SSA PERFORMANCE ASSESSMENT OF CISLUNAR PERIODIC ORBITS FOR FRAGMENTATION EVENTS MONITORING

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ABSTRACT

Cislunar missions have significantly increased in recent decades due to their relevance in scientific, military, and commercial sectors, leading to a rise in space traffic, risk of fragmentation events, and the potential creation of debris clouds dispersing throughout the whole region. To mitigate these risks, an effective Space Traffic Management infrastructure for monitoring space objects is essential. However, current sensors are insufficient for extensive Cislunar Space Situational Awareness, with only strategically placed passive optical sensors showing promise. This study addresses a literature gap by assessing the observational capabilities of key Cislunar orbital families in detecting debris clouds from multiple catastrophic collisions, providing critical insights for the sustainable and strategic planning of future Cislunar missions. Simulations indicate moderate risks to celestial bodies and no significant threats to the Geostationary Earth Orbit belt, while the L2 Halo family emerges as the most effective for debris monitoring, offering extended visibility.

Keywords: Cislunar; STM; SSA; Space Debris; Fragmentation Events; Collisions.

1. INTRODUCTION

Decades of space exploration have driven significant advancements in technology, science, and human capability. Nevertheless, this progress has also resulted in increased orbital congestion and a rising threat from space debris [1]. As the density of objects in orbit continues to grow, effective risk mitigation becomes critical, necessitating precise, real-time tracking through a robust Space Traffic Management (STM) framework [2, 3, 4, 5, 6, 7, 8]. The expansion of human activity into Cislunar space - driven by goals of exploiting lunar resources, establishing long-term lunar habitats, and constructing deep-space infrastructure, such as NASA Gateway [9, 10, 11] - introduces additional challenges. This anticipated increase in space traffic elevates the risk of fragmentation events and widespread debris proliferation under the complex and chaotic orbital dynamics of Cislunar space, threatening both lunar and Near-Earth assets. However, current surveillance capabilities remain inadequate for large-scale monitoring, emphasizing the necessity for a specialized STM infrastructure tailored to Cislunar operations [12, 9]. Passive optical sensors show promise for debris detection, but achieving comprehensive coverage requires strategically deployed observational spacecraft optimized for Cislunar orbits.

Although prior studies have investigated the observability of individual targets within Cislunar orbital families [13, 12, 14, 15, 16, 17, 18, 19], a critical gap remains in correlating fragmentation events and debris propagation to observational capabilities. This study addresses this gap by evaluating the observational potential of key orbital families in detecting debris clouds and assessing the risks associated with catastrophic Cislunar collisions. These findings surpass existing literature on Cislunar fragmentation events analysis and provide essential foundational knowledge for developing an advanced STM infrastructure. This advancement supports the long-term sustainability of space activities and the strategic utilization of resources in this vital region.

2. TEST CASE DESIGN

The first objective of this work focuses on the simulation and risk assessment of catastrophic break-ups along different Cislunar trajectories.

Therefore, the NASA Standard Break-Up Model (SBM) is implemented and validated [20] to characterize debris clouds resulting from space collisions and explosions.

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The statistical distributions for fragment mass, velocity, area-to-mass ratio, and characteristic length are retrieved through this model. For collision scenarios, fragments are assigned to their respective parent bodies following the methodology introduced by Schuhmacher [21].

Given that Cislunar space is defined as the region influenced by the gravitational forces of both the Earth and the Moon, the Circular Restricted Three-Body Problem (CR3BP) is employed to describe the motion of spacecraft and debris within this environment [9]. Around the CRTBP equilibrium points, relevant different families of periodic closed trajectories, repeating over a constant period, exist. Particular focus is posed on the more stable ones, with stability evaluated through the stability index $\nu = \frac{1}{2}(|\lambda_{max}| + |\frac{1}{\lambda_{max}}|)$, defined exploiting the Monodromy Matrix eigenvalue of maximum modulus λ_{max} [22].

