirements for the U.S. Air Force and Space Force, and NASA Standard 8719.14,[6] which levies similar requirements on NASA missions. The purpose of this requirement-by-requirement review was to identify where and how the ODMSP, AFI, and NASA Standard fare when applied in their current form to cislunar operations. The review documented cislunar-related shortfalls or gaps in the requirements and developed recommendations for policymakers to incorporate cislunar concerns into the nation's framework for space sustainability.

This study has found that many aspects of operating in the cislunar regime are incompatible with the current guidelines and requirements. In fact, more than half of the requirements in AFI 91-202 applicable to spacecraft have unaccommodated cislunar implications, and the largely equivalent requirements in the NASA Standard that apply to civilian missions are in a similar state. These challenges include both policy shortfalls, where the guidelines are missing requirements uniquely necessary for cislunar missions, and capability shortfalls, where the standards may be adequate *per se*, but the community lacks quantitative insight or the tools to perform verification of compliance in cislunar space.

This paper provides an overview of Aerospace's findings on the shortfalls in current debris and disposal guidelines when applied to cislunar operations and subsequently offers a set of recommendations on where and how the community should begin to address these shortfalls. The recommendations fall into three over-arching categories: (1) Lunar impact as a disposal option, (2) Cislunar collision risk and collision avoidance (COLA), and (3) Long-term cislunar disposal.

The recommendations in this paper do not go so far as to propose specific requirement language to change or include. The scope of Aerospace's study was to identify where the shortfalls are but not yet to resolve them. The recommendations highlight where and why an update is needed for cislunar operations and, where appropriate, what features an update should have. Furthermore, a cost-benefit analysis for each recommendation was outside the study's scope. Some recommendations identify the need for new capabilities (e.g., cislunar COLA), but an estimation of each capability's cost was not performed. And some recommendations to update requirements—although not requiring an acquisition of capability—may require substantial investment to determine their technical solutions. It

Collision on Launch Assessment (COLA): Identifying and reducing the probability of spacecraft collisions.

Low Earth Orbit (LEO): An orbit around Earth roughly 2,000 km or less from the Earth's surface.

Kepler's Laws of Planetary Motion

1. Planetary bodies orbit the sun in an ellipse.
2. Planetary bodies sweep out the same area of space in a given interval of time anywhere on their orbits.
3. A planetary body's orbit period is proportional to the size of its orbit.

is presumed that policymakers and community stakeholders would perform this assessment before acting on such recommendations.

Resolving the gaps and carrying out the recommendations with new requirement language will require a whole-of-government approach with input from civil, military, and commercial stakeholders and buoyed by extensive analysis. As the number of cislunar missions grows to include actors in the DOD and commercial industry, ad hoc agreements on waivers are not a sustainable option. Without an urgent effort to revise the ODMSP and its downstream requirements, the community runs the risk of setting bad precedents with a patchwork of exceptions, waivers, and idiosyncratic interpretations of the rules that will imperil the long-term sustainability of space beyond GEO.

Complications to Orbital Motion in Cislunar Space

In familiar low Earth orbit (LEO) or GEO, the gravity of the Earth dominates a spacecraft's motion, and the spacecraft follows an elliptical orbit. These orbits are also called "Keplerian," because they obey Kepler's laws of planetary motion and therefore admit straightforward solutions for their behavior. Even if other small perturbing forces act on a Keplerian orbit, the motion remains mostly elliptical and predictable.

However, as the orbit's altitude increases, the moon's gravity becomes another dominating force. At around 100,000 km altitude, which is roughly three times higher than GEO, the moon can no longer be considered a small perturbation. In this "three-body problem," the comparable gravitational attractions from the Earth and moon on the spacecraft cause much more complex behavior that does not allow for simple solutions. Gravitational interactions with the Earth and moon in this cislunar (or "multi-body") regime destabilize the system from familiar Keplerian ellipses and can cause chaotic behavior.

A chaotic orbit is an orbit whose behavior is highly sensitive to small changes in initial conditions. Tiny differences in the starting position or velocity of the spacecraft can result in vastly different outcomes for its motion over time. A chaotic orbit may be unpredictable in the long term, as the slightest perturbation can cause the orbit to evolve in a completely different way. This sensitivity can make it very difficult to accurately predict the future position and velocity of a spacecraft following a chaotic orbit, even if its initial conditions are known with high precision.

Nonetheless, some predictable periodic orbits do exist in the three-body problem, and spacecraft have utilized them for several decades. For any pair of large bodies (e.g., the Earth and moon), there exist five locations, called "Lagrange points," where the gravitational forces of the two bodies balance the centrifugal force felt by the spacecraft in orbit. At a Lagrange point, it is theoretically possible to remain stationary with respect to the two large bodies

Perturbation: A disturbance in the motion of celestial objects which can be caused by several factors including, but not limited to, atmospheric drag, distortions in a gravitational field, and the presence of other gravitational bodies.

Multi-body System: The motion of multiple celestial bodies or objects under mutual gravitational interactions.

The "three-body problem" describes a multi-body system under the interaction of three celestial objects (e.g., Sun-Earth-Moon, Earth-Moon-Spacecraft).

Centrifugal Force: An apparent outward force on an object when it is rotated.

Station-keeping: Maintaining a spacecraft in a fixed position or orbit.

Station-keeping maneuvers are minor maneuvers required to compensate for perturbations to maintain a spacecraft's orbit.

indefinitely. In practice, it is preferable to enter special periodic orbits around these Lagrange points, called Lyapunov orbits and halo orbits. These orbits are especially useful at the two Lagrange points closest to the moon (in the Earth-moon system) because they allow a spacecraft to stay close to the moon and on the Earth-moon line for extended periods. However, Lyapunov orbits and halo orbits here are technically unstable. Small disturbances such as perturbations from the sun can upset the desired behavior. These orbits require regular station-keeping maneuvers to keep the spacecraft on the proper periodic orbit. Without this maintenance, the spacecraft would fall away from the vicinity of the Lagrange point and follow a chaotic orbit in and around the Earth-moon system.

