STATUS OF THE SPACE ENVIRONMENT: TOWARDS ZERO DEBRIS THROUGH ORBITAL CLEARANCE

Emma Stevenson(1), Francesca Letizia(2), Saskia Hawkins (3), Stijn Lemmens(2)

(1) IMS Space Consultancy at ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands, Email: emma.stevenson@ext.esa.int
(2) European Space Agency, ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands, Email: {francesca.letizia, stijn.lemmens}@esa.int
(3) European Space Agency, ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, Email: Saskia.hawkins@esa.int

ABSTRACT

Space debris mitigation is crucial for ensuring the safety and sustainability of space activities. However, global adherence to internationally recognised guidelines is currently insufficient, prompting stricter regulations, including ESA's "Zero Debris Approach" which significantly reduces the post-mission orbital lifetime limit in Low Earth Orbit (LEO) from 25 to 5 years and incorporates cumulative collision probability requirements for orbital clearance. This paper details updates to ESA's annual space environment report in response to these new requirements, including enhancements in lifetime estimation methodologies to account for solar activity variability, and the relationship to cumulative collision probability. Finally, global compliance trends are analysed, emphasising the potential impact of stricter regulations on long-term space sustainability.

Keywords: space debris mitigation, space environment, zero debris, orbital clearance, lifetime estimation

1 INTRODUCTION

The proliferation of space debris presents a growing challenge to the sustainability of space activities, threatening both current and future missions. To address this, Space Debris Mitigation (SDM) activities employ both design and operational strategies to curb space debris generation by preventing on-orbit fragmentations and minimising collision risks.

Since 2017, the European Space Agency (ESA) has published an annual space environment report to provide a transparent overview of global space activities and adherence to internationally endorsed SDM guidelines, namely those laid out by the Inter-Agency Space Debris Coordination Committee (IADC) [1]. Despite ongoing efforts, current levels of compliance to SDM guidelines remain insufficient for maintaining a sustainable space environment in the long-term [2]. Consequently, there is a growing trend in advocating for stricter guidelines, with policy shifts coming into force across major launching states across the globe. As a part of this, 2023 saw the introduction of ESA's "Zero Debris Approach", including an updated SDM Policy and Standard applicable to ESA projects [3], alongside the Zero Debris Charter.

One of the core elements of the new ESA SDM Standard is the set of requirements on orbital clearance. These requirements mandate timely clearance of objects from protected orbital regions at the end of their operational lifetime to mitigate risk of interference and collision with other objects. In particular, the new Standard lowers the post-mission orbit lifetime limit from 25 years to 5 years for Low Earth Orbit (LEO) and introduces additional requirements on the cumulative collision probability, which can further limit the allowed duration of the permanence in orbit after the end of life.

In this paper, we present updates to ESA's annual space environment report in response to these new requirements. Firstly, we detail advancements in the methodologies and processing pipeline for lifetime estimation of objects reaching end of life. In particular, the introduction of a 5-year lifetime limit necessitates a probabilistic approach to lifetime estimation that considers the variability of solar activity, a key driver of orbit evolution in LEO, over a full 11-year solar cycle to ensure robust compliance assessment. Secondly, we introduce the computation of the cumulative collision probability for objects in the end-of-life pipeline for the first time. In this context, an assessment of the corresponding 1-in-1000 threshold is also discussed.

Finally, we present global compliance trends, showing the status of the space environment through this new lens and highlighting the potential impact of more stringent orbital clearance requirements and guidelines on advancing global space sustainability.

2 LIMITING DEBRIS PROLIFERATION

Due to the presence of atmospheric drag in the lower levels of the LEO regime, a natural cleansing of space debris from these regions occurs. A payload or rocket

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)

body operating in the LEO protected region, with either a permanent or periodic presence, shall limit its post-mission presence in the LEO protected region to avoid the generation of debris through collisions or explosions. In practice, the reduction of the residual orbital lifetime after the end of a mission for a space object in the LEO protected region has often been used as a proxy to mitigate the risk of collision [1]. The so called "25-year-rule" as maximum limit a space object could linger in the LEO protected region after the end of life has been increasingly adopted globally in the 2000's and 2010's as a core value for implementing SDM measures. It is acknowledged that this limit by itself will not lead to a long-term reduction in the amount of space debris but is an important step towards limiting the space debris growth rate in LEO.

The orbital lifetime proxy efficacy to mitigate collision risk (the less time in orbit, the less collision probability), is however strongly dependent on space traffic conditions. To further capture the risk an object poses to the environment by remaining on orbit after end of life, beyond the remaining orbital lifetime, an additional more direct metric can be introduced for orbital clearance – the cumulative collision probability (CCP). Much like the initial justification of a 25-year rule, an effective and achievable threshold needs to yield a demonstrable improvement on the space environment in order to be adopted.

The first step in defining any CCP environmentally derived threshold value at space object level, CubeSat platform and large launch vehicle alike, is to find a suitable dataset of long-term space debris environment simulations to base the analysis on [4, 5, 6]. As part of an internal task within the IADC, a simulation campaign provided 24 parallel studies with varying post-mission disposal (PMD) lifetimes (1, 5, 10 25 years), compliance rates (90%, 95% and 99%) and deorbit strategies (circular or eccentric). ESA's long-term environment simulator, DELTA (Debris Environment Long-Term Analysis) [7], provides the number of collisions and number of objects per year under these conditions.

For each simulated scenario, the aim is to define a single CCP metric that encompasses the collision risk for a representative object across the mean effects of the whole environment over 200 years. This metric is therefore independent of altitude or simulation epoch. The simulation environment collision probability with a defunct object $P_{def,}$ is defined as the mean annual collision probability over the 200-year simulation. This simulation campaign assumed 100% collision avoidance success rate during active lifetime, therefore all collision risk is accumulated over the PMD lifetime.

