Cislunar Space Traffic Management based on Operational Zones

By Sourav GHOSH,[1)] Prathap M SHARMA,[2)] Samarth BADGUJAR,[3)]
and Siddhartha PUNDIT,[2)]
[1)]*Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan*
[2)]*Independent Researchers, Bengaluru, India*
[3)]*Department of Industrial Engineering, University of Padua, Padua, Italy*

Following the rising space traffic observed around the Earth, mankind is slowly looking to expand further outwards, firstly towards the Moon. NASA's Artemis missions plan to have a functional manned space station in a Near Rectilinear Halo Orbit (NRHO) around the Moon (referred to as the Lunar Gateway program), and several other probes and manned missions are planned in the cislunar region within the next decade. In parallel, private players are also looking at potential constellations around the Moon for purposes such as telecommunications, lunar observation, and astronomy. Missions like these are expected to increase traffic in cislunar space by several orders of magnitude over the next few decades, and if unchecked, could give rise to issues currently observed in Earth orbit such as uncontrolled space debris related events and multi-satellite conjunctions. Previous studies have shown that dividing the cislunar region into multiple "operational zones" is a promising approach for managing traffic. It is done by characterising the zones based on the type of orbits. This study looks to explore the potential challenges for space traffic management in the cislunar space and propose a novel STM architecture based on the concept of Operational Zones. Novel relative motion based surveillance systems are also proposed for spacecraft and debris tracking, and end-of-life strategies are examined based on several performance parameters to determine which is the most efficient method. Orbits are modeled for all the mentioned scenarios and conclusions are drawn based on the observed phenomena.

Key Words: Cislunar Space, Space Traffic Management, Space Surveillance

Nomenclature

μ	:	mass ratio
Ω	:	pseudopotential
E	:	jacobi's constant
m	:	apparent magnitude
C	:	Cross section
Φ	:	phase function
H	:	apparent magnitude

Subscripts

d	:	deputy
c	:	chief

1. Introduction

The rising space traffic in the Low Earth Orbit has been a massive point of contention between most space powers in the world. The United Nations Office of Outer Space Affairs (UNOOSA) estimates that there will be over 50,000 satellites in Low-Earth Orbit within the next decade, most of which will likely belong to constellations such as those of Starlink by SpaceX and OneWeb by Eutelsat. This rise in traffic is also expected to shift outwards as mankind's ambitions move towards permanent settlements on the Moon. Navigation and Communication systems would be among the first to crowd the region, followed by orbital space stations and scientific payloads.

Improper management of LEO satellites has led to several operational challenges in recent years, which primarily includes scheduling, conjunctions with other satellites, and night sky visibility. If unchecked, operations in the cislunar region may become a nightmare due to the nonlinear nature of dynamics in the cislunar region. Trajectories of objects are chaotic, and if uncontrolled, may be a potential threat to other objects in the region, compromising operations.

1.1. Case Study: J002E3

In November 1969, the Saturn V of the Apollo 12 mission blasted off the Kennedy Space Center. The first two stages of the rocket were capable of sending the heavy payloads (the Lunar module) to LEO at an altitude of 175 miles above ground (over 280 km). The third stage of the rocket is meant to perform the Trans Lunar Injection (TLI), which is supposed to put the rocket into a lunar trajectory. Post completion of the maneuver, the remaining propellants were ejected and then the third stage would be usually guided towards the trailing edge of the Moon to be slingshot into a Solar orbit by escaping the cislunar region.

During Apollo 12, however, operational errors caused the third stage (now named J002E3) to be guided towards the leading edge of the Moon instead of the trailing edge, and thus this maneuver slowed down the spacecraft to enter a chaotic orbit in the cislunar region. The dynamics of the region caused the body to escape the system in 1971.

After J002E3 escaped Earth's gravity in 1971, it raced Earth in circles around the Sun, but it had an inner lane, so it completed 33 solar orbits in the time it took Earth to complete 31. In 1986, the object lapped Earth on the inside, too far away to be snagged by Earth's gravity. In 2002, it was about to lap Earth again but passed too close to the L_1 portal and Earth captured it.

This is the first time a capture into Earth orbit has been verified, according to Chodas[23)]. The theoretical understanding of the shift between Earth-centered dynamics and Sun-centered dynamics has been utilized for years to design the trajectories of various spacecraft. This type of transition into Jupiter's orbit occurred several decades prior to the 1994 impact of Comet Shoemaker-Levy 9. A comparable manoeuvre will be used for a low-energy return to Earth with the samples in 2004 from NASA's Genesis mission, which is now gathering samples of solar-wind material close to the L_1 point.

When this nomadic piece of space debris broke free from its sixth orbit in mid-2003, Earth hadn't yet seen the last of J002E3. In the upcoming decades, it will once more go from solar to Earth orbit. The object will probably impact the Earth or the Moon at the end of its journey in a few thousand years. However, that is not a reason for alarm. Several rocket stages spontaneously destroyed when they re-entered Earth's atmosphere, while five rocket stages purposefully crashed into the Moon for seismic research[1].

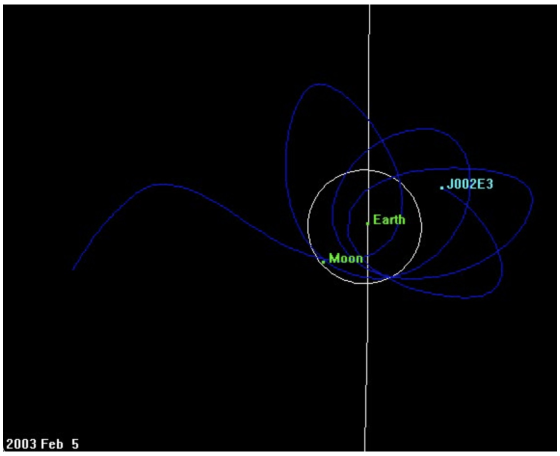

Fig. 1. J002E3's Trajectory[1].

1.2. Objectives of this Study

The main objectives of this study include:

1. To demonstrate the necessity of Operational Zones in the Cislunar Space.
2. To examine strategies for traffic management in the cislunar region.
3. To analyse the efficacy of surveillance systems using relative motion in the cislunar space.
4. To recommend policies for management of traffic and for space situational awareness in the cislunar space.

Upon studying the trajectory of J002E3, we can visualise how chaotic the dynamics of the region is. The above defined objectives can help understand the implementation of traffic management systems in the region, and can also act as a guide for creation of new space policies in the future.

The first and second sections of this paper describes the problem of space traffic management, while also defining the dynamics observed in the region, and also modeling the sensors and observation techniques used in the study. Section 3 describes existing STM techniques, followed by new approaches to surveillance and management in the region. Section 4 compares the types of surveillance orbits in terms of certain parameters, and section 5 describes policy recommendations in the cislunar region.

2. Dynamical and Systems Model Overview

2.1. CR3BP

The Circular Restricted 3-Body Problem (CR3BP) is a simplified model of the cislunar region, where motion of bodies is influenced by the gravitational forces of both the Earth and the Moon. Accounting for the force exerted by the third body (the spacecraft) on the primary body (Earth) and the secondary body (Moon) gives us a nonlinear differential equation, which is chaotic and has no analytical solutions. Thus, we may simplify the problem by assuming that:

1. The primary and secondary masses are in a circular orbit around the barycenter of the system.
2. The third body has a point mass, and exerts no force on the primary and the secondary bodies.

As observed in figure 1, the corresponding equations of motion of the system are given by[2]:

$$\ddot{x} - 2\dot{y} = \Omega_x \tag{1a}$$

$$\ddot{y} + 2\dot{x} = \Omega_y \tag{1b}$$

$$\ddot{z} = \Omega_z \tag{1c}$$

Where, Ω is the pseudo-potential term, given by:

$$\Omega = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{r_1} + \frac{\mu}{r_2} \tag{2}$$

$$r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2} \tag{3a}$$

$$r_2 = \sqrt{(x+(1-\mu))^2 + y^2 + z^2} \tag{3b}$$

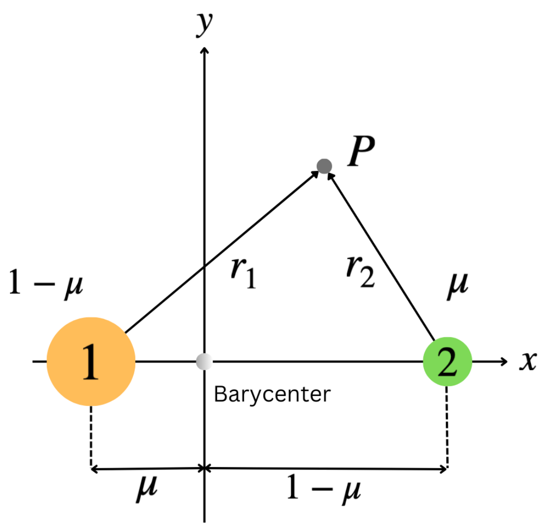

Fig. 2. CR3BP Model[3].