These fundamental differences in behavior between cislunar and near-Earth orbits have substantial implications on the composition of rules related to debris mitigation, safety of flight, and disposal. If you indeed cannot predict long-term behavior in cislunar space, how can you write a rule about disposal that should apply to a spacecraft for a century or more? If cislunar orbits are extremely sensitive to initial conditions, how can a spacecraft vent its propellant tanks at the end of its life without upsetting its targeted disposal orbit? What role should the moon have in cislunar spacecraft disposal, as we allow atmospheric reentry at the Earth today? These questions and others have not yet been investigated in depth. The purpose of this paper is to uncover these areas where cislunar complications cause a disconnect with today's rules and requirements and to recommend a path forward for answering these pressing questions. Their answers, which are beyond this paper's scope, will require further joint effort and consensus from across the national space enterprise.

Current Policies and Requirements

The foundational guidelines for debris mitigation, disposal, and flight safety in the United States are the ODMSP, which cover three broad topics: (1) The creation of debris through explosions or release (intentional or unintentional), (2) The collision risk of planned flight profiles with debris and catalogued resident space objects (RSOs), and (3) The disposal and persistence of bodies in the space environment. Organization-specific documents translate and codify the ODMSP into requirements, such as AFI 91-202 for the Air Force and NASA-STD-8719.14 for NASA. In the commercial domain, debris mitigation and flight safety for spacecraft are regulated by the Federal Communications Commission (FCC), through which commercial space operators obtain their spectrum licenses. The FCC largely defers to NASA's requirements, with some exceptions.[7] Each organization decides how stringent its requirements should be and how compliance with the requirements should be verified. The DOD and NASA must be at least as stringent the ODMSP, but because the ODMSP apply only to government missions, the FCC has more latitude in levying requirements on commercial missions.

Most government space platforms in the United States are subject to either AFI 91-202 or NASA-STD-8719.14. The former applies to U.S. Air Force and Space Force missions, and the latter applies to NASA missions. Other civil U.S. government organizations that operate spacecraft, such as the National Oceanic and Atmospheric Administration (NOAA), usually defer to NASA but also incorporate the ODMSP to a large degree.[8] The AFI covers many safety-related subjects simultaneously, of which disposal and safety of flight of space vehicles is one. The section of the AFI covering space operations imposes several dozen requirements on space vehicles that cover expectations on where and how Air Force space systems shall carry out flight-safety and disposal activities during operations consistent with the ODMSP. NASA-STD-8719.14 is NASA's counterpart to AFI 91-202, and its requirements are very similar to the AFI's. NASA-STD-8719.14 provides more technical detail on the recommended or required methodologies for verifying a space system's compliance with the requirements. Figure 1 provides a simplified overview of the relationship among policy, requirements documents, and stakeholders.

Irrespective of their destination, all space missions must demonstrate compliance with applicable debris mitigation, flight safety, and disposal requirements. Missions subject to AFI 91-202 document their compliance with an artifact called a Space Debris Assessment Report (SDAR), which breaks down the AFI's requirements into multiple sections and shows a requirement-by-requirement verification accompanied by quantitative analysis. For NASA-STD-8719.14, civil missions produce a similar artifact called an Orbital Debris Assessment Report (ODAR). An ODAR (or similar form) must accompany all spectrum applications as a prerequisite for the FCC to issue a license. The ODAR and SDAR have some differences in format and in methodologies for demonstrating compliance, but the technical content between the two is comparable. The production of an ODAR or SDAR is mandatory for all government space missions, and many commercial missions also produce an ODAR to document compliance with the FCC's rules. Waiving any requirement is an onerous process that requires concurrence by leadership at high organizational levels.

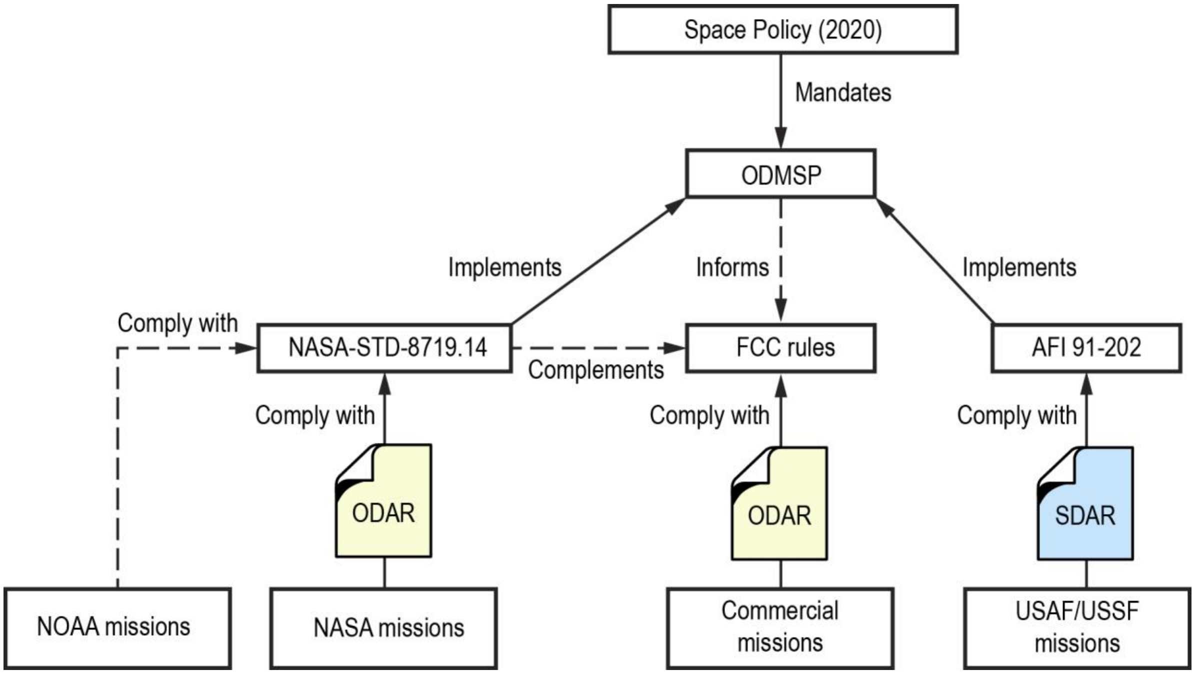

Figure 1: Policy requirements and guidelines on orbital debris mitigations.

