ESA ESOC
Robert-Bosch-Strasse 5
D-64293 Darmstadt
Germany

ESA'S ANNUAL SPACE ENVIRONMENT REPORT

Prepared by	ESA Space Debris Office
Document Type	LOG
Reference	GEN-DB-LOG-00288-OPS-SD
Issue/Revision	9.1
Date of Issue	21 October 2025
Status	Final

Table of contents

EXECUTIVE SUMMARY

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. A major step in this direction was taken in 2002, when the Inter-Agency Debris Committee (IADC) published its first Space Debris Mitigation Guidelines. This document, and subsequent updates, 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 having a consistent set of measures is paramount to tackle the global problem of space debris, it is still up to the individual nations, operators, and manufacturers to implement them.

In order to have an overview of the ongoing 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 since 2017. The document is updated yearly, it is publicly available, and it supports the awareness raising guideline laid out in United Nations Committee on the Peaceful Uses of Outer Space's (UNCOPUOS) Guidelines for the Long-Term Sustainability of Outer Space Activities published in 2019. The purpose of this report 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.

In this report, the status of the space environment is presented in various facets, focusing on the time evolution of catalogued and asserted objects in terms of number, mass, and area, as well as addressing the global adherence to space debris mitigation measures. Most internationally accepted space debris mitigation measures can be traced back to the following objectives:

- The limitation of space debris released during normal operations;
- The minimisation of the potential for on-orbit break-ups;
- Post mission disposal;
- Prevention of on-orbit collisions.

These objectives are translated in design and operation guidelines that can be measured and the consequences can be assessed. Aspirationally, these objectives lead to future in which space debris is not an issue.

Whereas the presentation of numerical values associated to launch and re-entry activities are essentially absolute, it is important to point out that metrics dealing with the adherence to space debris mitigation measures are *estimates*. These estimates depend on complex physical problems such as estimating orbital lifetime and require under-determined interpretations of observational quantities. As such, the conclusions on the state of the space environment presented hereafter need to be taken with appropriate care and can vary between yearly releases of the report. Notwithstanding such caveats, all care is taken in the design of the methodologies to minimise such variability and some summarising statements can be derived from the presented data.

The **amount of objects**, their combined **mass**, and their combined **area** has been **steadily rising** since the beginning of the space age, leading to the appearance of involuntary collisions between operational payloads and space debris. Ever increasing **improvements in space surveillance sensor capabilities** during the last decades have brought down the size limits where debris can be reliably tracked and catalogued. This, in turn, implies that we know about significant amounts of space debris, but not all their originating events. The **space traffic** itself is also undergoing **notable changes** since 2015, particularly in Low Earth Orbits, fuelled by the **miniaturisation** of space systems and deployment of **large constellations**, with a shift towards **commercial operators**. While the exponential growth in the **number of new payloads slowed** in 2024, the **number of launches continued to rise**, and in terms of mass and area, launch traffic is still at the highest rate seen thus far. These three elements (i.e. volume of traffic, type of spacecraft, type of operators) are all of relevance when one considers the adequacy of space debris mitigation guidelines and possible ways for sustainable space operations, especially when looking at the **Earth's orbital environment as a finite resource**, in line with the UN Long-Term Sustainability Guidelines [1].

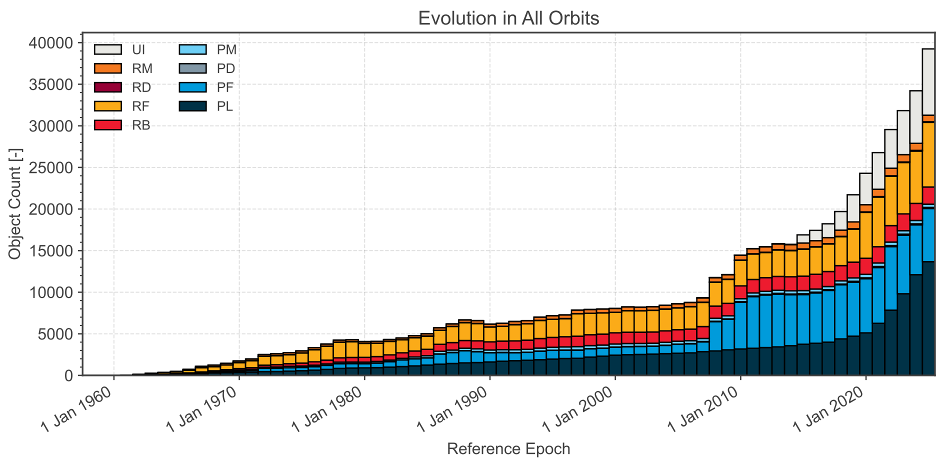


Figure 1: Evolution of number of objects in geocentric orbit by object class. Please consult Section 1.1 for the definitions.