2.2. The Realms of Possible Motion

In the Circular Restricted Three-Body Problem (CR3BP), the *realms of possible motion* are regions in space where a spacecraft can move, constrained by its energy level, which is captured by a conserved quantity known as the Jacobi constant, given by:

$$E = 2\Omega - v^2 \tag{4}$$

These realms are visualised in figure 3, using zero-velocity surfaces (ZVS), which represent the boundaries beyond which a spacecraft cannot travel without additional energy. The shape and extent of these regions are determined by the combined gravitational and centrifugal potential in the rotating reference frame of the Earth–Moon system. At a given Jacobi constant, the motion is restricted to the regions where the kinetic energy is non-negative; outside of these regions, motion is forbidden. The boundaries of these realms—termed zero-velocity curves (ZVCs) in 2D projections—act as dynamic gates that can open or close depending on the object's energy, determining whether a spacecraft can pass between zones (e.g., from Earth to Moon vicinity) or is confined to a local region.

These motion constraints play a central role in trajectory design and mission planning in the cislunar environment. For example, Lagrange points such as L_1 and L_2 are located at narrow 'necks' in the ZVS, acting as gateways between regions—allowing transfers between Earth-bound orbits and lunar vicinities only when the spacecraft has sufficient energy. This property is exploited in designing low-energy transfers (e.g., via ballistic lunar capture or invariant manifold trajectories). Furthermore, understanding these realms is essential for passive containment or exclusion strategies in space traffic management: by placing a spacecraft at a specific Jacobi constant, it can be confined to a region where it poses no risk to other operations. Thus, the realms of possible motion serve both as a navigational map and as a control framework for shaping and predicting spacecraft behavior in the complex dynamical environment of the CR3BP.

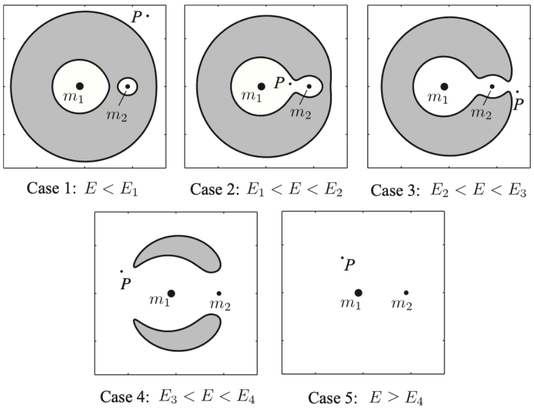

Fig. 3. Realms of Possible Motion for different E. The grey shaded regions signify the forbidden regions, and the black lines signify the zero-velocity surfaces[2)].

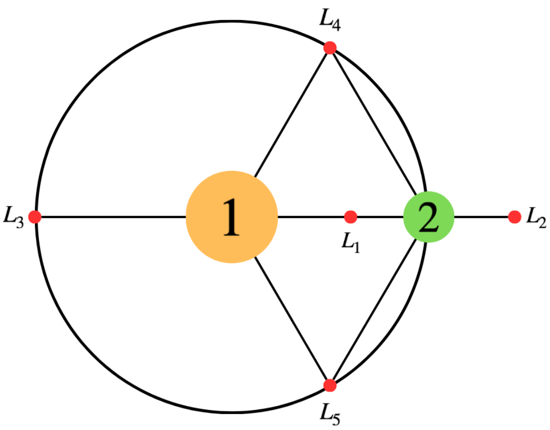

Fig. 4. Location of the Lagrange Points[3)].

2.3. Demarcation of the Cislunar Region

The Lagrange points can now be used to enclose a certain region of space in the Earth-Moon system. This region will be the hub of lunar mission activity and would be witness to major space traffic. STM, like air traffic control (ATC) systems on Earth, will be significantly more efficient. if this region can be demarcated. This demarcation can be done with establishing operational zones. Once again using the example of ATCs on Earth, each zone would behave as a different controller, managing different phases of flight. An ideal representation of the demarcation of cis-lunar space, given by Cunio et. al. (2021) [3] is depicted in figure 5.

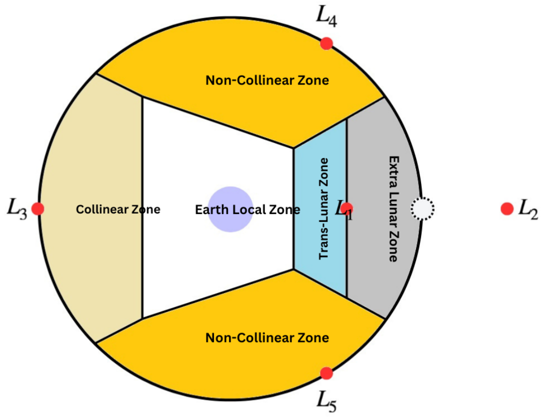

Fig. 5. Demarcation of Cislunar Region[3)].

2.4. Orbit Characterisation

The orbits that occupy the zones defined in cislunar space (seen in figure 5) can be characterised into a number of distinct orbits per zone.

2.4.1 Earth Local Zone

The Earth Local Zone is defined by regions where motion can be accurately described using two-body dynamics. The boundary often ends where trans-lunar injection would begin in lunar missions and mainly consists of the following orbits:

1. Low Earth Orbits
2. Medium Earth Orbits
3. Geostationary Orbits
4. Geosynchronous Orbits
5. Sun-Synchronous Orbits

2.4.2 L_3 Collinear Zone Orbits

The L_3 libration point being one of the collinear points, inherits identical dynamics around it as to those near L_1 and L_2. Thus we observe the following orbits:

1. Halo Orbits
2. Lyapunov Orbits
3. Vertical Orbits
4. Axial Orbits

2.4.3 L_4 and L_5 Non-Collinear Zone Orbits

The stability of L_4 and L_5 makes them unique in the Earth-Moon system. They are ideal for long duration space observatory missions and parking orbits. These orbits vary from those found in collinear points and include:

1. Vertical Orbits
2. Axial Orbits
3. Short Period Orbits
4. Long Period Orbits

2.4.4 Trans and Extra-Lunar Zone Orbits

Located near the L_1 and L_2 points, this region is often comprised of highly elliptic orbits that are part of orbital transfers such as Trans-Lunar and Trans-Earth injections. Trans and Extra Lunar Zone Orbits will see an increase in traffic with the increase in lunar exploration, particularly with manned missions due to their relatively lower radiation environment.

2.5. Relative Motion in the CR3BP

To enable accurate navigation, tracking, and control of spacecraft operating in the Earth–Moon system, it is essential to comprehend relative dynamics within the framework of the Circular Restricted Three-Body Problem (CR3BP). Significantly different trajectories can result from minor changes in beginning conditions, unlike the two body issue. This is especially true in areas close to Lagrange points where centrifugal and gravitational forces are balanced. Modelling the relative motion of spacecraft is crucial for mission safety and success in this setting, such as when a servicing mission approaches a defunct satellite or a spy satellite tracks a target. STM in this increasingly crowded field depends on the ability to predict future states, construct ideal rendezvous pathways, and detect possible conjunctions —all made possible by relative motion analysis.

Moreover, onboard estimate algorithms and autonomy in deep-space missions are theoretically based on relative dynamics. Spacecraft frequently have to rely on onboard sensors to determine the motion of nearby objects because ground-based observations are scarce and connection delay is high in cislunar space. One can create filters (such as Extended Kalman Filters or Unscented Kalman Filters) that precisely estimate a target's full six-degree-of-freedom state vector from sparse measurements by simulating relative motion within the CR3BP framework. This is especially helpful in situations like autonomous docking, close-proximity activities, and continuous observation from NRHO or L_1 halo orbits.

Let us now assume two satellites, a chief and a deputy in two different orbits in the cislunar space. The relative position of both bodies may be represented using:

$$\mathbf{r}_c = [x_c, y_c, z_c]^\top \tag{5a}$$

$$\mathbf{r}_d = \mathbf{r}_c + \delta\mathbf{r} = [x_c + \delta x, y_c + \delta y, z_c + \delta z]^\top \tag{5b}$$

$$\delta\mathbf{r} = [\delta x, \delta y, \delta z]^\top \tag{5c}$$

Upon linearising the equations, we can obtain the relative equations of motion as:

$$\delta\ddot{\mathbf{r}} + 2\Omega_\times \delta\dot{\mathbf{r}} = \nabla^2\Omega(\mathbf{r_c}) \cdot \delta\mathbf{r} \tag{6}$$

2.6. Visibility Magnitude of Objects

Optical systems are key to surveillance in the region. Such may be done primarily using sensors and systems which can measure the visibility magnitude of objects they are tracking.

