Cislunar Missions End-of-Life Disposal Strategies

Joshua Wysack
BAE Space & Mission Systems

ABSTRACT

Increasing traffic in cislunar space and the on-going return to the Moon requires strategies for spacecraft disposal when missions come to the end-of-life (EOL). These strategies must consider the future space environment where more objects will reside in orbit near the Moon and Earth-Moon Lagrange points. This work will present an examination of EOL disposal strategies for spacecraft in cislunar space. It is hoped that this technical perspective will assist policy makers to render informed decisions for national and international guidance on cislunar EOL spacecraft disposal. Effective EOL disposal plans are essential to ensure the safety of human spaceflight and the future of cislunar spaceflight.

1. INTRODUCTION

The lack of a binding Earth-orbit end-of-life (EOL) policy in the early stages of spaceflight resulted in many objects that will remain in Earth orbit for centuries. These objects pose a collision threat that may result in a debris cloud that could be crippling to active missions and the services that rely on those missions. In 2001 the Orbital Debris Mitigation Standard Practices (ODMSP) were established to address spacecraft EOL disposal for Earth-orbiting missions. A robust policy is lacking for missions in cislunar space. This could lead to future risk to lunar human spaceflight missions and the growing number of missions going to the Moon and other cislunar orbits.

Despite the vastness of cislunar space, several areas are certain to become more congested with spaceflight traffic as countries and private enterprise continue the push to the Moon and surrounding space. These include regions near the Moon and the five Lagrange points, particularly L1 and L2.

In this paper, we examine several EOL disposal options for cislunar missions. This involves evaluation of the risk to cislunar spaceflight as well as potential harm to future lunar surface infrastructure. Candidate strategies include,

- Leave Earth-Moon system
- Transition to a graveyard orbit
- Controlled re-entry into Earth's atmosphere
- Crash into the lunar surface

Many factors contribute to the selection of a disposal strategy. The choice is influenced by the mission orbit and its stability, the maneuver capability of the spacecraft, and the long-term risk of close approaches to the Earth or Moon. Maneuver plans will be shown for each disposal strategy and the maneuver magnitudes will be compared, since this is one of the prime considerations in the disposal strategy choice.

Finally, we will discuss implications for future lunar and cislunar missions and how this work may guide future space policy. This will start with a survey of current policy and guidelines. An example is The Policy on Planetary Protection from the Committee on Space Research (COSPAR), which provides guidelines on lunar impacts.

The safety of future space missions, lunar infrastructure, and lunar natural resources are dependent upon the mission design choices that are made in the coming decades. Without clear guidance and strategies on EOL disposal it will be up to each individual operator to make smart choices for the greater good of the cislunar space environment. A thorough examination of the various strategies and the best choices will aid policy makers in putting forth clear guidance.

2. THE CISLUNAR END-OF-LIFE DISPOSAL PROBLEM

The number of objects in Earth orbit has increased dramatically since the launch of Sputnik in 1957. Figure 1 [1] [2] shows the historic growth of the number of objects in space separated by orbit family. This data shows a steady increase until a large increase near 2010 of the number of objects in Earth orbit. Given the growing space object population, in 2001 NASA published the Orbital Debris Mitigation Standard Practices (ODMSP) that provided guidance for the disposal of spacecraft when they would no longer be actively maintained. Possibly deactivated and without maneuver capability. These disposal guidlines dictate that spacecraft be removed from active regions of space by deorbiting via Earth atmosphere reentry or transition to a graveyard orbit where they will not interfere with current and future missions.

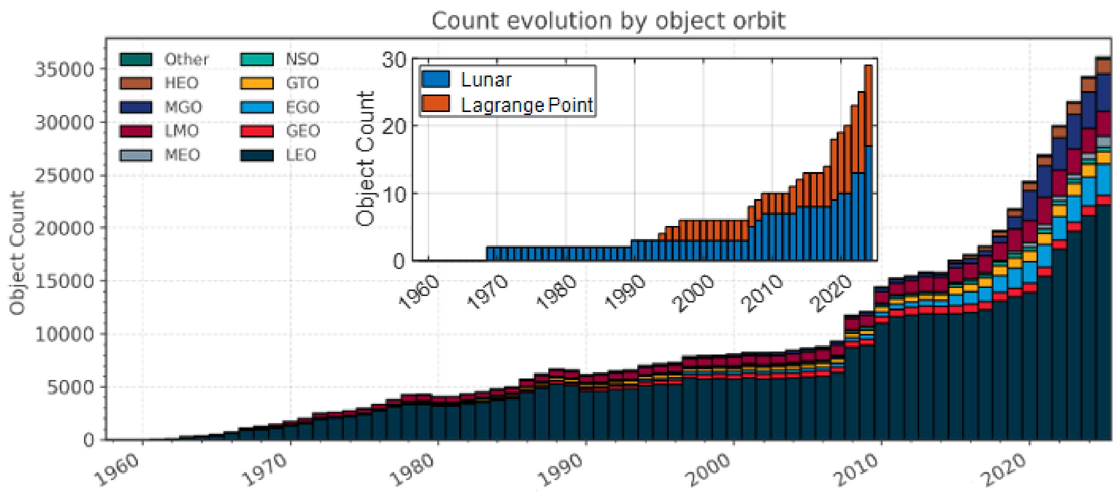

Fig. 1: Historical count of objects in Earth orbit [1] and Lunar and Lagrange Point orbits [2]

