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# IMPACT AND EVOLUTION OF ZERO DEBRIS FOR LUNAR ORBITS

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BASED ON: TM-2234-OHBG_02

# AGENDA

1. Debris Challenge in cislunar environment
2. Study scope and representative cases
3. Mission Analysis Results
4. Disposal and orbit dependency
5. Preliminary Consolidated Lunar Zero Debris requirements
6. Requirements study cases Compliance and impact
7. Identified gaps and enabling capabilities

# DEBRIS CHALLENGE IN CISLUNAR ENVIRONMENT

- Earth orbit assumptions do not transfer directly:
  - No mature, **operational debris mitigation framework** dedicated to lunar/cislunar regimes
  - **Very different dynamical regimes**: LLO, frozen orbits, NRHO, halo, DRO, high elliptical and cislunar trajectories
  - **Weak or absent natural “self-cleaning”** in several cislunar regions
  - **Tracking and catalogue maintenance** are not yet comparable to Earth orbit
  - **Surface operations** introduce additional environmental effects: impacts, plume-regolith interaction, ejecta

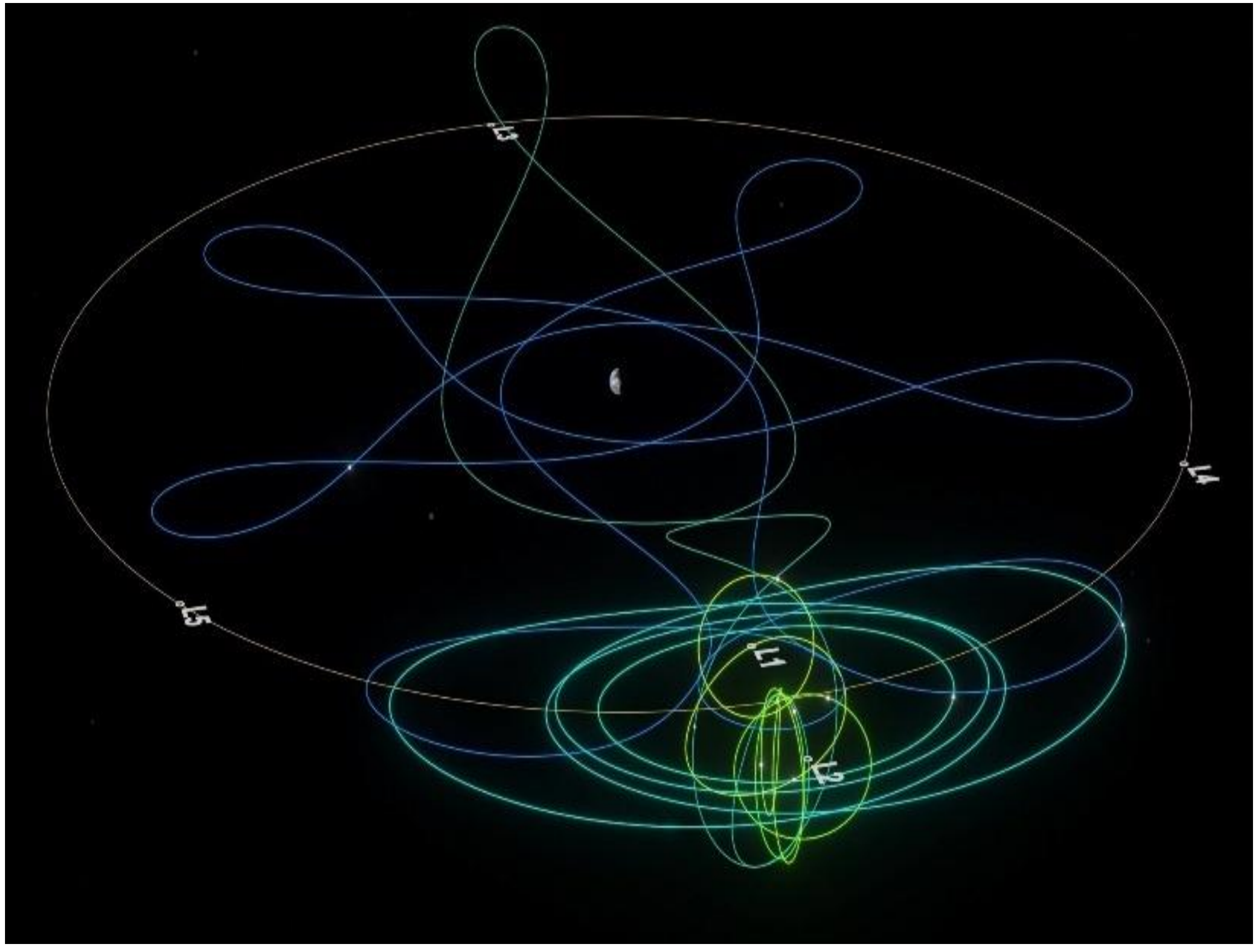

Figure 1: Cislunar space orbital families

Johns Hopkins University Applied Physics Laboratory. Cislunar Science and Technology. https://www.jhuapl.edu/work/expertise/cislunar-science-and-technology

# STUDY SCOPE AND REPRESENTATIVE CASES

- The activity considered **representative mission classes**:

| | CubeSat | Lunar Observer 1 | Lunar Observer 2 | Lunar Lander |
|---|---|---|---|---|
| **Orbit** | Halo orbit at EML 2 | LLO | Elliptical Lunar Frozen Orbit (ELFO) | Descent from LLO |
| **Size Class** | S-class | M-class | M-class | L-class |
| **Disposal Strategy** | Controlled Lunar Impact | Controlled Lunar Impact | Heliocentric Disposal | Lunar Landing |

- Technical areas assessed:
  - Orbit predictability and disposal options
