ITT 7210 – End-of-Life Disposal Concepts for Lagrange-Points and HEO Missions

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Motivations

The awareness of the risk of uncontrolled accumulation of man-made objects became significant in the late 70's and since then, a number of space debris mitigation guidelines have been published by various organizations. The general aim is to reduce the growth of space debris by ensuring that space systems are designed, operated, and disposed in a manner that prevents them from generating debris throughout their lifetime, assuring the sustainable space utilization. In particular, by recognizing their unique nature, two protected regions have been defined for Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). The fulfillment of such requirements must be accounted for in the management of current and future Lagrangian Points Orbit (LPO) and Highly Elliptical Orbit (HEO) missions. In fact, spacecraft in these orbital regimes might interfere with LEO and GEO protected regions or crash in the Earth's surface with inadmissible casualty area, as well as collide with other spacecraft in MEO (Medium Earth Orbit), HEO and LPO.

Objectives

The main objectives of this work are:

1. to define mitigation recommendations for LPO and HEO missions;
2. to formulate feasible and optimal disposal strategies, possibly including different options for each class or subclass of missions;
3. to design disposal strategies for GAIA and EUCLID missions;
4. to investigate the effects of uncertainties on GAIA's disposal strategies.

To achieve the above-mentioned goals, the following activities were carried out:

1. Analysis of current and planned LPO and HEO missions, identifying additional future potential applications.
2. Identification of the requirements (including as a minimum clearance of protected regions, integral collision and on-ground casualty risk mitigation) and constraints for the mitigation strategies.
3. Identification of a variety of feasible disposal options and definition of a framework for their validation and ranking. The framework is defined by the dynamical models, the objective functions, and the design and operational constraints adopted for the evaluations.
4. Assessment of the compliancy of the disposal strategies with technical and sustainability constraints and requirements.
5. Trade-off analysis based on different criteria, such as safety, robustness, operational complexity, ΔV requirements, sustainability.
6. Definition of technical constraints for GAIA and EUCLID missions, such as the maximum available propellant mass for disposal operations and the duration of disposal phase.

7. Assessment of robustness of proposed disposal strategies for GAIA mission through Monte Carlo Simulations (MCS).
8. Assessment of sensitivity to some design parameters for EUCLID disposal strategy through the parametric analysis.

Main Results

In this study three different disposal concepts were defined and studied:

- Lunar impact
- Earth reentry
- Disposal on graveyard orbits

For the lunar impact and Earth reentry options, controlled, semi-controlled and uncontrolled strategies were considered, depending on the specific mitigation requirements. For what concerns the third option, instead, both geocentric and heliocentric graveyard orbits were considered.

Solutions for LPO missions were obtained for all these options. As these solutions exploit the highly nonlinear dynamics typical of the n-body models, their derivation is not trivial. Specific two-step approaches were developed for the lunar impact and the Earth reentry. Preliminary feasible trajectories were computed via genetic algorithms, whereas a local constrained optimization was exploited for the second step to ensure the compliance with technical and sustainability constraints.

For the heliocentric graveyard option, two different approaches are proposed. The first is a simple fully-numerical method, whereas in the second we propose to permanently close the Hill's regions and confine the spacecraft motion in a region beyond the Earth's orbit (see Figure 1).

Solutions compatible with mission constraints were found for SoHO, GAIA, and EUCLID. In addition, disposal solutions for GAIA were optimized to consider new technical constraints set by ESA.

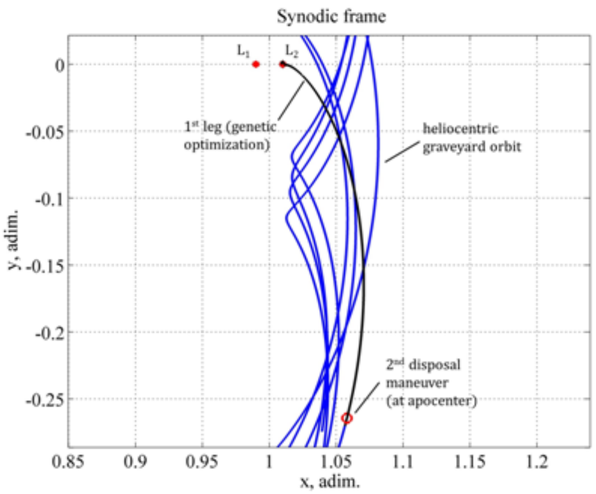

Figure 1 – Heliocentric graveyard orbit for GAIA (energetic approach).

More specifically, it is found that for GAIA and SoHO missions all disposal strategies can be performed with the on-board available ΔV. Differently, only the Earth reentry and the disposal on heliocentric graveyard orbit with the numerical approach can be implemented for the disposal of EUCLID spacecraft (see Table 1).

Disposal Options	GAIA	SoHO	EUCLID
Lunar Impact	49.45 m/s	27.6 m/s	17.29 m/s
Earth Reentry	88.56 m/s	27.8 m/s	6.18 m/s
Heliocentric Graveyard Orbit (Numerical Approach)	0.00218 m/s	2.1 m/s	0.01 m/s
Heliocentric Graveyard Orbit (Energetic Approach)	84.07 m/s	49 m/s	272.52 m/s

Table 1 – Summary of ΔVs for studied LPO missions. Note that the above values refer to minimum ΔV

For what concerns the HEO missions, the orbital configuration at EoL has a significant role in the definition of feasible disposal strategies. For this reason, not all options are (see Table 2).