The second objective focuses on assessing debris visibility, and the Baker-McEvilly methodology is employed to evaluate the capability of space-based optical sensors in detecting fragments [16]. A fragment is considered observable if its apparent visual magnitude is below 20 and if the angular separation between the observer-target vector and the target-celestial body vector exceeds the following thresholds: 50° for the Sun, 35° for the Earth, and 30° for the Moon.
The magnitude of the space object is determined through:

$$mag_{sc} = mag_{sun} - 2.5 \log_{10} \frac{I_{sc}}{I_{sun}} \qquad (1)$$

where mag_{sun} represents the Sun apparent reference magnitude, I_{sc} the irradiance of the spacecraft, and I_{sun} the reference irradiance of the Sun. As both the target fragments and the observing spacecraft are modeled as Lambertian spheres with a reflection coefficient of 0.5, the irradiance reflected by the target is retrieved by:

$$I_{sc} = \frac{I_{sun}}{\|\mathbf{r_{sc-obs}}\|^2} \frac{2}{3} \frac{C_d}{\pi^2} r^2 (\sin\alpha + (\pi - \alpha)\cos\alpha) \qquad (2)$$

where r represents the fragment characteristic length, C_d is the diffuse reflection coefficient, α is the phase angle between the Sun and the observer as viewed from the target and $\mathbf{r_{sc-obs}}$ denotes the distance vector between the target and the observer, expressed in the Inertial J2000 reference frame. SPICE Ephemerides [23] are used to retrieve the celestial bodies states in the J2000 reference frame, for each epoch t of the time window considered. For the same instants, the positions of observers and fragments are transformed from the time-independent Synodic reference frame to the time-dependent J2000 frame [24]. Once the position vectors are known in the J2000 frame, the required phase and exclusion angles are computed.

A demanded starting point of the study is understanding and selecting the most promising orbits capable of optimally covering the Cislunar regions of interest and managing traffic operating within those regions. Relevant target locations for current and planned missions are the CRTBP periodic families, regarded to be at higher risk for potential catastrophic fragmentation events. Furthermore, due to their periodicity, low station-keeping costs, and wide coverage of the Cislunar region also represent the most valuable candidates for a Cislunar Space Situational Awarness (CSSA) network [11, 25, 15, 16, 9, 26, 27, 12, 13].
Therefore, nine families of periodic orbits are selected for potential Cislunar observation: DRO, L4 Planar, L5 Planar, L1 Lyapunov, L1 Northern Halo, L1 Southern Halo, L2 Lyapunov, L2 Northern Halo, and L2 Southern Halo. Despite some of these orbits (the L2 Halo and NRHO [26, 28], the DRO [26], and the L2 Lyapunov orbit [29]) have already been considered in explosion-cases studies, due to their particular significance for upcoming scientific and SSA missions, they are also considered in this study, highlighting the differences in outcomes based on the type of break-up, expanding the existing literature and establishing relevant test cases for the following observational performance assessment.

Eleven collisions, illustarted in Fig. 1 and 2 are simulated on ten orbits belonging to these families, considering two additional ones occurring on the larger DRO, added to deeply analyze the threats posed by a Near-Earth break-up event and on the LUMIO (LUnar Meteoroid Impacts Observer) Halo [30].

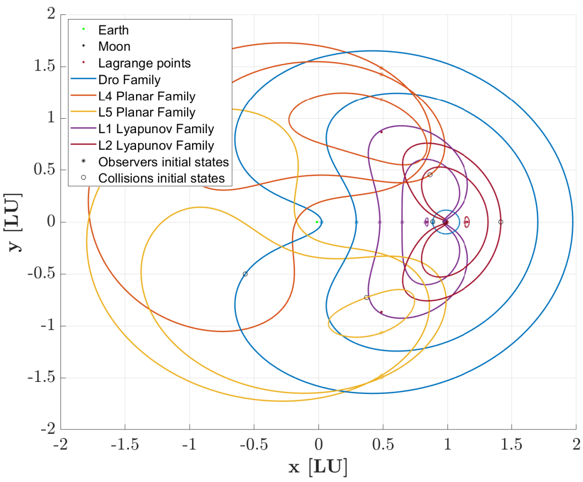

Figure 1. Collisions locations (empty circles) and observers initial positions (asterisks) on planar orbits in Synodic reference frame - Plane x-y view.