The CCP (P_{ccol}) for an object is then defined as the probability of at least one collision over the PMD lifetime, L_{def}, where the lifetime is an average for all

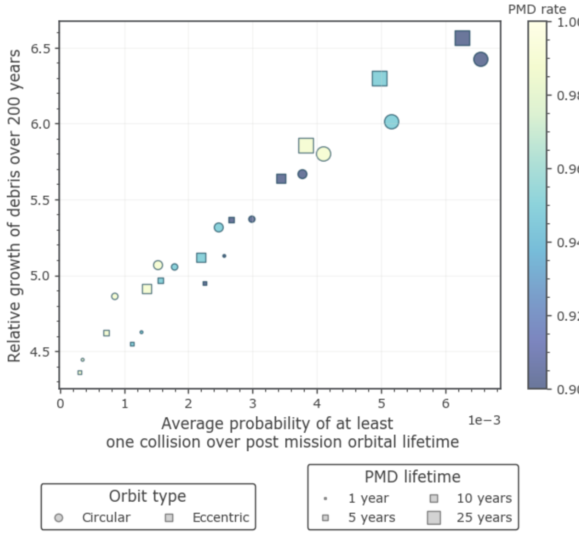


Figure 1. Space debris population growth over 200-year simulation time against probability of at least one collision over post mission orbital lifetime.

objects and is derived from the simulation PMD inputs,

$$P_{ccol} = 1 - (1 - P_{def})^{L_{def}} \tag{1}$$

It is important to note that the dataset only considered space objects larger than 10 cm, while in the LEO protected region, objects larger than 1 cm can also destroy a spacecraft or launch vehicle stage in a collision. Even for collision events at much lower speeds in the GEO protected region, a 1 cm sized object is predicted to penetrate the average spacecraft wall. Any CCP threshold aimed at limiting the impact on the space environment should reflect the collisions with object in the size range that can create further significant amounts of space debris and hence 1 cm is deemed a minimum cut-off, whereas historically 10 cm corresponds to sizes deemed trackable (and hence potentially avoidable by doing collision avoidance manoeuvres) in the LEO protected region. Using population scaling factors, we transform these results from the > 10 cm regime to the > 1 cm regime. Further details on the study and the method for defining an aggregated CCP are provided in Appendix A.

To understand the effect the CCP and the PMD lifetimes have on the population, the 'relative growth' is defined as the ratio of debris objects from the start and end of the simulation. It is noted that only the growth in space debris objects, i.e. excluding active object such as operational constellation satellites, is used in order not to skew the results with increasing traffic levels, and that the effects of solar activity were smoothed.

The results are presented in Figure 1 for each simulated scenario. As expected, decreasing the PMD lifetime and increasing PMD compliance both reduce the probability of collision and the relative growth of debris. The plot demonstrates that reducing the cumulative collision probability reduces the relative growth of the debris population. When limiting the CCP with space objects above 1 cm to below 1-in-1000 over the residual orbital lifetime, e.g. by reducing the residual orbital lifetime more than the 5- or 25-year lifetime limits, the space debris population growth can be further reduced.

3 ORBITAL CLEARANCE REQUIREMENTS

The extrapolation of the current changing use of orbits and launch traffic, combined with continued fragmentations and limited post mission disposal success rate could lead to a cascade of collision events over the next centuries. Even in case of no further launches into orbit, it is expected that collisions among the space debris objects already present will lead to a further growth in space debris population in LEO [2].

Based on these findings, among others, there is a growing consensus that stricter space debris mitigation practices need to be implemented globally, and, eventually, remediation might need to be considered.

In line with this, recent years have seen significant policy shifts come into force across major launching states across the globe, including ESA's own Zero Debris Policy and updated Space Debris Mitigation Standard. The orbital clearance requirements for the LEO protected region are as follows [3]:

5.4.2.3 The orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions:

1) *the orbit lifetime is less than 5 years starting from either:*
    a) *The orbit injection epoch, if it is injected into an orbit crossing the LEO protected region and has no recurrent manoeuvre capability*
    b) *The end-of-life epoch, if it operates in the LEO protected region and has a recurrent manoeuvre capability*
2) *the cumulative collision probability from its end of life until re-entry with space objects larger than 1 cm is below* 10^{-3}

4 ASSESSING GLOBAL COMPLIANCE

4.1 End of Life Pipeline

To assess the compliance of the space object population to orbital clearance requirements, the first step is to derive which space objects have reached the end of their operational lifetime.

For catalogued objects, this orbital activity can be derived from surveillance data. This method is preferred over direct investigation, intelligence, or communication with the owners of a payload or a rocket body, which could increase the accuracy of the prediction, but it might be unbalanced as the request for such data might not be answered nor can all owners be clearly identified and approached.

As some rocket bodies have been found to perform direct (controlled) re-entries before they can be considered catalogued objects, additional asserted objects are used as to make sure that such positive cases are correctly considered in the resulting statistics [2].

The methodology to determine the end of the operational phase of an object in LEO employed here is described in depth in [8].

For satellites without orbit control capacity (OCC), i.e. no propulsion system, or for satellites that never exhibited any orbit manoeuvre otherwise, the assessment of the mission end is not possible from orbit information alone. Therefore, a statistical approach is pursued for those objects. The source of the statistics for mission lifetimes are the measurable missions with orbit control capacity. Observed mission lifetimes are processed into histograms by mission category, e.g. science, communications, military, etc. They are then applied to generate mission lifetime estimations for the objects without orbit control capacity of the same category.

