ESA Environmental Report on Space Debris Mitigation

Ever since the start of the space age there has been more space debris in orbit than operational satellites. As space debris poses a problem for the near Earth environment on a global scale, only a globally supported solution can be the answer. This creates the need for a set of internationally accepted space debris mitigation measures, in addition to national standards and licence processes.
A major step in this direction was taken in 2002, when the Inter-Agency Debris Committee (IADC) published its Space Debris Mitigation Guidelines. This document has since served as a baseline for non-binding policy documents, national legislation, and as a starting point for the derivation of technical standards. The standardisation of mitigation measures is important in order to achieve a common understanding of the required tasks leading to transparent and comparable processes. Even if a consistent set of measures is paramount to tackle the global problem of space debris, it is then up to the individual nations, operators, and manufacturers to implement them.

In order to have on overview of the on-going global debris mitigation efforts and to raise awareness of space activities in general, the European Space Agency, ESA, has been publishing a Space Environment Report. The document is updated yearly and it is publicly available[1].

The purpose of this document is to
• provide a transparent overview of global space activities,
• estimate the impact of these activities on the space environment,
• quantify the effect of internationally endorsed mitigation measures aimed at improving the sustainability of space flight.

1 STATE OF THE ENVIRONMENT

To provide a transparent overview of space activities based on observable facts, one can start by analysing trends such as the historical evolution of the number of objects in the environment. In more than 60 years of space activities, more than 5800 launches have resulted in more 44000 tracked objects in orbit, of which more than 20000 remain in space and are regularly tracked by the surveillance networks around the globe, including the US Space Surveillance Network.

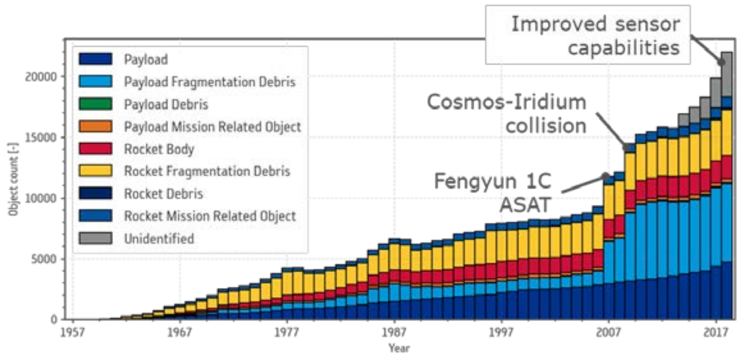


Figure 1. Evolution of number of objects in geocentric orbit by object class.

About 26% of the catalogued objects are satellites and only a small fraction - about 2000 - are still operational satellites today. About 17% of the tracked objects are spent upper stages and mission-related objects such as launch adapters and lens covers. More than half of the population is made by fragments generated by more 500 break-ups occurred in space, with the two major fragmentation events clearly visible as jumps in the population.

[1] https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

Finally, we can also see how the number of objects reflects the improvement in the capability of the space surveillance systems used as sources for the report. When new objects are detected due to increased sensor performance, they can generally not be traced back any longer to an event or source and a growing category of "Unidentified" objects appear in the plots.

2 A CHANGING ENVIRONMENT

One of the most relevant observations contained in the last editions of the report is the remarkable change in the launch in traffic in Low Earth Orbit.

The number of payloads has reached now four times the level of ten years ago, with a steep increase in particular in the last two years. This growth in numbers is driven by the launch of small satellites, with around half of the satellites launched in the last two years having a mass smaller than 10 kg. This change in traffic is also related to a shift towards a more commercial exploitation of Low Earth Orbit and a diversification in the actors on stage. A similar trend was observed in GEO many decades ago and there it lead to collaboration among the different actors to ensure an effective exploitation of the available orbital slots. Similarly in LEO, new collaborations among operators may emerge, as more and more operators take an active role in promoting best practices to limit the proliferation of space debris.