The object population in cislunar and lunar space is also increasing. The spike in the number of objects in the late 1960's was followed by a lull in launches, but the count began to climb in the 2010's and 2020's and is anticipated to grow over the coming decades. Several cislunar regions are likely to become highly populated as strategic locations near Lagrange points, such as Earth-Moon L1 (L1), are used for spacecraft providing services such as communication, navigation, Space Domain Awareness (SDA) & Space Traffic Management (STM), and other services. Spacecraft in these cislunar orbits should perform disposal near EOL to limit the risk of future debits events due to collisions or impacts with the Earth or Moon.

2.1 Disposal Guidelines & Requirements

In this section an overview is provided for some of the guidelines and requirements for space object disposal at end of life. The sources are from both national and international organizations. For each document, the key takeaways concerning disposal are summarized.

NASA - Orbital Debris Mitigation Standard Practices (ODMSP) [3] This document provides guidance on end-of-life or end-of-mission disposal, with the primary purpose to provide guidelines for mission operating practices that will limit the amount of debris in space. The disposal of spacecraft is an important part of this. The content focuses on spacecraft in Earth orbit, with no direct mention of orbits beyond GEO. Objective 4 on Postmission Disposal of Space Structures states:

- "Disposal for final mission orbits: A spacecraft or upper stage may be disposed of by one of the following methods:
- a. Direct reentry or heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit at the end of mission into (1) a reentry trajectory or (2) a heliocentric, Earth-escape orbit. These are the preferred disposal options."

NASA Orbital Debris Program Office - TECHNICAL STANDARD NASA-STD-8719.14 Version C – Process for Limiting Orbital Debris [4] provides specific technical requirements for limiting orbital debris and methods to comply with the NASA requirements for limiting orbital debris generation. Postmission disposal is described in requirement 4.6.3.14,

- "For missions to Sun-Earth Lagrange Points and Earth-Moon Lagrange Points, projects should plan for post-mission disposal to not interfere with future missions to those regions."

NASA - Orbital Debris Assessment Report (ODAR) [4] is part of NASA-STD-8719.14 that requires a description of plans for postmission disposal. This document is delivered and reviewed in the mission planning phase. Section A.1.5 states,

- "Lunar, Mars, Sun-Earth, and Earth-Moon Lagrange point missions must assess the mission compliance in the near-Earth space, up to GEO, and the applicable requirements at the mission destinations."

ESA - Space Debris Mitigation Requirements [5] is developed by the European Space Agency's (ESA) Independent Safety Office that provides authority for space debris mitigation. The requirements document provides detail for disposal from lunar orbit. These include the strategies and requirements,

- "1) heliocentric orbit, 2) lunar impact, Earth re-entry, or lunar graveyard." (in order of preference)
- "Free drift trajectories shall be analyzed for 100 years to evaluate the probability of Earth re-entry or lunar impact."
- "The suitability of possible impact area locations on the Moon surface are analysed with respect to points of interest such as space heritage artifacts, or operational assets on the lunar surface."
- "The selected disposal orbit remains with bounded variations of its orbital elements for at least 100 years."

Inter-Agency Space Debris Coordination Committee (IADC) - Space Debris Mitigation Guidelines [6] The Inter-Agency Space Debris Coordination Committee (IADC) has 10 international members such which includes NASA, CNSA, ESA, JAXA, and ROSCOSMOS. These guidelines state in Section 5.3.3,

- "Other Orbits (other than LEO and GEO), Spacecraft or orbital stages that are terminating their operational phases in other orbital regions should be manoeuvred to reduce their orbital lifetime, commensurate with LEO lifetime limitations, or relocated if they cause interference with highly utilised orbit regions."

Committee on Space Research (COSPAR) - Policy on Planetary Protection [7] - COSPAR is a part of the International Science Council with an objective to promote international level scientific research in space. The Policy on Planetary Protection provides guidelines on the biological contamination of space and celestial bodies. The document classifies lunar landers is two categories differentiated by the landing location:

- Category IIa. "All missions to the surface of the Moon whose nominal mission profile does not access areas defined in Category IIb ..." must report volatiles released by their propulsion
- Category IIb. "All missions to the surface of the Moon whose nominal profile access Permanently Shadowed Regions (PSRs) and the lunar poles, in particular latitudes south of 79 deg S and north of 86 deg N..." need to report their full organic inventory.'