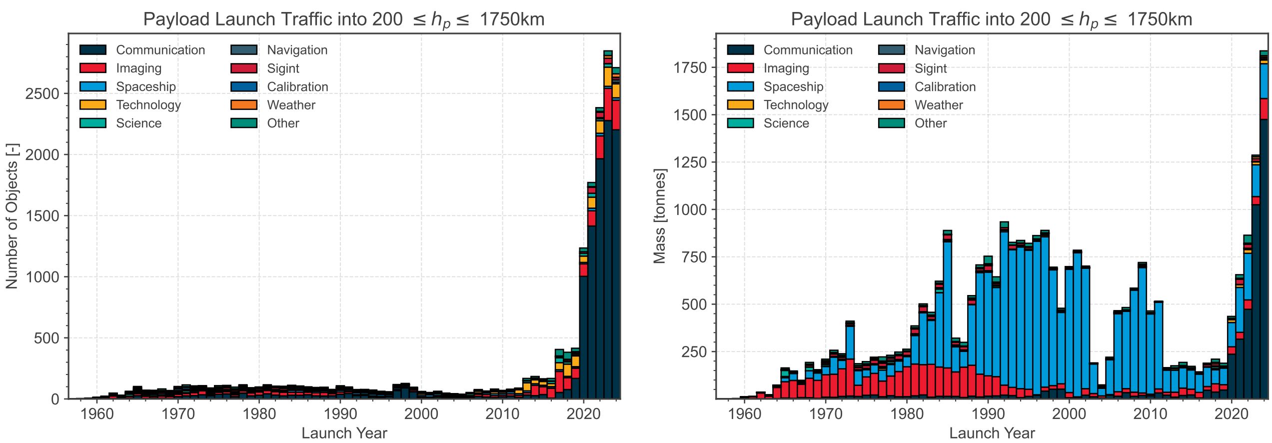


Figure 2: Evolution of the launch traffic near LEO_{IADC} per mission type in object number (left) and mass (right).

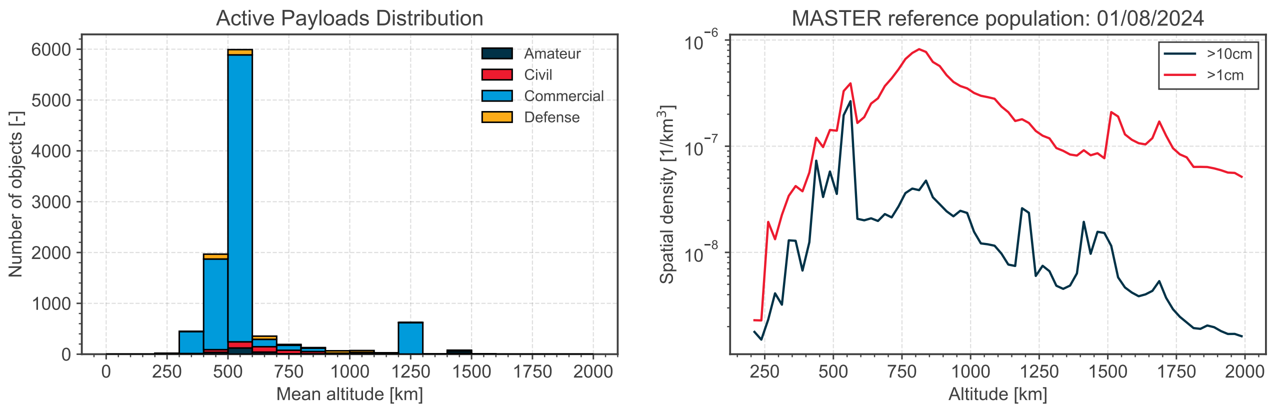


Figure 3: Distribution of active payloads with altitude (left) and density profiles in LEO_{IADC} for different space object size ranges from the 01/08/2024 MASTER reference population (right).

Preferential altitude ranges for communication constellations continue to show a clear **peak in payload concentration** (Fig. 3). The updated 2024 population from ESA's space environment modelling tool MASTER reflects this peak around the 500 km - 600 km altitude regime. While the 1 cm space object population has historically consisted of fragments, this paradigm has now changed, and the **density of active payloads is approaching that of space debris** in these heavily populated altitude bands.