  - Passivation and fragmentation prevention
  - Trackability and SSA/SST constraints
  - Conjunction assessment and collision avoidance compatibility
  - Lunar impact and plume/regolith ejecta effects
  - Platform level implications and technology roadmap

# MISSION ANALYSIS RESULTS

## CONJUNCTION ANALYSIS IN CISLUNAR SPACE

### Quantify the cost of CAM as a function of required miss distance and lead time to the conjunction event

1. Analytical Euler-Lagrange **Optimal control problem** formulation:
   - Computes **minimum control** magnitude and direction
   - **Miss distances:** 200 m to 1 km (linearity assumption)
   - **Manoeuvre window:** 30 min to 4 days before the event
2. Exploit same population, filtering out close approaches below minimum miss distance
3. Low thrust propulsion with **unconstrained thrust** and **saturation at 0.3 N** thrust limit

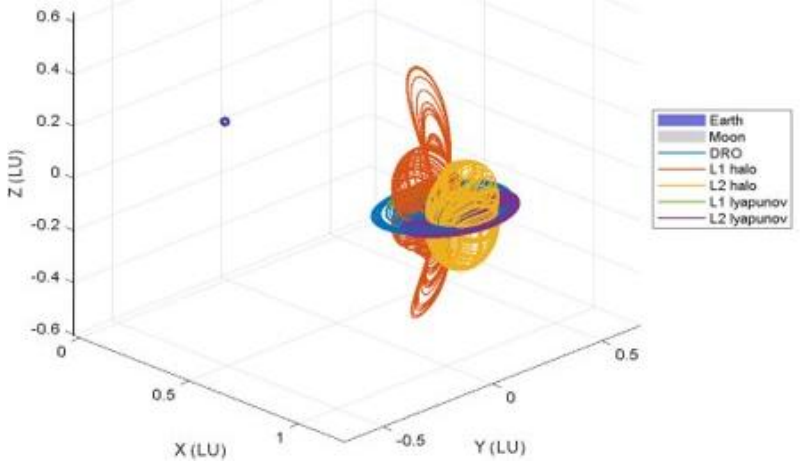

Figure 2: Statistically meaningful population of possible events at TCA

Final Report Public, Lunar Zero Debris activity, LZD-OHB-SYS-FR-001, issue 2

### Conclusions

- **Feasibility Confirmed**: CAMs dynamically tractable in cislunar space; effective separation can be achieved with ΔV below 1 m/s
- Exponential Cost of Delay: There is **a critical inverse exponential relationship between lead time and cost**; <48 h = rapid surge in thrust and propellant
- Optimal Lead Time: The "sweet spot" for manoeuvre planning is **72–96 hours before the event**, where thrust drops to the order of $\mathbf{10^{-6}}$ N
- **Electric Propulsion Compatibility:** required thrust levels are low enough to be compatible with modern low-thrust electric propulsion systems, provided the manoeuvre is not performed last-minute
- **Miss Distance Sensitivity**: Increasing the required safety distance (e.g., from 200 m to 1 km) increases ΔV costs, but primary driver is the lead time

