7. ENVIRONMENT METRICS

7.1. Environmental Index in 2024

The effect of adherence to space debris mitigation guidelines and regulations on a global level has a direct influence on the avoidance of the Kessler syndrome in Low Earth Orbit. In order to quantify the relation between them, the concept of an environment index is introduced via a general risk metric. The risk associated to an event is traditionally computed as Risk $=$ Probability $\times$ Severity.

This definition can be applied to space objects to measure the *fragmentation risk* associated to them and use this as a metric of their potential contribution to the space debris environment. The term *probability* represents the probability of a catastrophic collision, which is dependent on the flux of debris able to trigger a collision and the cross-sectional area of the object. The flux values are obtained from MASTER-8 [28] considering for each object the last available orbit in DISCOS. The physical properties and the activity status of the objects are also retrieved from DISCOS. The term *severity* measures the effect of such a fragmentation on operational spacecraft. This is done by simulating the generation of the cloud with the NASA breakup model [29] and modelling the evolution of its density over time under the effect of atmospheric drag. A representative set of target spacecraft is defined as proxy of the population of operational satellites. For each of these target spacecraft, the resulting cumulative collision probability over 25 years due to the fragment cloud is computed and their sum is used as a *severity* measure.

The risk is evaluated along the mission profile of an object, simulating its orbit evolution over 100 years. For active and manoeuvrable objects, the implementation of a Post-Mission Disposal (PMD) manoeuvre and its estimated success rate are considered when computing the trajectory evolution. More details on the approach can be found in [5]. The risk metric can be used to compare objects or missions against each other, and the cumulated risk taken by all objects in space at a given time, and their behaviour in the future, thus introduces the notion of capacity of the environment.

Fig. 7.1 shows the distribution, in mean altitude and inclination, of the analysed objects in LEO. The colour of the marker indicates the category of the objects, i.e. whether it is a rocket body, an inactive payload, an active one or a constellation. The size of the marker indicates the debris index value and an aggregated score is shown for constellations. The values are obtained assuming a 90% PMD success rate for active objects. Areas with high risk concentration can be observed around 850 km of mean altitude and 70-80 degrees in inclination. Fig. 7.2 shows the distribution of the total index among object categories: By far, most of the risk is associated to inactive objects (96%), with the largest contribution coming from spent rocket bodies.

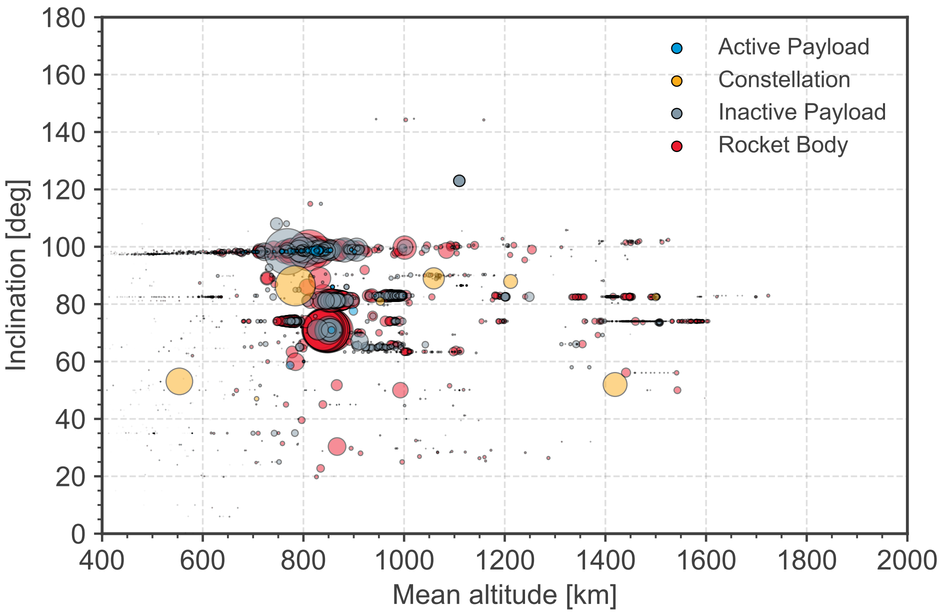

Figure 7.1: Index value for objects in LEO. The size of the marker is proportional to the debris index of the object or constellation.