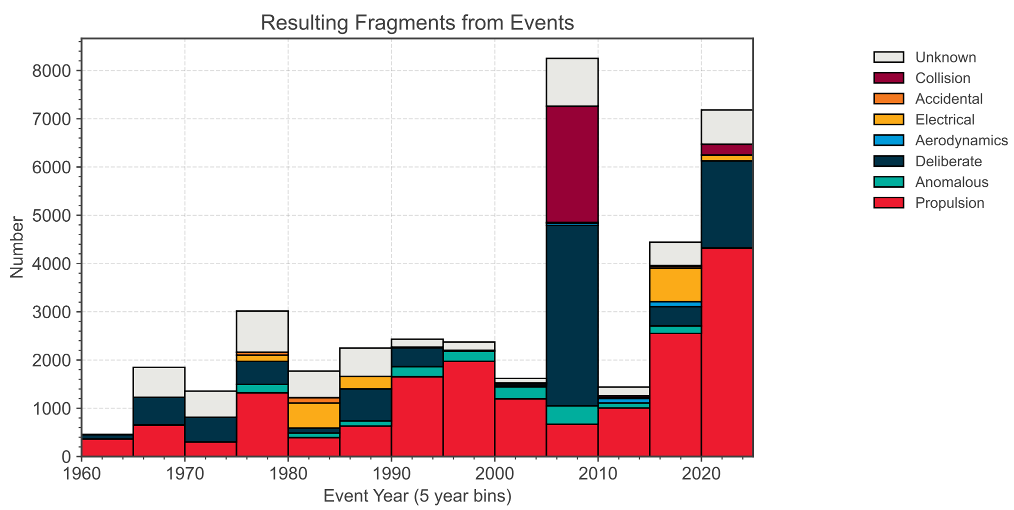


Figure 4: Historical trend of numbers of fragments produced by fragmentation events. The last bin covers until the end of 2024.

On average over the last two decades, **10.5 non-deliberate fragmentations** continue to occur in the space environment **every year**. This number is stable, however the impact of each event is variable. This number drops significantly to **1.7** per year when the **lifetime of the generated fragments** is considered a factor of importance, and even **0.4** per year when **systematic** and **unexplained** events are **excluded** from the analysis. This suggests that non-collisional events with a large environmental impact are still taking place, partly due to the presence of designs with known issues. Further details are presented in Table 5.1 and Table 5.2. Fragmentations other than collision are currently the dominant source of space debris as can be seen from Figures 5.6 and 5.5. 2024 saw several significant fragmentations, with more than **3000** newly catalogued fragments attributed to these events.

A core space debris mitigation principle to reduce the risk of fragmentation is post-mission disposal. One facet of this is to restrict the time spent on orbit after end-of-life, with residual orbital lifetime limited to be as short as practicable and no more than a maximum of 25 years set out by the IADC for the LEO protected region [2]. Of the payloads injected into LEO_{IADC} that have reached the end of their mission since 2020, between **84% and 99%** of those with masses below 1000 kg operate in orbits that **naturally adhere to this “25-year rule”**. For the payloads with masses between 100 kg and 1000 kg in mass, this is dominated by the behaviour of constellations. For larger payloads, the level of adherence is much lower, with only **52%** set to remove themselves from orbit within 25 years.

Between **40** and **70%** of all **payload mass**, excluding human spaceflight, estimated as reaching end-of-life during the last decade in the **LEO** protected region does so in orbits that are estimated to **adhere** to the **25-year lifetime limit**, as shown in Fig. 6.7. The noted increase in small payloads reaching end-of-life in compliant orbit implies a rising share, as does an increasing share of objects with manoeuvre capabilities such as constellations. Between **60** and **90%** of all **rocket body mass** reaching end-of-life during the last decade does so in orbits that are estimated to **adhere** to the **25-year lifetime limit**, as shown in 6.9. A significant amount of this is due to **controlled re-entries** after launch, a practice which increased from 10% to over **65%** over the last decade. In 2024, controlled re-entries of rocket bodies outnumbered uncontrolled re-entries for the first time, as can be seen in Fig. 6.