All collisions are simulated as catastrophic for computational reasons [20] and, to ensure continuity and enable a robust comparison, collisions between the two same spacecrafts are replicated on 2000-01-01 at 12:00:00.000 UTC on eleven different locations, varying only the impact velocity of the two colliding bodies.
Each collision generates 1074 fragments, which are propagated in the CRTBP for three months. These fragments are then filtered by eliminating those with excessively high velocities, avoiding nonphysically plausible behaviors.

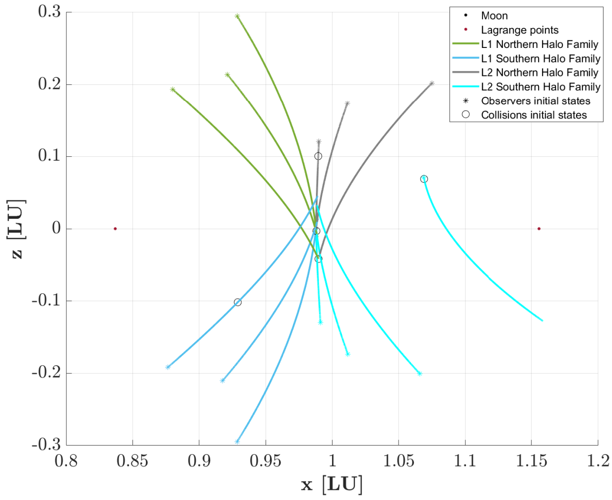

Figure 2. Collisions locations (empty circles) and observers initial positions (asterisks) on Halo orbits in Synodic reference frame - Plane x-z view.

For each of the nine families selected, three orbits are chosen to host the observers, prioritizing the most stable ones and of different periods, allowing the creation of a global network, able to traverse wide areas of Cislunar space and at the same time focus on relevant locations, as the Lagrange points or the Moon surface.

In total, twenty-eight orbits have been selected, illustrated in Fig. 3. An additional observer in an Elliptical Lunar

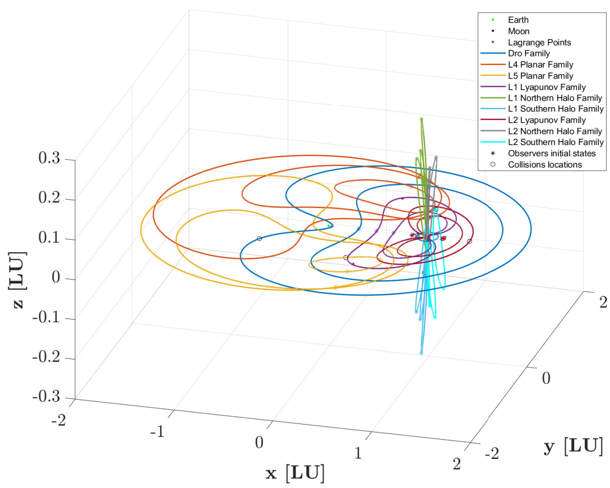

Figure 3. Observer orbits illustrated in Earth-Moon Synodic reference frame.

Orbit (ELO) is further included to assess the capability of a space-based observer orbiting the Moon. Lastly, to avoid invalid results in the visibility calculation and allow an acceptable view of sight, the initial position of the observers are shifted with respect to the collisions locations.

3. RESULTS

3.1. Debris Propagation and Risk Assessment

The initial phase of this study focuses on the analysis of the potential threats posed by the resulting debris to both celestial bodies and assets in the Geostationary Earth Orbit (GEO).

An impact or entry event is considered when the norm of the fragment position vector is less than or equal to the radius of the celestial body or overruns the GEO region bounds.

