IMPLICATIONS OF SPACE DEBRIS MITIGATION REQUIREMENTS ON MISSION DESIGN, PROPELLANT BUDGET, DISPOSAL LIFETIME AND OPERATIONS

Laura Moreschi[(1)], Ricardo Gomes[(2)]

[(1)] ESA, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, Email: laura.moreschi@esa.int
[(2)] Deimos for ESA, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, Email: ricardo.gomes@ext.esa.int

ABSTRACT

The increasing density of objects orbiting Earth raises the risk of collisions, creating more debris in a harmful cycle. Effective space debris mitigation is crucial for sustainability of space activities. As Space Debris Mitigation requirements evolve, especially with the reduction of the end-of-life orbital lifetime from 25 years to 5 years, understanding the engineering implications for satellite missions across all mission phasis vital. This paper provides a comprehensive review and analysis of the aspects involved in spacecraft disposal activities.

It integrates parametric analysis of Earth Observation missions, emphasizing the importance of propellant budgeting in early design and operational phases. Key factors like re-entry strategies, solar activity predictions, atmospheric model selection, and drag coefficient, are explored to understand their influence on mission lifetime and compliance with debris mitigation guidelines.

This work translates these complex requirements, into tangible delta-v and propellant mass ranges, guiding effective disposal strategy decisions.

1 INTRODUCTION

The objective of the paper its to encourage discussion and raise awareness regarding the impact that the space debris mitigation guidelines have on the propellant budget, disposal lifetime and operations. It should not be considered as a source or guideline that substitutes the official documentation as outlined in Section 1.2.

1.1 Main Definitions

Disposal phase: (de-orbiting and passivation): interval between the End of Mission (EoM) of a spacecraft and its End of Life (EoL) [1]. The EoM process involves a spacecraft's passivation and re-entry into the atmosphere for its ultimate demise or its movement (if necessary) to an orbit or trajectory considered acceptable for orbital debris limitation [2].

End of Mission: the instant when a spacecraft completes the tasks or functions for which it has been designed, other than its disposal, becomes incapable of accomplishing its mission, or has its mission permanently halted through a voluntary decision [5].

End of Life: the instant when a spacecraft is permanently turned off, nominally as it completes its disposal phase, completes its manoeuvres to perform a controlled re-entry, or can no longer be controlled by the operator [5].

Controlled re-entry: a type of re-entry where the time of re-entry is controlled and the impact of fragments on the Earth surface is confined to a designated zone [6].

Uncontrolled re-entry: a type of re-entry where the time of re-entry or the zone of impact of fragments on the Earth surface are not controlled [6].

Natural orbital decay: free drift ultimately leading to Earth atmospheric re-entry [5].

Re-entry: the permanent return of a space object into the Earth's atmosphere [1]. A process in which atmospheric drag causes deceleration of a spacecraft or launch vehicle orbital stage (or any part thereof), leading to its destruction or return to Earth [2].

Passivate: the act of permanently depleting, irreversibly deactivating, or making safe all on-board sources of stored energy capable of causing an accidental break-up [2].

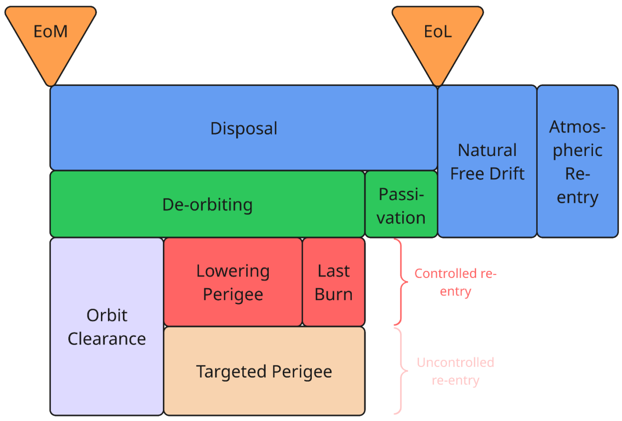

Figure 1. Post End of Mission life cycle of a S/C

The disposal phase is part of the S/C Normal Operations phase [6].