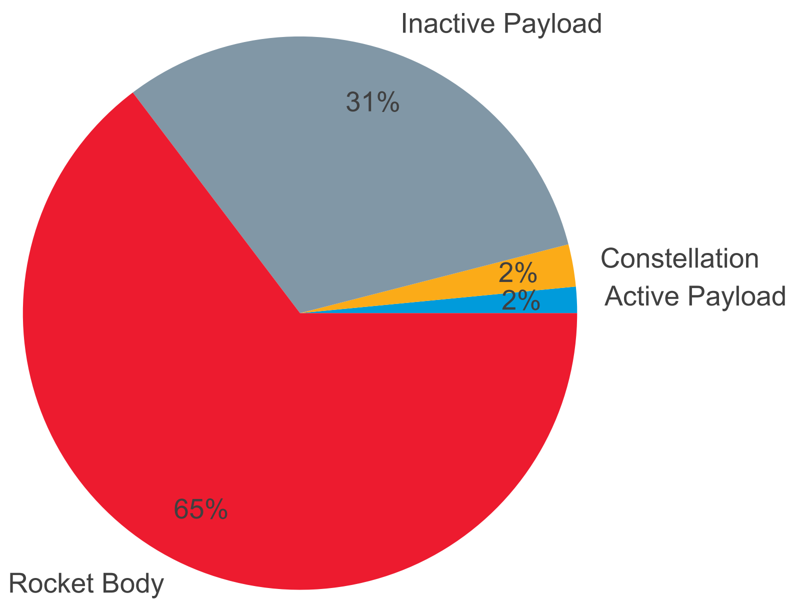

Figure 7.2: Distribution of the total index among object categories.

7.2. Environment evolution

The simulation of the future evolution of the debris population can be used to assess the efficacy of proposed mitigation actions and of current behaviours. In particular, two scenarios are presented in this section:

- A defined *extrapolation* (Extr) of the current behaviour in terms of launch traffic, explosion rates, and disposal success rates;
- *No future launches* (NFL), where it is assumed that no launch takes place after 2024.

The definition of trends in launch traffic, explosion rates, and disposal success rates is based on the data available in DISCOS and on the analysis contained in this report. DELTA-4 [30] was used to simulate the evolution of the environment over 200 years, performing 100 Monte Carlo runs per scenario. The parameters for the scenario definition are summarised hereafter.

For both scenarios, the reference population used for the analysis is an extraction of the DISCOS population at the reference epoch (1st January 2025). For each object, physical characteristics such as mass, cross-sectional area, and orbital parameters are retrieved, while for Rocket Bodies and Payloads, launch information is also stored. For Payloads specifically, it is also stored in which orbital region they are active and whether they belong to a constellation, following the definitions in Section 1.1.

The annual explosion rate is taken from statistics on non-system related fragmentations over the last 18 years (Table 5.2). In the *No future launches* scenario, we assume a linear decline in the explosion rate, reaching zero after the first 18 years. No explosion event is simulated after this period, as Fig. 5.8 shows that 95% of non-system-related fragmentation events occur within 18 years of launch, as described in Section 5.2.

For the *extrapolation* scenario, a launch traffic model is also needed as input for the simulations. This was obtained by repeating the launch traffic between 2017 and 2024, discounting the contribution from constellations. For each constellation, in-orbit or planned (according to the definition given in Section 1.1), a model of deployment and replenishment was defined using publicly available data. For these constellation Payloads, a capability to successfully perform collision avoidance manoeuvres is assumed for objects with propulsion for as long as they are active in the simulation.