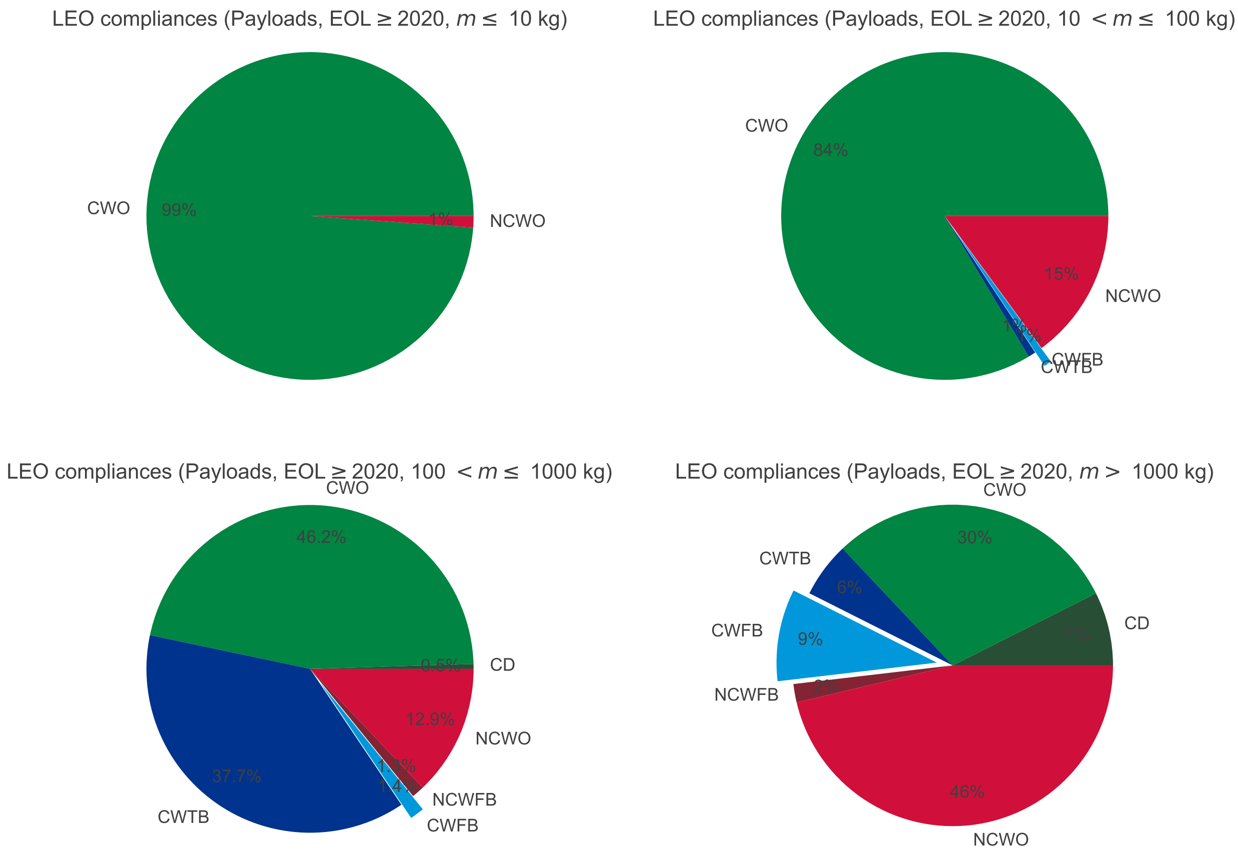
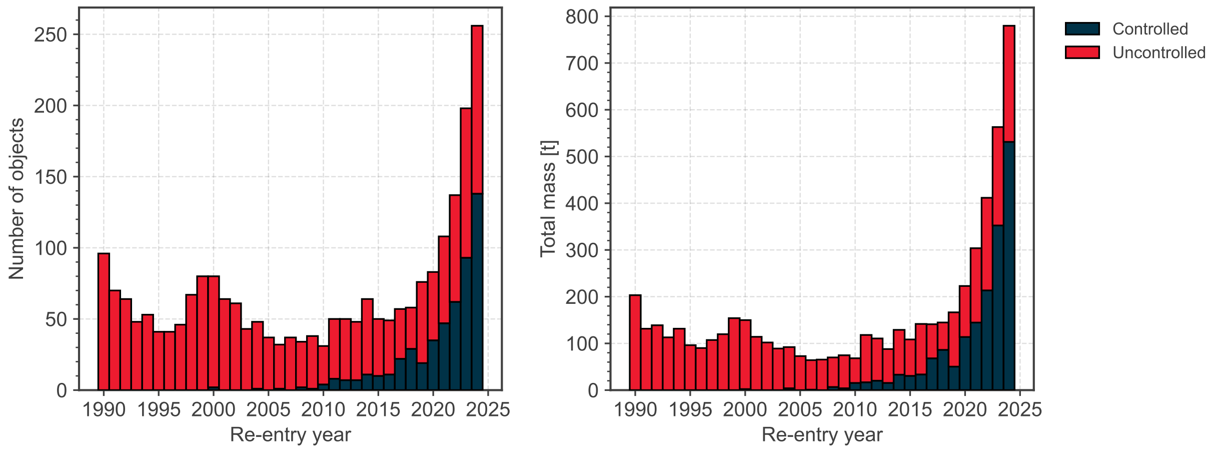


Figure 5: Breakdown of the 2020 decade of observed behavioural classes for payloads per mass category, for a lifetime limit of 25 years. Please consult Section 6.1 for the definitions.