Policy and Requirement Shortfalls in Cislunar Operations

To uncover the cislunar shortfalls in the ODMSP and their derived requirements, a team of space-debris and orbital dynamics experts at Aerospace participated in an exercise to produce an SDAR for a fictitious but plausible DOD cislunar mission. The team assumed a five-year mission in a halo orbit at the Earth-moon L1 Lagrange point with a spacecraft comparable in size to others that have flown to the moon in recent years (e.g., the Lunar Reconnaissance Orbiter). The team was tasked to work through AFI 91-202 requirement by requirement and uncover where or how they could demonstrate the mission's compliance in an SDAR. The team documented ambiguities that arose in the requirements when translated to the cislunar domain, the inability to verify requirements, and inconsistencies when applied to cislunar space. Although this was not a full-scale mission-design exercise, the team performed some technical analyses as good-faith attempts at verifying compliance, using either mandated compliance-verification tools, internally available tools, or both.

The review found that more than half of the requirements necessary for an SDAR have cislunar implications. Requirements related to debris release, collision-risk assessments, collision avoidance, disposal, passivation, and casualty risk all had new implications with varying degrees of complexity when translated to the cislunar regime. The handful of requirements *without* these cislunar implications were largely related to hardware reliability, such as ensuring a low probability of explosion. Although the team pursued a DOD-centric mission design that required compliance with AFI 91-202, comparison with NASA-STD-8719.14 showed that the shortfalls detailed below would apply equally to a civil or commercial mission. The team found that the shortfalls fell into two broad categories: requirement/policy shortfalls and capability/knowledge shortfalls.

Requirement/policy shortfalls

In this category, the governing documents fall short on definitions, are missing new requirements uniquely necessary to accommodate cislunar operations, or need fundamental change at a policy level. The review found the following:

- ***Not addressing the release or creation of debris near the moon or in cislunar space.*** The ODMSP and AFI include several requirements related to the "persistence of intentional debris and debris from planned explosions" that do not account for the markedly different dynamics beyond Earth's orbit. The current rules for debris release in LEO limit the total lifetime assuming atmospheric reentry, and in GEO the rules specify a keep-out region and duration near GEO altitude. Debris in the cislunar regime may not be confined to regions traditionally defined in terms of orbital elements or altitudes, and in lunar orbit no atmosphere is available to clear out debris.

- ***Not addressing lunar impact as a disposal option.*** Controlled or uncontrolled reentry is a viable disposal option at the Earth, where the atmosphere ensures the destruction of the reentering vehicle. The ODMSP and AFI do not address whether space platforms in cislunar space or lunar orbit can use impact on the moon for disposal. In fact, because the ODMSP enumerate the viable disposal options, lunar impact is implicitly forbidden. However, for

Orbital Dynamics: How objects move in space.

Orbital Elements: Parameters used to uniquely describe an orbit.

Passivation: The removal of internal stored energy, usually at a spacecraft's end of life.

Heliocentric Earth Escape: Escaping the Earth's gravitational field to enter a primarily sun-influenced orbit.

spacecraft in lunar orbit, the only cost-effective disposal option may be impact, just as reentry may be the only feasible option from LEO. To date, many spacecraft and rocket bodies have impacted the moon at end of mission, but historically this option has been coordinated with the scientific community and occurs only a few times a decade. With a larger cislunar population, it is unclear if or how a higher frequency of lunar impacts could have deleterious effects to the lunar environment both in space and on the surface from impact ejecta, dispersed wreckage, and toxic propellants, and possibly endanger any human presence there.

- ***Insufficiency of "storage above GEO" disposal option.*** The region "above GEO" as used in the ODMSP has no upper limit and includes all cislunar space, without regard for whether any of those regions should be protected. Under the current ambiguous guidance, it would technically be compliant to leave a derelict in place near highly trafficked cislunar regions (e.g., Lagrange points), in lunar orbit, or impact the moon.

- ***No technically rigorous definition of "escape."*** The ODMSP offer "heliocentric Earth escape" as a disposal option and offer no further elaboration. In the regime of multi-body dynamics, the term "escape" is not rigorously defined, and objects that have left Earth's sphere of influence can in fact return. For example, a spent Saturn IV-B upper stage from Apollo 12 escaped the Earth in 1971 and returned in 2002.[9]

- ***Lack of cislunar-specific disposal orbits or graveyards.*** Regions near GEO and in MEO have been earmarked as orbital graveyards by balancing the interests of space sustainability with the practical limitations of spacecraft propulsion capacity, but no such regions have yet been allocated beyond GEO, aside from the ambiguous "storage above GEO" option addressed above. Because of the complicated dynamics in the multi-body regime, it is not obvious whether or where viable long-term disposal orbits in cislunar space exist.

- ***Not addressing planetary protection.*** Missions to the moon, and especially those that may contact its surface, must comply with planetary protection requirements per Article IX of the Outer Space Treaty and, for NASA missions, via NASA Interim Directive (NID) 8715.128. The Outer Space Treaty requires that states should conduct exploration to celestial bodies "so as to avoid their harmful contamination." NASA more specifically identifies the lunar polar regions and historic landing sites as having sufficiently significant scientific interest to warrant the reporting of biological materials introduced there, although such materials are not prohibited. However, the ODMSP do not address whether or how planetary protection should be observed.