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

1.2 Space Debris Standards Overview

The aim of this paper is to consolidate the information regarding Space Debris within the Mission Analysis activities. Until 2023, the main references were:

- ✓ ESSB-ST-U-004 (2017) ESA Re-entry Safety Requirements
- ✓ ECSS-U-AS-10C (2012) Space sustainability
- ✓ ECSS-U-AS-10C (2019) Space sustainability
- ✓ ESA/ADMIN/IPOL (2014) ESA Space Debris Mitigation Policy for Agency Projects
- ✓ ISO 24113 (2010) Space systems – Space debris mitigation requirements
- ✓ ISO 24113 (2011) Space systems – Space debris mitigation requirements
- ✓ ISO 24113 (2019) Space systems – Space debris mitigation requirements

After 2023 the following documents were updated or *published for the first time*:

- ✓ ECSS-U-AS-10C (2024) Space sustainability
- ✓ ESA/ADMIN/IPOL (2023) ESA Space Debris Mitigation Policy
- ✓ ISO 24113 (2023) Space systems – Space debris mitigation requirements
- ✓ *ESSB-ST-U-007 (2023) ESA Space Debris Mitigation Requirements*
- ✓ *ESSB-HB-U-002 (2023) ESA Space Debris Mitigation Compliance Verification Guidelines*

The main changes related to Mission Design and Mission Analysis from previous requirement to now are:

- A spacecraft (S/C) in Low Earth Orbit (LEO) protected region (i.e. from an equatorial radius of 6378 km up to an altitude of 2000 km) should have a natural orbit decay duration no longer than 5 years according to [5], whereas this number was 25 years in the past [6].
- Additionally, a cumulative collision probability calculation has been added, where this number from its EoL until re-entry with space objects larger than 1 cm, shall be below 10^{-3}.

1.2.3 Casualty Risk Analysis

For ESA Space Systems for which the System Requirements Review has not yet been kicked off at the time of entry into force of ESA/ADMIN/IPOL(2014)2, the casualty risk shall not exceed 1 in 10000 for any re-entry event (controlled or uncontrolled). If the predicted casualty risk for an uncontrolled re-entry exceeds this number, an uncontrolled re-entry is not allowed and a targeted controlled re-entry shall be performed in order not to exceed a risk level of 1 in 10000 [2].

Therefore, for a S/C that are disposed by controlled re-entry, an analysis shall be performed to determine the characteristics of fragments that might potentially survive ground impact, and to assess the total casualty risk for the population on ground assuming an uncontrolled re-entry.

If the S/C decays naturally within 5 years and guarantees a total **casualty risk** on ground:

- **lower than 10^{-4}**: no EOL disposal manoeuvre is required
- **higher than 10^{-4}**: a controlled re-entry into a defined uninhabited area such as the South Pacific Ocean Uninhabited Area (SPOUA), to reduce the casualty risk to acceptable levels. This is the case for S/C above a certain mass and depends on their structure and composition

1.2.4 Cumulative Collision Probability

A space object in Earth orbit without the capability of performing collision avoidance manoeuvres and with a cumulative collision probability with space objects larger than 1 cm above 1 in 1000 is considered environmentally hazardous. The cumulative collision probability calculation aims at preventing the generation of space debris and considers the operational configuration and design of the space objects, e.g. to assess the resilience to damage of different elements such as appendages [5].

1.3 Uncontrolled vs Controlled Re-entry

During re-entry, the object loses altitude and speed gradually. The air resistance slows the object progressively, attempting to circularize the orbit, which becomes noticeable with decreasing apogee altitude. At this stage, depending on the aerodynamic characteristics and dimensions of the object, the aerodynamic force attempts to align the centre of mass and pressure on the direction of the velocity in an aerodynamically stable attitude. At an altitude of about 120 km, the atmosphere is rarefied, and its density varies between 2.5×10^{-8} and 2.8×10^{-10} kg/m3. Under these conditions, the body speed is around 7000 m/s [7].

In the case of uncontrolled re-entry, a natural free drift phase happens after the disposal activities. The S/C will decay over less than 5 years. Therefore, there is no control over the re-entry area.

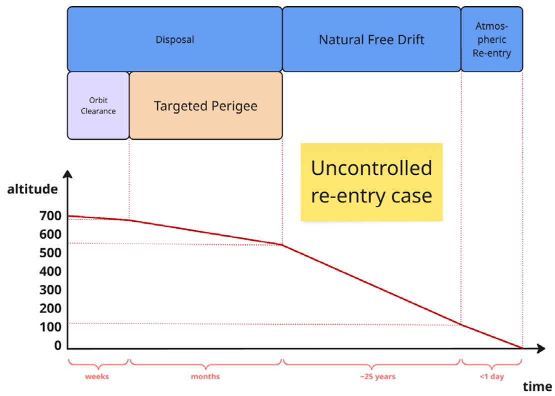

Figure 2: Uncontrolled re-entry considering 25 years

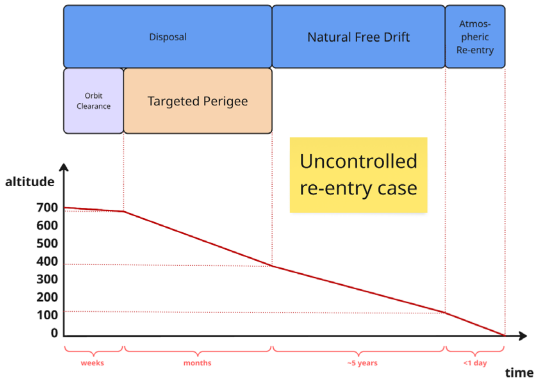

Figure 3: Uncontrolled re-entry considering 5 years

Passivation of the energy sources is always performed when an uncontrolled re-entry is foreseen [2].