In summary, these documents highlight the importance of specific Earth orbits, specifically LEO and GEO, by providing specific requirements for removal of spacecraft near EOL from those orbits. Precise definitions are often provided for each Earth-orbiting regime. For cislunar and lunar orbits these specifics and definitions are lacking sufficient detail. While the ESA requirements state a 100 year analysis period for no impact verification, a similar requirement was not found in the NASA documentation. Further adherance to space safety may occur during verfication of the ODAR, which is a necessary step for each NASA mission.

Little detail is provided on disposal using a lunar impact strategy. Mention of keep-out regions for lunar impacts is provided by ESA requirements, with a high-level definition for areas to be avoided for potential use in the future. The Policy of Planetary Projections does provide specific lunar region bounds, though the document if focused on lunar landing and guidelines for prevention of contamination from biological contamination.

2.2 No EOL Disposal Strategy

In addition to active EOL disposal strategies, the implications of no disposal strategy is analyzed. The quasi-stable dynamics of the three-body Earth-Moon system cause objects in many cislunar orbits to deviate from their nominal orbit path over long durations if not maintained by an orbit maintenance maneuver strategy. The long-term stability of three cislunar orbits (northern L1 halo, Near-Rectilinear Halo Orbit, and Distant Retrograde Orbit) are investigated. These orbits are propagated with no maneuvers for 100 years using high-fidelity dynamics.

The spacecraft in the northern L1 halo and Near-Rectilinear Halo Orbit (NRHO) both deviate from their nominal orbit path and then remain in the Earth-Moon region for several years. Figure 2 shows the evolution of the distance from Earth during the first three years, the time span of the 100-year total when the objects are closest to Earth. Both orbits pass relatively close to Earth orbits with a close approach of 1.5 XGEO for the northern L1 halo orbit.

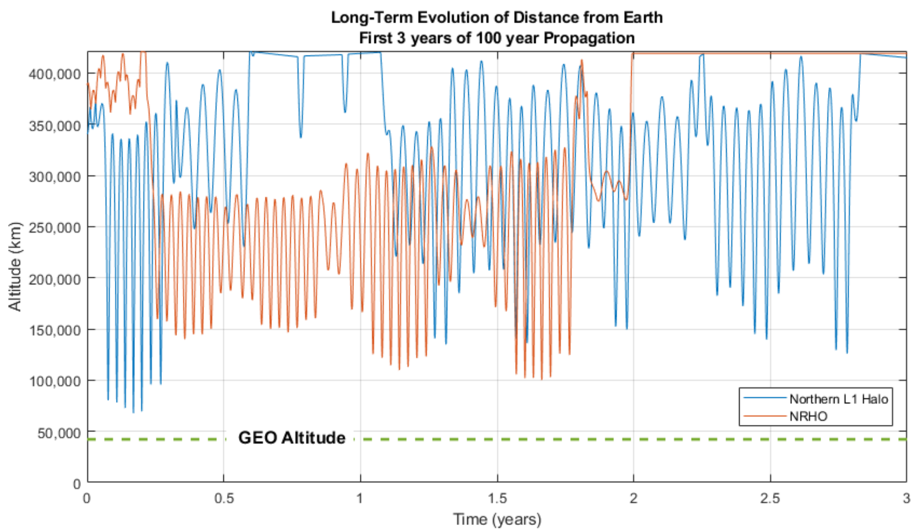

Fig. 2: Earth altitude evolution of northern L1 halo and NRHO with no disposal strategy

Members from some cislunar orbit families can remain in stable orbits for long periods of time. For instance, DRO are one of the most stable cislunar families. Figure 3 show the evolution of a sample DRO over a 100 year propagation. The Earth and Moon altitude are shown for the first and last year. It is shown that there is little deviation in the DRO's Earth or Moon altitudes over that long span. This behavior was maintained over the entire time span, meaning that the DRO will not impact the Earth or Moon even when the orbit is not actively maintained. We will utilize this property later to show that it is a good candidate for a cislunar graveyard orbit.

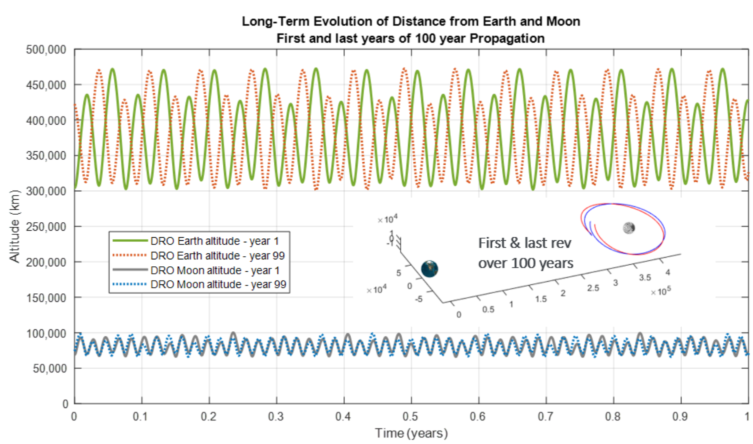

Fig. 3: No disposal strategy orbit evolution for a DRO at start and end of 100 year propagation

The next Section will provide analysis and results for the four cislunar EOL disposal strategies. The analysis steps will be presented first. For each disposal strategy, results will be analyzed through example maneuver sequences.