The boundaries between having an orbital control capacity or not is not always clearly defined by the underlying technology. This is because the effects observed by the space surveillance system may not be reliably discerned in all cases. Impulsive manoeuvres, multi-revolutions use of electrical propulsion, and large drag sail deployments are reliably picked up and hence objects exhibiting those features are categorised as having OCC. On the other hand, smaller orbital changes, such as drag sailing, where the change in ballistic coefficient is smaller than the error margin or the orbit determination capacity of the space surveillance system, are not picked up.

However, the most important metric is to assess whether the lifetime of the object after end of life (EOL) is compliant, which is measured independently of the OCC categorisation.

We note that, in the case of payload objects, at least one calendar year without orbit control actions needs to pass for an object to be classified as reaching end-of-life unless it performs a controlled re-entry. This is done to mitigate the implications of the detection algorithm described above, and to avoid a potentially large number of reclassifications in future assessments as some operators implement less frequent actions near the end-of-life.

4.2 Lifetime Estimation

In order to estimate the remaining orbital lifetime of the objects that have reached EOL but not yet re-entered (and thus have known orbital lifetimes), the general processes as laid out in Standards [3, 9] are followed. In particular, the verification and validation requirements from the ESA Space Debris Mitigation requirements for the LEO protected region [3] state that:

6.2 The orbit lifetime of a space object shall be assessed probabilistically, including at least the variability by moving the starting point through a full solar cycle.

To apply these processes to all objects, a Ballistic Coefficient (BC) first needs to be estimated for each of them. The BC estimation is based on least root-mean-square orbit fitting during the longest periods free from estimated manoeuvres, generally after end of life is reached in case of OCC classified objects. In case this can't be achieved, the BC is defined based in the available physical properties in DISCOS [10].

The lifetime is then assessed for each object by propagating the last orbital state, at the end of 2024, until re-entry in combination with a long-term space weather forecast, here from ESA SOLMAG [11]. To propagate the orbits to re-entry, DRAMA/OSCAR was used for objects with lifetimes less than 100 years. OSCAR uses the FOCUS semi-analytical propagator, which uses the NRLMSISE-00 thermosphere model for atmospheric drag modelling [12]. Objects with lifetimes greater than 100 years were propagated using DELTA/DELTOP, a fast analytical propagator which uses King-Hele orbit theory.

The introduction of a 5-year lifetime limit necessitates a probabilistic approach to lifetime estimation that considers the variability of solar activity, a key driver of orbit evolution in LEO, over a full 11-year solar cycle. Therefore, objects with a nominal estimated lifetime of between 5 and 50 years (to ensure robust assessment to both the 5- and 25-year thresholds), as well as high eccentricity objects (eccentricity > 0.1) were additionally assessed probabilistically by uniformly sampling the solar cycle.

In practice, this involves varying the start epoch of the propagation with yearly steps over the 11-year solar cycle, as illustrated in Figure 2. The lifetime used for compliance assessment is then taken to be the median for circular orbits, while the significant influence of the atmosphere on the spread in orbital predictions for eccentric orbits (> 0.3) is captured by using the 90% percentile, according to [3]. From Figure 2 it can be seen that higher lifetimes are associated with lower levels of solar activity, and in the case of the top example, the object would not be compliant to the 25-year rule if it reached EOL during solar minimum but is compliant when considering the median. From a mission design perspective, this decouples potential launch delays from the dependency on solar activity for achieving compliance to the 5-year lifetime rule.

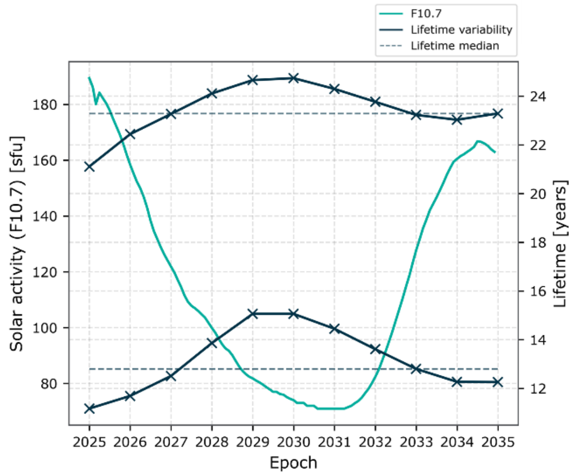


Figure 2. Variation of remaining orbital lifetime with the solar cycle. Solar cycle, represented by the solar radio flux at 10.7 cm, shown in green. Variation in lifetime of two objects, and their associated median lifetime, shown in dark blue.

4.3 Cumulative collision probability

Having obtained the propagated trajectory for the lifetime analysis, this can then be used to calculate the cumulative collision probability over the remaining orbital lifetime. For compliance verification, the trajectory with lifetime closest to the median value (in the case of circular orbits) is taken for this analysis.

The trajectory is first discretised into a series of orbit slices, using a 10 km change in perigee altitude as the discretisation criterion. This is illustrated in Figure 3. A 10 km interval is chosen to reflect the altitude resolution

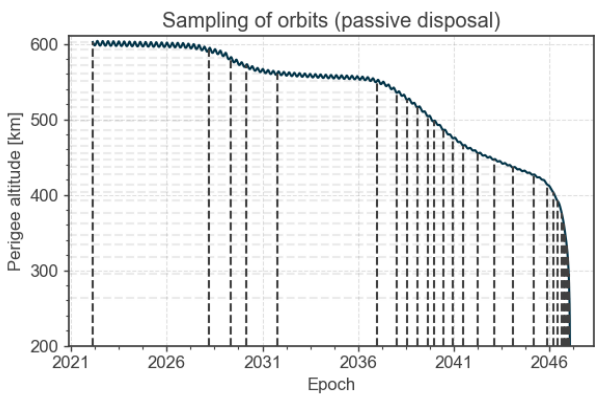


Figure 3. Discretised trajectory for cumulative collision probability computation. Discretisation based on 10 km change in perigee altitude.

used in flux calculations in LEO by MASTER [7].