S/C performing disposal by controlled re-entry at EoM do not need to implement passivation measures if they comply with the requirements on disposal reliability and re-entry safety [2].

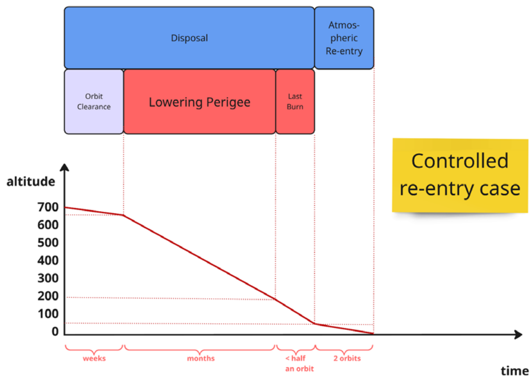

Figure 4: Controlled re-entry

Controlled re-entry involves designing a sequence of manoeuvres to lower the perigee to an altitude low enough to guarantee re-entry in the SPOUA region, based on a defragmentation analysis of the dispersions at the end of the last manoeuvre, in order to assess the footprint of satellite remaining parts in the targeted area, and the subsequent computation of casualty risk

1.3.3 Passivation

Passivation is a crucial strategy for avoiding break-ups in Earth orbit. The rationale behind the requirements for passivation includes depleting stored energy to prevent in-orbit break-ups of space objects that have completed their mission. This approach ensures that passivation capabilities are included regardless of the de-orbiting strategy, allowing for the mitigation of risks associated with internal break-ups in case of a failure to successfully de-orbit. Additionally, it involves assessing the risks related to the design implementation and setting targets for the probability of successful passivation, thereby enhancing the overall safety and reliability of space missions:

a. A spacecraft operating in Earth orbit shall include passivation capabilities

b. A spacecraft operating in Earth orbit shall be passivated before the EoL unless a successful controlled re-entry is performed

c. A spacecraft operating in Earth orbit shall be designed to guarantee a probability of successful passivation through to the EoL [5]

1.4 Controlled Re-entry Compliance

To properly demonstrate a low casualty risk, the analyses must cover four phases, as identified in Figure 5:

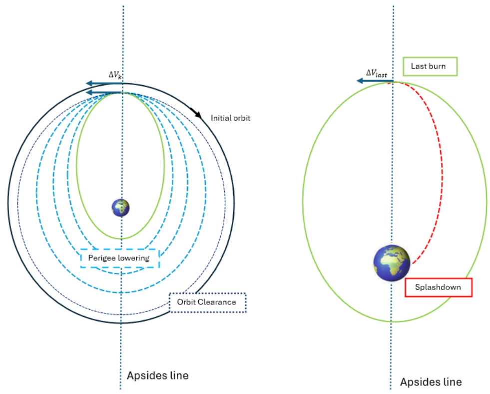

Figure 5. Illustration of the four-phase controlled re-entry sequence: from Orbit Clearance, Perigee Lowering, Last Burn and final Splashdown.

• Phase 1 (Orbit Clearance): In this orbit nominal operations are still allowed while the preparation for the controlled re-entry is taking place. For most of the missions, it is assumed a 5 km orbit clearance will be performed.

• Phase 2 (Perigee Lowering): From the free operational orbit a series of burns will lower the perigee to reach the penultimate perigee at a geodetic perigee between around 200 and 120 km. The number of burns depends on spacecraft capabilities, the possibility for validation of correct disposal system function and correction in case of manoeuvre errors.

• Phase 3 (Last Burn): A final burn will then initiate the targeted re-entry and break up in the atmosphere. The targeted perigee may vary between 80km to 50km, subject to detailed analysis regarding the debris dispersion.

• Phase 4 (Splashdown: atmospheric re-entry): Defragmentation analysis down to Earth surface, based on the dispersions at the end of last manoeuvre, to assess the footprint of satellite remaining parts in the targeted area, and the subsequent computation of casualty risk.