Visible magnitude is a logarithmic measure of how bright an object appears to an observer, such as a surveillance satellite or a telescope. In space traffic management, particularly in cislunar space, it is used to determine whether an object is optically observable, given its location, orientation, reflectivity, and lighting conditions. Apparent magnitude is a critical parameter because many STM assets rely on passive optical detection, where detection is only possible if the object's brightness exceeds a given sensor threshold (typically denoted by the sensor's limiting magnitude). This study assumes the tracked object to be a Lambertian sphere, which can be defined as an ideal physical model used to describe the total reflection of incident light from the sphere's surface, where the incident is related to the intensity of light hitting the sphere, and the cosine of the angle at which it is incident.

Visibility magnitude is computed using the relation[4]:

$$m = H + 5\log_{10}(\mathbf{r} \cdot \Delta) + \Phi(\alpha) \tag{7}$$

Where, H is the absolute magnitude of the object, which is the apparent magnitude of the object at a distance of 1 AU from both the sun and the observer (i.e, the phase angle α, which is the angle between the sun, the object and the observer, becomes 0). r is the Heliocentric distance, while Δ is the observer-object distance. $\Phi(\alpha)$ is the phase function, also referred to as the illumination angle. Mathematically, we may write it as[4]:

$$\Phi(\alpha) = -2.5\log_{10}\left(\frac{1+\cos\alpha}{2}\right) \tag{8}$$

3. Space Traffic Management Strategies

3.1. Strategies in Earth Local Zone Orbits

Over the past few decades, the exponential increase of satellite installations, especially in Low Earth Orbit (LEO), has led to a substantial evolution in Space Traffic Management (STM) systems in Earth orbit. In this context, preventing in-orbit collisions, reducing the production of space trash, maintaining the sustainability of the orbital environment, and safeguarding vital infrastructure are the main goals of STM. Mega-constellations like Starlink and OneWeb are major contributors to the more than 10,000 active satellites in orbit, as was previously indicated. Sensor networks, data processing infrastructure, object cataloguing, conjunction analysis, and coordinated avoidance manoeuvres are all integrated into STM techniques to overcome these obstacles.

A global network of sensors, including ground-based radar and optical telescopes, that are used to watch and describe space objects lies at the core of STM in Earth orbit. For accurate range and velocity readings, radar equipment like LeoLabs' phased-array radars and the U.S. Space Surveillance Network (SSN) are utilised. Optical sensors are particularly useful for tracking objects in Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) and provide high-resolution angular data. Space Situational Awareness (SSA) systems, like the 18th Space Defence Squadron (18 SDS) of the U.S. Space Command (USSPACECOM), use these sensor data to maintain a public object catalogue and provide conjunction alerts[5].

Conjunction assessment, a fundamental operational component of STM, is the act of forecasting possible collisions between space objects. Two-Line Element (TLE) data is used by automated systems to propagate satellite orbits, and pairwise analysis is used to detect near approaches. Operators may start a collision avoidance manoeuvre if a conjunction event drops below a predetermined miss distance threshold (for example, 1 km in LEO). These actions are carried out either by human-in-the-loop decision-making or autonomously (as with more recent AI-powered systems like those created by Kayhan Space or LeoLabs). When several satellites are involved, coordination problems make collision avoidance even more difficult, which has led to suggestions for common goals and communication protocols amongst operators[6].

Measures to lower the possibility of creating new debris are also part of STM tactics. Within 25 years following the end of their mission, satellites in low Earth orbit (LEO) should return to the Earth's atmosphere, according to the Inter-Agency Space Debris Coordination Committee (IADC). Design features including fuel reserves for de-orbiting, drag enhancement devices, and passivation (venting of wasted propellants) promote adherence to these rules. It is anticipated that GEO mission operators will place satellites in graveyard orbits, which are at least 300 km above the GEO belt. To deal with legacy debris in important orbits, organisations such the ESA have also created active debris removal (ADR) demonstration missions (like ClearSpace-1)[7].

International STM frameworks are still dispersed, despite attempts to increase collaboration. Guidelines for the long-term viability of space operations have been released by the United Nations Committee for the Peaceful Uses of Outer Space (UN COPUOS), and bilateral accords like the Artemis Accords encourage openness and cooperation. To enhance military tracking data and communicate with commercial operators, NOAA's Office of Space Commerce in the US is creating an open-access civil STM system. The EU SST framework, which keeps an eye on high-risk events and notifies European stakeholders of them, is similarly maintained by the European Space Agency (ESA)[8].

3.2. Existing COPUOS Recommendations

The United Nations Office for Outer Space Affairs (UNOOSA), through the Committee on the Peaceful Uses of Outer Space (COPUOS), has developed a comprehensive set of guidelines titled the "Guidelines for the Long-term Sustainability of Outer Space Activities" (LTS Guidelines)[8]. These guidelines, adopted by consensus in 2019, provide voluntary, non-binding best practices aimed at enhancing the safety and sustainability of space operations, including those in Low Earth Orbit (LEO). LTS Guidelines encompasses 21 recommendations in four main categories:

1. The Policy and Regulatory Framework for Space Activities guidelines encourages states to establish and maintain comprehensive national regulatory frameworks governing space activities. This includes adopting, revising, and amending national legislation to ensure the long-term sustainability of outer space activities, supervising national space activities, and ensuring the equitable, rational, and efficient use of the radio frequency spectrum and orbital regions.
2. Safety of Space Operations guidelines focuses on enhancing the safety of space operations through measures such as sharing information on space objects and events, performing conjunction assessments, and developing and implementing procedures for collision avoidance. It also addresses the mitigation of space debris and the risks associated with the uncontrolled re-entry of space objects.
3. International Cooperation, Capacity-Building, and Awareness promotes international cooperation to support the long-term sustainability of outer space activities. This includes sharing experience and expertise, supporting capacity-building in developing countries, and raising awareness of the importance of space sustainability.
4. Scientific and Technical Research and Development encourages research into and the development of sustainable space technologies and practices. It also advocates for the investigation of new measures to manage the space debris population in the long term.

These guidelines are intended to be implemented to the greatest extent feasible and practicable based on the contemporary technological circumstances and capabilities of each State and international intergovernmental organization. They serve as a framework for developing national and international practices and safety frameworks for conducting outer space activities.

3.3. Implementation in the Cislunar Region

As the Earth–Moon system becomes a focal point for space exploration and commercial activity, the implementation of space traffic management (STM) and long-term sustainability (LTS) policies in the cislunar region is of growing importance. While current guidelines by the United Nations Office for Outer Space Affairs (UNOOSA) and the Committee on the Peaceful Uses of Outer Space (COPUOS) primarily address Earth-centric orbits, their core principles must be adapted to meet the unique challenges of cislunar space. This region is expected to host a variety of mission types—from the NASA-led Gateway and Artemis programs to private lunar landers and telecommunication constellations. The sustainability and safety of such operations will require a combination of dynamical modeling, coordinated policy frameworks, and international governance mechanisms.

Cislunar space is characterized by complex gravitational dynamics, including non-Keplerian trajectories, multiple equilibrium points (e.g., L_1, L_2), and sensitivity to initial conditions. These features reduce the predictability of spacecraft motion, particularly near the Moon and the Lagrange points. Moreover, the scarcity of persistent tracking infrastructure in this region further increases operational risk. To address these concerns, policy adaptations are necessary. These include establishing operational zones analogous to orbital shells in LEO/GEO, mandating real-time ephemeris updates for all cislunar-bound missions, and designating graveyard orbits or controlled lunar impact zones for spacecraft disposal.

For example, missions in Near Rectilinear Halo Orbit (NRHO), such as NASA's Lunar Gateway, will require formalised station-keeping protocols, pre-coordinated maneuver windows, and intent-sharing mechanisms for visiting spacecraft. Additionally, surveillance satellites stationed at Earth–Moon L_1 and L_2 could serve as autonomous tracking and data relay nodes, extending space situational awareness (SSA) coverage and supporting object catalog maintenance. Such space-based assets would complement ground-based deep space tracking radars and optical telescopes, providing full-coverage STM capabilities.

An effective implementation strategy will also necessitate multilateral coordination. A proposed Cislunar STM Accord—building on the precedents of the Artemis Accords and IADC debris mitigation guidelines—could define rules of behavior for orbit access, spectrum allocation, data transparency, and liability sharing. It could establish an international cislunar registry managed by UNOOSA, aggregating live telemetry, conjunction alerts, and risk event notifications. Collaborative platforms between civil, commercial, and military entities would also enable rapid response to anomalies or emerging threats in the region.