# MISSION ANALYSIS RESULTS

## LONG TERM POLLUTION OF SPACE DEBRIS & GRAVEYARD STABILITY

**Quantify the stability and stability boundaries of graveyard orbits over decadal to century time scales**

  - DRO initial Orbits, 5 – 15 days periods, 30000 to 90000 km altitudes from Lunar surface
  - Single HELO initial orbit case
  - Reference Epoch Jan 1, 2025, 00:00:00 UTC

- **Geocentric high fidelity N bodies propagation** with planetary impact, **with and without SRP,** to elaborate its effects
- **Break up Event modelling:**
  - 4 events randomly positioned within the orbital period for phase coverage, accounting for HELO periapsis drift
  - 100 fragments randomly sampled from collision and explosion events
  - Breakups modelling based on NASA SBM modified through ESA Master


Figure 3: Fragments Propagation in Cislunar Space


**Orbits Database** → **Conversion to J2000** → **Apply Fragmentation** → **100 years Propagation** → **Results Analysis**

**Figure 4**: Long term fragments propagation pipeline flowchart

# DISPOSAL AND ORBIT DEPENDENCY

- **LLO** is **dynamically fragile**: lunar gravity anomalies drive eccentricity growth and make uncontrolled long-term evolution difficult to predict. Many LLOs decay or impact within weeks to months if uncontrolled.
- **Frozen LLOs** improve stability, but they still remain in regions that future operational missions may cross -> **not ideal passive graveyard**
- **NRHO** and **halo** orbits require **active management**: NRHOs are only marginally stable, while halo orbits can diverge on short timescales without control.
- **DROs** are the most promising **long-term stable** regime for **intact spacecraft**, with minimal natural drift compared with halo-type trajectories.

- **Disposal** options therefore differ **by regime**:
  - **LLO**: **controlled lunar impact** is generally preferred.
  - **NRHO/halo**: heliocentric disposal, lunar impact, Earth re-entry or transfer to DRO may be possible **depending on geometry and Δv**.
  - **DRO**: **continued parking** or **heliocentric** disposal may be considered, but only with coordination and tracking.

# DISPOSAL AND ORBIT DEPENDENCY

- Stable distant regimes such as **DROs** may retain intact spacecraft for long periods, but **fragmentation** products can spread into loosely bound cislunar trajectories.
- In the DRO fragmentation analysis, approximately **40-55% of DRO fragments** can persist in bound classes depending on fragmentation parameters and area-to-mass ratio. A small but non-zero Earth-impact or re-entry branch was also observed.
- **HELO-like graveyard** candidates were **less robust** after breakup: post-fragmentation evolution was dominated by wandering trajectories, with lunar impacts also appearing as a relevant outcome.
- This makes **passivation** a primary mitigation measure.
- **Trackability** is a limiting capability: small objects become difficult to detect at cislunar distances. Optical surveillance is currently the most credible near-term approach, but it requires adequate performance and revisit rates. Detectability rapidly degrades with range and unfavourable phase angle.