Table 1: Controlled re-entry phases

Phase	Geodetic apogee	Geodetic perigee	Depends on	Comments
Operational orbit	x km	x km		
Phase 1: EoL lower orbit	(x-5) km	(x-5) km	SDO	S/C burn (2 burns)
Phase 2: Perigee lowering	(x-5) km	[200 - 120] km	AOCS	S/C burn (~10 man)
Phase 3: Last single burn	(x-5) km	[50 - 80] km	SPOUA	S/C burn (< half an ort duration)
Phase 4: splashdown - atmospheric re-entry	0 km	0 km	atmosphere, structural model	

1.4.3 Phase 1 - Orbit Clearance:

The satellite is cleared from its operational orbit in order to avoid jeopardizing the other satellite(s) of the trailing formation. This is achieved by lowering the semimajor axis (SMA) by x km.

1.4.4 Phase 2 - Perigee Lowering

A series of post-mission disposal manoeuvres lowers the perigee as close to Earth as the AOCS can maintain control of the spacecraft and changes the argument of perigee to target the SPOUA. According to AOCS disturbance torque analysis, a penultimate perigee height of [200 - 120] km is estimated.

The delta-v budget is independent of the available thrust. However, it is too large to be covered with a single manoeuvre. Therefore, it is necessary to estimate the number of manoeuvres required to lower the perigee. The number of burns will depend on spacecraft's capabilities and operational constrains.

1.4.5 Phase 3 - Last Burn

A single burn decelerates the spacecraft such that it lands in the desired area due to the high atmospheric density and drag force, targeting the SPOUA.

The final burn extends over a significant portion of the orbit arc, but less than half an orbit period.

The manoeuvre is designed such that the final perigee is located at the descending node over southern latitudes and at an altitude of around 50 km It is not necessary to target for a lower altitude as the atmospheric drag is sufficiently strong to stop the horizontal movement.

1.4.6 Phase 4 - Re-entry Analysis:

As a continuation of the last burn analysis, the Right Ascension of the Ascending Node and the Argument of Perigee should be tuned in order to ensure an impact latitude and longitude with in the SPOUA region. The structural Model of the platform and the instrument, and the atmospheric drag are considered the main sources of altitude reduction.

2 PROPELLANT BUDGET IMPLICATIONS

For controlled re-entry the solution usually adopted is to use chemical propulsion system, providing a high thrust value, allowing to easily control the perigee location. This provides the necessary thrust while being the most cost-effective solution among all possible propellant systems. The thrust is affected by the efficiency associated with the thruster configuration at the S/C level and the EoL operations, which is decisive in the propellant mass evolution during the controlled re-entry. This efficiency may underperform due to:

- Thrust tilt: thruster not aligned with the S/C delta-v direction
- Thruster misalignment: thruster angle with respect to their nominal direction of thrust during EoL
- Thruster plume loss: reduction due to the thrusters' plume impinging on S/C exposed surfaces (e.g. solar arrays)
- Thruster modulation loss: effect of the thrusters on/off modulation on the total thrust
- Thruster gravity loss: associated with the long firing of the thrusters (not impulses)

The Mission Analysis should provide a computed delta-v, and propellant mass. The propellant computation could start with the propellant required to perform the de-orbiting activities and then proceeds backward in the mission timeline in an iterative process [7]. This analysis would then conclude with either:

a) the maximum satellite dry mass that allows a complete re-entry considering a total filling of the tank, or
b) the propellant needed for the different mission phases (beginning of life, mission operations, FDIR and EoL)

Spacecraft mass budgets are then computed at spacecraft design level, considering this propellant component.

3 DISPOSAL LIFETIME AND OPERATIONS

Different strategies have been widely used to minimize the debris (controlled, uncontrolled and assisted re-entry).

3.1 Uncontrolled Re-entry

3.1.1 Circular vs Elliptical Orbit

For an uncontrolled re-entry, circular or elliptical orbits leads to different remaining lifetime. Considering a S/C of around 2100 kg, with an orbit altitude near 700 km, if the main driver for analysing the remaining lifetime is the available propellant mass after EoM, then the epoch of the EoL also becomes crucial for accurately computing the delta-v and propellant mass used during the disposal activities:

