IMPACT OF SPACE DEBRIS MITIGATION REQUIREMENTS ON THE MISSION DESIGN OF ESA SPACECRAFT

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ABSTRACT

Since the space debris mitigation requirements went into force at ESA in 2007 each new space mission has to demonstrate compliance. For Earth orbiting satellites, the "25-year lifetime rule" requires to bring sufficient fuel into orbit to perform an orbit lowering at the end of the mission. If simulations show that the spacecraft does not burn up during re-entry, the fuel budget, an adequate propulsion system and the whole spacecraft have to be designed for a controlled re-entry. Also interplanetary spacecraft are required to mitigate the risk of collision with other spacecraft or during re-entry back to Earth. The impact of the mitigation requirements on the mission design is illustrated on five spacecraft missions.

1 INTRODUCTION

In March 2007 ESA released its Requirements on Space Debris Mitigation for ESA Projects [1] to contribute to the efforts to limit the continuous growth of debris in orbit. Since then the requirements are applied during the mission design process of every new satellite. The Mission Analysis Section at ESOC is responsible for the trajectory design, the delta-V budget and the End-of-Life scenario definition for all ESA science missions as well as for most Earth observation and application satellites. Especially in CDF sessions, the mission analyst is responsible for the delta-V budget.

Two debris mitigation requirements have a significant influence on the delta-V budget of a mission: First the "25-year lifetime rule" and then the controlled de-orbit requirement, if the casualty risk during re-entry has a probability of more than 10^{-4}. In this paper the implications of these two rules are described for the XIPE and CHEOPS mission.

- XIPE is a X-ray Observatory in LEO currently in competition for ESA's M4 mission. A re-entry analysis based on a preliminary design gave an on-ground casualty risk of about 10^{-4}. Therefore a controlled re-entry had to be analysed.
- CHEOPS is a 300 kg Exoplanet Observatory. It shall be launched as a piggyback spacecraft into an orbit between 500 and 800 km. The fuel for re-orbiting at end-of-life to comply with the "25-year lifetime rule" needs to be calculated.

But also missions to Lagrange points and even interplanetary spacecraft have to comply with the space debris mitigation requirements. This is illustrated for these three examples:

- Athena is a 5-ton X-ray Observatory to be launched in 2028 to a Sun-Earth libration point. End-of-life disposals to reduce the risk that it will eventually re-enter into the Earth atmosphere are studied. Also disposal manoeuvers for the mirror cover that shall be ejected a few days after launch are intensively investigated.
- Lisa Pathfinder currently in orbit about the Sun-Earth Libration Point 1 had no Delta-V allocation for the end-of-life scenario due to the status of the project when the space debris mitigation requirements came into place. However, a disposal will be performed on a best effort basis using the remaining propellant after end of the scientific phase. The probability of re-entry was studied over a period of up to 500 years to understand the long-term orbital behaviour.
- BepiColombo, a 4-ton composite of two spacecraft bound to Mercury, shall be launched in 2018 on an Ariane 5 rocket. Mission analysis is tasked to find the best disposal manoeuvre for the upper stage that will minimise the long-term re-entry risk during a launch window of 30 days.

2 EXAMPLES OF SPACE MISSIONS AFFECTED BY MITIGATION REQUIREMENTS

2.1 XIPE

XIPE is a 1.2-ton X-ray Observatory in LEO. An orbital altitude range from 500 to 650 km is analysed [2]. The ΔV budget is largely affected by the initial orbital altitude. Figure 1 shows the ΔV needed for re-orbiting and for orbit maintenance. It was calculated that the altitude at End-of-Life must not be higher than 630 km in order to comply with the 25-year lifetime rule. If the altitude is higher a re-orbit manoeuvre must lower the altitude to 630 km at EoL.