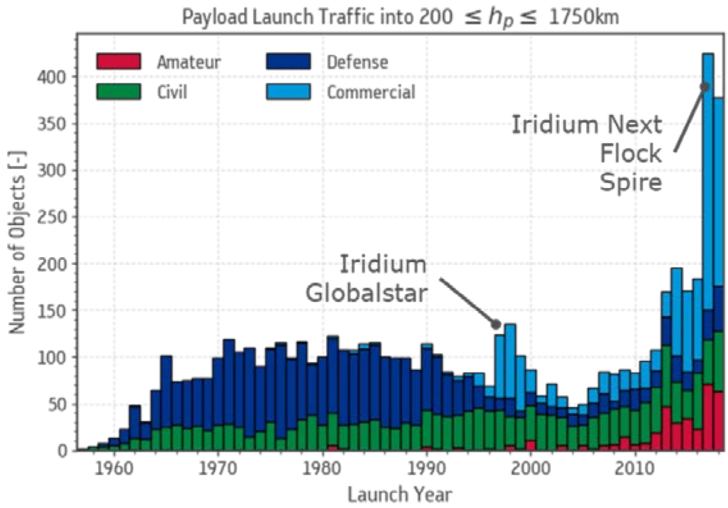


Figure 2. Evolution of the launch traffic near LEO per mission funding

In the Environment Report, several metrics are identified that serve as proxies for the global adherence to space debris mitigation guidelines, which have been put in place to protect the space environment from adverse effects such as the Kessler syndrome. These metrics are described in the report considering both their historical evolution and the different performance achieved by different class of spacecraft. The analysis of the progress made in the last years in terms of the compliance to space debris mitigation guidelines should consider that the change in the traffic that we have observed so far is only a tiny fraction of what will experience once large constellations are operational.

3 FRAGMENTATION EVENTS

One of the first metrics analysed in the report is the number of on-orbit break-ups. The potential for break-up should be minimised both during operational phases (for example, by a careful analysis of the failure trees) and after the end-of-mission, by releasing stored energy on-board, as the one in tanks and batteries. Intentional destruction and other harmful activities should also be avoided.

Currently, we observe on average 8 non-deliberate fragmentations per year and this number has not improved in the recent years. One third of the events are related to failures in the propulsion system of the spacecraft. Even if the more systematic application of passivation strategies has contributed to slightly reduce this type of breakups, failures of the propulsion and of the electrical systems still represent a significant contribution to the population of fragments observed in Earth orbits.

It is well known that the distribution of these failures is not uniform across the population of objects in orbit, but rather some specific designs have exhibited over the time a higher tendency to break-up. This is particularly evident if we look at the distribution of events by cause and by the time between launch and breakup. Whereas for what we call "Anomalous" events, i.e. the separation at low speed of fragments from a parent object, the time appears to be rather uniformly distributed, for certain classes of propulsion and electrical failures, the breakups are clustered around specific times.

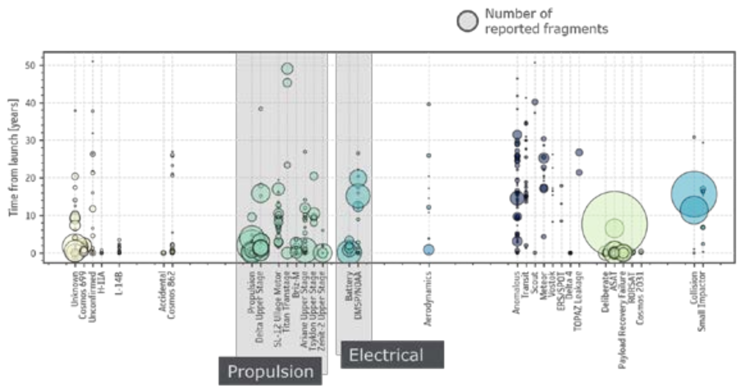


Figure 3. Distribution of fragmentation events by estimated cause and elapsed time between launch and breakup.