3. EOL DISPOSAL OPTIONS AND DESIGN APPROACH

The primary software utilized to develop disposal maneuver plans for this work is Systems Tool Kit (STK) utilizing Astrogator. STK was used for its targeting capability and to ensure that solutions could be verified using high-fidelity dynamics. Astrogator sequences were designed for each maneuver within a particular disposal strategy. The maneuver time, maneuver vector, and transit time were left as free variables to find a solution that met targets dictated by the disposal strategy. These may not be the optimal maneuvers in terms of timing or total magnitude, however, they are representative of possible solutions

The orbits analyzed herein were obtained from the JPL Periodic Orbit website [8]. They are provided in the Circular Restricted Three Body Problem (CR3BP) reference frame. For use within STK they are converted to cartesian coordinates in the Earth-Centered Inertial reference frame. A shooter method is utilized to obtain several revs of near-periodic motion under high-fidelity dynamics. This method modifies the seed velocity components to enforce the boundary condition of an orthogonal crossing of the CR3BP X-Z plane. This process is required when the trajectory is propagated under high-fidelity dynamics because trajectories modeled with CR3BP dynamics are often not periodic when subject to realistic dynamical forces. The Moon's true position is the primary perturbing force on the dynamics.

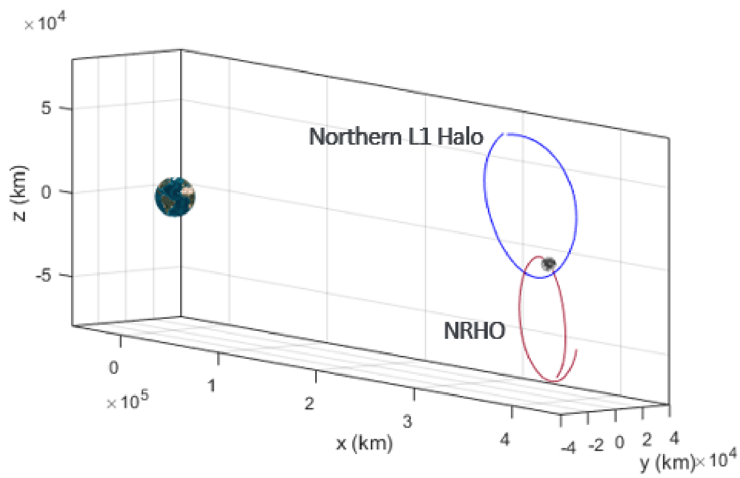

Fig. 4: Northern L1 Halo and NRHO orbits shown in CR3BP frame

Table 1: Orbit properties

Orbit	Period (days)	Stability
Northern L1 Halo	9.7	1.000
NRHO	6.3	1.016

This paper will examine disposal maneuver plans for example orbits from cislunar families northern L1 halo and NRHO. These orbits are shown in Figure 4 in CR3BP reference frame. These orbits were chosen for their viability for future cislunar missions. In particular, the Near Rectilinear Halo Orbit orbit is the chosen orbit for the future NASA's planned lunar space station, Gateway. The orbit period and stability of each orbit is provided in Table 1. Both orbits have stability near 1, with 1 being the best value possible. At higher values of stability, orbits will drift away from their periodic paths [9].

The remainder of Section 3 is dedicated to providing example maneuver plans for each EOL disposal strategy. The maneuver plans will be summarized and the considerations that went into planning them will be explained. Maneuver sequences were planned for both of the orbits. In this section detailed results are provided for the northern L1 halo orbits. The final section of the paper will show results for both orbits.

3.1 Crash into the Lunar Surface

Designing a maneuver strategy to crash into the Moon is straightforward when using a single maneuver and not considering the impact location. Hohmann-like maneuvers can be modeled that place the maneuver at the apolune crossing and target impact for perilune. This solution can be refined using STK Astrogator to verify lunar impact under high-fidelity propagation and a lunar terrain model. When a specific area on the surface must be targeted, cislunar orbits may require a set of maneuvers to setup a low altitude circular staging orbit, from which the final descent can be achieved. A target location that is in-line with the orbital plane would require minimal additional fuel to achieve. Whereas, a plane change could be required for other target areas. The staging orbit provides access to more of the surface for impact locations.