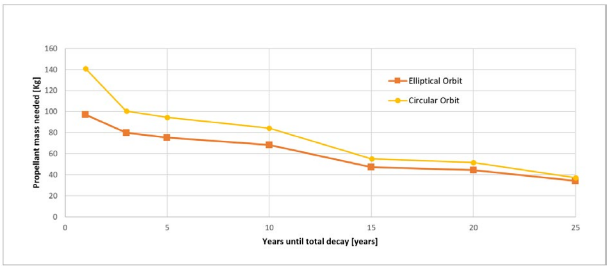

Figure 6: Decay starting in 2025

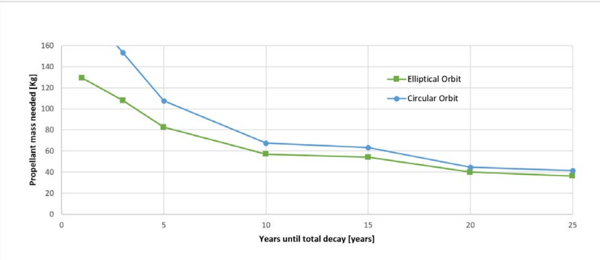

Figure 7: Decay starting in 2031

3.1.2 Cross Sectional Area and Cd Implications

A specific attitude could be set after passivation. The spacecraft frontal area is then defined, and a range of Cd identified. Cd could vary, for example, with [7]:

a) the attitude, i.e. for a whole range of an S/C attitude, and a fixed altitude, the Cd could vary in one unit (Figure 8).
b) the altitude, where max Cd condition leads to the min delta-v and propellant mass.

Considering a S/C in a generic orbit of 700 km altitude, and 2 T dry mass, a fixed Cd could have an impact on ~15% more/less fuel.

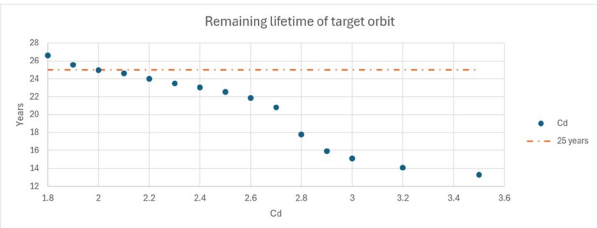

Figure 8: Cd implication on remaining lifetime (generic example)

The cross-sectional area also impacts the perigee altitude required to match the lifetime limit (e.g. Figure 9). The difference between considering a cross-sectional area from the operational phase, or a random tumbling/gravity oriented one could be translated in a different propellant mass estimation.

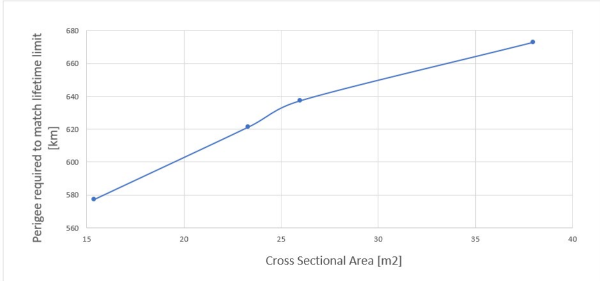

Figure 9: Cross sectional area implication on perigee required to match lifetime for a 2 Tons S/C

3.2 Controlled Re-entry

3.2.1 Assessing Perigee Adjustments for Each Phase

There are two main altitudes to be selected: the targeted perigee for the lowering phase, and the perigee of the last burn. For this last one, there is a maximal altitude at which it is safe to re-enter with respect to the space debris dispersion within SPOUA, so the cases above this altitude can be neglected.

On the other hand, there is there is potential to adjust the perigee of the last burn and therefore optimise the propellant budget.

Within a defined controlled re-entry strategy, all phases' perigees are known. To understand the potential savings of propellant mass, let's consider a generic satellite of 1.5 T and around 600km altitude, and let's assume that the orbit clearance for the phase one, and the last targeted perigee for phase three are fixed at 5 km and 50 km, respectively. By moving the perigee in phase two from 150km to 200km, even though the delta-v for this phase is reduced, the overall delta-v for the EoL activity could increase by nearly 10 m/s.

On the other hand, if the perigee for phases one and two are fixed, raising the perigee of the last burn could potentially save of 15 kg of propellant, as the delta-v for phase 3, and the overall strategy would be reduced by ~15 m/s.

The major reduction of propellant mass is achieved by modifying the targeted perigee. An assessment of the targeted perigee could be performed, fulfilling the SPOUA requirement, to analyse whether some propellant mass could be saved in the last phase.

Deorbiting to an 80 km perigee altitude instead of 50 km could potentially save around 10 kilos of propellant during the last manoeuvre burn. However, a more cautious fragmentation analysis should be performed to ensure that all potential debris falls within the SPOUA.

3.2.2 Cross Sectional Area and Cd Implications

While evaluating a de-orbiting scenario, different cross-sectional areas could be considered.

The minimum frontal area represents the worst-case scenario for the spacecraft during free decay, leading to longer decay time, and requiring more propellant mass, which results in less accurate SPOUA.

An intermediate frontal area could lead to a more accurate SPOUA.

The max frontal area for de-orbiting results in less propellant mass and a shorter decay time, which improves the accuracy of the breakdown analysis on debris casualty area.