Finally, the principles of the LTS Guidelines—such as transparency, interoperability, capacity building, and responsible end-of-life planning—should be extended explicitly to cislunar operations. These principles must be embedded in both national licensing procedures and multilateral mission planning efforts. With increasing interest in lunar surface infrastructure, lunar orbital constellations, and resource extraction, a robust STM policy foundation is essential to ensure the long-term safety, stability, and sustainability of the Earth–Moon ecosystem.

3.4. STM Strategies for the Cislunar Region

1. Operational Zoning of the Cislunar Region

As described in previous work by the authors, dividing the cislunar space into distinct operational zones is a foundational STM strategy that allows traffic to be managed locally based on dynamical properties and mission functions. These zones may include Earth-centric transit corridors for TLI and return trajectories, L_1 and L_2 halo orbit zones for staging and surveillance, lunar proximity zones for operations near the Moon (e.g., NRHO, LLO, DRO), and Lagrange parking zones near L4 and L5. Each zone can be assigned specific coordination protocols, safety margins, and surveillance thresholds to ensure deconflicted access and operation, much like air traffic corridors in terrestrial aviation.

2. Cislunar Surveillance Infrastructure

Due to limitations in Earth-based tracking, in-situ surveillance systems are essential for cislunar STM. These may include optical or radar payloads positioned at Earth–Moon L_1 or L_2, lunar-orbiting sentry satellites for persistent local observation, and even Moon-based beacons or transponders to assist with passive ranging. Together, these assets form a decentralised "space traffic control" network that enhances real-time space situational awareness and supports catalog maintenance in a region with otherwise sparse observability.

3. Ephemeris Reporting and Intent Sharing Protocols

To promote predictability and transparency, all spacecraft operating in cislunar space should periodically transmit their ephemerides in standardized formats such as CCSDS OEM or TLE. Additionally, operators should be required to submit maneuver plans to an international STM registry and respond to automated or human-issued conjunction alerts. These practices mirror systems like ADS-B in aviation and enable preemptive deconfliction between cooperative space actors.

4. Conjunction Analysis Using CR3BP

Conjunction prediction in cislunar space cannot rely solely on classical two-body propagation. Instead, STM strategies should incorporate CR3BP dynamics, N-body perturbations, and invariant manifold analysis to accurately project relative motion, especially near Lagrange points. Tools like STK or FreeFlyer must be upgraded to include these dynamical regimes. Probabilistic risk analysis methods, which consider navigation errors and dynamic instability, can also improve decision-making under uncertainty.

5. End-of-Life (EOL) Management

Cislunar-specific EOL strategies should be built around the safe removal or containment of non-operational spacecraft. Disposal options include transferring to dynamically unstable graveyard orbits, executing controlled lunar impacts, or returning small satellites to Earth via low-energy trajectories. Long-lived spacecraft should be passivated to prevent fragmentation. Mission planners can use decision trees based on spacecraft mass, orbit family, and fuel margins to select the optimal disposal method.

6. Accord-Based STM

Given the multi-actor nature of cislunar space, STM governance will require multilateral agreements akin to the Artemis Accords or ICAO conventions. A dedicated "Cislunar STM Authority" could oversee orbital registries, coordinate traffic access to high-density zones, and manage shared data services. Such a body, backed by institutions like UNOOSA, would enhance trust and cooperation among spacefaring nations and commercial providers alike.

7. AI-Driven Autonomous Collision Avoidance

The increasing autonomy of spacecraft and the communication delays inherent in deep space demand that vehicles be equipped with onboard STM logic. AI-powered navigation and threat detection systems using vision-based sensors (e.g., optical or lidar) can identify conjunctions and execute avoidance maneuvers without Earth-based intervention. Cooperative autonomy protocols could allow nearby spacecraft to negotiate maneuvers dynamically—vital for operations near platforms like the Lunar Gateway.

8. Space Object Identity and Authentication

To reduce the risk of untracked or misidentified objects in the cislunar environment, each spacecraft should carry a verifiable digital identifier or active transponder. This enables telemetry authentication and ensures that STM systems can positively associate observations with specific missions. Such identity mechanisms are analogous to transponder-based identification in civil aviation and help enforce accountability in STM frameworks.

3.5. Relative Motion based Tracking

Surveillance using relative motion analysis in the cislunar region is a promising strategy for implementing practical and autonomous space traffic management (STM). Unlike ground-based observation systems that suffer from limited visibility and communication delays, a space-based surveiller satellite operating in proximity to cislunar traffic can enable continuous, high-resolution tracking of nearby objects using onboard sensors—particularly optical (angle-only) systems. This is especially useful near dynamic regions like Earth–Moon L_1, L_2, NRHO, and transfer orbits, where multi-body gravitational influences make trajectories highly sensitive to perturbations.

In this framework, the surveiller satellite tracks a target spacecraft by modeling the relative dynamics between the two objects in a non-inertial, rotating reference frame, typically using the Circular Restricted Three-Body Problem (CR3BP). The surveiller does not require precise absolute navigation; instead, it estimates the target's position and velocity relative to its own orbit using extended or unscented Kalman filters (EKF/UKF) fed by angular measurements. This allows for the reconstruction of the target's full 6D state vector over time—even with limited information—thus enabling real-time orbit determination, maneuver detection, and anomaly assessment.

3.5.1 Surveillance Orbits

As studied in section 2, each demarcated region in the cislunar space is characterized by different kinds of orbits, and each have their own pros and cons in terms of operations and surveillance. A thorough comparison must be made to understand the benefits of using certain orbits for surveillance, and also to understand their coverage area.

The different types of surveillance orbits may be studied using several criteria as follows:

1. Visibility Coverage
2. Orbital Maintenance
3. Frequency of Surveillance.

Visibility coverage may be defined as the time averaged fraction of observation period during which the object's apparent magnitude is brighter than the optical sensor's limiting magnitude m_{lim}. Mathematically, it may be described as:

$$V = \frac{1}{T}\int_0^T 1_{|m(t)<m_{lim}|}dt \qquad (9)$$

Orbital maintenance refers to the stability of the orbit the surveiller is in. Depending on the same, a surveiller satellite may require many stationkeeping maneuvers, and hence may not be a suitable candidate for long-term operations.

Frequency of surveillance refers to the number of times a surveiller may visit a certain density, i.e the time-period of the orbit of the surveiller.

Based on these parameters, some of the key orbits examined include:

1. 4:3 Resonant Orbits
2. Distant Retrograde Orbits
3. Near Rectilinear Halo Orbits
4. L_2 Halo Orbit

This study assumes that the tracked object is a Lambertian sphere, and also that there is only one surveiller satellite, and only one object to be tracked in the cislunar space. For this study, the object is placed in a Near Rectilinear Halo Orbit. Observations and results are discussed in section 4.

3.6. End of Life Solutions

One of the last pieces of the puzzle in Space Traffic Management is decoding end-of-life solutions in this region. In the near-earth region, satellites usually make a final plunge into the earth's atmosphere to finish their operations, while also ensuring that no residual debris is left in orbit, while higher orbits have a certain graveyard orbit located at the recommended perigee altitude given by the equation:

$$\Delta h = 235 \text{ km} + C_R \frac{A}{m} \cdot 1000 \text{ [km]} \qquad (10)$$

as specified by the Inter-Agency Space Debris Coordination Committee (IADC)[9].

Implementation of graveyard orbits in the cislunar space, however, is not simple. As observed in the case of J002E3, the determination of graveyard orbits and End-of-Life solutions is necessary to avoid any long term consequences. Let us study some EOL techniques that have been used before, and some potential sustainable techniques.

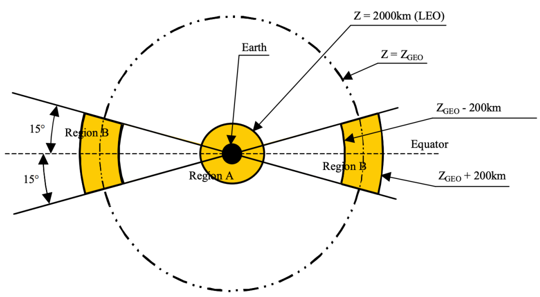

Fig. 6. Protected Zones around Earth designated by IADC.[9]

3.6.1. Controller Lunar Impact

Controlled lunar impact is a widely used EOL disposal technique where a spacecraft is deliberately directed to crash into the Moon's surface. This method is favoured in cislunar missions due to its simplicity, reliability, and low energy requirements. Several Apollo missions, notably Apollo 12 through Apollo 17, used controlled impacts for their spent S-IVB upper stages, which were deliberately crashed into the Moon to create seismic waves recorded by lunar seismometers deployed by astronauts. These intentional impacts provided invaluable data about the Moon's internal structure and validated the concept of lunar impact as a scientific and disposal tool.