The contribution of each orbital slice to the total cumulative collision probability can then be calculated using the DRAMA/ARES tool, under the assumption that the orbit may be considered constant over each slice [13]. For this analysis, the collision risk is computed with objects larger than 1 cm. As discussed in Section 2, the cumulative collision probability metric is taken as a proxy for the fragmentation risk for an inactive satellite, and thus the 1 cm population represents the set of objects that pose a risk of catastrophic collision. In this work we use the 1 cm population of the latest MASTER reference population, from August 2024, as illustrated in Figure 4.

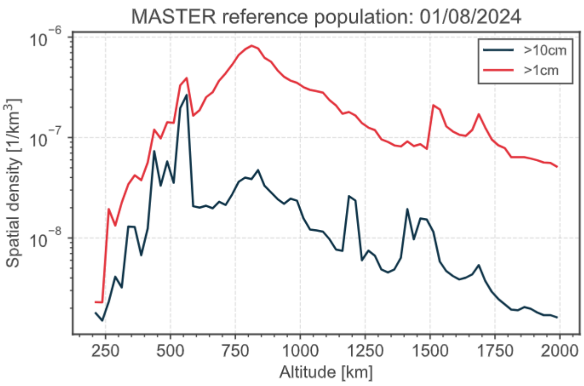


Figure 4. Density profiles in LEO for different space object size ranges from the 01/08/2024 reference population [2].

The annual collision probability returned by ARES for each slice is scaled according to the slice duration (Δt), using:

$$P_{col}(\Delta t) = 1 - (1 - ACP)^{\left(\frac{\Delta t}{yr}\right)} \quad (2)$$

where *Δt/yr* is the year fraction of the analysis interval and ACP is the annual collision probability resulting from the DRAMA/ARES analysis.

The resulting values of each orbit section is aggregated to calculate the final cumulative collision probability using the multiplication rule (the probability of at least one collision occurring) as follows:

$$P_{ccol}(t_{total}) = 1 - \prod_{i=1}^{n} \left(1 - P_{col,i}(\Delta t_i)\right) \quad (3)$$

5 RESULTS

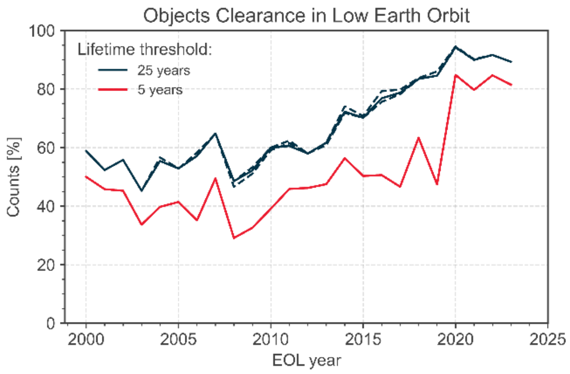
5.1 Probabilistic lifetime

In this section, we show global compliance trends to the 25- and 5-year lifetime requirements. These results cover payload and rocket bodies having been determined to reach end of life, as described in Section 4. For analysing these trends, we exclude human spaceflight related missions, as they skew results in terms of mass and count affected. These missions include crew vehicles as well as cargo payloads, but not the rocket bodies that bring them into orbit.

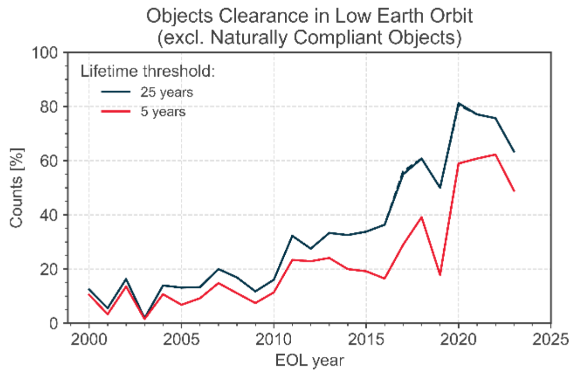
The end-of-life behaviour of space objects can be categorised in seven behavioural classes to illustrate disposal success rates:

- NCWO: (Not Compliant WithOut attempt) the 5 or 25-year rule is not met by the mission orbit and no disposal action has been taken;
- NCWFB: (Not Compliant With attempt False Before) the 5 or 25-year rule is not met by the mission orbit, a disposal action has been attempted but it was unsuccessful or insufficient;
- NCWTB: (Not Compliant With attempt True Before) the 5 or 25-year rule was met by the initial mission orbit, a disposal action has been attempted but it was unsuccessful or the mission orbit was otherwise altered, and the new orbit is not compliant;
- CWFB: (Compliant With attempt False Before) the 5 or 25-year rule is not met by the mission orbit, but a disposal action has been taken and was successful;
- CWTB: (Compliant With attempt True Before) the mission orbit allowed to meet the 5 or 25-year guideline, but a disposal action has been taken nonetheless;
- CWO: (Compliant WithOut attempt) the mission orbit allowed to meet the 5 or 25-year guideline, no action was taken (nor needed);
- CD: (Compliant with Direct re-entry) a controlled re-entry has been performed.

