Long Term Evolution of Space Debris Clouds in the Cislunar Region

Sourav Ghosh[1], Prathap S. Sharma[1], Siddhartha Pundit[1], Rishikesh Bitla[1], Subhasmita Prusty[1], Samarth Badgujar[1]

[a]*The University of Tokyo, Tokyo, Japan*
[b]*ISAE-SUPAERO, Toulouse, France*
[c]*Independent Researcher, Bengaluru, India*
[d]*Jain (Deemed-to-be University), Bengaluru, India*
[e]*VIT Bhopal University, Bhopal, India*
[f]*University of Padua, Padua, Italy*

Abstract

As humanity pushes beyond Earth toward a sustained presence around the Moon, we face a familiar problem in a new neighbourhood: space debris. Decades of activity in near-Earth orbits have already filled space with fragments too small to track reliably yet large enough to threaten spacecraft, and if we repeat that pattern in the vast cislunar region between Earth and the Moon, routine lunar operations could become riskier, costlier, and more fragile. This study looks to understand the complex implications of the formation of debris clouds and their evolution in the cislunar space, and how they affect operations near the Lunar region. We focus on the orbits most likely to matter, Near-Rectilinear Halo Orbits (planned for NASA's Gateway), Distant Retrograde Orbits, lunar frozen orbits, and Low Lunar Orbit, and simulate debris created by collisions or random breakups, then follow those fragments for months to years. To keep things realistic, we combine the insight of Earth–Moon circular restricted three-body dynamics with higher-fidelity multi-body models that include the Sun's pull, solar radiation pressure, eclipses, and detailed lunar gravity, so we can capture both the broad transport trends and the messy details. We quantify the chance that debris ultimately strikes the Moon and map where those impacts concentrate over time; we also track how fragments ride natural phase-space "highways," migrating among orbit families and occasionally threading through a defined keep-out corridor around Gateway. Because risk depends on what we can actually observe, we model a space-based sensor that uses photometry and line-of-sight angles under real-world constraints (glare, geometry, cadence), and we test estimation filters to see when short, imperfect arcs are enough to retain custody of a fragment's orbit. The result is a set of practical outputs, risk maps, survival timelines, and conjunction flux estimates, along with sensitivity to fragment size and reflectivity, all aimed at informing near-term operations. We close with concrete mitigations operators can adopt now, from keep-out zones and station-keeping choices to safer disposal strategies, so today's small mishaps don't become tomorrow's systemic hazard for the Artemis era.

Keywords: Space Debris, Space Situational Awareness, Cislunar Space

1. Introduction

The cislunar region, the vast expanse between the Earth and Moon, is emerging as the next frontier for space exploration and development. With growing ambitions from governmental space agencies and private enterprises alike, humanity is preparing to establish a sustained presence beyond low Earth orbit. A manned lunar outpost, once a distant aspiration, now lies within reach. To support such a presence, a wide array of space infrastructure will need to be deployed in the cislunar environment. These include communication relays, navigation systems, surveillance platforms, scientific instruments, and logistics modules, all of which will play crucial roles in enabling long-term human operations on and around the Moon. However, as with any expansion into new orbital regimes, the issue of space debris becomes an inevitable and pressing concern. History has shown us in near-Earth space that operational satellites and platforms are susceptible to malfunctions, fragmentation events, and collisions, all of which generate hazardous debris. In the cislunar region, the problem is compounded by the complex and often chaotic dynamical environment governed by the gravitational interplay between the Earth, Moon, and Sun. These dynamics can cause debris to evolve in unpredictable ways over time, posing significant collision risks not only to other operational assets but also to lunar surface installations and future crewed missions.

This study seeks to address the emerging challenge of debris risk in the cislunar space environment. By modeling and simulating key scenarios, including in-orbit break-up events, high-energy impact trajectories, and long-term orbital evolution, we aim to assess potential debris propagation patterns and their associated hazards. In particular, we investigate how fragments from operational failures or collisions might interact with valuable regions such as Earth-Moon Lagrange points, lunar transfer corridors, lunar orbit, and also near-Earth regions such Geostationary and Geosynchronous orbits. These insights are critical for informing the design of future space traffic management protocols, shielding strategies, and operational policies that will ensure the safety, sustainability, and success of humanity's next great leap into space. Results presented demonstrate the spread of the debris field over time based on Monte-Carlo simulations of a breakup event in the NRHO and the Distant Retrograde orbit (DRO).