A fixed operational lifetime of eight years is assumed for Payloads not belonging to a constellation instead of the values derived in this report, in line with current long-term space debris environment modelling practices. Specific values are used for Payloads belonging to constellations, based on the available information on the current constellation designs where possible. Post-mission disposal success rates are derived from the observed values reported in Section 6, considering the performance of objects with End-Of-Life equal or later than 2017. In particular, the post-mission disposal success rate is set to 70% for rocket bodies and 15% for payloads, to reflect the slow but upwards trend in compliance in combination with the shifting traffic towards destination orbits with lifetimes below 25 years. For constellation Payloads, specific values for the post-mission disposal success rate and lifetime are again taken depending on currently available information, else are assumed to be 90% and 25 years respectively. These baseline values reflect the bare minimum identified in [14], whereas in practice, far higher rates of compliance would need to be observed over time to limit the long-term growth of the space debris population.

The evolution of the number of objects larger than 10 cm and the cumulative number of *catastrophic collisions*, i.e. collisions leading to the complete destruction of target and impactor, are shown in Fig. 7.3 and Fig. 7.4: the bold line for each scenario represents the mean value over all the Monte Carlo runs, while the lighter-coloured lines indicate the outcome of each individual run. This representation was selected to visualise the variability across the single runs without introducing standard deviation bands as they may be not representative of the result distribution [31].

The results from the evaluation of the scenario indicated that even when spaceflight is completely halted today, the amount of space debris objects in Low Earth Orbit is likely to increase. The extrapolation of our current behaviour, which assumes the continuation of explosion in orbits at current rates, adherence by constellations to at least the minimum desirable post-mission disposal success rates, and continuation of the currently estimated post-mission disposal success rates for all other objects, leads to an unstable environment with collision rates increasing exponentially. While a shift in launch traffic to orbits with low orbital decay as observed in Section 2.7 improves the situation [32], the implementation of all space debris mitigation strategies are necessary to avoid an adverse future.

Establishing the space debris growth rates based on the status of annual environment snapshots provides an estimate for the consequences of the current levels of global space debris mitigation. To analyse trends in the predicted environment evolution, additional scenarios can be simulated using different starting epochs, while adopting the logic laid out above for what concerns deriving space traffic settings for the model.

In particular, in addition to the starting points generated from past and current editions of the report, other two reference epochs (at 2014 and 2005) were defined, for which the corresponding launch traffic, explosion rate, and disposal rates were extracted from the data in DISCOS. The years 2014 and 2005 are not chosen arbitrarily, but respectively correspond to the last year before the fundamental change in launch traffic (due to the increase in usage of small satellites) and the adoption of the IADC mitigation guidelines in national practices [33].

The number of objects larger than 10 cm in the final population and the final cumulative number of catastrophic collisions at the end of the simulation are shown in Fig. 7.5 and Fig. 7.6, where red is used for the *extrapolation* scenarios and dark blue for *no further launches*. For each simulation, this end date is 200 years after the starting point. A further scenario is included, in green, representing the *target environment*. Any target environment is a subjective choice, but to facilitate a transparent evaluation of global steps towards space sustainability, a good candidate can be the scenario reflected largely in most space debris mitigation standards world-wide. This corresponds to a high-level implementation of the IADC guidelines [34] (in particular a 90% success rate of 25-year PMD) based on observed launch traffic at 2014, and can be considered a baseline, or *orbital sustainability threshold*, for measuring the long-term sustainability of the space environment as a whole. In Fig. 7.7, the same scenarios are evaluated by the risk index introduced in Section 7.1. In this approach, a clear analogy can be drawn to climate science, where the Paris Agreement established the 1.5 °C global average temperature threshold with respect to pre-industrial levels as the acceptable limit on global warming.

Boxplots are used to visualise the spread of results over the runs: the box covers the range between the first and the third quartile, with the horizontal line within the box indicating the median; the whiskers indicate the distance of 1.5 the interquartile range in both directions and any datapoint outside this range is considered an outlier and indicated with a small dot. For Fig. 7.5, the number of objects at each starting epoch is further denoted by a grey triangle. It is important to note that in all extrapolation scenarios the simulated space debris environment continues to deteriorate. Under the current extrapolation conditions, the amount of catastrophic collision could rise quickly. Even under the no further launches scenarios, the amount of space debris objects is observed to increase in all cases. With respect to the target environment, the level of risk associated with the extrapolation scenario is predicted to be 4 times greater than the acceptable threshold for long-term sustainability.