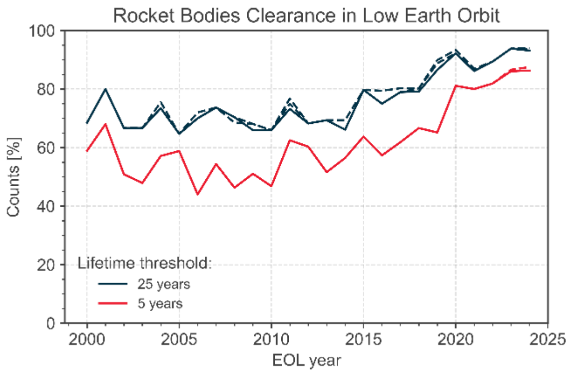
In Figure 5 we show the share of compliance for payloads and rocket bodies for the two lifetime limits. Here, successful attempts include CD, CWTB and CWFB, as well as CWO where naturally compliant orbits are included. The solid lines represent the compliance share using the median (or 90% percentile for eccentric objects) lifetime, while the dashed lines represent the compliance share for the 25th and 75th percentiles of the lifetimes. As discussed in Section 4.1, a grace period of at least one calendar year without orbit control actions need to pass for payloads before being classified as



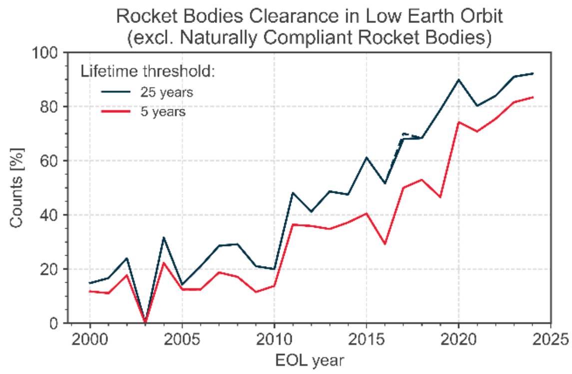
(a)



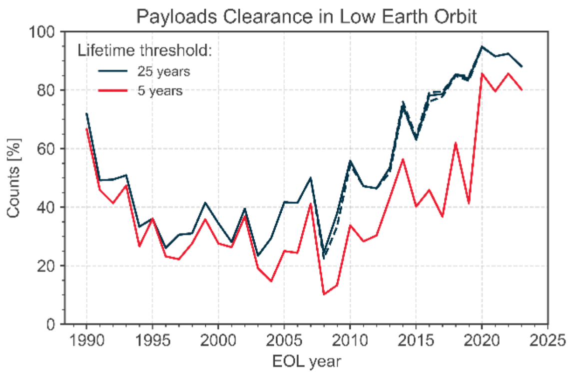
(b)



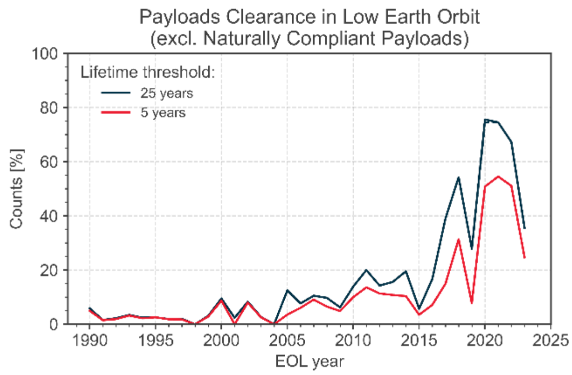
(c)



(d)



(e)

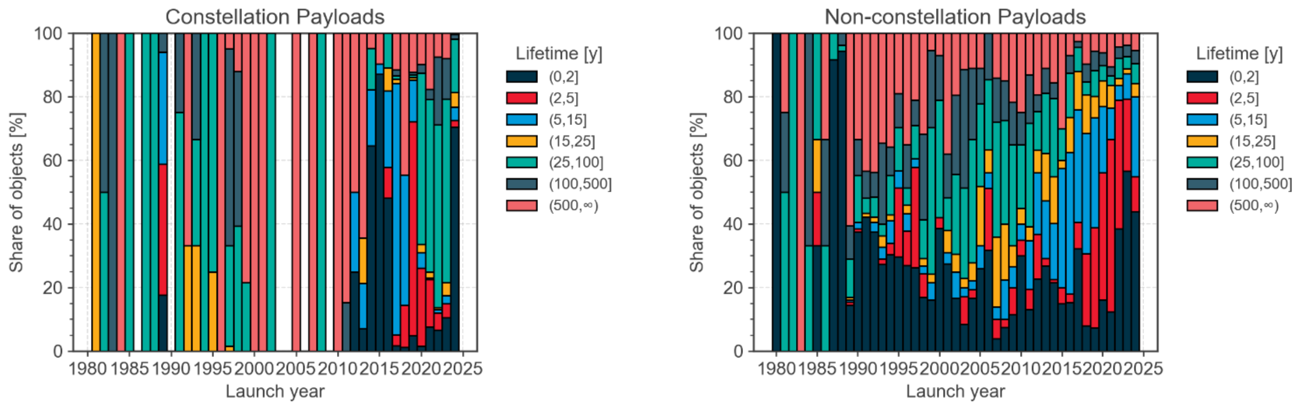


(f)

Figure 5. Trend of adherence to 5- and 25-year lifetime clearance thresholds by share of space object count, excluding objects associated with human spaceflight. For (a, b) objects, (c, d) rocket bodies, (e, f) payloads, including (left) and excluding (right) naturally compliant space objects where no action was needed or taken.

reaching end of life. This implies that the statistics for objects (payloads and rocket bodies), and payloads extends to 2023, while the statistics for rocket bodies extend to 2024.