In the short term, controlled impacts remove inactive spacecraft from congested cislunar trajectories, eliminate long-term collision risk, and offer scientific value when the impact is observed. They are especially effective for uncrewed orbiters or transfer stages that lack long-term maneuverability.

However, long-term disadvantages include the potential contamination of high-priority lunar sites, such as the lunar poles or heritage zones. Repeated impacts without international coordination could also lead to cumulative alteration of the lunar environment. Additionally, as lunar exploration increases, uncontrolled debris on the surface may hinder surface operations or scientific instrumentation. Thus, future use of this method should be aligned with global policy and lunar protection standards.

3.6.2. Natural Ejection from the Cislunar Region

Manifold-based ejection is a passive, fuel-efficient end-of-life (EOL) disposal strategy that leverages the natural dynamics of the Earth–Moon system, particularly in the framework of the Circular Restricted Three-Body Problem (CR3BP). Spacecraft operating in unstable periodic orbits around Lagrange points, such as Earth–Moon L1 or L2 halo orbits, inherently possess associated unstable manifolds—natural pathways through phase space that guide the object away from the vicinity of the periodic orbit.

At the end of a mission, instead of performing a large Δv maneuver to enter a graveyard orbit or impact trajectory, a satellite can be released along one of these unstable manifold trajectories. Over time, the spacecraft drifts into a quasi-resonant or distant Earth–Moon flyby trajectory, avoiding active orbital regions. This form of "natural disposal" minimizes fuel use and requires only minimal initial perturbation to initiate the divergence.

The primary benefit is that it eliminates the need for complex propulsion at the end of the mission. However, the final trajectory can be chaotic and hard to predict long-term, possibly posing risks if re-encounters with Earth or Moon occur. Therefore, while dynamically elegant and low-cost, manifold-based ejection must be carefully simulated to ensure long-term deconfliction from future cislunar traffic.

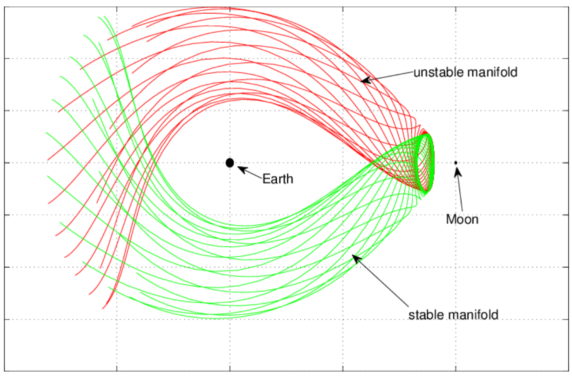

Fig. 7. Natural Manifolds from L_1 Halo[11]

3.6.3. Graveyard Orbits in the Cislunar Region

Suitable graveyard orbits in the cislunar space may be long-term stable or quasi-stable orbits that may be used to retire defunct or completed spacecraft away from critical operational regions. Unlike in Earth-centric regimes like GEO, where a graveyard orbit is typically a few hundred kilometers above the active zone, the cislunar environment is governed by complex multi-body dynamics, making the selection of such orbits more nuanced. The goal is to identify orbital regimes that require minimal station-keeping and remain predictably separated from future mission traffic, thereby reducing collision risks and minimising space debris proliferation.

In the Earth–Moon system, examples of graveyard orbits include higher-energy Distant Retrograde Orbits (DROs) or halo orbits around L1 or L2 with Jacobi constants slightly offset from operational values. These orbits are chosen because small perturbations cause divergence from active paths without immediate risk of Earth or Moon impact. In particular, post-mission ARTEMIS spacecraft (part of NASA's THEMIS mission) demonstrated successful use of Earth–Moon L1 and L2 halo orbits as dynamically quiet parking regions after completing science objectives, offering a real-world precedent for graveyard orbit strategies in cislunar space.

The major advantage of using graveyard orbits is that they offer passive stability, requiring minimal Δv for insertion and limited maintenance afterward. However, long-term stability must be carefully verified using high-fidelity models, as lunar gravity, solar perturbations, and third-body effects can still cause gradual drift over decades. Moreover, as cislunar traffic grows—particularly near Lagrange points and transfer corridors—defining standardized, internationally recognised graveyard zones becomes essential. Without such governance, today's graveyard orbit may intersect tomorrow's operational route. As such, while dynamically appealing, graveyard orbits must be carefully cataloged, simulated, and coordinated with broader space traffic management efforts to remain a sustainable EOL solution.

4. Simulations and Results

4.1. Surveillance Observations

As described in earlier sections, four main surveillance orbit candidates are studied as follows.

4.1.1. 4:3 Cislunar Resonant Orbits

A 4:3 resonant orbit in cislunar space, where a satellite completes four orbits for every three lunar revolutions, offers a compelling balance between dynamical stability and repeated geometric coverage. This resonance leads to a repeatable ground track and predictable geometry relative to the Moon, which is valuable for structured surveillance schedules. It enables regular revisits of key cislunar transit regions, such as NRHO or L1/L2 corridors, allowing the satellite to intercept and observe objects that follow typical Earth–Moon trajectories. The resonant nature also allows optimization of phase angles and lighting conditions for optical visibility.

However, the 4:3 resonance may also introduce orbit maintenance challenges. Resonances can amplify perturbations if not carefully phased, especially from solar gravity or solar radiation pressure, requiring periodic station-keeping maneuvers. Additionally, depending on inclination and eccentricity, certain geometries may lead to periods of reduced visibility, particularly if the orbit does not pass over regions of interest during lunar night. Finally, the coverage is inherently periodic—not continuous—so events outside the revisit windows may be missed.

Figure 8 demonstrates the effectiveness of a resonant surveillance architecture for cislunar space monitoring. As observed, the improved regional coverage is apparent, as this orbit is capable of covering larger regions of the cislunar space. Having a constellation in this orbit may prove to be beneficial, providing continuous coverage without continuous maneuvering. The apparent magnitude plot reveals that visibility is highly time-dependent, driven by range and phase angle, but remains within detectable limits during specific intervals. Variations across different coefficients of reflectivity (C_d) confirm that while higher reflectivity improves visibility, it cannot fully compensate for poor geometry. Thus, these results validate that a resonant surveiller orbit provides structured, low-maintenance, and predictable surveillance capabilities, ideal for autonomous monitoring of cislunar traffic and high-interest transit corridors. However, limited visibility during out-of-phase periods may prove to be a challenge.

Evaluating the orbit based on the main criteria of:

1. Visibility Coverage

Figure 8b illustrates how the apparent magnitude of the tracked object varies over time for different reflectivity values. The repeated dips in magnitude indicate periodic visibility windows, which align with the orbital phasing. Despite fluctuations caused by geometry and phase angle, the surveiller's orbit enables regular intervals of observability. This suggests high visibility coverage in a time-averaged sense, even though continuous tracking is not guaranteed. Resonant geometry helps synchronise favorable viewing conditions with mission needs. This issue may be overcome by the use of a constellation of surveillance satellites, which may provide continuous coverage.

2. Orbital Maintenance

4:3 resonant orbits are not inherently stable, but may be designed to be stable using proper design, mission timescale, and perturbation modeling. We may consider them to be quasi-stable, suitable for long-duration missions with minimal Δv corrections (e.g., 10s of m/s/year), thus making it ideal for long duration surveillance.

3. Coverage Frequency

As described earlier, increasing the number of satellites in a constellation may improve coverage frequency.

Thus, overall, resonant orbits are found to be a good surveillance orbit candidate. Their widespread coverage and orbital stability makes them a better candidate compared to the other orbits studied. However, they are not very effective unless in a constellation with other surveiller satellites.

4.1.2. Distant Retrograde Orbits

Distant Retrograde Orbits (DROs) are dynamically stable, high-altitude lunar orbits in which a satellite orbits the Moon in the direction opposite to the Moon's orbit around Earth. They are particularly attractive for cislunar surveillance due to their inherent long-term stability, requiring minimal station-keeping even over several decades. This makes them ideal for persistent monitoring platforms with limited propellant. DROs also maintain a relatively constant viewing geometry of the Earth–Moon system, enabling continuous surveillance of key transit corridors such as those used for Earth–Moon transfers or Near Rectilinear Halo Orbits (NRHOs). Additionally, their high-altitude placement allows for wide-area coverage with fewer satellites.