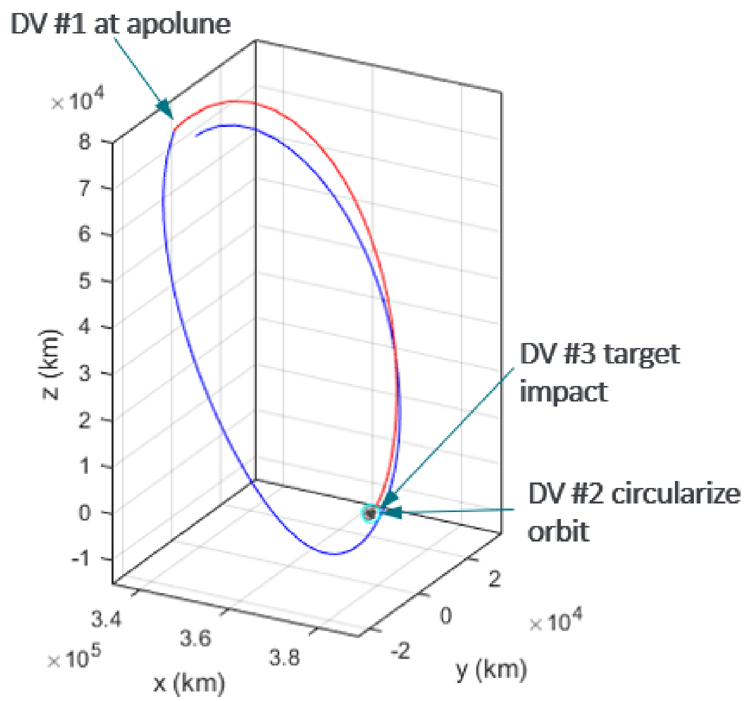

Fig. 5: Maneuver sequence resulting in lunar impact from northern L1 halo orbit shown in CR3BP frame

Here an provide an example lunar impact scenario for a spacecraft initiating a disposal via lunar impact from a northern L1 halo orbit. The goal is to target a bounded region on the Moon to avoid impacts near the polar regions. To accomplish this a sequence of manuevers is planned that utilize a circular staging orbit at 100 km.

The Moon does not lie in the orbital plane of this northern L1 halo, though the periline is close to the Moon. The maneuver sequence is illustrated in Figure 5. An initial maneuver (dark blue to red line transition) is performed to create a lunar orbit with a perilune at the staging orbit altitude of 100 km. A second maneuver (red to light blue line transition) is performed at perilune to bring apolune down to the staging orbit altitude to circularize the orbit. This maneuver is the most expensive usage of fuel which is a result of targeting a more precise landing location by using a staging orbit. By executing a final maneuver 1/2 rev prior to the crossing of the targeted impact point, the sequence can accomplish the lunar impact. Table 2 provides the maneuver data for this sequence.

There are scenarios where a single maneuver could be used to accomplish the lunar impact. This could occur if no importance is given to the impact location or the timing of the first maneuver can be planned such that the impact location can be targeted directly from the halo orbit. For the halo orbit examined here, the manuever magnitude for that scenario would be similar to the value for the first maneuver listed in Table 2.

Table 2: Summary of the maneuver plan used to impliment
a lunar impact with an staging orbit for a northern L1 halo orbit

	Days from Epoch	Magnitude (m/s)
Maneuver #1	7.3	91.8
Maneuver #2	11.5	1,308.4
Maneuver #3	12.1	20.5

3.2 Earth Return and Reentry

The Earth return disposal option considered here was evaluated using a single maneuver and a transit time on the order of single digit days. Longer transit times are possible with a possible fuel savings. That could come at the cost of additional maneuvers and transit times on the order of weeks or months.

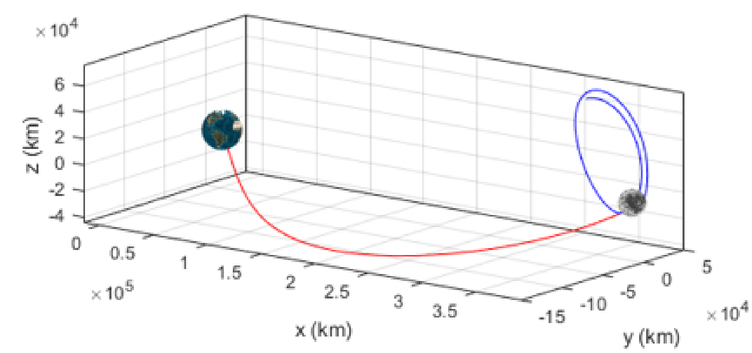

Fig. 6: Earth return trajectory from a northern L1 halo orbit shown in CR3BP frame

To illustrate an example of an Earth return for a cislunar orbit, the northern L1 halo is used as a starting orbit. The return trajectory is shown in Figure 6. To design a maneuver plan for this disposal strategy, Astrogator was used to iterate on the maneuver vector and maneuver time. The transit time was also allowed to vary with a seed of four days. The result was a single maneuver executed near perilune with a magnitude of 778.1 m/s within a transit time to Earth of 3.9 days . Though not modeled here, additional constraints on the Earth reentry would add to the compelixity of the maneuver sequence.

3.3 Transition to Graveyard Orbit

Neither the northern L1 halo or the NRHO we have examined are long-term stable orbits. As was shown in Section 2.2, the trajectory of both orbits will depart from their nominal orbit path if they are not maintained by a stationkeeping stategy. This means these orbits cannot be used for the long-term storage of spacecraft as graveyard orbits. Moreover, both orbit pass through areas that are likely to be populated by operational spacecraft in the future. Particularly the NRHO which is the future home for the NASA Gateway missions and passes close to the Moon.