From Figure 5, we can see that the difference in compliance share between the 25- and 5-year lifetime limits is approximately 10%. To understand these compliance levels, it is important to understand current operational trends. To put this in context, in Figure 6, we show a breakdown of the estimated lifetime for payload *operational* orbits with launch year. From these we see a clear trend towards targeting lower operational orbits that are naturally compliant with SDM guidelines and requirements. In 2024, 80% of new constellation and non-constellation payloads use an operational orbit



(a) *(b)*

Figure 6. Estimated lifetime for the payload operational orbits by launch year by share of space object count [2]. For (a) payload objects belonging to constellations; (b) payload objects not belonging to constellations.

which is naturally compliant to the 25-year rule. For constellation payloads, 70% use an operational orbit with a natural decay lifetime of 5 years or significantly less.

5.2 Cumulative collision probability

For these objects, we also obtained the cumulative collision probability from the last orbital state, at the end of 2024, until re-entry. While this does not capture the full cumulative collision probability from end of life until re-entry, it provides a snapshot of the inactive objects currently on orbit. For this analysis, only objects with lifetimes less than 100 years were considered. The correlation of cumulative collision probability with perigee altitude, and remaining orbital lifetime is shown in Figures 7 and 8 respectively.

Of particular interest is the correlation between the lifetime and the cumulative collision probability to understand cases where missions may be compliant with one requirement but not the other. We can see that very few objects are compliant with the cumulative collision probability requirement with a lifetime of greater than 5 years. However, a large number of objects compliant with the lifetime threshold are not compliant with the cumulative collision probability and thus would not be compliant to the ESA orbital clearance requirements. In fact, this behaviour can be seen for objects with lifetime as low as two years, emphasising the importance of considering this additional metric.

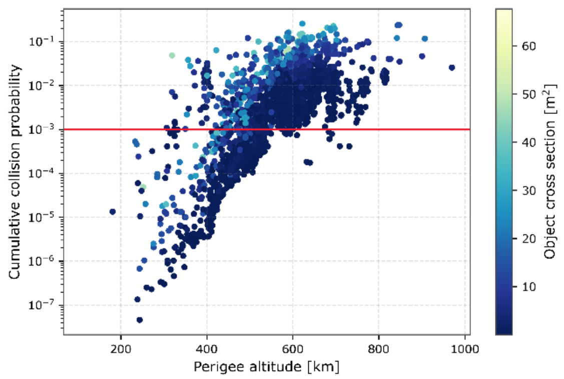


Figure 7. Cumulative collision probability as a function of perigee altitude for the objects in the end-of-life pipeline. ESA requirement threshold depicted in red: 1-in-1000 cumulative collision probability.

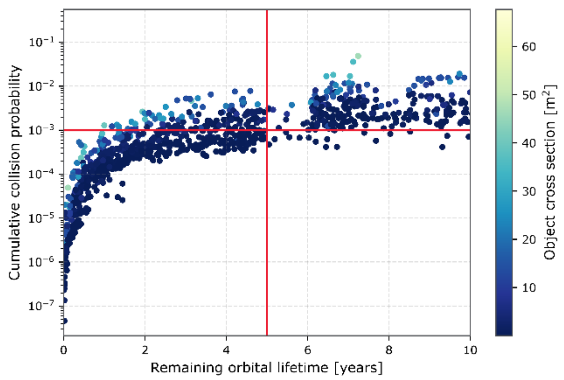


Figure 8. Relationship between orbital lifetime and cumulative collision probability for the objects in the end-of-life pipeline. ESA requirement thresholds depicted in red: 5-year lifetime limit and 1-in-1000 cumulative collision probability.

5.3 Environment evolution

To understand the efficacy of more stringent mitigation measures in moving towards a "Zero Debris" future, the effect of their uptake on long-term evolution of the space environment can be simulated. Details of the extensive simulation campaigns used to derive the 5-year lifetime limit with this approach are described in [14]. Instead, here we show how global uptake of the measures outlined in the ESA Space Debris Mitigation Standard [3], including the 5-year lifetime threshold, could shape a more sustainable evolution of the space environment.

For this, we follow the approach described in [15] and adopted in the ESA Annual Space Environment Report [2], where more details may be found, using DELTA. Three scenarios are presented:

- An extrapolation of current behaviour in terms of launch traffic, explosion rates, and disposal success rates;
- A baseline of no further launches (NFL), where it is assumed that no launch takes place after 2024;
- A Zero Debris baseline, where it is assumed that the principles laid out in [3] are followed after 2024.

The definition of trends in launch traffic, explosion rates, and disposal success rates for the extrapolation scenario is based on the data available in DISCOS on the 1st of January 2025 and on the analysis in [2]. For the Zero Debris case, the scenario parameters were defined as follows. With regards to post mission disposal, a de-orbit lifetime of a maximum of 5 years was adopted with 90% success rate, and 95% success rate for members of large constellations (as defined in [3], those with more than 100 members). For the explosion rate, the same scenario was used as for NFL, assuming that no explosion events occur after 18 years after the start of the simulation. This value is selected as [2] shows that 95% of non-system related fragmentation events occur within 18 years of launch, and thus we assume that perfect levels of passivation are accomplished, alongside a 100% collision avoidance success rate.

The results of the three scenarios are shown in Figure 9 in terms of the growth in the number of objects over 200 years. While global compliance to more stringent space debris mitigation requirements in a Zero Debris scenario may only capture an ideal, it can be seen that these measures would effectively curb the unsustainable exponential growth seen in the extrapolation scenario.