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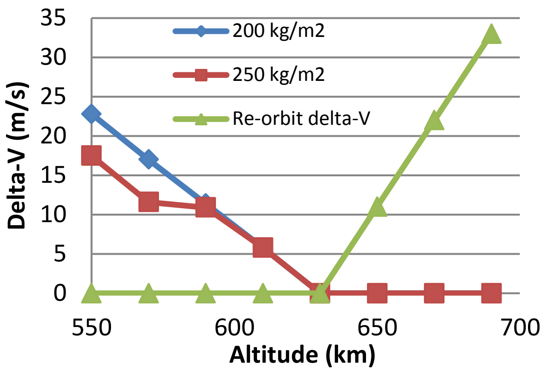

Figure 2-1. ΔV for re-orbiting to an altitude compliant with the 25-year lifetime rule (green line) and for orbit maintenance for two different area-to-mass ratios.

In case that the casualty risk is below 10^{-4} when the spacecraft re-enters the atmosphere, the only requirement is that the spacecraft will remain in orbit less than 25 years after end of its mission.

The design of XIPE as proposed in the CDF study may not be the final one. The current preliminary reentry analysis done with DRAMA indicates that XIPE may have a casualty risk which comes close to the value of 10^{-4}. In case the final analysis indicates that this threshold will be exceeded, XIPE will have to be deorbited in a controlled way.

In order to reduce the debris fall-out area it is important to reenter with a sufficiently large flight path angle. Also the perigee of the last full orbit cannot be too low because the spacecraft needs to be fully controlled and quite large aerodynamic torques will be experienced at altitudes below 200 km. Therefore the last burn is foreseen to lower the perigee from 185 km to 40 km. The 40 km was the result of a trade-off done for the LOFT satellite where ΔV and debris ground swath were considered [3].

Table 1 shows the ΔV budget for the XIPE satellite. It can be seen that the part for deorbiting and collision avoidance makes almost 90 % of the total budget.

Table 1: XIPE ΔV budget in case a controlled re-entry is required.

	ΔV	Margin
Collision avoidance manoeuvres	2.0 m/s	100 %
Orbit manoeuvre capability	25.0 m/s	5 %
Deorbit	193.2 m/s	5 %
Total	220.2 m/s	

2.2 CHEOPS

CHEOPS is a 300 kg Exoplanet Observatory currently in competition for ESA's M4 mission. It shall be launched as a piggyback spacecraft into an orbit between 500 and 800 km [4]. At the end of the mission the orbit has to be lowered to an altitude where the lifetime of the spacecraft is limited to 25 years. Figure 2 shows the orbital lifetime of a satellite as function of area-to-mass ratio and altitude assuming circular orbits. For a conservative approach an area-to-mass ratio of 0.01 m^2/kg is assumed. The figure shows that the spacecraft must be put in a 610 circular orbit to comply with the 25-years lifetime rule.

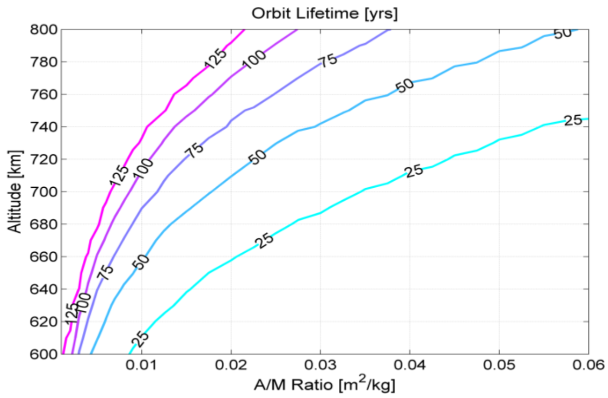

Figure 2-2: Orbital lifetime of objects as function of area-to-mass ratio and altitude.

The ΔV to go from 800 km altitude to 610 km is 101 m/s. A cheaper option, however, is to move the spacecraft to an eccentric orbit with the same orbital lifetime. This is the proposed baseline approach for EOL-reorbiting. For an area-to-mass ratio of 0.01 m^2/kg the perigee has to be lowered to 490 km which costs 83 m/s. Table 2 shows the required EOL orbit and the corresponding ΔV to reach this orbit for altitudes from 650 to 800 km.