The percentage of fragments impacting the Earth, the Moon or entering the GEO region during the three-month period considered is then calculated, quantifying the threats posed by each collision.

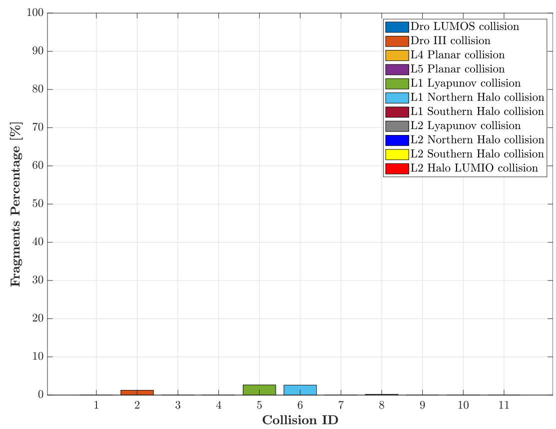

Figure 4. Percentage of fragments impacting the Earth over three months for each collision.

As illustrated in Fig. 4, collisions 5 and 6, which occur in the L1 Lyapunov and L1 Northern Halo orbits, respectively, present the highest risks for Earth impacts, with 2.7% and 2.6% of fragments impacting the surface.

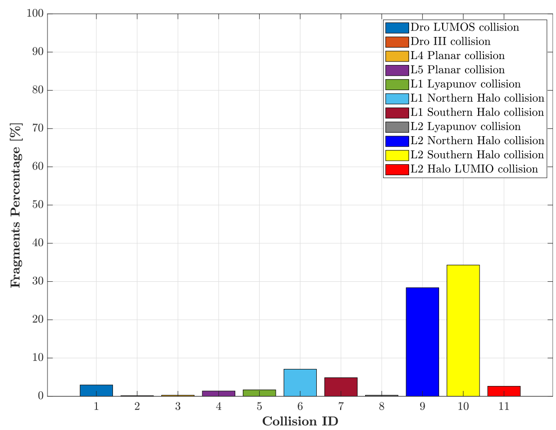

Figure 5. Percentage of fragments impacting the Moon over three months for each collision.

Regarding the risk to the lunar surface, as shown in Fig.

5, the threats are slightly higher: with values of 34.3% and 28.5% are registered from the closer collisions 10 and 9, located on the Southern and Northern L2 Halo orbits, respectively.

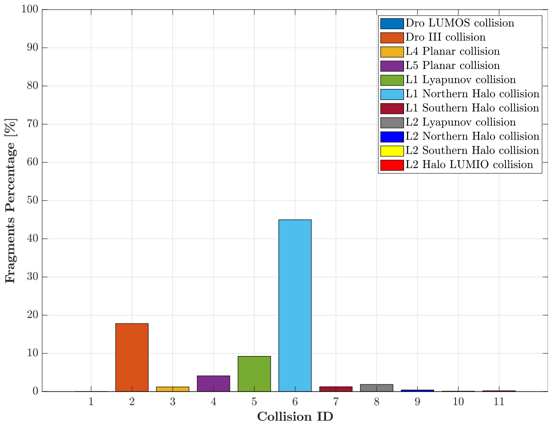

Figure 6. Percentage of fragments impacting the GEO sphere over three months for each collision.

For operational spacecraft in GEO, Fig. 6 clearly identifies collisions 6, 2, and 5 - already identified for the Earth impact case - as presenting the most significant threats, with 44.9%, 17.8% and 9.2 % of fragments, respectively, entering the GEO sphere. However, this threat diminishes significantly when focusing on the GEO belt, where only 0.7% of fragments from collision 2 and 0.3% from collision 6 are registered.
Therefore, the assessment suggests that the densely populated GEO belt region faces a relatively low risk, as the majority of hazardous fragments targeting the GEO region are detected along the out-of-plane dimension.

To further analyze how debris evolves and their dynamics, it is observed that, after three months, the majority of fragments remain dispersed throughout the entire region, as highlighted in Fig. 7.