(a) Rocket Bodies: Count

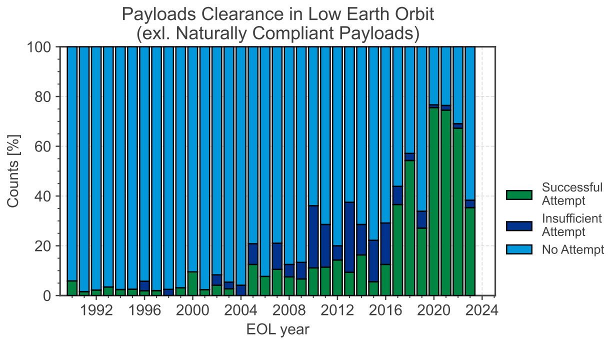
(b) Rocket Bodies: Mass

Figure 6: Controlled and uncontrolled re-entries for Rocket Bodies.

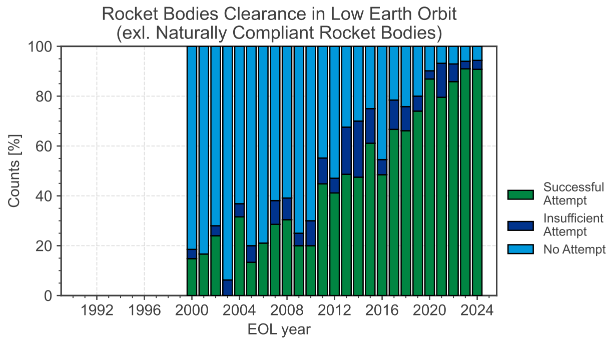
Despite this, current levels of compliance to space debris mitigation guidelines at large are **insufficient for achieving a sustainable space environment** long-term, and there is a growing consensus that stricter mitigation practices need to be implemented globally. In line with this, the early twenty-twenties saw some significant policy shifts come into force across major launching states across the globe, including ESA's own Zero Debris Approach and updated **Space Debris Mitigation Standard** and associated policy [3, 4]. Among the measures introduced by this Standard in 2023, was the **reduction of the post-mission lifetime limit from 25 down to 5 years**. Specifically, the Standard requires that the orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions: first, that the orbit lifetime is **less than 5 years**; and secondly, that the **cumulative collision probability** from end of life until re-entry with space objects larger than 1 cm is **below** $\mathbf{10^{-3}}$ [3]. While this is only binding for ESA projects, one goal of the Zero Debris Approach is to lead by example, and thus compliance to both the 25- and 5-year thresholds is reported on here. While a common target for successful post-mission disposal is 90%, this practice will not by itself reduce the amount of debris in orbit, and will need to increase to near 100% in the near future.

Between **20** and **75%** of **payloads**, excluding human spaceflight, reaching end-of-life during the last decade in the LEO protected region in a **non-compliant orbit attempt to comply** with the **25-year** lifetime limit. The difference in behaviour between constellation and non-constellation objects can be significant as shown in Fig. 6.6. Between **5** and **75%** do so **successfully** and a rising trend is evident. Similar trends can be seen when applying the **5-year threshold**, with between **5** and **55%** successfully complying over the last decade (Fig. 6.28). Between **50** and **95%** of **rocket bodies** reaching end-of-life during the current decade in the LEO protected region in a non-compliant orbit **attempt to comply** with the **25-year** lifetime limit. Between **45** and **90%** do so **successfully**, with the compliance trend linearly increasing, but stabilising. Similar trends can be seen when applying the **5-year threshold**, with between **30** and **85%** successfully complying over the last decade. Between **85%** and **100%** of all **payloads** reaching end-of-life during the last decade in the GEO protected region **attempt to comply with space debris mitigation measures**. Between **70%** and **95%** do so **successfully**, with the compliance trend asymptotically increasing, but notable exceptions in 2015 and 2022.