- ***Lack of rigorously defined protected regions in cislunar space.*** The latest version of the ODMSP defines protected regions of LEO, MEO, and GEO in terms of orbital altitude. Beyond GEO, no formal guidance exists. In addition to the space immediately around the moon, regions of

Sphere of Influence: The region around a celestial body where that body's gravitational force is the main force acting on an object orbiting around it.

Medium Earth Orbit (MEO): An orbit around Earth roughly between 2,000 km and 36,000 km from the Earth's surface.

Planetary Protection: Protecting celestial bodies from contamination by Earth life.

Orbit Propagation: The prediction of the orbital position of an object at some future time given current orbital parameters.

high operational value—such as the Earth-moon and Earth-sun Lagrange—points may warrant similar protection. However, the spatial and temporal extents of such protection remain undefined, and rigorous definitions of these cislunar protected regions are not likely to permit straightforward single-parameter specifications such as altitude.

Capability/knowledge shortfalls

Some requirements, which otherwise appear adequate in translation to the cislunar regime, require special analysis or new capabilities to realize or verify compliance in cislunar space. Our review found the following shortfalls in this category:

- ***Lack of best practices for long-term cislunar propagation.*** Orbital motion in cislunar space is chaotic; trajectories are highly sensitive to initial conditions and to the choice of algorithm used to predict them. Long-term orbit propagation in cislunar space, which is necessary on centuries-long timescales for several requirements, is susceptible to substantial errors if the algorithm is not properly suited to the regime. Many of the commonly used propagators for geocentric orbits cannot be immediately applied to a three- or multi-body system. A great body of work exists on long-term propagation in chaotic systems and multi-body orbits, but no community consensus or set of best practices exists on the most appropriate gravitational force models and propagation methodologies to ensure the accurate assessment of cislunar flight-safety metrics requiring timescales of decades or greater. Furthermore, most professionals in the space community do not have experience designing or propagating trajectories in this regime, increasing the danger of misapplication of extant propagators and arriving at erroneous conclusions about risk.

- ***Poorly understood cislunar debris dynamics.*** The chaotic dynamics of cislunar space also complicate the evolution of debris fields from breakups and explosions. The spreading or concentration of debris due to multi-body orbital dynamics may be qualitatively different from that in Earth's sphere of influence, where concepts such as a "pinch point"—a region where debris concentrates due to the periodic nature of Keplerian orbits[10]—have served to simplify the composition of rules related to debris creation.

- ***No framework for cislunar collision-risk assessment.*** Conjunction assessments and COLA have extensive heritage in LEO, MEO, and GEO, but many of the underlying algorithms and processes include assumptions that break down in the cislunar regime. For example, most current algorithms assume that close-approach encounters occur on very short timescales (order ten seconds) at high relative velocity (order ten kilometers per second). These short timescales permit some simplifying assumptions in the calculation of probability of collision. However, in cislunar space the orbital velocity is much lower than in planetary orbits (e.g., ~100 m/s in halo orbits at Lagrange points), and close-approach encounters could persist for many minutes or hours. Many deployed COLA processes also use techniques that depend on the two-body problem as a baseline reference for algorithmic simplification, and these techniques do not yet have equivalents in the cislunar regime. Furthermore, meaningful and actionable conjunction assessments require realistic estimates of orbit uncertainty, which today are largely unavailable and may not become available until a more extensive architecture of space domain awareness assets comes online in cislunar space.

- ***Lack of cislunar debris and population models.*** Compliance with many requirements entails the estimation of collision risk against large or small objects via debris models. The two most common models are NASA's Orbital Debris Engineering Model (ORDEM) and the European Space Agency's Meteoroid And Space-debris Terrestrial Environment Reference (MASTER).[11] However, the debris models do not extend beyond 40,000 km altitude.[12] The NASA Meteoroid Engineering Model can be used to provide a risk estimate for collision with naturally occurring objects in interplanetary space, but no estimate is available for the man-made debris in cislunar space or in lunar orbit.[13] The U.S. space catalog does include objects with orbits beyond GEO, but only those whose dynamics are dominated by the Earth's gravity. Objects in lunar orbit or that follow cislunar-unique orbits (e.g., Lyapunov or halo orbits) are absent.

- ***Lack of a native DOD cislunar COLA process.*** In addition to the lack of a collision-risk framework noted above, the DOD lacks the capability to provide COLA services to its missions beyond GEO. AFI 91-202 requires Air Force and Space Force missions to use the 18th Space Defense Squadron (18 SDS) for its COLA products and planning, but 18 SDS (or 19 SDS, its designated alternative for cislunar space domain awareness) cannot provide those services today or in the immediate future.

- ***Unknown sensitivity of disposal compliance to initial or insertion conditions.*** The long-term behavior of cislunar orbits is very sensitive to initial conditions, and if disposal or graveyard orbits were available in cislunar space, it is unclear how precise the insertion into the disposal orbit must be to ensure the long-term viability of the graveyard. Even for currently accepted disposal methods, such as escape and atmospheric reentry, achieving these modes of disposal from cislunar space may require sophisticated execution and long (days or weeks) transfers. The reliability of propulsions systems to deliver a desired impulse degrades over time as tanks empty and hardware ages, and disposal in cislunar space may require more precision than typically expected in LEO, MEO, or GEO.

Recommendations

The Aerospace team consolidated the bulk of these requirement-specific shortfalls into three over-arching themes: 1) The sustainability of lunar impact for disposal, 2) Cislunar collision risk and COLA, and 3) Long-term disposal in the cislunar regime. For each theme, the team developed a recommendation for the community, including an evaluation of the motivating concerns from the ODMSP and requirement shortfalls, the desired outcomes of executing the recommendation, and the quantitative analyses needed to address these concerns.

Sustainability of Lunar Impact

Recommendation: Policy and requirements should be updated to address lunar impact either as a valid disposal option or restricting or prohibiting its use.