As shown previously in Figure 3, orbits from the DRO family are long-term stable. The following analysis will examine an example of a transition from the northern L1 halo orbit to a stable DRO. Figure 7 shows the full maneuver sequence and the resulting transition trajectory. The first maneuver of the sequence (blue to red line transition) is a small maneuver that perturbs the orbit resulting a trajectory that is near the DRO lunar altitude at the Earth-Moon (X-Y) plane intersection. The DRO is entirely within the X-Y plane and its trajectory is orthogonal to the X-Z plane as it passes that crossing. The second maneuver (red to black line transition) uses this as a target to setup transition to the DRO. This is the largest maneuver of the three because it must accomplish the majority of the necesssary plane change. A final maneuver (black to yellow line transition) is accomplished at the X-Z crossing point. This maneuver targets future X-Z plane crossing to ensure orthogonal crossings which result in the long-term stability of the DRO. A summary of the timing and maneuver magnitudes is provide in Table 3.

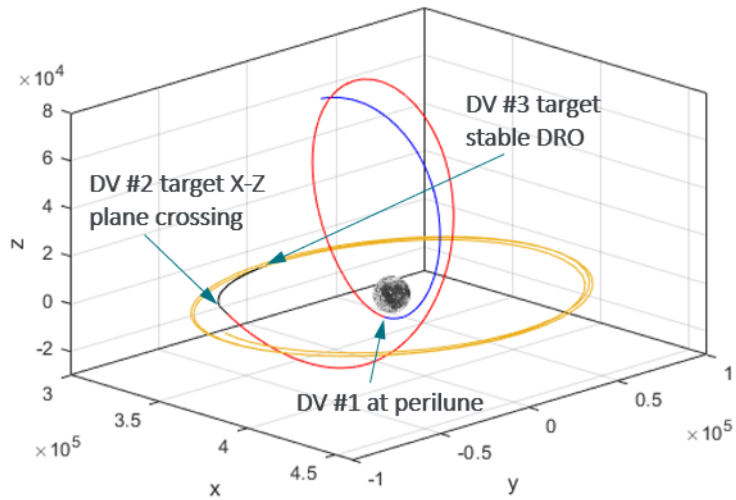

Fig. 7: Maneuver sequence to transition northern L1 halo orbit into a DRO graveyard orbit shown in CR3BP frame

Table 3: Summary of the maneuver plan used to transition the northern L1 halo orbit to a DRO graveyard orbit

	Days from Epoch	**Magnitude (m/s)**
Maneuver #1	4.2	14.0
Maneuver #2	15.8	345.7
Maneuver #3	17.9	89.5

3.4 Leave Earth-Moon System

To find a solution for leaving the Earth-Moon system, the concept of the Jacobi constant is introduced. This quantity is the only constant of integration for the CR3BP system. It is an energy-like quantity that is a function of the pseudo potential energy and the specific kinetic energy. The equation for the Jacobi constant is formulated as,

$$C = 2U^* - \vec{v}^2 = (x^2 + y^2) + 2(1-\mu)/d + 2\mu/r - n^2(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) \quad (1)$$

Where U^* is the pseudo potential energy, μ is the mass ratio $\mu = M_{moon}/(M_{earth} + M_{moon})$, n in the nondimensional mean motion, d and r are the distance between the spacecraft and the Earth and Moon, respectively as shown in Fig 8.

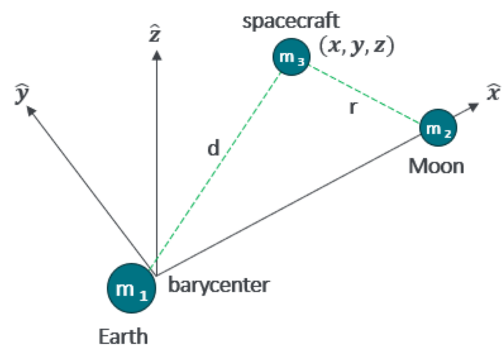

Fig. 8: Definition of the CR3BP frame

In the absence of external non-gravitational forces, a trajectory will maintain a constant Jacobi constant. At positions where the spacecraft has puts all energy into the potential the velocity goes to zero and the concept of Zero Velocity Curves (ZVC) is introduced. These curves, or surfaces in 3 dimensions, bound forbidden regions where the trajectory can not enter with its current Jacobi constant value [10]. Applying an external force such as a maneuver changes the shape of the ZVCs, which can create an opening near L2. Figure 9 displays the concept and shows that there are energy levels that provide an opening near L2 while no other openings to the Earth-Moon system are available. Thus, under the CR3BP dynamics, the object is unlikely to reenter the Earth-Moon system once it has escaped.