For the HEO missions considered in this work, INTEGRAL and XMM-NEWTON, the ΔV necessary for lunar impact as well as for the direct Earth reentry exceeds available resources. To reduce the ΔV cost (and therefore the propellant mass), a perturbation-assisted disposal has been proposed (see Figure 2). The main idea is to take advantage of the orbital perturbations, crashing the spacecraft into a suitable region on the Earth surface, in compliance with the sustainability constraints. The maneuver, computed via genetic algorithms, allows the spacecraft to be effectively disposed, although the reentry takes few years.

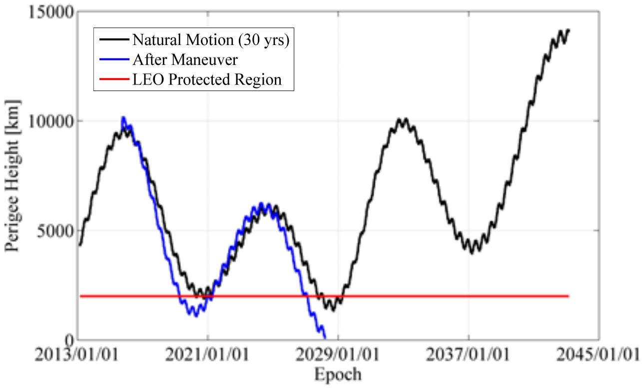

Figure 2 – Perigee altitude evolution for INTEGRAL Earth reentry.

Alternatively, the spacecraft could be injected into a geocentric graveyard orbit, with the perigee above the LEO region (super-LEO graveyard orbit). Despite its simplicity, interactions with GEO protected region couldn't be avoided. Genetic algorithms were exploited in order to at least minimize these interactions.

Disposal Options		XMM-NEWTON	INTEGRAL
Earth Reentry	Semi-controlled Earth Reentry (Perturbations-Assisted Reentry)	-	60 m/s
Disposal on super-LEO Graveyard Orbit		40 m/s	60 m/s

Table 2 – Summary of ΔVs for HEO missions.

Uncertainty Analysis for GAIA

An uncertainty analysis was carried out using Monte Carlo Simulation to assess the robustness of disposal solutions proposed for GAIA. In this study, only the uncertainties on ΔV, A/m, and on direction of thrust vector (through the thrust angles α and β) were considered (see Table 3). Particularly, for lunar impact and Earth reentry strategies, uncertainty analyses were performed on both the disposal maneuvers. From Monte Carlo analyses it was shown that the lunar impact and Earth reentry approaches are strongly affected by maneuvering errors, whereas the disposal on heliocentric orbit is more sensitive to the uncertainties on A/m parameter.

Uncertainties (3σ)			
ΔV (m/s)	α (deg)	β (deg)	A/M (m^2/kg)
$\pm$ 5 % of Nominal value	$\pm$ 1	$\pm$ 1	$\pm$10 % of Nominal value

Table 3 – Summary of uncertainties used in Monte Carlo Simulation.

Trade-off

Once the disposal strategies for candidate missions were designed, a trade-off matrix for candidate missions was compiled (see Table 4 and Table 5), evaluating their performances with respect to different criteria, such as ΔV requirement, disposal complexity, robustness (Monte Carlo analyses), safety and sustainability. Table 4 and Table 5 illustrate the trade-off matrices derived for LPO and HEO missions respectively. In these matrices the disposal options are organized in rows and each criterion occupies a column, such that final disposal recommendations for LPO and HEO missions can be easily obtained.

Disposal strategy	Main Criteria				
	ΔV	Disposal Complexity	Robustness	Safety	Sustainability
Controlled Earth Reentry	LOW	HIGH	LOW	HIGH	HIGH
Semi-controlled Earth Reentry	LOW	HIGH	MEDIUM	HIGH	HIGH
Controlled Lunar Impact	LOW	HIGH	LOW	HIGH	HIGH
Semi-controlled Lunar Impact	LOW	HIGH	MEDIUM	HIGH	HIGH
Heliocentric Graveyard (Energetic)	LOW	MEDIUM	HIGH	HIGH	MEDIUM
Heliocentric Graveyard (Fully-Numerical)	LOW	LOW	MEDIUM	HIGH	MEDIUM

Table 4 – Trade-off matrix for LPO candidate missions.

Disposal strategy	Main Criteria				
	ΔV	Disposal Complexity	Robustness	Safety	Sustainability
Disposal on super-LEO	LOW	LOW	HIGH	MEDIUM	LOW
Semi-controlled Earth reentry by Perturbation-Assisted strategy	LOW	MEDIUM	MEDIUM	MEDIUM	HIGH

Table 5 – Trade-off matrix for HEO candidate missions.

Conclusions

One of the ultimate goals of the present study was to assess the need of new protected regions for LPO and HEO missions and to identify possible new requirements for their disposal. From the performed analyses it turns out that no new protected regions need to be defined: HEOs are characterized by a low spatial density and don't have the "unique nature" mentioned in the IADC guidelines; on the other hand, LPO might have this feature, but low spatial density and the "self-cleaning" behaviour make the definition of protected region unnecessary. Nonetheless, it should be stated that the disposal maneuver is required for LPO and HEO spacecraft and potential new requirements may be introduced for the disposal on graveyard orbits.

As outcome of this study one can state that, whenever the sustainability represents the main issue in disposal strategy evaluation, the lunar impact and/or the Earth reentry strategies should be preferred, since they entail the physical elimination of the satellite. Otherwise, whenever robustness and disposal strategy complexity heavily weigh on strategy selection, the disposal on graveyard orbits represents the most preferred solution.