Design flaws can appear at different epochs from launch, but for fragmentations in space we generally observe a higher incidence of breakups in the first phase of operations, with half of the events occurring within 16 months from launch. This suggests that for the proposed large constellations operating at high altitude, where a repeating design is fundamental to the cost-model, the risk of breakups can be mitigated by testing the system at lower orbits before moving to their operational slot.

Large constellations also represent an important paradigm shift for what concerns satellite production and testing. This means that we will be moving from large handcrafted satellites (e.g. one-off specific payload for science missions) to mass-manufactured satellites with much lower cost per unit. On one hand, this change could be beneficial. Examples in other industries (e.g. automotive) have shown an improvement of reliability figures with the introduction of series production. In addition, the adoption of smaller and simpler platforms can also improve the reliability figures. On the other hand, the use of commercial-off-the-shelf components and the limited redundancy for critical functions may have a detrimental effect on reliability. For this reason, particular attention should be put on testing these platforms to verify adequate reliability level not only in fulfilling the mission objectives (where spare satellites can always be used) but also as a precondition to in-orbit operation compatible with debris mitigation standards and guidelines.

4 POST-MISSION DISPOSAL EFFORTS

Another aspect analysed in the report is the compliance with post-mission disposal guidelines in the two protected regions defined by IADC, i.e. the Low Earth Orbit (LEO) and the Geostationary Orbit (GEO). Historically, these regions represent where most operational spacecraft resides and where the collision probability is higher. These regions are protected because of their unique nature, which means that it is important to ensure access and operability in these regions for future missions and this requires to define their sustainable use with respect to debris generation.

For objects in LEO, the recommended action is to accelerate their orbital decay such that their permanence in the protected region is limited to 25 years after the end of mission; for objects in GEO, it is recommended to move any spacecraft to a graveyard orbit sufficiently above the GEO region and rocket bodies into orbits which don't intersect with it.

Currently, disposal plans and their expected success rate are not systematically shared by operators. Still, thanks to space surveillance data, the activity of a spacecraft can be derived and the orbital evolution predicted. This is what it is done in our report. For objects in LEO, the residual orbital lifetime is estimated and compared to the 25 years mentioned in the guidelines. In this way, one can classify a spacecraft as compliant or not. For GEO objects, the orbital evolution over 100 years is checked to detect any return to the GEO protected region from the orbit where the spacecraft was disposed.

If we look first at the LEO region, we observe that roughly 40% of the total number of payloads operate in in orbits which naturally adhere to the space debris mitigation measures, i.e. they will re-enter in the Earth's atmosphere within 25 years from the end of their mission. In particular, around 78% of small payloads [i.e. below 10 kg in mas] operate in such regions. This means that still 22% of these spacecraft are left in in potentially crowded orbital regions, without any manoeuvre capability.

If, instead, we look at the objects that operate in non-naturally compliant regions in LEO, we observe a low level of compliance, with only around 15-25% of the payloads [which have reached end-of-life during the current decade] that attempt to comply with the space debris mitigation measures. This class of objects is important as they represent roughly 50% of the objects in LEO and around 60% of the total mass in LEO. This means that these objects, if not disposed, can fuel the Kessler syndrome because of their mass (and so the number of fragments that they can generate) and because of their altitude (which results in a long residual lifetime).

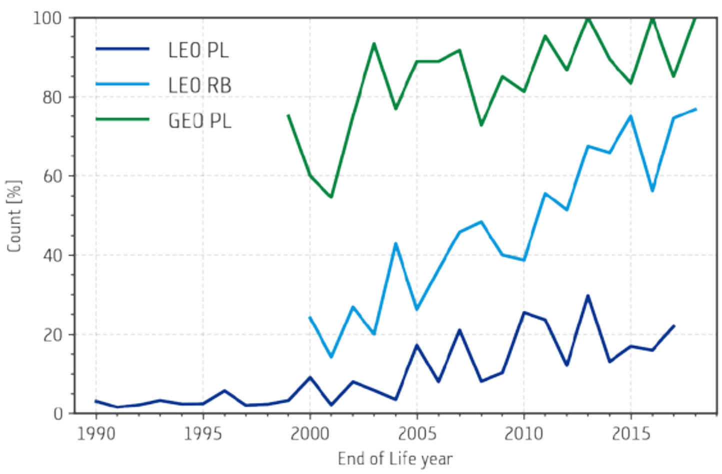


Figure 4. Disposal attempt rate for non-naturally compliant objects.