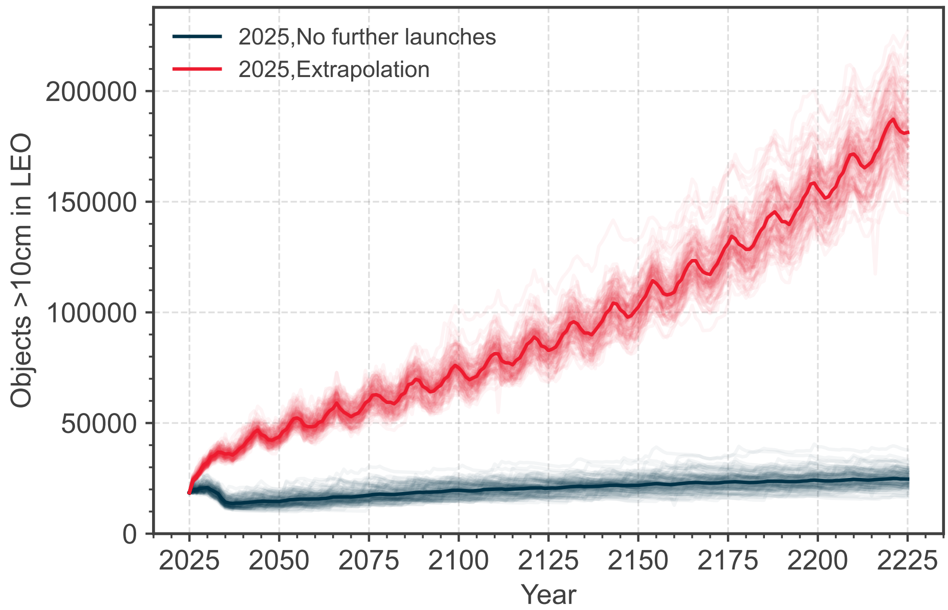

Figure 7.3: Number of objects in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