The Cd has an impact as well. Usually, a Cd =3 is considered for nominal operations, and 2.2 for re-entry. If more accurate information on Cd is provided, a better estimation can be computed. The lower the Cd, the longer the decay time, and a higher Cd results in shorter decay time.

3.3 Assisted Re-entry

When a satellite poses an acceptable risk, but there is not enough thrust to ensure the re-entry in a certain area, a less constraining approach is possible through the assisted re-entry. Instead of a specific region, the fall of the debris can be targeted within less than one/two revolutions. This allows for the selection of orbital paths that avoid densely populated areas.

The feasibility of assisted re-entry depends on the specific mission and is highly dependent on the platform characteristics, such as the power subsystem being able to support the last burns, the controllability of the platform by the AOCS system and the accuracy of the guidance system [16].

As part of the assisted strategy but not relying on low-thrust level, there is the possibility to use different attitude or extended surfaces to increase/decrease the drag area and thus control the point of re-entry. Most studies focus on increasing of the drag surfaces to increase the decay rate but this does not necessarily mean the targeting site could be controlled. Nevertheless, recent studies, again, depending on the platform design, show that under certain conditions by making use of differential drag would be possible to control the location of the last orbital path. In addition, this might be a future demisability capability of Startlink [17] and if successful this could be considered for other missions.

3.4 Operations

The developer and operator of a spacecraft in Earth orbit shall together define procedures to:

1) Assess the health status of the critical functions for the disposal operations
2) Update the probability of successful disposal based on in-flight collected telemetry

NOTE: These procedures are an input to re-assess the mission plan and mission lifetime.

Space debris is not uniformly distributed around the Earth. Because most of the present space debris is generated from a relatively small number of satellite collisions or explosions, the orbital parameters of these collided or exploded satellites determine where the large debris fields reside. For example, the debris object density is much greater in the 750-900 km altitude band than in other parts of LEO.

4 ATMOSPHERIC DENSITY AND SOLAR ACTIVITY

Accurate modelling of atmospheric density is crucial for missions operating in LEO. Atmospheric drag, driven largely by solar activity, significantly affects the orbital lifetime of satellites and the delta-v expenditure during the operations.

Atmospheric density undergoes continuous changes driven by solar activity. Indices such as the F10.7 flux and geomagnetic indices (e.g., Kp, Ap) are commonly used to estimate or forecast solar inputs into empirical atmospheric models. These models, such as NRLMSISE-00 or JB2008, are sensitive to short-term solar and geomagnetic fluctuations and longer-term solar cycles [10].

For the estimation of solar activity several models and methodologies can be taken into consideration. Current Space Debris Mitigation Guidelines [2] suggest the following by order of priority when considering the disposal phase: latest prediction (like the SOLMAG solar activity prediction from ESOC); Monte Carlo sampling with at least 5 sampled cycles; ECSS sample solar cycle. For operational phase it is recommended to follow the predictions made by the Marshall Space Flight Center [12], as these maintain a clear record of file history. In contrast, using SOLMAG would require saving the files without preserving their traceability.

These are commonly used by EO missions and allows to estimate the worst-case scenarios for both phases (operational and disposal). Specifically, adopting a 95th percentile during the operational phase provides additional margins for delta-v consumption, whereas using the 50th percentile for the F10.7 flux during the disposal phase accounts for worst-case decay duration.

These methodologies are suitable for mission design. Although, actual operational conditions may differ, it is important to understand the rationale behind these assumptions and maintain awareness of real-world satellite operations. The focus will be on the disposal phase. For the disposal assessment, depending solely on the median (50th percentile) F10.7 value may not accurately capture the average atmospheric density across various orbital altitudes, a concern particularly relevant for missions with altitude higher than 700–800 km. While at lower altitudes (~400 km) using the median F10.7 might yield density values close to the actual average.

To illustrate this effect at 800 km (see Figure 10), the authors compared the normalized median F10.7 index (set to 1) against its 5th and 95th percentile values. For this specific example of an SSO at 800 km altitude, the maximum F10.7 value was only about 1.6 times higher than the median, while the atmospheric density increased by nearly a factor of five. This pronounced asymmetry indicates that periods of high solar activity have a disproportionately larger influence on the mean atmospheric density than do periods of low activity.