Table 2: Required EOL orbits and ΔV to comply with the 25-years lifetime rule for an area-to-mass ratio of 0.01 m^2/kg (results of the DRAMA software assuming 50^{th} percentile for solar activity).

Mission Altitude	**650**	**700**	**800**	**(800)**
Required EOL orbit (km x km)	575 x 650	540 x 700	490 x 800	(610 x 610)
Reorbit ΔV (m/s)	20	43	83	(101)

2.3 Athena

Athena is a 5-ton X-ray Observatory to be launched in 2028 to a Sun-Earth libration point [5]. Athena has a 3-meter mirror cover that has to be disposed soon after launch. The separation should be as late as possible to prevent contamination of the mirrors during the trajectory correction manoeuvres, but not too late to allow a timely telescope commissioning. In order to define the best disposal strategy, the probability that the mirror cover returns to the Earth Moon system is investigated. Different separation ΔVs are investigated. The SNAPPshot tool [6] was used to simulate the orbit evolution of the mirror cover for a period of 100 years. The following assumptions were taken:

- Initial states: all separation states between 1 Jan and 31 Dec 2028 that fulfil the launch window constraints, propagated to day 12 after separation (including J_2). The perigee velocity is the result from the bisection method that gives the free transfer to L_2 (assuming that no perigee velocity correction manoeuvre takes place).

- Separation ΔV between 0 and 10 m/s in heliocentric velocity direction at day 12 after launch.

- Mass: between 50 and 104 kg

- Diameter: between 3160 and 3400 mm

Figure 3 shows in the top panel the Earth impact probability within 100 years for all possible launch dates assuming a mirror disposal velocity of 1 m/s. Averaged over the year the probability is 0.75 % which is about half of the value if no separation manoeuvre is performed. The second panel shows the probability that the mirror cover will return within 1 million kilometre of the Earth within 100 years. Averaged over the year it is about 20 %. On average in these cases the mirror cover crosses the Earth-Moon system 3 to 4 times in 100 years. Therefore the mean number of Earth returns is 0.6 (750 000 events in the total sample size of 1.3 million Monte-Carlo runs). The time distribution of all returns is plotted in the bottom panel. A first peak is around 12 years after launch.

Different separation manoeuvres were investigated. The risk is smaller for 1 to 3 m/s, but is increasing again with higher separation ΔVs. As a preliminary conclusion it can be said that the separation ΔV has no significant impact on the probability that the mirror cover will come back to the Earth or hit it.

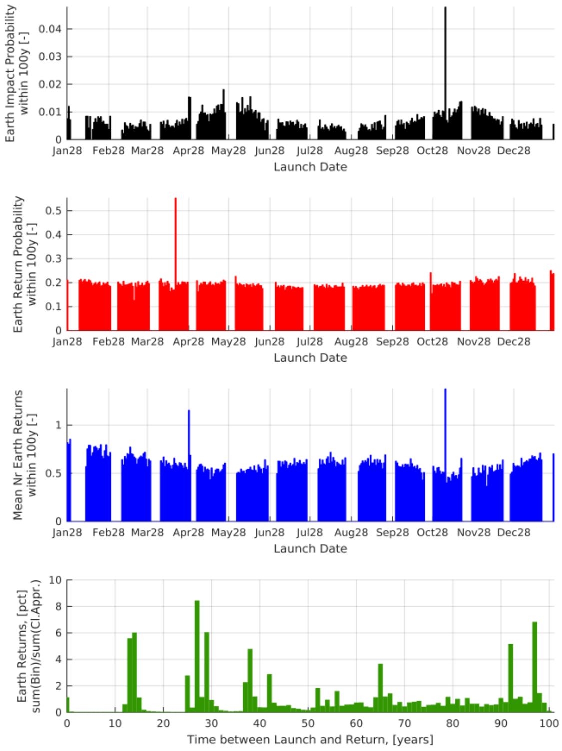

Figure 2-3: Impact probability of mirror cover with the Earth within 100 years (top panel), probability of return to the Earth-Moon system within 100 years (second panel), mean number of returns to the Earth-Moon system within 100 years (third panel) and distribution of time elapsed between launch and return (bottom panel).