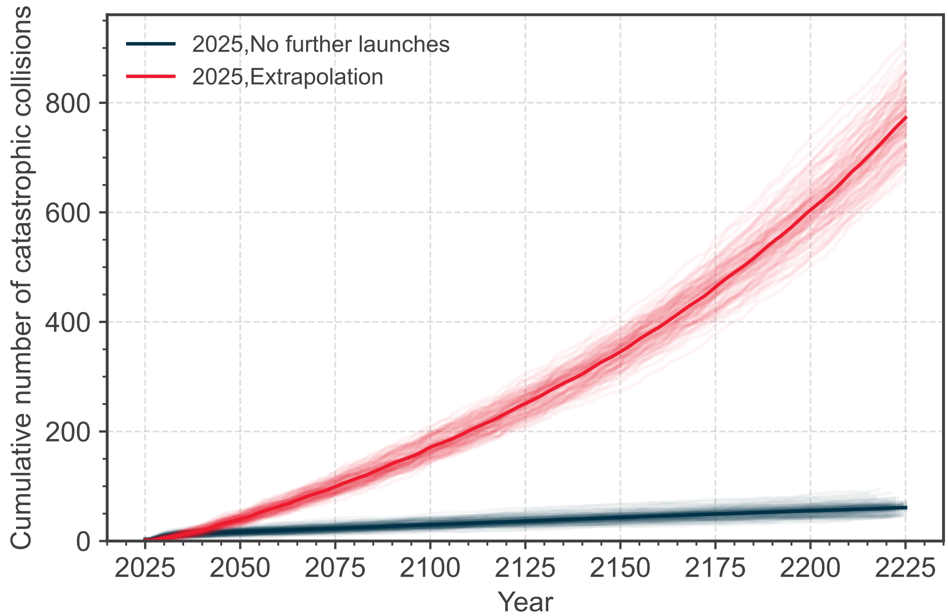

Figure 7.4: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

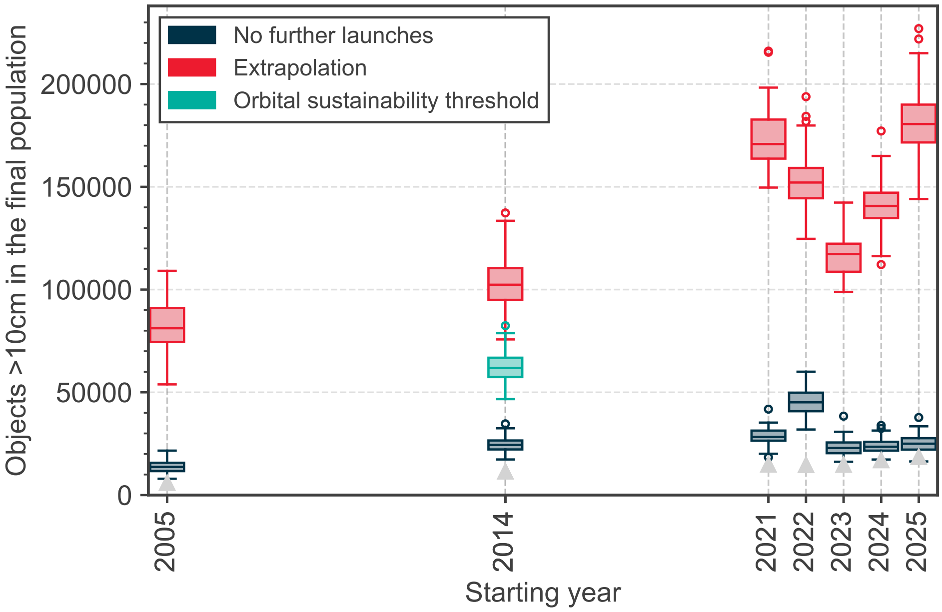

Figure 7.5: Number of objects in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment. The number of objects at each starting epoch is denoted by a grey triangle.