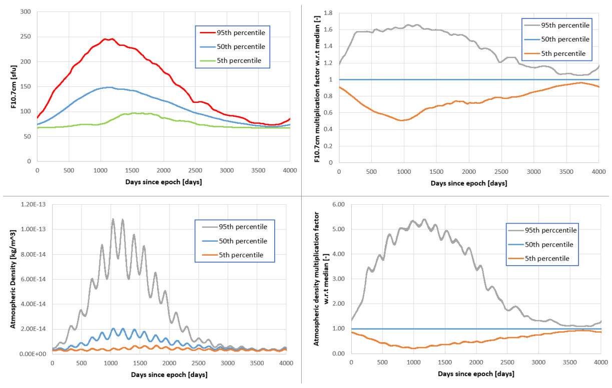

Figure 10. F10.7 solar flux and atmospheric density for different solar flux percentile scenarios (left), alongside normalized F10.7 and atmospheric density values relative to their median values.

The results above were obtained by setting up the NRLMSISE-00 model to compute the local atmospheric density and temperature at each time step (1 day), considering a fixed orbital altitude over a full 11-year solar cycle. For solar activity inputs, it relied on data from NASA's Marshall Space Flight Center, retrieved in January 2025.

4.1 Impact with altitude

During these periods of elevated solar activity, the density can increase significantly, thus raising the overall average density more than a simple median-based solar activity forecast would suggest. In effect, periods of high solar flux "weight" more on the integrated density, especially over long-term orbital decay. In addition, difference between median and mean-based density predictions increases with the orbital altitude (as depicted from Figure 11 to Figure 13).

For instance:

- **Lower orbits (~400 km):** Average density values often align closely with the 50th percentile F10.7 predictions (see).
- **Higher orbits (~800 km):** Higher solar flux can amplify the density by a factor of up to five, much larger than the factor of 1.6 observed in the F10.7 flux. These events contribute disproportionately to the mean density over time, w.r.t lower altitude orbits.

These results highlight that median-based flux indices may underestimate the impact of higher-than-average solar activity events.

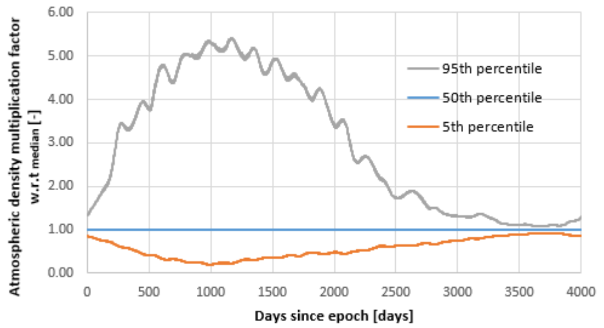

Figure 11. Atmospheric density evolution throughout the solar cycle, normalized for the median density for an altitude of 800 km.

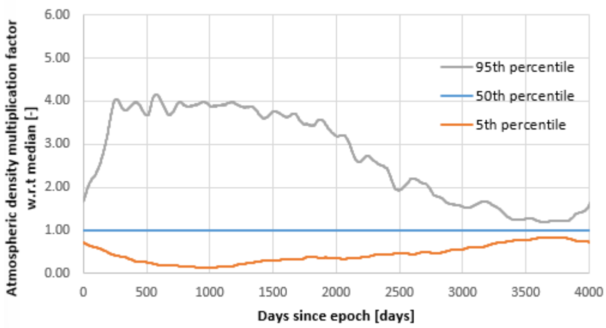

Figure 12. Atmospheric density evolution throughout the solar cycle, normalized for the median density for an altitude of 500 km.

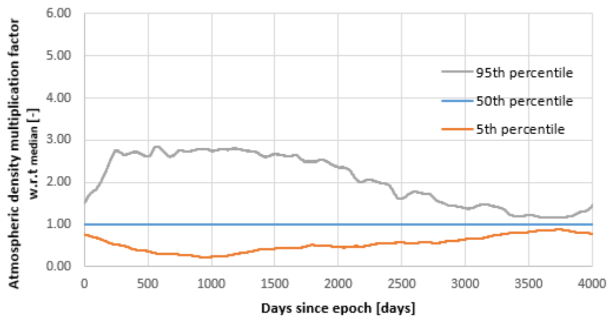

Figure 13. Atmospheric density evolution throughout the solar cycle, normalized for the median density for an altitude of 400 km.

This means that periods of heightened solar activity, though not dominant in frequency, significantly elevate average densities, leading to a faster than predicted decay.

4.2 In-orbit Data

Preliminary observations from various LEO satellites reveal that orbital decay lifetimes are consistently shorter than what standard models predict [13]. Moreover, it seems the thermospheric effect of the solar cycle persists in the thermosphere for over a year, effect that gradually manifests with increasing altitude [14]. This highlights the importance of estimating scale factors for thermospheric densities from empirical thermosphere models, such as NRLMSISE-00. Comparing the scale factors estimated from satellite laser ranging and accelerometer measurements yields similar trends, showing deviations of up to 30% at low solar activity and up to 70% at high solar activity [15].