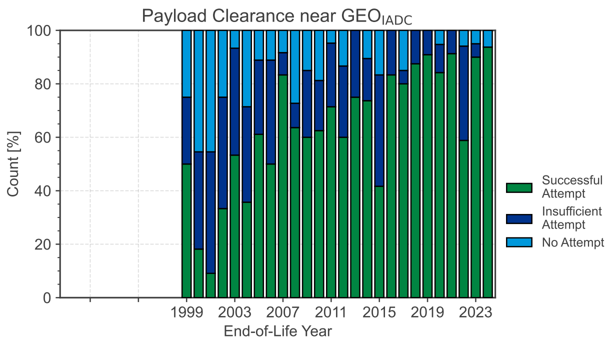
Whereas adoption of, and **compliance** to, space debris mitigation practices at a global level is noted as **slowly increasing**, it is of importance to note that the successful implementation of either lifetime threshold is still at a **too low level to ensure a sustainable environment** in the long-run. Notably, some of the **increase in uptake of mitigation measures** as analysed by the metrics above, such as controlled re-entries of rocket bodies or post mission disposal success rates for payloads in LEO, are linked with the deployment and retirement of **large**



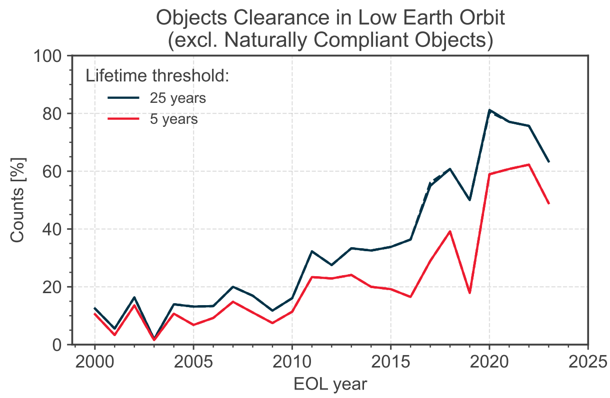
(a) Relative clearance of LEO_{IADC} by payloads, for a lifetime limit of 25 years.



(b) Relative clearance of LEO_{IADC} by rocket bodies, for a lifetime limit of 25 years.



(c) Relative clearance near GEO_{IADC} by payloads.



(d) Relative clearance near LEO_{IADC} by payloads and rocket bodies for 25 and 5-year lifetime limits.

Figure 7: Trend of adherence to clearance of the protected region over time in terms of numbers, excluding naturally compliant objects where no action was needed or taken.

constellations. Other effects, such as a shift in usage of operational mission orbits in Low Earth Orbit as show in Fig. 2.24, are however independent of the category of the payload.

Given these factors, combined with increasing launch traffic and high levels of solar activity, the number and size of re-entering objects is also increasing, with **1200 intact objects re-entering in 2024**.

Despite this, 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 Low Earth Orbit.

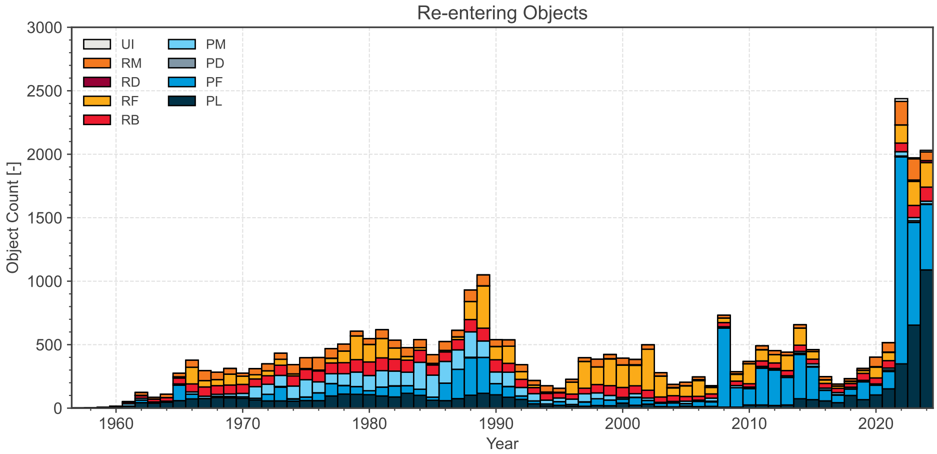


Figure 8: Evolution of re-entering objects in each year by object type without human spaceflight.