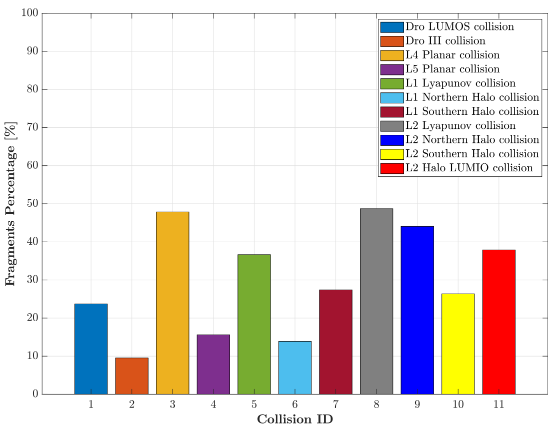

Figure 7. Percentage of fragments leaving the Cislunar region after three months. Cislunar region defined as: $x \in [-GEO, 12\,GEO],\ y \in [-9\,GEO, 9\,GEO]$

3.2. Observational Performance Assessment

The second goal of this study is to evaluate the capabilities of Cislunar observational spacecraft in monitoring the debris clouds generated by the fragmentation events. To assess the ability of the observers to detect the simulated debris clouds, the visibility of each fragment from each observer is evaluated for every time instant. Observations are made every two hours over the three-month period. The percentage of fragments successfully observed at least once by each observer-collision pair is presented in Fig. 8.

Notably, observers located on the right side of the x-axis and belonging to the L2 Lyapunov and Halo families consistently perform the best across most collision scenarios. Furthermore, collision 7, which occurs at the L1 Southern Halo orbit, yields the highest overall detection rates, making it the most well-detected event across the analyzed observers. Collision 7 is especially well-detected by observers 18 (L1 S Halo), 26 (L2 S Halo), 19, and 21 (L2 Lyapunovs), with observer 26 achieving complete fragment monitoring, and observers 18, 19, and 21 detecting 99.3%, 98.8% and 96.7% of fragments, respectively.
To address this, the number of re-observations of each fragment over the three months is analyzed. Observers capable of maintaining long-term detection, even of a limited number of fragments, are particularly valuable for constructing and refining a comprehensive debris catalog. Therefore, the preferred approach in this study prioritizes the observation of fewer fragments with greater accuracy and over longer durations.

The final missing piece of information concerns the duration of each re-observation, or in other words, the percentage of time each fragment is visible. As illustrated in Fig. 9, most observers detect a large number of fragments in the initial phase. However, this number gradually decreases over time as most fragments drift away within a few days and do not re-encounter observers within the three-month observation period. The primary factor contributing to the non-visibility of fragments within Cislunar space is the increasing distance between the observer and the fragments. Interestingly, fragments exhibiting lower delta velocities (initial $\Delta v < 0.4$ km/s) tend to remain confined within the inner Cislunar region, enabling extended and more consistent periods of detectability. Conversely, non-visible fragments encompass a wide range of initial velocities, both high and low. The non-detectability of these fragments is primarily influenced by their initial trajectory, which leads to their rapid dispersion across the region and eventual unobservability due to the significant distances involved.
It is important to note that these findings are specific to the time frame and initial epoch of propagation considered.

4. CONCLUSIONS

This study provides a comprehensive analysis of debris evolution and detectability within the Cislunar environ-