5 CONCLUSIONS

The mitigation of space debris is a critical aspect of ensuring the sustainability of space operations. With the increased awareness of space debris and recent revision of the space debris mitigation requirements, from 25 years down to 5 years, mission planners now face a stricter challenge on the satellite design, propellant budget and operational strategies. The transition to shorter disposal lifetime emphasises the need for reliable and robust analysis. This paper has explored the implications of space debris mitigation requirements on mission design, propellant budgeting, disposal lifetime, and operations.

Key findings highlight the importance of early-phase design considerations, such as propellant budgeting and re-entry strategies, which are crucial for compliance with debris mitigation guidelines. Its therefore important for each mission to understand the design choices and its impact on the operations, which most of the times are address completely separated. The study also underscores the need of controlled re-entry to minimize casualty risks. Also, the paper discusses the potential of assisted re-entry as a viable alternative when the full controlled re-entry is not feasible, then offering a balanced approach to debris mitigation.

The impact of atmospheric density and solar activity on orbital decay reveals that periods of higher solar activity can increase the decay rates more than what the standard models predict. These uneven influence of the solar activity at different altitudes confirms the limitation of only relying on the median values of the forecasts.

In conclusion, the space debris mitigation requirements need a comprehensive approach during the mission design. By understanding the relation between design choices and the impact on the operations it is then possible to leverage the challenges and contribute to a sustainable future in space exploration.

6 REFERENCES

1. ESA Director General's Office (2023) *ESA Space Debris Mitigation Policy*. ESA European Space Agency

2. ESA Space Debris Working Group (2023) *Space Space Debris Mitigation Compliance Verification Guidelines*. ESSB-HB-U-002, Issue 2, Revision 0, ESA European Space Agency

3. Office of the Chief Engineer. (2023). *NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook*, NASA National Aeonautics and Space Administration

4. ESA Re-entry Safety WG (2017) *ESA Re-entry Safety Requirements*. ESA European Space Agency

5. ECSS Space Debris Working Group (2024) *Space sustainability Adoption Notice of ISO 24113: Space systems – Space debris mitigation requirements*. ESA requirements and Standards Section

6. ISO (2019) *Space Systems – Space Debris mitigation* requirements.

7. L. Moreschi, W. Schulz (2016) *Aerodynamic resistance in upper atmosphere*. Computational and Applied Mathematics ISSN 0101-8205, DOI 10.1007/s40314-016-0320-1

8. B. Dellandrea, et al. (2018). *The assisted re-entry: development of a simulator and feasibility study*, A6 - 16th IAA Symposium on Space Debris, International Astronautical Conference.

9. E. Borobia, (2017). *Fast Re-Entry Deorbitation with acceptable risk level*, 7th European Conference on Space Debris, ESA Space Debris Office.

10. S. Bruinsma, C. Siemes, J. T. Emmert, M. G. Mlynczak (2023), *Description and comparison of 21st century thermosphere data*, Advances in Space Research, Volume 72, Issue 12, Pages 5476-5489, ISSN 0273-1177, DOI 10.1016/j.asr.2022.09.038.

11. European Cooperation for Space Standardization (ECSS). (2019), *Space Engineering – Space Environment*, ECSS-E-ST-10-04C Rev.1 DIR1, 30 January 2019.

12. European Space Agency (ESA). (2024). *Guidelines for the computation of the Delta-V and Propellant Mass budgets*, EOP-FM-2024-07-177, Issue 3, Revision 0, Technical Note, ESA.

13. R. Nallapu, at al. (2024). *Improved Forecasting of LEO Satellite Orbit Decay During the 25th Solar Cycle Maximum*, 38th Annual Small Satellite Conference, SSC24-I-02

14. A. Ashruf, et al. (2024), *Deciphering Solar Cycle Influence on Long-Term Orbital Deterioration of Space Debris in LEO and MEO orbits, Advances in Space Research,* https://arxiv.org/abs/2405.08837

15. L. Zeitler, et al. (2021). *Scale Factors of the Thermospheric Density: A Comparison of Satellite Laser Ranging and Accelerometer Solutions.* JGR Space Physics. DOI 10.1029/2021JA029708

16. J. Virgili, et al (2015), A*tmospheric Interface Reentry Point Targeting Using Aerodynamic Drag* Control, Journal of Guidance, Control, and Dynamics, https://doi.org/10.2514/1.G000884

17. Starlink, *Starlink Satellite Demisability*. [Online]. Available: https://www.starlink.com/public-files/Starlink_Approach_to_Satellite_Demisability.pdf [Accessed: Mar. 25, 2024].