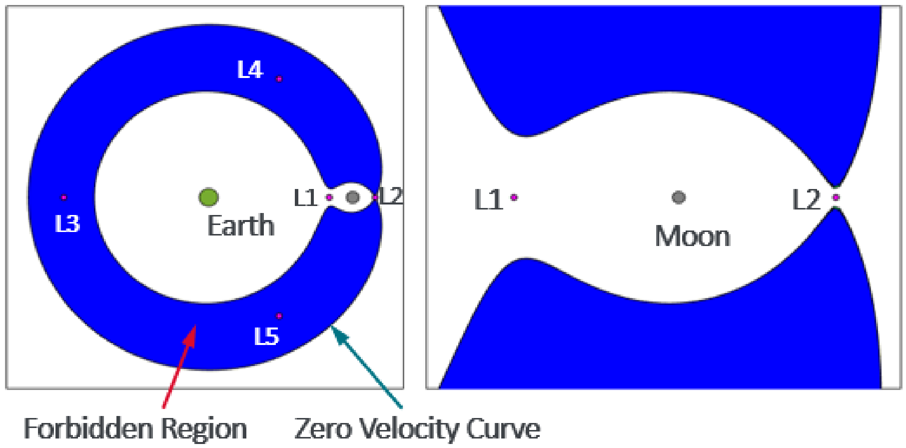

Fig. 9: Forbidden regions defined by Zero Velocity Curves, viewed in CR3BP frame X-Y plane cross section. Entire three-body system (left), close up of opening near L2 (right).

Boudad [11] used this method for a NRHO to show that maneuvers on the order of 1 m/s can be applied to achieve the energy that will result in a trajectory that exits through this L2 passage opening. This concept is applied for the cislunar orbits considered in this paper. For the NRHO, a 1 m/s maneuver was applied, then the maneuver direction and time were adjusted until a trajectory was found that exited the sytem through the L2 opening. The long-term effectiveness of this disposal strategy was evaluated through a 100-year propagation to ensure that there were no encounters with the Earth or Moon over that time. Figure 10 shows the example departure trajectory for the NRHO orbit.

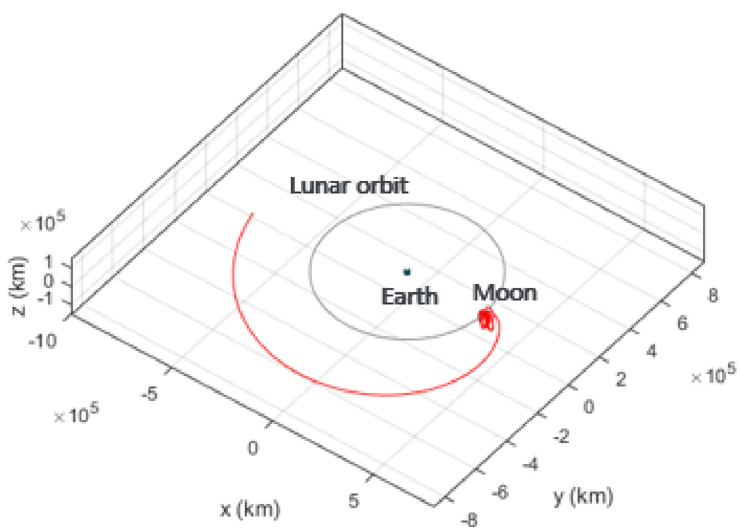

Fig. 10: Earth-Moon system exit trajectory for NRHO shown in CR3BP frame

The same method was utilized for the northern L1 halo. A solution could not be found that led to a direct exit of the Earth-Moon system through the opening near L2. However, many solutions for small maneuver magnitudes were found that resulted in trajectories that 'bounced' within the forbidden zone before exit. Figure 11 shows the trajectory for one of these solutions for a 10 m/s maneuver with a trajectory that remained in the system for 82 days. The trajectory stayed clear of Earth-orbiting objects during that time span.

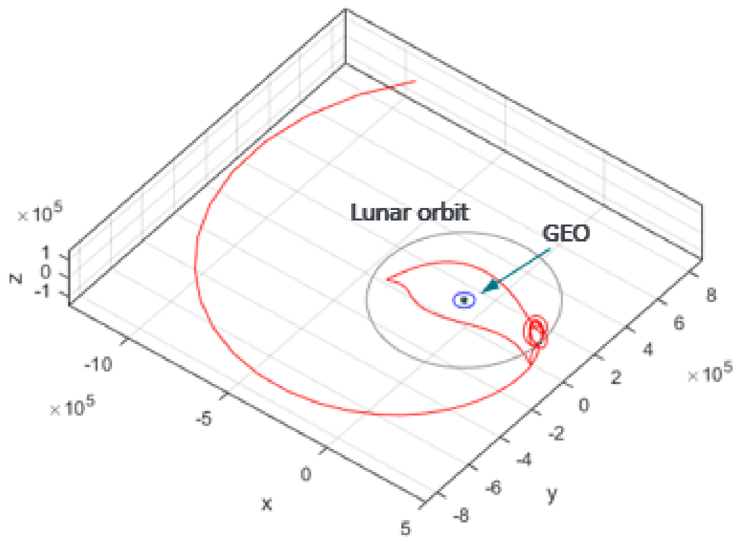

Fig. 11: Earth-Moon system exit trajectory for northern L1 halo orbit shown in CR3BP frame. Orbits of the Moon and GEO are shown to add perspective.