Impulse: Force over time, in space applications total impulse is the average thrust times the total firing time.

Delta-V (ΔV): The change in a spacecraft's velocity from a maneuver.

Periapsis: The point on an orbit closest to the central body (e.g., the Earth).

Apoapsis: The point on an orbit furthest from the central body.

CubeSat: A nanosatellite standard form factor that is roughly 10-30 cm in size.

Impact with the lunar surface has been a favored disposal option since the beginning of the space age, both for NASA (e.g., GRAIL, LCROSS, LADEE, etc.) and other nations (e.g., Japan's Kaguya and China's Longjiang-2). The advantages of impact are two-fold: it permanently removes the spacecraft from the space environment, and it provides an incidental opportunity to advance lunar science via observation of the impact ejecta. Recent impacts have used residual propulsion capability to control and target the location of impact, eliminating the risk to sensitive sites on the lunar surface and maximizing the scientific return from observations. However, uncontrolled impact is the fate of most objects left in lunar orbit because the moon's non-uniform gravity destabilizes most orbits over time. The absence of a lunar atmosphere has made very low altitude lunar orbits popular (e.g., with periapsis altitudes measured in tens of kilometers), but these orbits decay and impact in a matter of days or weeks due to the perturbations of the moon's gravity and that of the Earth and sun.

Lunar impact may be the only feasible or affordable option for missions that enter lunar orbit or cislunar orbits near the moon. Within the moon's sphere of influence (i.e., within ~40,000 km of the moon), the moon's gravity dominates orbital motion, and large changes in velocity (ΔV) are necessary to effect substantial changes in the orbit. Disposal from lunar orbit via heliocentric escape or delivery to a long-term stable graveyard orbit could require hundreds of meters per second of ΔV, an amount that could equal or exceed the ΔV allocated to the primary mission. Doubling the propellant requirement on missions to lunar orbit could exclude the community that seeks to leverage small-satellite technologies to achieve its goals of interplanetary flight or that cannot afford to fly on larger launch vehicles. In contrast, lowering periapsis for a controlled impact is measured in tens of meters of ΔV or less, which can be accommodated on platforms as small as CubeSats.

The ODMSP, AFI, and NASA Standard do not directly address lunar impact as a disposal option. References to "natural" and "direct" reentry do not limit themselves to Earth per se, but subsequent references to "atmospheric drag" make the implicit geocentric application manifest. The documents also address impact energy and the probability of human casualty, where geocentric application is implied but not explicit. This disconnect is unsurprising, as the ODMSP were not developed to apply to non-geocentric missions.

We foresee four substantial concerns related to lunar impact that must be addressed when considering if or how it could be adopted as a sustainable disposal option. Some of these concerns are accompanied by a discussion of the quantitative analyses needed either to evaluate their severity or to resolve them entirely.

1. ***Planetary protection.*** As discussed above among the requirement shortfalls, NASA's guidelines for lunar planetary protection are captured in NASA Interim Directive (NID) 8715.128 and identify regions near the lunar poles and sites of historical interest (e.g., Apollo landing sites) that merit increased scrutiny in advance of disposal there. NID 8715.128 was developed as part of the United States' obligations to Article IX of the 1967 Outer Space Treaty. It remains to be seen if or how those obligations should be translated into requirements for commercial actors at the moon or for missions in the Department of Defense.

Atmospheric Drag: Drag that occurs due to the motion of an object through atmospheric particles.

Geocentric: Earth-centered

Suborbital: A trajectory which does not complete a full orbit around a celestial object.

2. ***Surface- and space-environment effects of lunar impact.*** Lunar impacts will kick up dust and debris that could endanger other lunar orbiters and activity on the surface. Most ejecta return to the lunar surface, but an impact's high velocity may create suborbital debris trajectories with very high apoapses in the space of other orbiting objects. Furthermore, the unusual features of the moon's gravity may cause some ejecta to become orbital from perturbations before returning to the surface.

3. ***Casualty risk.*** The return of a human presence on the moon in the mid-2020s introduces the concern of human casualty risk from impacting objects. Lunar impact as a disposal option must consider how to coordinate these impacts with human activity on the surface. At Earth, atmospheric breakups eliminate most risk to the population, and statistical models are used to estimate the risk for components that might survive reentry. No such process exists in an environment where the population is so low but survival of the derelict to the surface is assured.

4. ***Controlled vs. uncontrolled impact.*** Many lunar orbits are naturally unstable due to the nonuniformities in the moon's gravity. Most uncontrolled orbits will impact the moon eventually, and randomly. In addition to questions of planetary protection above, a notional lunar impact disposal option must consider the risk to the rest of the lunar and cislunar population if missions are allowed to die in place and impact naturally (i.e., uncontrolled) or if they should target their reentry.

This recommendation to address lunar impact disposal options should ultimately culminate with new language in the ODMSP either introducing it as a valid disposal option or restricting or prohibiting its use. The new language should address whether it is limited to natural decay or only to controlled impact, limitations on post-mission lifetime, specification of if and how missions must comply with planetary protection (potentially with regions where impact is prohibited or where the probability of impact is below some to-be-determined threshold), and how to evaluate casualty risk on the moon. Requirements documents, such as AFI 91-202 and NASA-STD-8719.14, could be updated to require coordination with civil agencies before disposal to minimize human casualty risk on the lunar surface. They could also require a plan or mechanism to evaluate and minimize casualty risk, akin to what is done today for geocentric reentry risk.

The composition of this update to the ODMSP will require substantial quantitative analysis. First, the community must evaluate how severely lunar impacts affect the lunar surface and local space environment, including the danger to other lunar orbiters and surface assets (robotic and human), the threshold size for the lunar orbiter population to make impacts untenable for disposal, and make a comparison of risk to natural lunar impact rates. Complementary analysis should develop a methodology to quantify risk to a sparse human presence on the lunar surface from spacecraft impacts (including direct impact or secondary impacts from unsettled debris), determine how precisely a cislunar or lunar mission must know and control its orbit to target impact without risking human life, and determine a human population threshold—if it exists—where lunar impact could become unsustainable as a disposal option.