2.4 LPF

Lisa Pathfinder is the third libration point S/C to be disposed by ESA following Herschel and Planck. However, the situation for LPF is very different, since the S/C does not carry a chemical propulsion module anymore and thus the disposal manoeuvre can only be implemented using the low-thrust cold gas propulsion system. The DeltaV available on the S/C is also extremely limited and thus solutions with a disposal manoeuvres of up to only 2 m/s were investigated. This essentially means that only the unstable manifold of the libration point orbit can be excited and the S/C will then drift away into a heliocentric orbit. While in principle such a strategy would also allow for a return to Earth or a lunar impact these strategies were not further investigated due to the limited navigation capability and the sparseness of events, respectively. In addition the S/C does not easily allow manoeuvres to be performed into the anti-Sun direction. The focus was thus placed on the remaining heliocentric disposal option and the optimization of the departure epoch.

While with a manoeuvre of 2 m/s a future return to the Earth-Moon system cannot be excluded, the departure epoch has a significant impact on the Earth-Moon system return probability.

In a first step this relationship between the Earth-Moon system return probability and the departure epoch was investigated. The designated departure epoch interval provided by the LPF project was scanned with randomly selected epochs and a fixed departure manoeuvre of 2 m/s.

The number of trajectories with an Earth-Moon system return event within a 100 year propagation time frame were recorded. The result of this initial scan is provided in Figure 2-4 as a histogram.

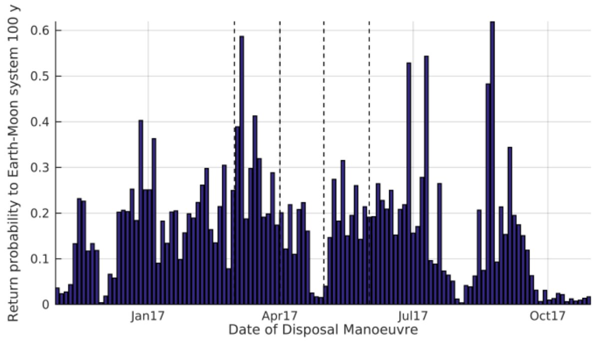

Figure 2-4: LPF Earth-Moon system return probability considering a 2 m/s heliocentric disposal manoeuvre and a 100 year propagation period.

The regions with high and low Earth-Moon system probabilities are clearly visible in the Figure. At this point the area-to-mass ratio had been kept fixed and the disposal manoeuvre had been assumed without manoeuvre execution errors.

In a second step a departure interval was selected based on the project planning and allowing for additional science after the departure manoeuvre. The choice was the April 2017 timeslot, which was now further investigated adding an area-to-mass ratio variation in the long-term propagation. Now only the specific departure interval was sampled.

The results of the detailed departure interval investigations with and without area-to-mass ratio variations are depicted in Figure 2-5. The Earth-Moon system return probability for the reference date is almost unaffected by the area-to-mass ratio variation. The return probability remains about 1 % within a 100 year propagation period.

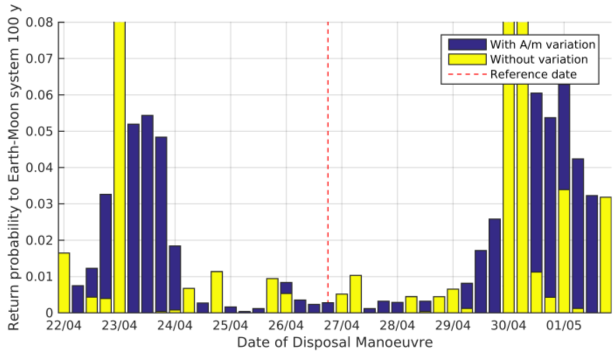

Figure 2-5: Detailed investigation of the low probability Earth-Moon return interval resulting from a 2 m/s heliocentric departure manoeuvre including an area-to-mass ratio variation.