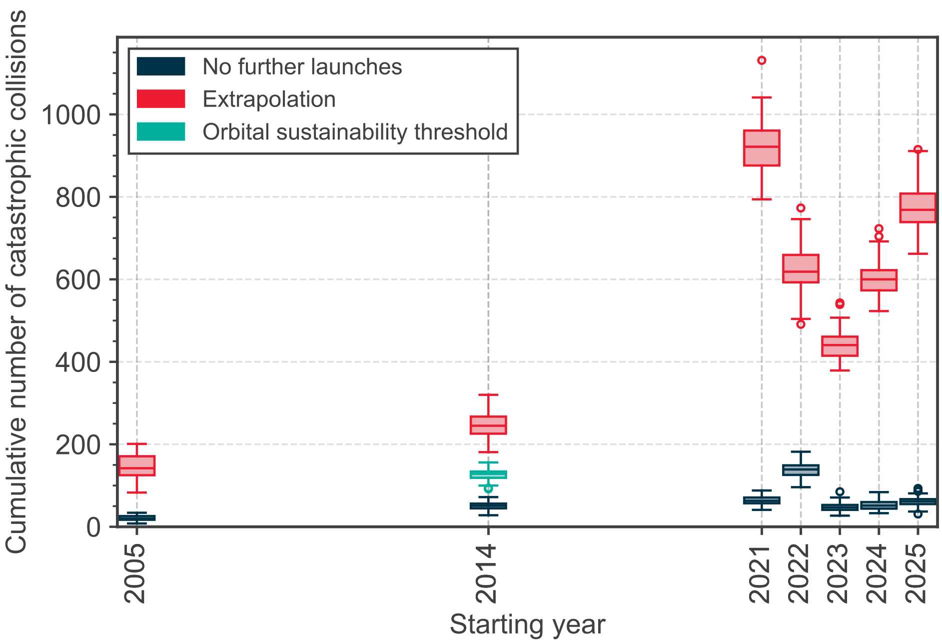

Figure 7.6: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

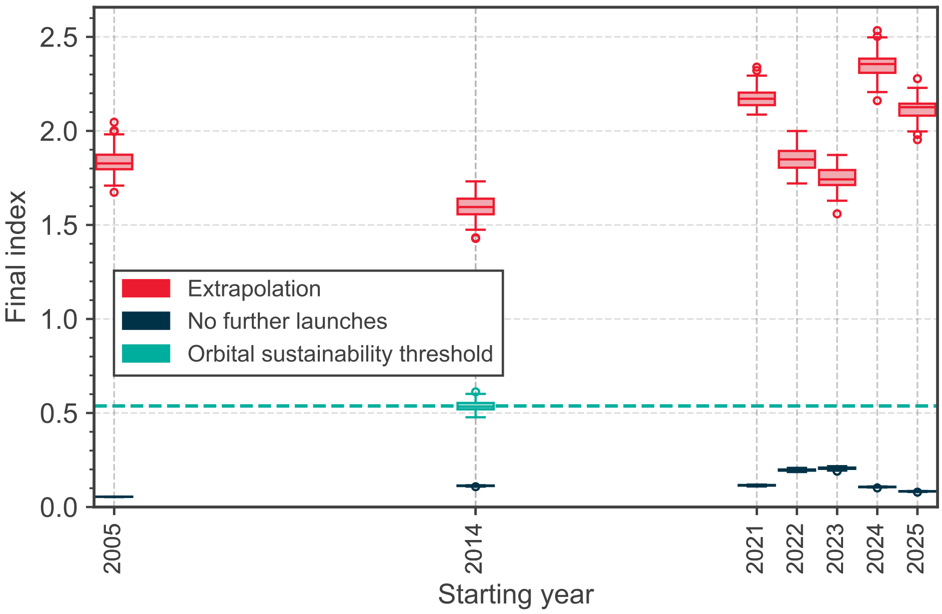

Figure 7.7: Index values in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

References

[1] United Nations. Guidelines for the long-term sustainability of outer space activities (A/AC.105/C.1/L.366), 2019.

[2] Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, IADC-02-01, Revision 4, 2025.

[3] European Space Agency. ESA Space Debris Mitigation Requirements, ESSB-ST-U-007, Issue 1. https://technology.esa.int/upload/media/ESA-Space-Debris-Mitigation-Requirements-ESSB-ST-U-007-Issue1.pdf, 2023.

[4] European Space Agency. ESA Space Debris Mitigation Policy, ESA/ADMIN/IPOL(2023)1. https://technology.esa.int/upload/media/ESA-ADMIN-IPOL-2023-1-Space-Debris-Mitigation-Policy-Final.pdf, 2023.

[5] F. Letizia, S. Lemmens, B. Bastida Virgili, and H. Krag. Application of a debris index for global evaluation of mitigation strategies. *Acta Astronautica*, 161:348–362, 2019.

[6] D. J. Kessler and B. G. Cour-Palais. Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research*, page 2637–2646, 1978.

[7] United Nations. Convention on International Liability for Damage Caused by Space Objects, 1972.

[8] Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, 2002.

[9] International Standards Organisation. Space systems - Space debris mitigation requirements, ISO TC 20/SC 14 24113:2019, 2019.

[10] European Space Agency. Database and information system characterising objects in space. https://discosweb.esoc.esa.int/, 2021. Accessed: 2024-06-01.

[11] T.S. Kelso. CelesTrak. https://celestrak.com/.

[12] Union of Concerned Scientists. Satellite Database. https://www.ucsusa.org/resources/satellite-database.

[13] International Standards Organisation. Space systems - Estimation of orbit lifetimes, ISO TC 20/SC 14 27852:2016, 2016.

[14] Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, IADC-02-01, Revision 3, 2021.

[15] United Nations Office for Outer Space Affairs. United Nations Register of Objects Launched into Outer Space. http://www.unoosa.org/oosa/en/spaceobjectregister/index.html.