Cislunar Collision Risk and COLA

Recommendation: Requirements documents and tools should be updated to calculate collision risk and perform collision avoidance in cislunar space and lunar orbit.

A robust ecosystem of tools and techniques exists for the calculation of collision risk and collision-avoidance maneuvers. Space operators in the government and commercial industry leverage decades of experience processing space situational awareness data into actionable outputs via public or proprietary algorithms. Today, a spacecraft operator can receive conjunction warnings from the government or from a commercial provider with several days' notice, with each warning containing position information about the conjoining spacecraft or debris, its uncertainty, the point of closest approach with the operator's spacecraft, and an estimate of the probability of collision. These data are sufficient for the operator to determine whether a maneuver is necessary—based on their risk tolerance—and when and how to perform a collision-avoidance maneuver that eliminates the identified risk without creating new potential collisions.

Close approaches and COLA are becoming increasingly relevant beyond Earth's orbit. The increasing population of spacecraft in cislunar and lunar (and Martian) space is increasing the risk to all operators there. One notable close encounter over the moon occurred in November 2021 between the Lunar Reconnaissance Orbiter and the Indian research satellite Chandrayaan-2, when a conjunction was close enough to prompt a collision-avoidance maneuver.[14] This COLA maneuver in lunar space became necessary with only a handful of active objects in lunar orbit. As the population increases to dozens from a growing community of international, commercial, and military actors—and as the monitoring of lunar space debris begins with the arrival of new space domain awareness capabilities—frequent COLA may become the norm in lunar space as it is at the Earth.

The ODMSP, AFI 91-202, and NASA-STD-8719.14 cover debris collision risk and collision avoidance in detail. Some requirements address prospective risk evaluated during mission development, such as setting maximum probability thresholds over centuries-long timescales for collision with small- and large-object debris. These metrics are affected by the selection of operational orbit and a spacecraft's physical dimensions. Other requirements address whether or how an operational mission should perform screening for close approaches and conduct collision avoidance. For example, AFI 91-202 requires Air Force space systems to have a COLA process and to use conjunction-assessment products from the 18th Space Control Squadron (now 18th Space Defense Squadron). A mission subject to the AFI's authority must show that it can 1) Identify upcoming close approaches, 2) Calculate the probability of collision of a close approach, and 3) Take action to reduce the probability of collision below specified thresholds.

The requirement shortfalls described above addressed several concerns relevant to this recommendation, including the breakdown of COLA algorithms in the cislunar regime, the lack of cislunar debris and population models, and the lack of best practices for long-term cislunar orbit propagation. All of these shortfalls must be addressed for an adequate resolution of this recommendation.

Additionally, this recommendation anticipates the need to produce cislunar COLA products. The DOD is not currently capable of natively producing operational COLA products for cislunar or lunar orbits. The heritage capabilities developed for geocentric safety of flight do not admit a ready translation to another central body or other multibody reference frame. Furthermore, the two-line element set (TLE), which is the standard artifact

Space Situational Awareness (SSA): Current and predictive knowledge of the space environment.

Space Domain Awareness (SDA): The effective identification, characterization, and understanding of any factor associated with the space domain that could affect space operations.

produced by the DOD containing satellite state information and used for collision avoidance by many operators, is defined only for elliptical orbits. The leading alternative for cislunar flight safety is the Multimission Automated Deepspace Conjunction Assessment Process (MADCAP), which is an operational process at the NASA Jet Propulsion Laboratory that screens ephemerides for spacecraft not orbiting the Earth.[15] Participation in MADCAP is voluntary for operators outside of NASA, and MADCAP can perform conjunction assessments only if it receives ephemeris data from those volunteers. MADCAP's conjunction assessments have prompted many collision-avoidance actions, beginning with COLA maneuvers between Mars orbiters in 2005. However, an Air Force mission that participates in MADCAP's services is still not technically compliant with AFI 91-202's requirements. Because uncertainty (also known as "covariance") information is often unavailable, MADCAP calculates conjunction assessments via close-approach distance. The AFI, however, requires that a mission perform screenings based on probability of collision, which depends on both position and uncertainty information, and be capable of verifying the reduction of probability of collision via a COLA action. Because MADCAP does not have this information, it is not possible to comply with these two requirements today, even when using MADCAP.

This recommendation for updating calculations for collision risk and avoidance maneuvers requires a multifaceted outcome. First, a series of technical publications should document best practices for robust and computationally efficient long-term propagation of orbits in cislunar space for flight safety and disposal purposes. The community should develop guidance or standards for different tiers of fidelity depending on application (e.g., the level of fidelity necessary for disposal compliance vs. collision avoidance), as is common in geocentric applications, where community standards exist on when and where to use "low" or "high" fidelity propagation around the Earth. No *formal* rules exist for propagation of even geocentric orbits, and similarly they are unlikely to be necessary for cislunar orbits, but the community's lack of familiarity with cislunar flight suggests that guidelines would be valuable to ensure the proper use of propagation tools. This outcome may also include incorporating a blessed cislunar orbit propagator into the U.S. government's Standardized Astrodynamics Algorithm Library (a.k.a., the "Astro standards").

Second, a similar series of technical publications should recommend algorithms for robust covariance calculation and propagation in cislunar space, calculation of probability of collision, and best practices for planning cislunar COLA maneuvers. This analysis should include an assessment of where and how current assumptions for covariance realism break down in the cislunar regime and how to implement computationally efficient covariance propagation. Accompanied by this technical effort, commercial industry and the government should invest in the development of an operational cislunar COLA process that ingests both cislunar orbit information and uncertainty to yield decision-quality COLA products.