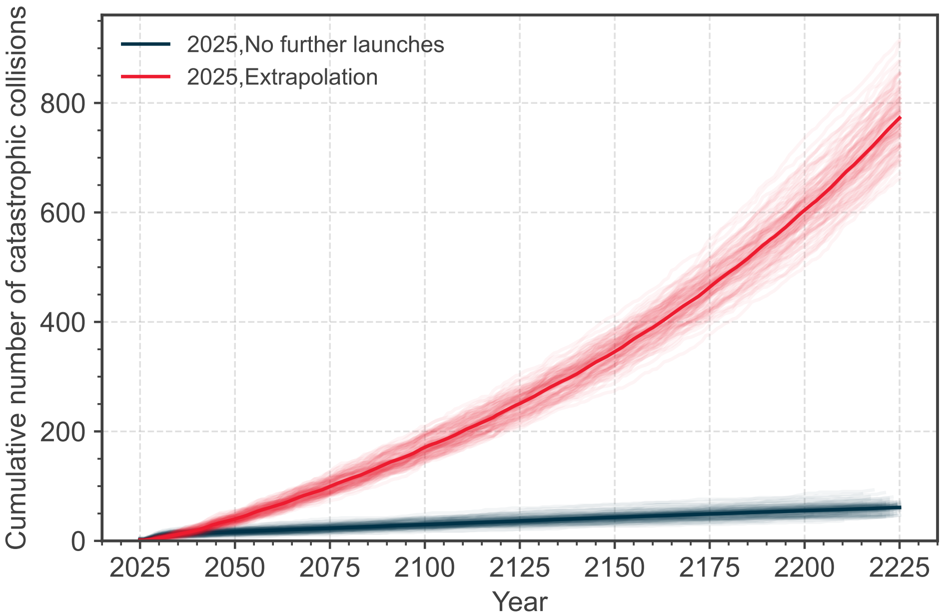


Figure 9: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

To track the **long-term sustainability** of the space environment as a whole, in line with the UNCOPUOS Long-term Sustainability of Outer Space Activities, two elements are required: a metric and a baseline that characterises a sustainable environment. For space, this metric can be captured by a single **risk index** [5], which quantifies the contribution, or criticality, of each space object to long-term sustainability through their potential to generate debris and trigger subsequent collisions. This index can then be evaluated against a **target environment**, based on pre-constellation launch traffic and a high-level implementation of the IADC guidelines, representing the level of risk that was considered acceptable for long-term sustainability before the fundamental change in launch traffic associated with the New Space era. The evolution of the risk index for the space population in Low Earth Orbit, projected 200 years into the future, is shown in Figure 10. Here, the status of the space environment can be compared to an **orbital sustainability threshold**, representing the index value of the target sustainable environment. In the business as usual extrapolation scenario, the level of risk associated with the environment is predicted to be **4 times higher** than this acceptable threshold for long-term sustainability.

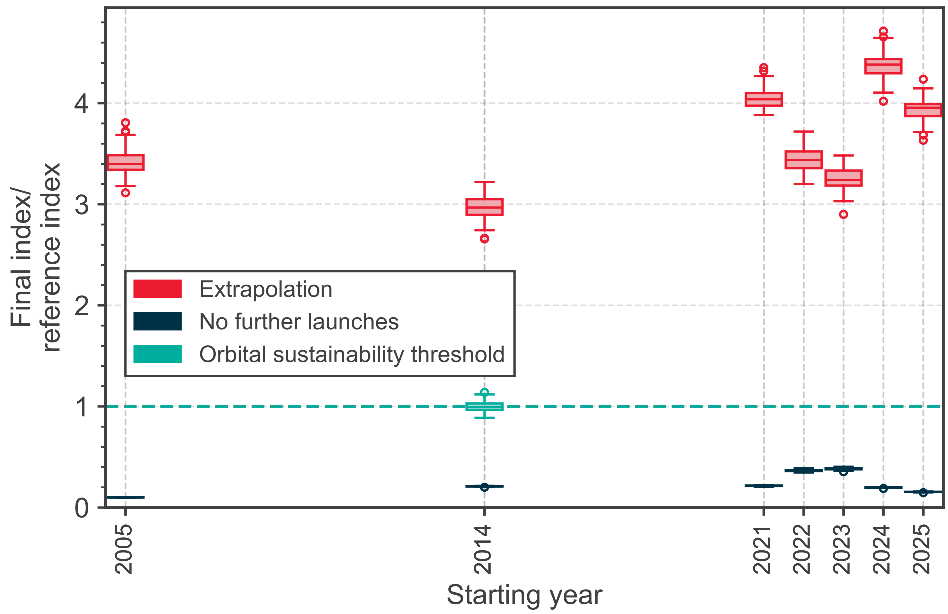


Figure 10: Index value in different scenarios, normalised against the target sustainable environment based on observed launch traffic at 2014.