[16] United Nations. Convention on Registration of Objects Launched into Outer Space, 1974.

[17] European Space Agency. ESA's Fragmentation Database. https://fragmentation.esoc.esa.int/, 2020. Accessed: 2024-06-01.

[18] K. Merz, B. Bastida Virgili, V. Braun, T. Flohrer, Q. Funke, H. Krag, S. Lemmens, and J. Siminski. Current collision avoidance service by ESA's space debris office. 7th European Conference on Space Debris, Proceedings of the conference, 2017.

[19] United States Space Force's 18th Space Control Squadron. Space-track.

https://www.space-track.org/, 2021. Accessed: 2024-06-01.

[20] K. T. Alfriend, M. R. Akella, J. Frisbee, J. L. Foster, D. J. Lee, and M. Wilkins. Probability of collision error analysis. *Space Debris*, 1(1):21–35, 1999.

[21] ESA Space Debris Office. Assessment of Risk Event Statistics (ARES). https://sdup.esoc.esa.int/drama/downloads/documentation/Technical-Note-ARES.pdf, 2019.

[22] C. Wiedemann, E. Gamper, A. Horstmann, V. Braun, and E. Stoll. Release of liquid metal droplets from Cosmos 1818 and 1867. 67th International Astronautical Congress, Proceedings of the conference, 2016.

[23] S. Flegel, J. Gelhaus, M. Möckel, C. Wiedemann, and D Kempf. Maintenance of the ESA MASTER Model. Final Report of ESA contract 21705/D/HK, 2010.

[24] S. Lemmens and H. Krag. Two-line-elements-based maneuver detection methods for satellites in low earth orbit. *Journal of Guidance, Control, and Dynamics*, 37(3):860–868, 2014.

[25] R. Mugellesi-Dow, D. J. Kerridge, T. D. G. Clark, and A. W. P. Thompson. Solmag: an operational system for prediction of solar and geomagnetic activity indices. 1st European Conference on Space Debris, Proceedings of the conference, 1993.

[26] S. Lemmens, B. Bastida Virgili, V. Braun, T. Flohrer, Q. Funke, H. Krag, F. Mclean, and K. Merz. From End-of-Life to Impact on Ground: An Overview of ESA's Tools and Techniques to Predict Re-entries from the Operational Orbit to the Earth's Surface. 6th International Conference on Astrodynamics Tools and Techniques, Proceedings of the conference, 2016.

[27] ESA Space Debris Office. Classification of Geosynchronous Objects. Issue 26. *GEN-DB-LOG-00290-OPS-SD, ESA/ESOC, Darmstadt, Germany*, 2024.

[28] C. Wiedemann, A. Horstmann, S. Hesselbach, V. Braun, H. Krag, S. Flegel, M. Oswald, and E. Stoll. Particle flux analysis with the updated MASTER model. 67th International Astronautical Congres, Proceedings of the conference, 2018.

[29] N. L. Johnson and P. H. Krisko. NASA's new breakup model of EVOLVE 4.0. *Advances in Space Research*, 28(9):1377–1384, 2001.

[30] A. Horstmann, S. Hesselbach, C. Wiedemann, S. Flegel, and M. Oswald. Enhancement of S/C Fragmentation and Environment Evolution Models. Final Report of ESA contract 4000115973/15/D/SR, 2020.

[31] A. A. Lidtke, H. G. Lewis, and R. Armellin. Statistical analysis of the inherent variability in the results of evolutionary debris models. *Advances in Space Research*, 59(7):1698–1714, 2017.

[32] H.G Lewis. Evaluation of debris mitigation options for a large constellation. *Journal of Space Safety Engineering*, 7:192–197, 2020.

[33] F. Letizia, B. Bastida Virgili, and S. Lemmens. Assessment of orbital capacity thresholds through long-term simulations of the debris environment. *Advances in Space Research*, 72(7):2552–2569, 2023.

[34] Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, IADC-02-01, Revision 1, 2007.