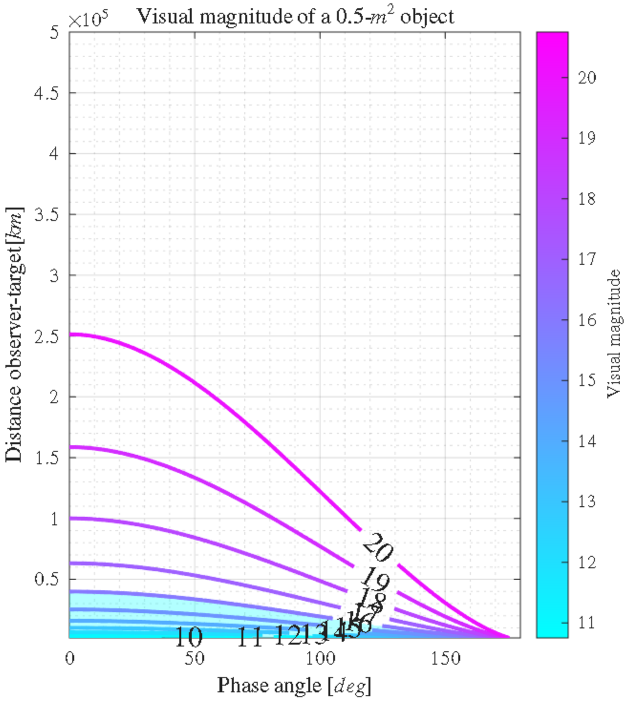

Figure 5: Example visibility map for a 0.5 m² object

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# DISPOSAL AND ORBIT DEPENDENCY

- **Controlled lunar impact** was assessed using hypervelocity impact simulations to evaluate crater depth, regolith ejection angles and ejecta velocities for CubeSat and lunar orbiter cases.

| | CubeSat | CubeSat | Lunar Observer 1 | Lunar Observer 2 |
|---|---|---|---|---|
| **Surface Type** | Regolith | 1 m regolith then megaregolith | Regolith | Regolith |
| **Ejecta velocity (m/s)** | ~225 | ~450 | ~300 | ~550 |
| **Ejecta angle (deg)** | ~45 | ~60 | ~60 | ~60 |

- **Governing factor** for plume behaviour = **ejecta velocity field**, which depends on highly non-linear interactions among:
  - local regolith depth (from cm to >10 m)
  - impact angle
  - impact location and local geological structure (transition to bedrock)
  - material response under high strain rate
  - spacecraft fragmentation behaviour
- Shallow regolith/hard surface transition can increase ejecta velocity by 2 times