The studies on the long-term evolution of the environment have shown how the current level of compliance is not sustainable, in the sense that if the same level is maintained also in the future, we will observe an exponential growth of the population of objects and undergo the associated consequences in everyday operations.

In the case when also the presence of large constellations in LEO is considered, the studies carried out within the IADC, in a joint effort across 13 space agencies, have shown how a potentially stable evolution of the environment is achieved only in the cases where not only the disposal rate is at least 90%, but specifically for constellation objects is at least 95%.

These target values are very far from the 15% value that we currently observe, so an important shift in how to deal with disposal operations is needed. If one wants to be optimistic, we can look back to 20 years ago and see that a similar shift is already happening for rocket bodies in LEO. While around the year 2000 the attempts of disposal accounted to less than 20%, we currently observe a value close to 80%. Even better performances are reached in GEO, where the disposal attempts have been consistently above the 80% level in the recent years. The case of GEO, where there is a clear commercial interest in keeping the operational orbits free from defunct satellites, may be an interesting parallel for large constellations that will also have a similar interest in keeping their orbits clean.

5 EFFECTIVENESS OF MITIGATION MEASURES

This brings us to the question: what are the desirable conditions to gain access to space from a space debris mitigation point of view?

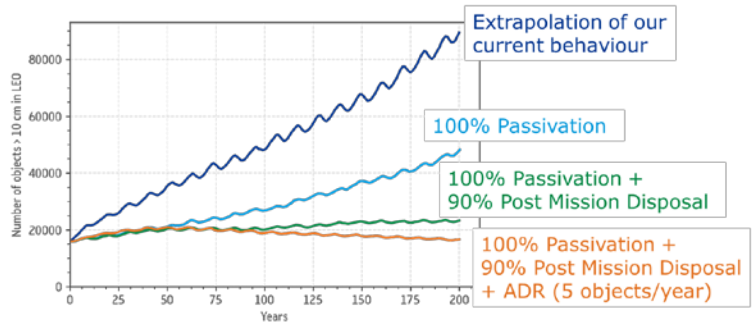


Figure 5. Predicted long-term evolution of the environment in different mitigation scenarios.

As indicated before, studies of the long-term evolution of the environment show us that addressing these two main aspects (fragmentations and disposal) would dramatically affect the growth rate of the debris population. For example, if look at the population of objects larger than 10 cm in LEO, we find that in 200 years we would have roughly an increase of more than three times in the number objects, should the current trends in terms of explosions and disposal continue. The successful passivation of any spacecraft would already halve the final number of objects. If also a rate of 90% in the successful implementation of post-mission disposal is achieved, the increase of the number of objects over 200 years is *only* 30%.

Reaching these levels of compliance would probably require doing things differently from now, not only at an operational level, but also in terms of technology, with developments, for example, on how to effectively passivate a spacecraft.

6 COLLISION AVOIDANCE

While the previous two points are already captured in the guidelines and are mostly related to long-term effects on the debris population, the changing scenario in terms of traffic and constellations has an impact also on the short-term operation of satellites.

At ESA, we provide an operational collision avoidance service to more than 20 missions. If we look at which objects are encountered by our satellites at lower orbits, we discover that for these missions we can observe an increasing contribution coming from intact satellites, such as the ones belonging to constellations and other small satellites (mass lower than 15 kg). This trend will further increase (and extend) once more and more constellations will operate in LEO.