Lastly, the community should publish debris models for the beyond-GEO, cislunar, and lunar regimes that incorporate both natural and man-made sources of debris flux. These models must have sufficient fidelity and accuracy to meet the needs of pre-flight collision risk assessment, as currently expected for missions to LEO, MEO, or GEO. These debris models may be extensions to current capabilities

Two-Line Element Set (TLE): A data format for specifying an object's orbital elements.

Ephemeris Data: The data set that provides position information of a celestial object.

(e.g., ORDEM and MASTER) or separate tools, and they will evolve over time as our understanding of the cislunar debris involvement matures with the advent of new systems for cislunar space domain awareness.

Long-Term Cislunar Disposal

Recommendation: Policy and requirements documents should be updated to be consistent with cislunar orbital mechanics, accommodate long-term disposal, and protect cislunar regions of interest.

Missions to cislunar space need options for disposal that are consistent with the realities of operating there. Cislunar space is vast, and it may not be feasible or affordable for most missions to default to currently sanctioned disposal options, such as reentry at Earth or transferring to approved graveyard orbits (e.g., near GEO). However, the great volume of cislunar space does not mean that derelict missions should be left in place, which was the historical practice for geocentric missions until the late twentieth century. In the multi-body gravity of the Earth-moon system, objects tend to traverse the entire volume of cislunar space over years-long timescales. A derelict abandoned in a random state in cislunar space has a high probability of passing through regions of great interest, such as Lagrange points, at random intervals and posing a risk to active spacecraft there.

The ODMSP recognize a valid disposal option of “storage above GEO,” where a spacecraft must maneuver “sufficiently above GEO to ensure the structure remains outside GEO for >100 years.” If applied literally to the cislunar regime, this requirement yields unintended consequences: strictly speaking, all cislunar and lunar space is “above GEO” and could be exploited for disposal. The ODMSP’s most recent updates in 2019 deliberately did not address the implications for missions beyond GEO, but we recommend that the next cycle revisits the language’s current equal treatment of all space above GEO. Storage “above GEO” likely requires a ceiling. Furthermore, the ODMSP admit “heliocentric Earth escape” as a disposal option, but no further guidance or definitions are provided. “Earth escape” has meaning in the Keplerian two-body sense, but in the three- and multi-body problem it is possible technically to have escaped in the Keplerian sense but still return.

The need of future cislunar mission for long-term disposal options raises the following concerns:

- ***Lack of cislunar-specific disposal options.*** The disposal options in the current ODMSP may require infeasible amounts of propellant to return from cislunar or lunar space to Earth or to enter a MEO or GEO graveyard. But there are no alternative disposal options or graveyards in cislunar space. Cislunar disposal regions might be defined in terms of altitude, specific regions (e.g., the stable L4 and L5 Lagrange points may be candidates), or other variables that ensure the long-term sustainability of the regime overall. This absence of disposal regions has an impact on early mission planning: without cislunar-specific disposal options, mission developers must proceed with the design of a spacecraft and its propulsion system while uncertainty persists in where they will be permitted to dispose of the spacecraft at end of mission.
- ***Insufficient understanding of cislunar debris dynamics.*** The long-term, high-precision propagation of a single object in the multi-body regime is challenging, and the accurate evolution of a debris cloud is even more so. The development of viable disposal options in cislunar space will require an understanding of how debris—either intentionally released or

Debris Flux: The amount of debris passing through a given area in a given amount of time.

created from unintentional collisions or explosions—evolves in this regime over time and whether it disperses throughout the system uniformly or if regions of concentration persist over longer periods of time.

- ***No definitions of protected cislunar orbits.*** Many orbits in the Earth-moon system have great utility for manned and unmanned spaceflight, but no policy exists to codify whether or how they should be protected. The ODMSP clearly define LEO, MEO, and GEO regions where flight safety and long-term disposal rules apply, but no such definitions yet exist for useful cislunar orbits, including: Lyapunov or halo orbits near the Earth-moon or Earth-sun Lagrange points, near-rectilinear halo orbits and distant retrograde orbits near the moon, or frozen orbits around the moon. These regions of high utility in cislunar space are vast—far larger than the protected volumes of LEO, MEO, or GEO—and do not admit easy definitions in terms of, say, altitude bounds, and orbital elements have no meaning in the multi-body regime. It is not clear how best to categorize cislunar orbits into regimes that are general enough to be documented succinctly in policy but are also quantitative enough for flight safety and disposal purposes. Furthermore, consensus does not exist on the meaning of "protected" in the cislunar regime. The ODMSP require that satellites in the GEO graveyard not cross the protected region of GEO itself for more than 100 years after disposal. Is a century-long timescale also appropriate for cislunar? How reliably can current modeling capabilities determine whether a derelict will remain outside a protected region for a century or more?

The resolution of these questions of cislunar disposal will require several updates to the ODMSP and its derived requirements documents, bolstered by extensive technical analysis. One such update should introduce rigorous definitions of terms that are currently insufficient when translated to the cislunar regime, such as "heliocentric Earth escape" and "storage above GEO." Specifically, ODMSP Section 4-1a should include a new definition of "heliocentric Earth escape" to capture the spirit of the original requirement (namely, to ensure that a disposed vehicle will not return to the Earth-moon system for a decades- or centuries-long period of time). The new definition could eschew the "escape" language entirely and instead define a period of time over which the disposed satellite should not return to a defined volume of space, similar to how "storage above GEO" is currently defined (i.e., no passage within the protected regions for more than 100 years).

Another update to the ODMSP should identify new long-term disposal orbits or graveyard orbits in the cislunar regime, if any are appropriate and meet criteria for sustainability. The viability of a candidate cislunar graveyard will require an evaluation of 1) The graveyard's sustainability (i.e., whether the region is stable enough to ensure the confinement of derelicts over a long period of time, whether the derelicts in the graveyard pose a risk to active missions nearby, and what the carrying capacity of the graveyard may be), 2) Opportunity costs to using the graveyard in light of active missions that may want to use the same region of space, and 3) The graveyard's reachability and costs in terms of transfer time, propellant, and operational

Near-Rectilinear Halo Orbit: An orbit near one of the L1, L2, or L3 Lagrange points with nearly straight sides between passes with the orbiting celestial object.