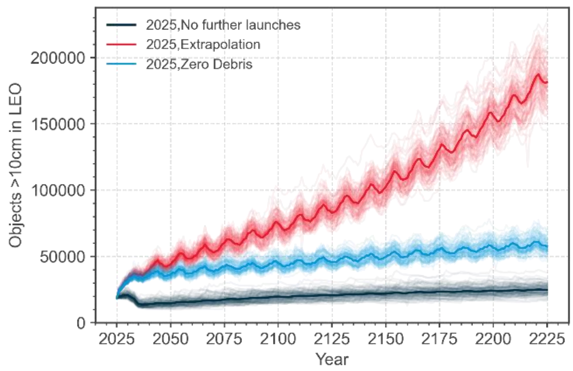


Figure 9. Number of objects > 10 cm in LEO in the simulated scenarios of long-term evolution of the environment over 200 years.

6 CONCLUSIONS

In 2023, ESA introduced new, more stringent requirements for orbital clearance to reduce the risk associated with objects left in orbit after the end of their operational life. This included reducing the internationally accepted 25-year lifetime threshold to 5 years, as well as introducing an additional requirement on the cumulative collision probability, which shall be below 1-in-1000. Introducing a 5-year threshold necessitated a more robust assessment of orbital lifetime based on the 11-year solar cycle, and in this paper, we introduced the expanded methodology used for assessing this lifetime for global compliance assessment. While reducing the lifetime limit to 5 years is a significant decrease, statistics on global compliance to this threshold show that the difference with respect to the 25-year threshold is lower than might be expected, as objects tend to launch towards lower, naturally compliant altitudes. In addition, we showed the correlation between remaining lifetime and cumulative collision probability for these objects, exemplifying the need for this second metric to further drive down the rate of debris growth in the long-term. Finally, we highlight the potential impact of more stringent mitigation requirements on advancing space sustainability by simulating the effect of global compliance to the "Zero Debris Approach" on the long-term evolution of the space environment.

7 REFERENCES

1. Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, 2002.
2. ESA Space Debris Office. ESA's Annual Space Environment Report. GEN-DB-LOG-00288-OPS-SD, Issue 9.0, ESA/ESOC, Darmstadt, Germany, 2025.
3. European Space Agency. ESA Space Debris Mitigation Requirements, ESSB-ST-U-007, Issue 1, 2023.
4. Schaus, V., Letizia, F., Bastida Virgili, B. and Lemmens, S. (2021). Leveraging space debris simulation results: Revisiting guideline values for

explosion and cumulative collision rate. In *Proc. 8th European Conference on Space Debris* (virtual), Darmstadt, Germany, 20-23 April 2021.

5. Lewis, H. G., Beck, J., Anderson, P., Oswald, M., Radtke, J. and Rossi, A. Impact Risk in LEO as a result of the Increase of Nano and Micro-Satellites. ESA ref. GSP-SIM-SOW-00167-HSO-GR, Version 1.1, 2017.
6. Lewis, H. G., Radtke, J., Rossi, A., Beck, J., Oswald, M., Anderson, P., Bastida Virgili, B. and Krag, H. (2017). Sensitivity of the space debris environment to large constellations and small satellites. In *Proc. 7th European Conference on Space Debris*, Darmstadt, Germany, 17-21 April 2017.
7. Horstmann, A., Hesselbach, S., Wiedemann, C., Flegel, S. and Oswald, M. Enhancement of S/C Fragmentation and Environment Evolution Models. Final Report of ESA contract 4000115973/15/D/SR, 2020.
8. Lemmens, D. and Krag, H. Two-line-elements-based maneuver detection methods for satellites in low earth orbit. *Journal of Guidance, Control, and Dynamics*, 37(3):860–868, 2014.
9. International Standards Organisation. Space systems - Estimation of orbit lifetimes, ISO 27852, Third Edition, 2024.
10. McLean, F., Lemmens, S., Funke, Q. and Braun, V., (2017). DISCOS 3: An improved data model for ESA's Database and Information System Characterising Objects in Space. In *Proc. 7th European Conference on Space Debris*, Darmstadt, Germany, 17-21 April 2017.
11. Mugellesi-Dow, R., Kerridge, D. J., Clark, T. D. G. and Thompson A. W. P. SOLMAG: an operational system for prediction of solar and geomagnetic activity indices. 1st European Conference on Space Debris, Proceedings of the conference, 1993.
12. Ayala Fernandez, L., Wiedemann, C., Braun, V. and Lemmens, S. (2023). Uncertainty in remaining orbital lifetime estimation after post-mission disposal. In *Proc. Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS)*, Maui.
13. ESA Space Debris Office. Assessment of Risk Event Statistics (ARES), MIT-SW-TN-00280-OPS-SD, Issue 3, 2021.
14. Letizia, F., Bella, D., Weber, D., Bastida Virgili, B., Lemmens and S., Soares, T. (2023). Long-term environment simulations and risk characterisation in support of a Zero Debris Policy. In *Proc. 2nd International Orbital Debris Conference (IOC II)*, Sugar Land, Texas, USA, 4-7 December 2023.
15. Letizia, F., Bastida Virgili, B. and Lemmens, S., Assessment of environmental capacity thresholds through long-term simulations. *Advances in Space Research*, Vol.7(7), 2023.

APPENDIX

A. DERIVING AN AGGREGATE CUMULATIVE COLLISION PROBABILITY

To study the impact of lower post mission disposal (PMD) lifetimes on collision risk, the IADC proposed a new simulation campaign. 24 studies were conducted with varying PMD rates (90%, 95% and 99%), disposal lifetimes (1, 5, 10 25 years) and deorbit strategies (circular or eccentric). All other background parameters such launch traffic and explosion rate were kept constant. The simulation runs were performed using ESA's long-term simulation tool DELTA, covering from the year 2022 to 2222, where the initial population is the population data from January 2022. 100 Monte Carlo runs were performed. The launch traffic from the years 2017 to 2021 is used on a repeating 5-year cycle (within this, no constellations are included). Large constellations are added and maintained across the duration of the simulation. For satellite explosions, data from the past 18 years is used.