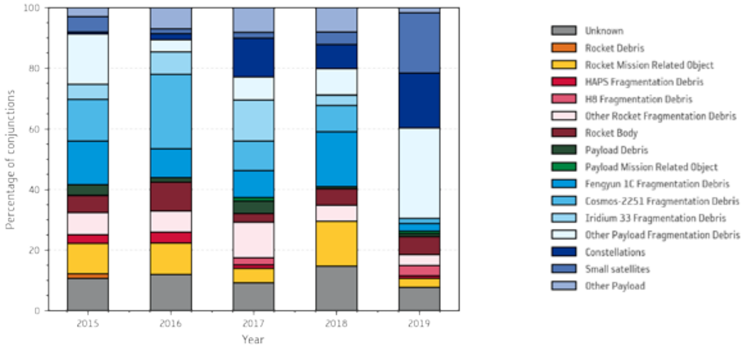


Figure 6. Close approaches for ESA missions at low altitude LEO.

This will push operators to reconsider their current setup for the collision avoidance activities. For example, last year we performed 28 collision avoidance manoeuvres. Two of these manoeuvres were performed to avoid operational small satellites (launched in the same year) and coordination was required to check their manoeuvrability status and whether any collision avoidance plan was in place on their side. Also this year we had another similar occurrence that once more made us ask whether emails or late night calls are the most efficient coordination mechanism and would be still valid in a scenario with thousands additional operational satellites.

A first step to ease the coordination among operators is to promote data sharing, for example for what concerns the manoeuvrability of an object and its predicted ephemerides. Some operators are already moving in this direction.
A second step is to develop more automated systems for collision avoidance. It is estimated that nowadays global satellite operators spend 14 million euro annually on debris impact avoidance manoeuvres, but more than 99% of the conjunction notifications are false alerts. The changing scenarios, in terms of launch traffic, associated to small satellites and large constellations and in terms of improvements in the sensor capabilities, will generate a much larger number of collision warnings to deal with. A possible approach for this is to use techniques such as machine learning to detect conjunctions that can result in risky close approach, where a reaction is needed. In the upcoming weeks, ESA will launch a global competition on this topic where we will release our historical data on conjunctions, anonymised for the purpose of the competition, and invite researchers to put their machine learning algorithms to the test.

Of course, the introduction of automated systems is not the final solution to the issue of collision avoidance, especially in the cases mentioned before where other operational satellites are involved. More effective protocols for timely communication are needed in the future, also to ensure a smooth interaction between automated systems and systems with human in the loop, together with a more defined space traffic rules. Also more transparency in terms of the risk accepted by missions and on how reaction thresholds are defined may be desirable.

7 TRACKABILITY & IDENTIFICATION

Another aspect to consider for what concerns the short-term effect of the change in the launch traffic in LEO is the increase in the average number of payloads delivered by each launch, with multiple launches carrying 30 or even 100 satellites in one go.

With so many satellites inserted into orbit at the same time, it is harder for any Space Surveillance system to distinguish the different satellites, with negative consequences both for the satellite operator (for example in the case where they are unable to establish communication and to initiate time-critical operations) and also for other operators in general, again in the case of conjunctions.

This last aspect is also relevant in consideration of liability issues in case of damage to other space assets: gaps in the identification process result in the risk of making less effective the applicability of the liability convention.

The examples in the past years show how this situation can be mitigated by ensuring communication and data sharing between operators and the Space Surveillance Network.
In this scenario, the identification of the satellites can be significantly sped up as in the case of a recent PSLV launch with more than 100 satellites on board, where the identification of 80% of the payloads occurred within one month; in other cases, we see how it can take even six months to reach the same level of identified satellites.