However, DROs also present limitations. Their high altitude (often >70,000 km from the Moon) results in

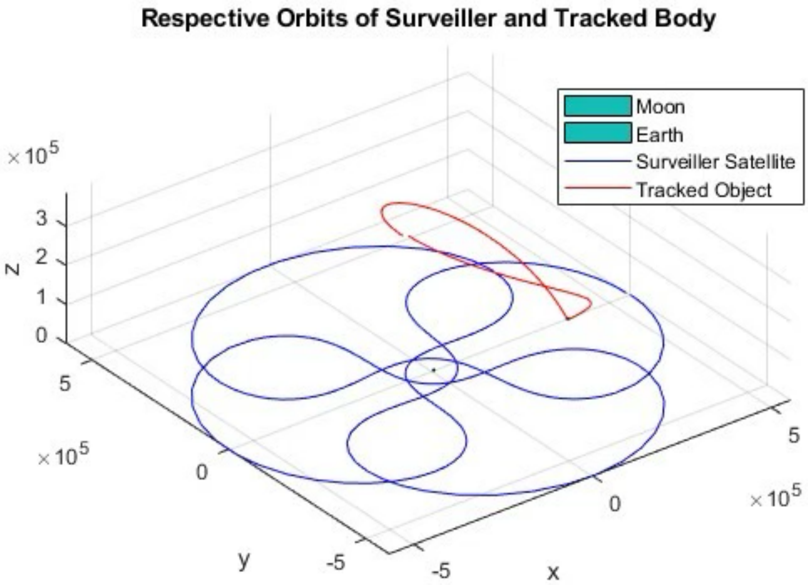

Fig. 8a. Plots of Trajectories of the Surveiller and the Tracked Object
4:3 Resonant Orbit

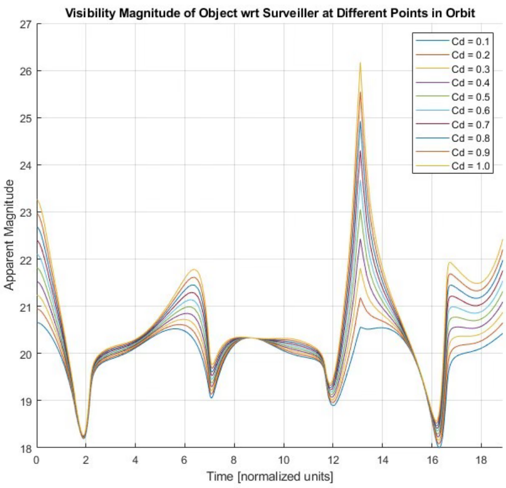

Fig. 8b. Plot of Visibility Magnitude of the object for different values of C_d

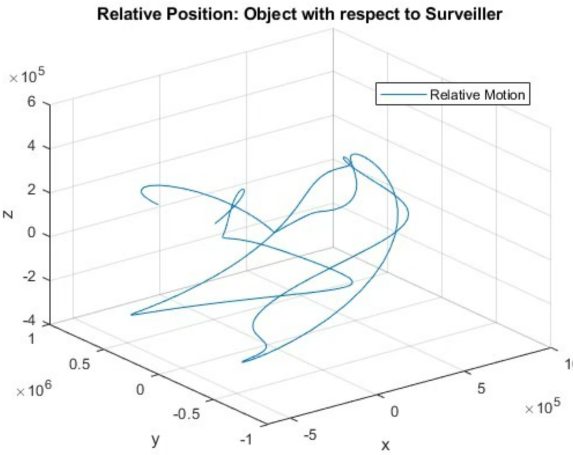

Fig. 8c. Plot of relative motion of the tracked body w.r.t the surveiller satellite in one orbit

greater range to observed targets, which can reduce optical resolution and visibility, especially for dim or small objects. This distance also causes light-time delays and lower angular rates, which may hinder fast-tracking of maneuvering spacecraft. Moreover, while dynamically stable, DROs are not ideal for close inspection or rendezvous with low lunar orbits or NRHO traffic. In summary, DROs offer a fuel-efficient, wide-coverage surveillance platform, best suited for strategic observation rather than tactical proximity operations. In terms of the three main criteria:

1. Visibility Coverage

The plot of apparent magnitude curves indicate clear periodic visibility windows, where the magnitude dips below 20, which is generally detectable by modern optical sensors. Although visibility is not continuous, it is predictable and repeatable, enabling scheduled tracking passes. The amplitude of these curves also confirms that visibility improves with higher reflectivity, but geometric factors dominate.

2. Orbital Maintenance

DROs orbit the Moon in the direction opposite to the Moon's motion around Earth. This configuration avoids strong resonances and minimizes gravitational perturbations, particularly from the Moon. DROs are relatively stable orbits, requiring minimal stationkeeping maneuvers. At large distances from the Moon (typically 70,000–80,000 km or more), the combined gravitational pull from Earth and Moon acts in such a way that the orbit remains naturally bounded. The satellite experiences slow, predictable dynamics that resist orbital drift.

3. Coverage Frequency

Despite good visibility of NRHOs from DROs, they are not a good at covering the other operational zones of the cislunar region. Hence, they are more suitable for local surveillance in the Earth Local Zone, Trans Lunar Zone and the Extra Lunar Zone.

Therefore, DROs may be a perfect solution for short-term local surveillance, especially for the initial phases

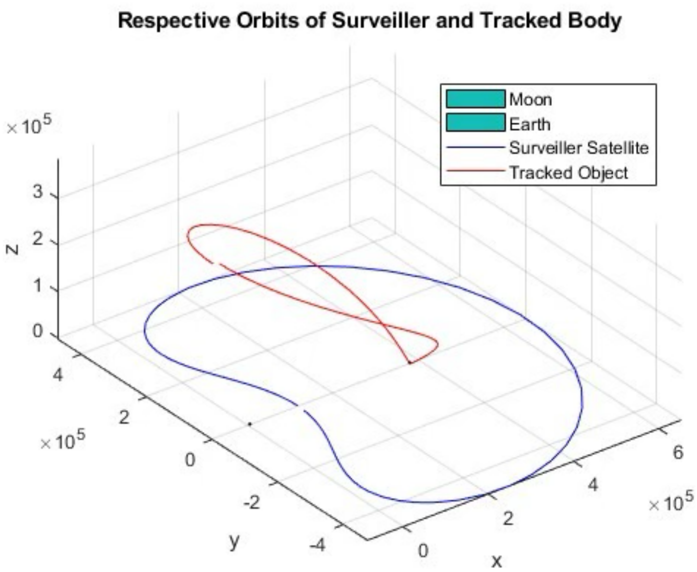

Fig. 9a. Plots of Trajectories of the Surveiller and the Tracked Object
Distant Retrograde Orbit

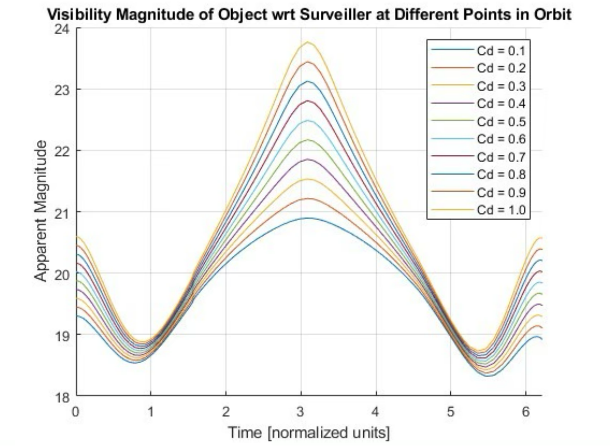

Fig. 9b. Plot of Visibility Magnitude of the object for different values of C_d

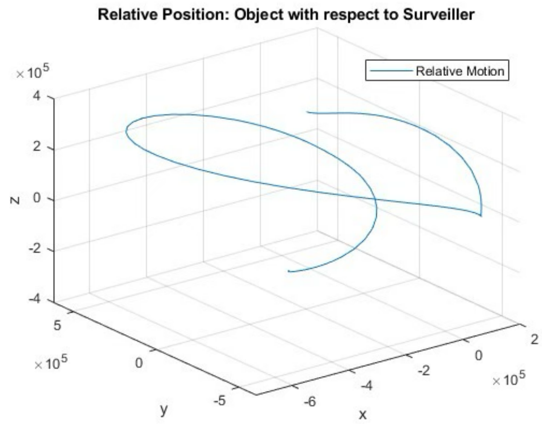

Fig. 9c. Plot of relative motion of the tracked body w.r.t the surveiller satellite in one orbit

of the ARTEMIS program and other lunar missions in the near future.

4.1.3. Near Rectilinear Halo Orbit

Near Rectilinear Halo Orbits (NRHOs) are a class of highly elliptical, three-dimensional orbits around the Moon that balance the gravitational forces of the Earth and Moon. Their unique geometry—closely approaching the Moon at perilune and swinging far out at apolune—makes them ideal for specific cislunar surveillance roles, especially for monitoring the lunar vicinity and NRHO-based infrastructure like NASA's Gateway.