4. CONCLUSIONS & RECOMMENDATIONS

The expected growth of satellites in cislunar space as part of the future lunar exploration and lunar economy will lead to congested orbits and raise the risk of collisions, much like near-Earth. Safe EOL disposal of spacecraft in cislunar orbits is necessary to maintain the safety of future spaceflight.

Leveraging existing EOL disposal policies for Earth-orbiting satellites, this paper discusses the lack of clarity in those policies as related to cislunar space. This work demonstrates the impacts of doing nothing for disposal, showing that for some orbits the quasi-stability of the orbits can lead to large orbital changes in the long-term trajectories, which can present threats to the cislunar environment. The modeled dynamics for some orbits however, are stable which leads to the conclusion that there may be opportunities for cislunar graveyard orbits, analogous to the GEO graveyard orbit.

The data show that for the modeled disposal strategies of: Earth re-entry, lunar impact, departing the Earth-Moon system, and a cislunar graveyard, each imparts a cost on the mission design, most measurable by the maneuver cost to transfer from a mission orbit to the EOL disposal orbit. Table 4 summarizes the maneuver magnitudes for the two cislunar orbits evaluated in this work and considerations for each disposal strategy assessed.

Table 4: Summary of the EOL disposal strategies

Disposal Strategy	**Maneuver Magnitude Northern L1 Halo**	**Maneuver Magnitude NRHO**	**Considerations**
Earth Return & Reentry	778.1 m/s	928.6 m/s	• Guidelines of burn up verification and no loss of life
Crash into the Lunar Surface (no impact location targeted)	1,311.8 m/s 91.2 m/s	716.4 m/s 23.7 m/s	• Avoiding sites due to resources, science, or historical reasons • Increased fuel cost of staging orbit
Transition to Graveyard Orbit	357.4 m/s	618.2 m/s	• Complexity increases if graveyard orbit is difficult to achieve • Verification of long-term safety of disposal orbit
Leave Earth Moon System	10.0 m/s	1.0 m/s	• Verification of long-term safety of disposal orbit

The best disposal option is dependent upon the initial mission orbit. For the Langrange point orbits analyzed herein, leaving the Earth-Moon system provides a favorable solution based on the low maneuver magnitude required to accomplish the disposal. This is just a sampling of possible results. Spacecraft in other orbits will have to evaluate the best option, though they should consider this in the mission design phase to budget the amount of fuel that will be required to accomplish the EOL disposal.

International policy should be implemented that outlines best policy recommendations for missions along with guidance on what safe disposal means. It is recommend that this include:

- Definitions of removal zones for lunar orbits or trajectories passing through lunar orbit zones
- Designated regions on lunar surface to avoid impacts
- Requirements for disposal solution verification
- Definition of graveyard orbits and guidelines for their use as a disposal orbit

These policy updates would allow cislunar missions to adequately plan for their spacecraft's EOL disposal plan and fuel requirement in the design phase. It would also lay the groundwork for a safer cislunar environment for future traffic in this region of space.

5. REFERENCES

[1] Philippe Pinczon du Sel. Space artefacts *https://spaceartefacts.com/*.
[2] Space Debris Office at ESOC/ESA. Space debris user portal *https://sdup.esoc.esa.int/discosweb/statistics/*.
[3] NASA Orbital Debris Program Office. U.s. government orbital debris mitigation standard practices, november 2019 update, (2019).
[4] NASA Orbital Debris Program Office. Process for limiting orbital debris nasa-std-8719.14c, november 2021 update, (2021).
[5] ESA Space Debris Mitigation Working Group. Esa space debris mitigation requirements, october 2023 revision 0, (2023).
[6] Inter-Agency Space Debris Coordination Committee. Iadc space debris mitigation guidelines, revision 2, (2020).
[7] Cospar policy on planetary protection. *Space Research Today*, 211:12–25, 2021.
[8] JPL. Three-body periodic orbits *https//ssd.jpl.nasa.gov/tools/periodic_orbits.html*.
[9] MJ Holzinger, CC Chow, and P Garretson. A primer on cislunar space. 2021.

[10] R. Wright, L. Tafur, N. Owens Fahrner, and J. Wysack. Monitoring and Tracking Accessible Invariant Manifolds in The Cislunar Regime. In S. Ryan, editor, *Proceedings of the Advanced Maui Optical and Space Surveillance (AMOS) Technologies Conference*, page 204, September 2023.
[11] Kenza Boudad, Diane Davis, and Kathleen Howell. Aas 18-289 disposal trajectories from near rectilinear halo orbits. 08 2018.