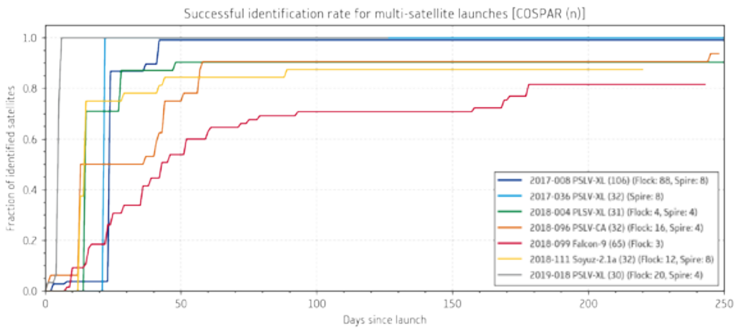


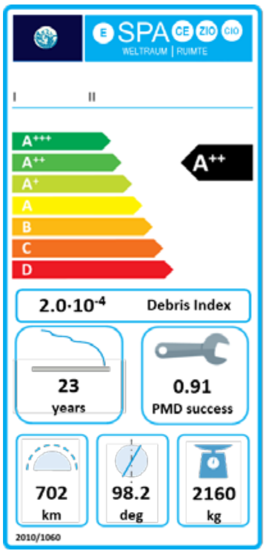
Figure 7. Successful identification rate for recent multi-satellite launches

The role of operators here is not only in ensuring proper communication with Space Surveillance systems, but also to realise which elements in the mission design can significantly impact the ability of identifying and therefore operating their satellites. This is applicable also to small satellites and where still we observe a level of dead-on-arrival around 10-20% that may become more and more problematic with the increase of the number of satellites.

8 TOWARDS ENVIRONMENT IMPACT ASSESSMENT

The aspects mentioned so far all contribute to define how a sustainable space traffic should look like. Different initiatives are currently on-going to put together these different components, that is short- and long- term effect on other operators and on the environment globally, into a single score. This process is similar to what has already happened in other fields, for example with the LEED classification in the US or with energy-labelling in Europe.

The idea here is to provide a single score that summarises the impact that a given mission has on the debris environment by considering which mitigation measures are implemented In addition, it is also evaluated how effective these measures are with respect to evolution of the environment. For this reason, this evaluation is not static (e.g. carried out only before launch for licensing purposes), but dynamic, to reflect how the mission operational concepts and mitigation measures are actually implemented.



At ESA we have been working on the development of such concepts for the last years and we have included this kind of analysis in the last two edition of the Environmental Report with the motivation that environment impact assessment can be a way of strengthen existing mitigation guidelines. In particular, the metric we present in the report is based on the potential collision risk posed by a mission to other operational satellites in case of fragmentation. We think that this metric is more effective in depicting the state of the environment than using the number of objects. In fact, with a risk metric you can capture different elements such as the orbit where a spacecraft is operating, its physical characteristics, the mitigation measures put in place. As any mission operates with certain assumptions in terms of reliability and accepted risk, there cannot be a zero-impact mission, but still it is possible to identify and quantify how to reduce such an impact and define which levels of performance are compatible with a desired maximum accepted footprint on the environment.

In addition, since last year we started a collaboration with MIT, University of Texas at Austin, and Bryce Space and Technology to develop a so-called "Space Sustainability Rating", following a call for proposal launched by the World Economic Forum. Also in this case, the purpose is to encourage more responsible behaviours by promoting mission designs and operational concepts that are compatible with a stable evolution of the environment. The approach envisioned for this initiative is to combine in a composite indicator elements such as the risk metric that we present in the Environment Report together with evaluation on the operators' actions in fields such as application of international standards, data sharing, trackability.

9 CONCLUSIONS

In conclusion, the observations from our yearly Environment Report show how the use of space is changing more rapidly than our compliance rate to existing mitigation measures. At the same time, new issues related to how to define an effective space traffic management system are emerging.

This makes us ask ourselves several questions on how to ensure a sustainable spaceflight.

- Space Debris Mitigation requires a level playing field to achieve long-term stability. How are we sure that this is reflected in static standards and licensing?
- How can guidelines evolve to ensure a more sustainable use of space? Which are the priorities from an operator perspective? How can better-than-required behaviour can be reflected?
- What is the most effective way to tackle short-term aspects, currently only partially covered by guidelines?
- How far can one go when asking transparency to operators? Should new formal requirements be introduced to promote data sharing and transparency? Would they work for all the aspects (i.e. manoeuvrability status, ephemerides, disposal plans, reliability figures)?