In the context of cislunar surveillance, NRHOs offer distinct advantages. Their close passes to the Moon allow high-resolution monitoring of lunar surface operations, low lunar orbit traffic, and critical orbital corridors such as the NRHO–LLO interface. The orbit's quasi-periodic nature ensures predictable viewing geometry, enabling scheduled observations with reliable lighting and visibility.

However, NRHOs are best suited for localised surveillance. Their field of view is narrow, and the orbit's low altitude and tight dynamics restrict wide-area observation of distant cislunar zones, such as transfer trajectories or Earth–Moon L1/L2 corridors. Tracking objects far from NRHO may result in large, diverging relative motion, complicating estimation and custody maintenance. Based on the main evaluation criteria:

1. Visibility Coverage

The NRHO-based surveillance satellite shows excellent optical visibility, with apparent magnitudes consistently below 16 for a range of reflectivity values. A broad, smooth visibility window appears due to the orbit's close lunar passes. This ensures reliable, periodic tracking of targets near the Moon with minimal interruption or visibility loss. Being close to the lunar surface, they also offer high-resolution views of near-lunar space. However, the tight and low-altitude orbit limits angular coverage, reducing the field of view for distant or wide-area surveillance unless augmented with gimballed sensors or wide-angle optics. It excels in focused, high-detail local monitoring.

2. Orbital Maintenance

The NRHO maintains a tightly bound, predictable path around the Moon, but requires periodic station-keeping, especially near perilune. Relative motion

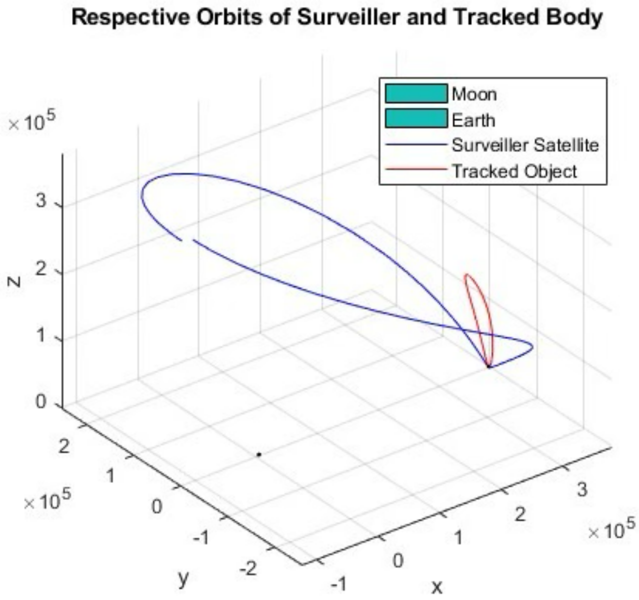

Fig. 10a. Plots of Trajectories of the Surveiller and the Tracked Object
Near Rectilinear Halo Orbit

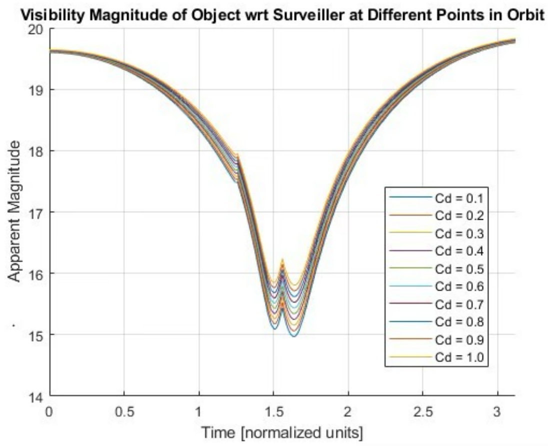

Fig. 10b. Plots of visibility magnitude of the object
for different C_d values

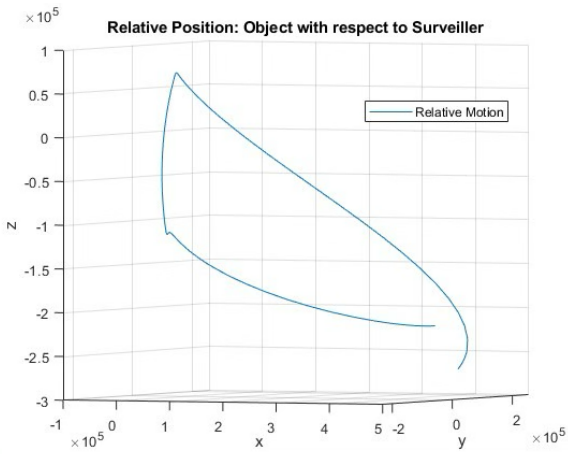

Fig. 10c. Plot of relative motion of the tracked body
w.r.t the surveiller satellite in one orbit

between the satellite and distant objects shows divergence, indicating that while the orbit itself is stable, tracking distant targets may introduce challenges due to growing relative position errors over time.

3. Coverage Frequency

NRHOs provide strong access to lunar vicinity operations like NRHO-based infrastructure or low lunar orbits. However, the object's drifting trajectory suggests poor alignment with distant cislunar corridors. Thus, while ideal for local surveillance, NRHOs are not optimal for monitoring Earth–Moon transit paths or libration point traffic without augmentation.

In summary, NRHOs are well-suited for tactical, close-range surveillance in lunar proximity but should be complemented with higher-altitude or Lagrange-point orbits for larger coverage.

4.1.4. L_2 Halo Orbit

Earth–Moon L2 halo orbits offer valuable advantages for cislunar surveillance due to their strategic placement beyond the Moon. From this location, satellites enjoy a wide field of regard, enabling persistent monitoring of the lunar far side and nearby orbital regimes such as NRHOs, DROs, and trans-lunar injection paths. L2 serves as a critical gateway for outbound traffic, making it ideal for early warning or tracking missions entering interplanetary space. These orbits also maintain line-of-sight to both the Earth and Moon, allowing uninterrupted communication and telemetry. Their geometry is highly predictable, making it easy to coordinate scheduled surveillance activities and relay operations.

Despite these benefits, L2 halo orbits come with operational challenges. They are dynamically unstable, requiring regular station-keeping to prevent divergence, which raises the Δv budget over long durations. Additionally, their distant location—tens of thousands of kilometers beyond the Moon—reduces the resolution of optical observations, making it difficult to track small or dim objects without advanced sensors. Insertion into these orbits involves complex multi-body dynamics and precise maneuvering. Furthermore, due to

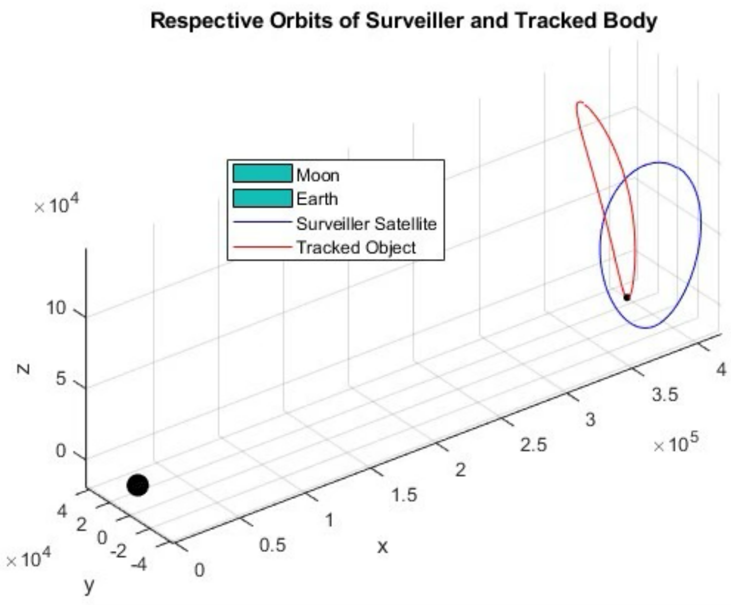

Fig. 11a. Plots of Trajectories of the Surveiller and the Tracked Object

L_2 Halo Orbit

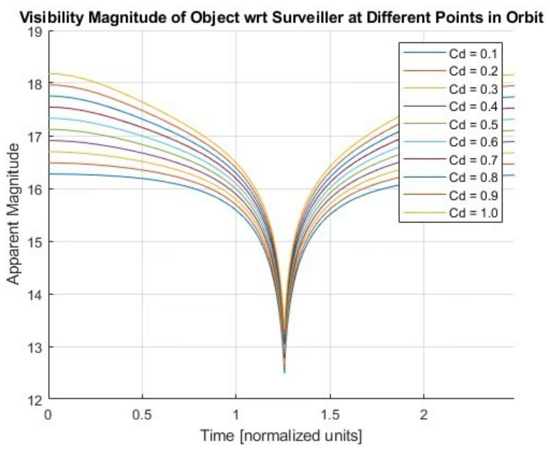

Fig. 11b. Plots of visibility magnitude of the object for different C_d values

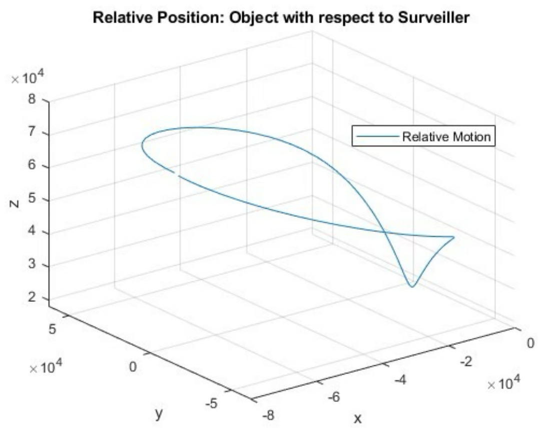

Fig. 11c. Plot of relative motion of the tracked body w.r.t the surveiller satellite in one orbit

their distance, L2 orbits are unsuitable for close-range tracking, inspection, or rendezvous tasks near lunar infrastructure, making them better suited for strategic monitoring than tactical surveillance.