To find a CCP for a single object, we first define a mean annual environment collision probability, denoted as P_{def}. Providing one value to summarise the risk across the 200 years of the simulation requires some simplification, namely that the collision probability is constant across the 200 years. We see that both object number and collisions grow, and the probability does not increase significantly.

The cumulative collision probability, P_{ccol}, can be defined as the probability that there will be at least one collision over an object's orbital lifetime. This can be split into two parts, the probability of collision per year P_{act}, during active lifetime (L_{act}), and the probability of collision per year P_{def}, during inactive (defunct) lifetime (L_{def}).

$$P_{ccol} = 1 - (1 - P_{act})^{L_{act}}(1 - P_{def})^{L_{def}} \quad \text{(A1)}$$

One of the conditions for these simulations is that all active objects perform collision avoidance manoeuvres with a success rate of 100%. The recorded collisions are between two defunct objects only, and thus P_{act} is zero. All collision risk is accumulated after a mission's operational lifetime. Assuming the collisions are independent, and every object has an equal probability of being involved in a collision, the probability that any one object undergoes an accidental collision within a given year, i, is

$$P_{def,i} = \frac{n_{col,i}}{n_{def,i}} \quad \text{(A2)}$$

As only the number of intact objects n_{int} may be provided, we need an approximation for n_{def}. For this, we define b as the ratio of the number of defunct objects to total intact, such that:

$$P_{def,i} = \frac{n_{col,i}}{b * n_{int,i}} \quad \text{(A3)}$$

DELTA provides snapshot population files, where the number of active and defunct objects within each year can be extracted. Due to the large size of these files and the computational intensity, this extraction has been run for 1 Monte Carlo run. The scale factor is then applied to find the number of defunct objects per year.

It is important to note that the dataset only considered space objects larger than 10 cm, while in the LEO protected region, objects larger than 1 cm can also destroy a spacecraft or launch vehicle stage in a collision. Even for collision events at much lower speeds in the GEO protected region, a 1 cm sized object is predicted to penetrate the average spacecraft wall. Any CCP threshold aimed at limiting the impact on the space environment should reflect the collisions with object in the size range that can create further significant amounts of space debris and hence 1 cm is deemed a minimum cut-off, whereas historically 10 cm corresponds to sizes deemed trackable (and hence potentially avoidable by doing collision avoidance manoeuvres) in the LEO protected region. We must therefore transform these results from the > 10 cm regime to the > 1 cm regime.

To transform from the > 10 cm to > 1 cm regime, we must scale the number of collisions and number of objects expected from each size regime. This may be done using the results of another IADC study, which evaluated the impact of cm-class objects on future risk to objects larger than 10 cm. The number of objects and number of collisions in each size class over the simulation can be used to provide a scaling from the > 10 cm to > 1 cm population. These values will be denoted with subscript C to indicate the study they originate from.

The probability in each year is therefore scaled as follows:

$$P_{def,i} = \frac{n_{col,i}}{b_i * n_{int,i}} * \left(\frac{n_{obj,i,10cm,C}}{n_{coll,i,10cm,C}} * \frac{n_{coll,i,1cm,C}}{n_{coll,i,1cm,C}}\right) \quad \text{(A4)}$$

The average post mission lifetime L_{def} is estimated using a combination of the scenario's assigned PMD success rate and targeted lifetime.

$$L_{def} = PMD(lifetime) + (1 - PMD)l_m \quad \text{(A5)}$$

Where l_m is the lifetime of objects that do not successfully complete post mission disposal. This is estimated as 185 years, which is the median lifetime of the MASTER population until 2017. The mean is avoided as it is skewed by long abandoned objects that will not undergo natural decay. The average probability of at least one collision over post mission lifetime for an object is:

$$P_{ccol} = 1 - \left(1 - \frac{1}{200}\sum_{i=0}^{200} \frac{n_{col,i}}{b_i * n_{int,i}} * \left(\frac{n_{obj,i,10cm,C}}{n_{coll,i,10cm,C}} * \frac{n_{coll,i,1cm,C}}{n_{coll,i,1cm,C}}\right)\right)^{L_{def}} \quad \text{(A6)}$$

To characterise the increase in the debris population over the simulation time we define a relative growth metric. It is noted that only the growth in space debris objects is used, i.e. excluding active object such as operational constellation satellites, in order not to skew the results with increasing traffic levels The total object population is the sum of the active objects and debris objects (composed of intact defunct objects and fragments). The total object number is also equal to the sum of the intact (both active and inactive) objects and the number of fragments. These can be rearranged to find the population in a given year to be:

$$n_{deb} = n_{tot} - (1 - b)n_{int} \quad \text{(A7)}$$

The relative growth is defined as the ratio of the debris in 2222 to 2022, where the effects of the Solar cycle have been smoothed using a Savitzky–Golay filter. We must also apply a scaling factor to transform from the > 10 cm regime to the > 1 cm regime. We may assume the number of intact object objects between 1 cm and 10 cm to be negligible, and therefore only n_{tot} is scaled. The total number of objects n_{tot} may then be scaled by the following factor:

$$SF = \frac{n_{tot,i=1,10cm,C}}{n_{tot,i=1,1cm,C}} * \frac{n_{tot,i=200,1cm,C}}{n_{tot,i=200,10cm,C}} \quad \text{(A8)}$$

The relative growth (RG) is then defined as:

$$RG = \frac{(n_{tot,i=200} * SF) - (1 - b)n_{int,i=200}}{(n_{tot,i=1} * SF) - (1 - b)n_{int,i=i}} \quad \text{(A9)}$$

The results comparing the CCP and RG are displayed in Figure 1.