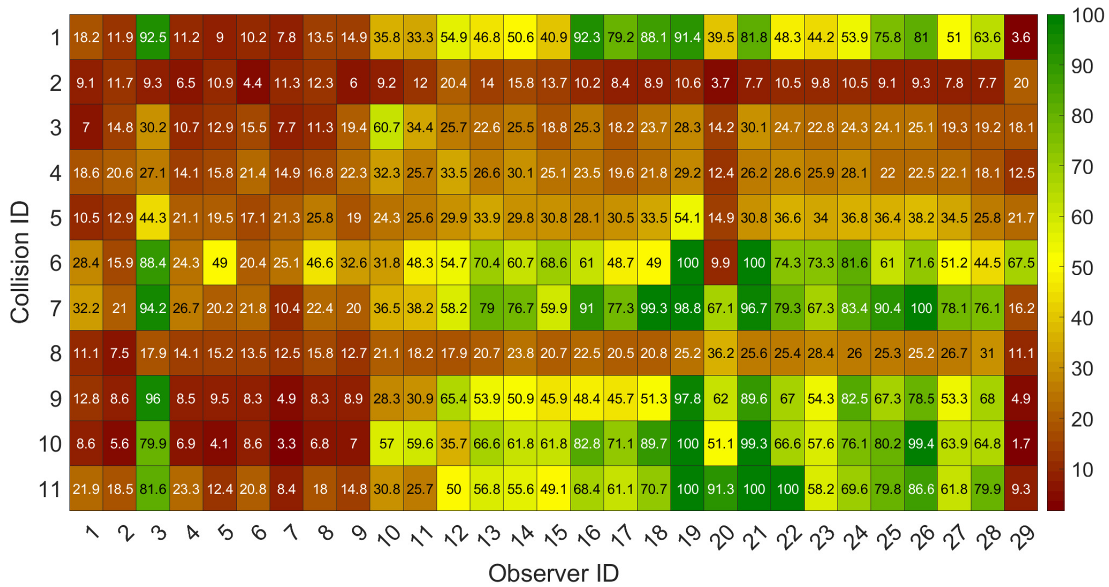

Figure 8. Percentage of fragments visible by each observer over three months for all eleven collision cases.

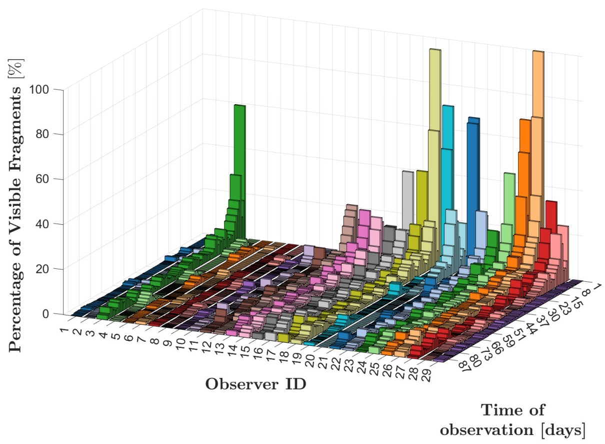

Figure 9. Number of fragments observable by each observer over three months.

ment, offering valuable insights into the complexities of this region. The findings further contribute to the development of requirements for an STM infrastructure, supporting the sustainable utilization of Cislunar space.
Moderate risks of impacts with celestial bodies, particularly the Moon, have been identified. In contrast, minimal risks are associated with the GEO belt region, as most debris fragments that intersect this region do so at nearly normal angles.
Over three months, most fragments disperse chaotically across the Cislunar region, with lower-velocity ones accumulating in the inner Cislunar area and allowing for prolonged detectability. Moreover, the debris initial trajectories result as a key factor for their non-detectability, leading to their rapid dispersion and non-observability due to the significant distances involved. Given the strategic importance of the L1 and L2 Halo regions for both SSA and scientific research, continuous and rigorous monitoring of assets and debris in these areas is recommended. Such a proactive approach is essential for mitigating debris-related threats, which have already been observed in the current Near-Earth environment, and will be critical to ensuring the long-term sustainability of operations within the Cislunar domain.
Future developments of the work here presented concern the study of a network of sensors placed on different orbits, among those considered to be the best by the performance analysis conducted in this paper, with related results on the capability to build an infrastructure of several satellites supporting the monitoring of various fragment clouds. Additionally, it would be worthwhile to investigate the potential, for fragments that are observed multiple times by the sensors, to generate optical measurements, thereby enabling the determination of their orbit and the assessment of the accuracy that can be achieved.

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