Based on the four main criteria:

1. Visibility Coverage

Similar to NRHOs, L_2 Halo orbits are demonstrating limited-term visibility.

2. Orbital Maintenance

L_2 Halo orbits are not very stable, requiring many corrections. Hence, they are not a very suitable candidate for surveillance.

3. Coverage Frequency

Similar to NRHOs, their coverage is limited.

All in all, L_2 halo orbits do not present as a suitable candidate for surveillance.

4.2. Conclusions about Surveillance Orbits

As observed from the simulations, we can make the following conclusions.

DROs demonstrated exceptional long-term stability and minimal station-keeping requirements, making them ideal for persistent surveillance platforms. Their high altitude provides broad field-of-view coverage, but their distance from the Moon introduces constraints on optical resolution and relative proximity. Nevertheless, their natural dynamical characteristics make them strong candidates for continuous background monitoring of cislunar space.

NRHOs, by contrast, offer excellent visibility of lunar surface activity and low lunar orbits due to their close perilune passes. However, they require more frequent orbital maintenance and provide limited access to wider cislunar corridors. Their utility is therefore strongest in localised, high-resolution surveillance of lunar infrastructure or gateway systems.

4:3 resonant orbits provide repeatable geometries and regular revisit opportunities for targets within the Earth–Moon system. These orbits achieve a balance between fuel efficiency and coverage but require precise phasing and may be susceptible to long-term perturbations without correction. They are particularly well-suited for time-structured surveillance architectures.

L2 halo orbits, while dynamically unstable, offer unmatched vantage points for observing far-side lunar operations, libration point missions, and interplanetary departure paths. Their geometric coverage is broad, but their distance from both Earth and Moon imposes observational limitations and demands frequent station-keeping.

In summary, no single orbit satisfies all surveillance objectives. An effective cislunar STM architecture will likely require a hybrid orbital framework, combining multiple orbit classes tailored to complementary coverage roles—ranging from wide-field strategic monitoring to high-fidelity local observation.

5. Policy Recommendations

1. Establish Cislunar Traffic Coordination Protocols

Develop and enforce shared operational rules for navigating Earth–Moon space, including identification, communication, and path deconfliction standards. A dedicated coordination authority could ensure safe, non-interfering passage for all actors operating across cislunar transit corridors such as NRHOs, DROs, and halo orbit regions.

2. Mandate Pre-Approved End-of-Life Disposal Plans

Require mission operators to submit and register detailed end-of-life strategies before launch. These should include options like lunar impact, Earth escape, or insertion into graveyard orbits to prevent long-lived debris and maintain the usability of critical orbital zones like L1/L2 or NRHO.

3. Develop a Cislunar Surveillance and Cataloging Framework

Establish an international object-tracking and monitoring system tailored to cislunar dynamics. This registry would integrate optical, radar, and on-orbit sensor data to build custody over active and inactive assets, supporting collision avoidance and traffic prediction far beyond traditional GEO tracking systems.

4. Create Norms for Dynamic Collision Risk Assessment

Adapt conjunction risk analysis and close-approach protocols for cislunar dynamics, incorporating nonlinear motion models like CR3BP. Operators should coordinate proactively when predicted proximity events occur in shared orbital paths to reduce the risk of collisions or misidentification.

5. Designate Protected Science and Heritage Zones

Define and map high-priority regions on the Moon—such as Apollo landing sites or permanently shadowed craters—as protected zones. These areas should be excluded from impact-based disposal strategies and safeguarded under international agreements to preserve lunar science and heritage.

6. Encourage Transparent Operations and Notification Mechanisms

Implement a requirement for timely public notification of key mission phases—maneuvers, lunar insertion, and disposal burns. A standardized reporting format would improve situational awareness, reduce confusion, and support early response in the event of an anomaly or trajectory deviation.

7. Support Dual-Use and Civil–Military Transparency

Recognize that many cislunar surveillance capabilities may be dual-use in nature. Promote confidence-building measures like voluntary tracking cooperation and data sharing agreements to minimize tensions, avoid misinterpretation, and ensure peaceful coordination between civil, commercial, and military operators.

8. Define STM Architecture Requirements for Gateway-Scale Missions

Establish operational standards for large missions near the Moon, such as NASA's Gateway. These should include guidelines on tracking beacons, orbital slotting, station-keeping corridors, and cooperative monitoring of spacecraft in NRHO and other high-traffic regions to ensure interoperability and safety.

9. Incentivise Passive Deorbiting and Smart EOL Autonomy

Encourage mission designs that include autonomous, fuel-efficient disposal options. This could involve leveraging unstable manifold trajectories or pre-programmed deactivation protocols that enable spacecraft to exit key regions safely even if contact is lost or the satellite becomes inoperable.

10. Establish International Working Groups for Cislunar Norms

Create dedicated expert subgroups under COPUOS or IADC focused on cislunar operational policy, technical standards, and STM. These groups would facilitate consensus-building, share best practices, and produce implementable guidelines for emerging actors in Earth–Moon space.

6. Conclusions and Future Work

6.1. Conclusions

This study presents a comprehensive approach to Space Traffic Management (STM) in the cislunar region, addressing the unique dynamical challenges of the Earth–Moon system through the concept of operational zones. By leveraging CR3BP dynamics, the paper models various surveillance architectures and evaluates their performance using criteria such as visibility coverage, orbital stability, and surveillance frequency. The use of relative motion tracking combined with visible magnitude modeling demonstrates that space-based surveillers can provide continuous, autonomous custody of cislunar traffic, especially when placed in well-chosen orbits.

The comparison of 4:3 resonant orbits, Distant Retrograde Orbits (DROs), Near Rectilinear Halo Orbits (NRHOs), and L2 Halo orbits confirms that no single orbit meets all surveillance goals, and that a multi-layered orbital architecture may be necessary for effective coverage. Furthermore, we highlight the importance of structured policy recommendations for STM, many of which are suitable for integration into international frameworks like those of UNOOSA, COPUOS, or IADC. Key policy areas include EOL planning, object tracking protocols, coordination zones, and collaborative registry systems.

Ultimately, the study affirms that STM in cislunar space must be treated as a multi-disciplinary endeavor involving dynamical modeling, sensor design, regulatory governance, and international cooperation, in order to ensure long-term sustainability and safety of future lunar and interplanetary activities.

6.2. Future Work

The findings of this work open several directions for future development. First, the current surveillance simulations are based on a single object and a single surveiller; future extensions will include multi-object tracking, constellation-based surveillance, and autonomous target switching in dynamically evolving environments. In addition, higher-fidelity dynamical models, including solar perturbations, Earth oblateness, and solar radiation pressure, will enhance the realism of trajectory prediction and station-keeping analysis. Sensor noise and saturation may also be accounted for, and Filters may be implemented for the purpose of cislunar orbit determination. Criteria for selection of surveillance orbits may be expanded upon, and more detailed analysis may be done to study the visibility of objects in the region.

On the policy front, more detailed simulations of policy compliance—such as response times to maneuver alerts, deconfliction windows, and registry-based coordination—could be implemented to assess the feasibility of proposed governance protocols. The development of onboard autonomy and AI-driven decision-making for deep-space STM, including cooperative avoidance behavior and self-custody tracking, also remains a critical area of research. Finally, real-world validation of these strategies may be achieved by integrating this framework with upcoming missions like the Lunar Gateway, Artemis, and commercial lunar constellations.

In summary, the integration of dynamical systems theory, surveillance infrastructure, and cooperative governance frameworks remains essential to shaping the future of cislunar space as a safe, shared, and sustainable domain for all spacefaring actors.

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