In a final step a single reference departure manoeuvre date was investigated adding also a manoeuvre execution error to the departure manoeuvre. The manoeuvre execution error has a similar effect as a shift in the departure epoch. As it can be seen in Figure 2-4 the return probability does not significantly increase around the reference departure date and thus robustness against the manoeuvre execution error could be expected, which was confirmed by the numerical simulations.

In addition to the 100 year propagation interval periods of up to 500 years were investigated. The results for these runs are depicted in Figure 2-6 and show that the April departure slot is also a good one considering propagation periods of several centuries.

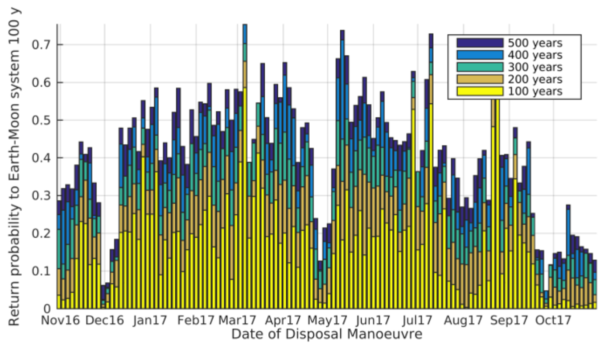

Figure 2-6: Long-term propagation Earth-Moon system return probabilities

While the investigations presented in this paper were conducted for an assumed manoeuvre of 2 m/s it was decided to use only 1 m/s for the actual departure manoeuvre. This required the manoeuvre to be executed earlier than the presented reference departure date and the actual LPF disposal manoeuvre was conducted around the 9^{th} of April 2017. Similar investigations as described above had also been conducted for the 1 m/s departure manoeuvre [7]

2.5 BepiColombo

BepiColombo, a 4-ton composite of two spacecraft bound to Mercury, shall be launched in 2018 on an Ariane 5 rocket. Mission analysis is tasked to find the best disposal manoeuvre for the upper stage that will minimise the re-entry risk in the next 100 years. The idea was discussed to even close individual launch dates, if the re-entry risk exceeds a given threshold.

Three options for the disposal manoeuver of the upper stage after separation were analysed (no manoeuver, 5 m/s along velocity vector and 5 m/s against velocity vector). For each of the 31 launch dates between 17 April and 17 May 2018, 10000 initial states (obtained by sampling the dispersion matrix of the upper stage at separation) were propagated for 100 years; the propagator used is based on Runge-Kutta method (RK78) with variable step size.

Table 3 shows the statistical results of the 3 simulations. The best strategy is to apply the ΔV against the velocity direction. The impact probability in this case is reduced by more than a factor of two, compared to the case if no disposal manoeuvre is performed. Further details and results for the October 2018 launch window can be found in [8].

Table 3: Number of simulated Earth impacts for the April 2018 Launch Window.

Disposal Manoeuvre Strategy	Earth Impacts (Percentage)
No ΔV	419 (0.1352 %)
+5 m/s ΔV	260 (0.0839 %)
-5 m/s ΔV	191 (0.0616 %)

3 SUMMARY

The space debris mitigation guidelines have a strong impact on the design of all new ESA missions. If it will turn out that a controlled re-entry of XIPE is required 88% of the 220 m/s delta-V budget are allocated for the re-entry manoeuvres.

To cover for the highest CHEOPS orbit option of 800 km, 83 m/s out of 105 m/s are allocated for re-orbiting at end-of-life to comply with the “25-year lifetime rule”.

But also interplanetary and libration point missions are required to minimise the risk they pose during possible re-entries: 10 m/s are currently allocated for the end-of-life disposal of Athena to reduce the risk that it will re-enter into the Earth atmosphere within 100 years. Also disposal manoeuvers for the mirror cover that shall be ejected a few days after launch are intensively studied.

For Lisa Pathfinder a best effort disposal was conducted with the limited resources available on board of the S/C, significantly reducing the long-term risk of a return into the Earth-Moon system.

For BepiColombo it is discussed to close launch dates if the re-entry risk of the upper stage exceeds a still to be defined threshold.

4 REFERENCES

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