2. Dynamics Model

2.1. Circular Restricted Three-Body Problem

The complex dynamics of the region can be simplified using the Circular Restricted Three-Body Problem (CR3BP). This model makes the assumptions as follows:

- The primary and secondary masses (Earth and Moon) are in a circular orbit around the barycenter of the system.
- The third body is assumed to be a point mass and exerts no force on the other masses.

The system may be described using the following relations.

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

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

$$\ddot{z} = \Omega_z \tag{3}$$

where, Ω is the pseudo-potential given by,

$$\Omega = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{r_1} + \frac{\mu}{r_2} \tag{4}$$

$$r_1 = \sqrt{(x+\mu)^2 + y^2 + z^2} \tag{5}$$

$$r_2 = \sqrt{(x-1+\mu)^2 + y^2 + z^2} \tag{6}$$

2.2. Realms of Possible Motion

In the Circular Restricted Three-Body Problem (CR3BP), a spacecraft's movement is restricted to specific spatial realms based on its energy level. This energy state is defined by a conserved value called the Jacobi constant, which determines the boundaries of where the craft can physically travel according to the following expression:

$$E = 2\Omega - v^2 \tag{7}$$

Figure 7 illustrates these realms through the use of zero-velocity surfaces (ZVS), which define the physical limits a spacecraft cannot exceed without an injection of energy. Within the rotating reference frame of the Earth–Moon system, the specific shape and reach of these regions are governed by the interplay of gravitational forces and centrifugal potential. Access is strictly governed by the Jacobi constant: motion is only possible in regions where kinetic energy is non-negative, effectively rendering the outside areas "forbidden." In 2D projections, these boundaries appear as zero-velocity curves (ZVCs) that function as dynamic gateways. Depending on the spacecraft's energy level, these gates may open or close, either confining the craft to a local vicinity or permitting transit between different zones, such as moving from Earth's influence to that of the Moon.

3. Example Section

Section text. See Subsection **??**.

3.1. Example Subsection

Subsection text.

3.1.1. Mathematics

This is an example for the symbol α tagged as inline mathematics.

$$f(x) = (x+a)(x+b) \tag{8}$$

$$f(x) = (x+a)(x+b)$$

$$\begin{aligned} f(x) &= (x+a)(x+b) \qquad (9) \\ &= x^2 + (a+b)x + ab \qquad (10) \end{aligned}$$

$$\begin{aligned} f(x) \quad &= \quad (x+a)(x+b) \\ &= \quad x^2 + (a+b)x + ab \qquad (11) \end{aligned}$$

1	2	3
4	5	6
7	8	9

Table 1: Table Caption

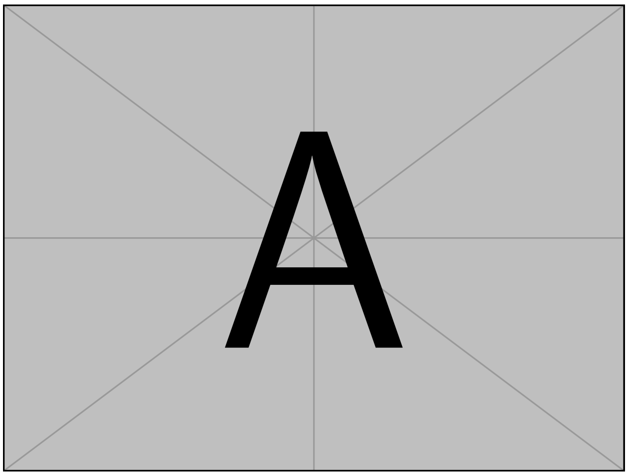

Figure 1: Figure Caption

$$\begin{aligned} f(x) &= (x+a)(x+b) \\ &= x^2 + (a+b)x + ab \end{aligned}$$

$$\begin{array}{rcl} f(x) & = & (x+a)(x+b) \\ & = & x^2 + (a+b)x + ab \end{array}$$

Appendix A. Example Appendix Section

Appendix text.

Example citation, See **?**.

References

Leslie Lamport, *LaTeX: a document preparation system*, Addison Wesley, Massachusetts, 2nd edition, 1994.