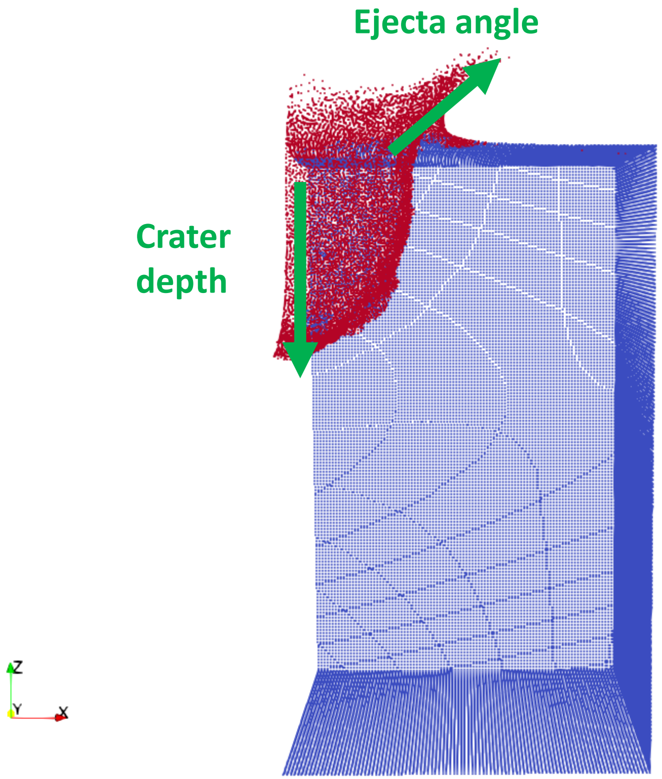

Figure 6: CubeSat study case impact analysis

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# PRELIMINARY CONSOLIDATED LUNAR ZERO DEBRIS REQUIREMENTS

| Req ID | Requirement |
|---|---|
| REQ-001 | The disposal of a spacecraft or launch vehicle orbital element operating in Lunar orbits shall achieve full **clearance** within **5 years**, measured from the injection epoch for systems without recurrent manoeuvre capability, or from the end-of-life epoch for systems with such capability. |
| REQ-002 | The spacecraft or launch vehicle orbital element in Lunar orbit shall **initiate its end-of-life disposal manoeuvre no later than 3 months** after the end of nominal mission operations. |
| REQ-004 | The spacecraft or launch vehicle orbital element shall be **passivated** before the end of life. |
| REQ-005 | The spacecraft or launch vehicle orbital element shall be designed to guarantee a **probability of successful passivation** through to the end of life of at least **0.9**. |
| REQ-007 | During the design, the developer of the spacecraft shall perform an **assessment** to **quantify the operational impact** during normal operations due to **conjunctions**. |
| REQ-008 | The spacecraft design (including the delta-v budget) shall be compatible with collision avoidance operations ensuring a **minimum miss distance** threshold of **500 m** per conjunction event. |
| REQ-009 | The spacecraft or launch vehicle orbital element shall be **trackable** by space surveillance segment supporting collision avoidance, demonstrated by either:<br>a) a minimum physical dimension of **1.5 m**, or<br>b) a **maximum apparent visual magnitude** of **16** as seen from tracking assets. |
| REQ-010 | A spacecraft or launch vehicle orbital element operating in Lunar orbit shall include **passivation capabilities**. |
| REQ-011 | The **passivation** shall be executed by one of the following means, in **order of preference**:<br>1) Permanently and irreversibly deplete and prevent future loading.<br>2) Demonstrate that a safe level is reached. |
| REQ-012 | The developer of a spacecraft or launch vehicle orbital element operating in cislunar space shall **assess** and **quantify** the **apparent visual magnitude** of the design as seen from Earth-based tracking assets. |

- NOTE: REQ-008, REQ-009 and REQ-012 assessment is based on current Earth-based tracking capabilities in the cislunar environment.

# REQUIREMENTS STUDY CASES COMPLIANCE AND IMPACT

- **All** study cases were assessed as **Compliant except the CubeSat to REQ-009**:
  - Max physical dimension < 1.5 m
  - VM > 20 with Earth-based tracking
- **Additional Δv** for compliance with CAMs and disposal consolidated requirements:
  - **< 1%** of baseline Δv
  - **within reserve Δv** typical allocations

| Req ID | Req topic summary | CS | LO1 | LO2 | LL |
|---|---|---|---|---|---|
| **REQ-001** | Disposal full clearance within 5 years | C | C | C | N/A |
| **REQ-002** | EoL disposal manoeuvre no later than 3 months | C | C | C | N/A |
| **REQ-004** | Passivated before EoL | C | C | C | C |
| **REQ-005** | Probability of successful passivation of at least 0.85 | C | C | C | C |
| **REQ-007** | Quantify operational impact of conjunctions | C | C | C | N/A |
| **REQ-008** | Compatible with CAM for minimum miss distance of 500 m | C | C | C | N/A |
| **REQ-009** | Trackability with min physical dimension 1.5 m or max apparent visual magnitude 16 | **NC** | C | C | C |
| **REQ-010** | Include passivation capabilities | C | C | C | C |
| **REQ-011** | Passivation execution means and order of preference | C | C | C | C |

# IDENTIFIED GAPS AND ENABLING CAPABILITIES

- Requirements alone are not sufficient. They require **supporting infrastructure, tools and standards:**
  - **Surface interaction mitigation infrastructure**: Landing and impact operations require mature surface interface materials, landing/impact pads and designated operational zones to limit plume/regolith ejecta and support repeatable safe operations.
  - **Cislunar tracking and orbit-determination capability**: Earth-based SSA alone is not sufficient for persistent custody in cislunar space. Improved lunar and space-based tracking infrastructure and accurate cislunar OD sensors are needed.
  - **Cislunar modelling and verification tools**: Mission designers need qualified tools for long-term propagation, uncertainty evolution, disposal verification, lunar impact simulation, regolith/environment modelling and conjunction assessment.
  - **Standardised SSA data interfaces and data fusion**: Cislunar STM requires common data formats, interoperable SSA interfaces and integration of heterogeneous data from Earth-based, lunar-based and space-based sensors.

# THANK YOU!