Distant Retrograde Orbit: A highly stable orbit around a planet-moon system due to the balanced gravitational pull of the bodies.

Frozen Orbit: An orbit in which the effect of perturbations on the mean orbital elements is minimized.

complexity for insertion, which would affect the graveyard's palatability to mission planners regardless of its sustainability.

Lastly, the ODMSP should be updated with rigorous definitions of protected regions and orbits in cislunar space. In these regions, disposal would be unacceptable, or defunct vehicles disposed elsewhere (e.g., in notional cislunar graveyards) would not be permitted to cross them. These protected regions should complement the definitions in the ODMSP for LEO, MEO, and GEO, which are defined in terms of altitude bands.

Summary and Conclusions

The results of this review indicate that updating policy and requirements to accommodate cislunar sustainability will not be a quick fix. The ODMSP and organization-specific requirements have more than a dozen significant disconnects and shortfalls if one attempts to extend them as-is to cislunar missions and operations. These shortfalls have both policy and technical implications and will require investment in quantitative analysis, national and international coordination, and the acquisition of new capabilities to resolve them.

We cannot count on a speedy resolution to many of these shortfalls or their associated recommendations above. Some actions, such as updating the definition of "heliocentric escape" as a disposal option, are well-bounded and primarily technical questions with a relatively clear path to closure. But addressing lunar impact as a disposal option has both deep technical questions that span multiple fields, from orbital mechanics to fluid mechanics to geology, and challenging policy questions, such as whether and how to incorporate planetary protection into the ODMSP. And addressing the lack of cislunar debris and population models will demand not only an initial investment to stand-up prototype and operational solutions but also long-term and potentially indefinite sustainment.

If the government and space community do not act to extend the ODMSP to cislunar operations, we foresee three substantial risks. First, mission priorities to cislunar space may be compromised. If disposal rules in cislunar and lunar space remain ambiguous or undefined, missions may be hesitant to plan for otherwise useful orbits because they cannot be sure they will survive ill-defined regulatory hurdles. For example, the standard

Table 1: Overview of Policy and Knowledge Gaps

Requirement/Policy Shortfalls	Capability/Knowledge Shortfalls
Not addressing the release or creation of debris near the Moon or in cislunar space	Lack of standards for long-term cislunar propagation
Not addressing lunar impact as a disposal option	Poorly understood cislunar debris dynamics
Insufficiency of "storage above GEO" disposal option	No framework for cislunar collision-risk assessment
No technically rigorous definition of "escape"	Lack of cislunar debris and population models
Lack of cislunar-specific disposal orbits or graveyards	Lack of a native DOD cislunar COLA process
Not addressing planetary protection	Unknown sensitivity of disposal compliance to initial or insertion conditions
Lack of rigorously defined protected regions in cislunar space	

disposal technique for missions in low lunar orbit is impact with the lunar surface, but it is not clear if lunar impact would pass regulatory muster now (e.g., for commercial missions seeking approval through the FCC) and if it will remain a viable option in the future with a larger population in lunar orbit. If that option's viability remains in limbo, potential missions may choose to avoid low lunar orbit entirely. If the ODMSP and other requirements documents remain silent on lunar impact and cislunar disposal orbits, future missions may compromise on baseline mission orbits, mission lifetime, and operational activities in cislunar space to achieve compliance with standards that were designed for geocentric operations.

Second, a lack of action may negatively impact the sustainability of DOD cislunar operations. As noted above, the DOD does not currently possess a native capability to provide COLA services in cislunar space. The only alternative, which the DOD could notionally participate in, was developed by NASA to deconflict science orbiters around Mars and the moon. Upcoming DOD cislunar missions may participate in these alternatives, but if the DOD does not act to develop a native cislunar COLA capability and update its own requirements for flight safety, it may have to rely on external organizations in perpetuity for its own flight safety beyond GEO.

Third and most concerning, a failure to update the ODMSP and requirements for cislunar operations may limit access to cislunar space in the coming decades. The opportunity exists today while cislunar is relatively pristine to avoid some of the mistakes that have increased the debris population in LEO and GEO. Near-term cislunar missions are likely to seek waivers to some requirements to complete their SDARs and ODARs. Although any one waiver may not be harmful on its own, the normalization of waivers for cislunar missions runs the risk of creating the same congested environment in cislunar space that has arisen in LEO and GEO. Without clarity and enforcement of acceptable cislunar disposal approaches, there will be less incentive for missions to perform design trades that incorporate sustainable disposal. The lack of mutually agreed requirements and norms combined with the institutional momentum behind executing programs may leave decisionmakers susceptible to the temptation to grant waivers and allow vehicles to die in place or dispose in an otherwise unsustainable fashion.

The number of planned or currently executing missions beyond GEO is growing, with many new participants across the U.S. government and around the world. At a minimum, the U.S. government can and should harmonize internally on a minimum set of standards for sustainable behavior in cislunar space. The Space Force is planning at least two missions to cislunar and lunar space by 2024, each of which must go through an SDAR process that is not currently suited for that orbital regime. And missions to the moon are being discussed by commercial industry, which will be obligated to go through the FCC and write an ODAR, but the ODAR process has the same shortfalls when translated to cislunar. If unified government action is not taken in the next two years, widely disparate standards of sustainability may be enforced by different organizations based on extemporaneous rulemaking in the absence of a concerted, quantitative effort to determine the best path forward.

Acknowledgments

The author thanks The Aerospace Corporation's Office of the Chief Technology Officer for funding the review and analysis presented in this paper. Many thanks also to the project's diverse team of subject-matter experts, including Carter Franz, Brian Hansen, Gregory Henning, Austin Huffman, Juan Maldonado, and Daniel Pachura, who made it a success.

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