1. INTRODUCTION

Ever since the start of the space age on the 4th of October 1957 there has been more space debris in orbit than operational satellites. Space debris poses a problem for the near Earth environment on a global scale, to which all spacefaring nations have contributed and for which only a globally supported solution can be the answer. The first awareness of the problem came about in the early 1960s, based on initial research activities undertaken in the United States of America, but it took some time to reach the international community. It eventually did by the mid 1970s via conferences organised by the International Astronautical Federation. The effect whereby the generation of space debris via collisions and explosions in orbit could lead to an exponential increase in the amount of artificial objects in space, in a chain reaction which would render spaceflight too hazardous to conduct, was first postulated by Donald Kessler in 1978 [6]. The first dedicated conference on space debris was held in 1982, organised by the National Aeronautics and Space Administration (NASA), followed by the first workshop on the re-entry of space debris in 1983, organised by the European Space Agency (ESA), in response to the re-entries of Skylab and Cosmos-1402.

The technical expertise on space debris, from re-entries to on-orbit break-up and hypervelocity impact testing, was gathered on agency and national level for much of the 1970s and 1980s. However, the global dimension of the issue called for bilateral knowledge transfer, which started on the initiative of NASA. These exchanges between experts resulted in multi-lateral meetings and lead to the creation of the Inter-Agency Space Debris Coordination Committee (IADC) in 1993, founded by ESA (Europe), NASA (USA), NASDA (now JAXA, Japan), and RSA (now Roscosmos, Russian Federation). Nine more agencies have joined the IADC since: ASI (Italy), CNES (France), CNSA (China), CSA (Canada), DLR (Germany), KARI (South Korea), ISRO (India), NSAU (Ukraine), and UKSA (United Kingdom). The IADC was founded as a forum for technical exchange and coordination on space debris matters, and can today be regarded as the leading international technical body in the field of space debris. Space debris has also been a recurring agenda item for the Scientific & Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space (UNCOPUOS) since 1994.

The threat of space debris to the future of spaceflight combined with the nearly universal adoption of the Liability Convention [7] created the need for a set of internationally accepted space debris mitigation measures. A major step was taken in 2002, when the IADC published the *IADC Space Debris Mitigation Guidelines* [8] and presented them to the UNCOPUOS Scientific & Technical Subcommittee. This document has since served as baseline for non-binding policy documents, national legislation, and as starting point for the derivation of technical standards. A consistent set of measures is paramount to tackle the global problem of space debris, but it is up to the individual nations, operators, and manufacturers to implement them, which can lead to variations on a case by case basis. As such, nations around the world have developed safety standards and specific guidelines building on the work of the IADC. However, standardisation of mitigation measures is important in order to achieve a common understanding of the required tasks leading to transparent and comparable processes. This is the task of normative international standardisation bodies such as the International Standards Organisation (ISO) [9].

In order to address the issues posed by space debris on spaceflight activities UNCOPUOS has taken the initiative to create a set of internationally agreed *guidelines for the long-term sustainability of outer space activities* [1]. These guidelines contain recommendations on the policy and regulatory frameworks for space activities, the safety of space operations, rules of engagement for international cooperation, capacity-building and awareness, and scientific and technical research and development.

The content of this document is written in response to those guidelines by raising awareness of space activities, and aims to:

- Provide a transparent overview of global space activities,
- Estimate the impact of these activities on the space environment,
- And quantify the effect of internationally endorsed mitigation measures aimed at sustainability of the environment.

The document is structured as follows: Section 1 contains the definitions, data sources, and methodologies used to compile this document. Section 2 contains the history of the space environment since the beginning of the space age. Section 3 contains a snapshot of the space environment for a specific year analysed. The content of Sections 2 and 3 are further analysed in depth in Sections 4, 5, and 6 where respectively the intentional release of objects, fragmentation events, and end-of-life operations of space missions are covered. Section 7 summarises the space activities in Low Earth Orbit up until the year of analysis into an environment index. Furthermore, an executive summary containing the main space environment trends identified is added to the beginning of this report.

1.1. Definitions

This document aims to describe the *space environment*. This environment is understood to contain all artificial objects, including fragments and elements thereof, which currently, or previously did, reside in an Earth bound orbit.

The space environment will be described since the beginning of the *space age*, understood to start with the launch of Sputnik 1 on the 4th of October 1957, unless explicitly stated otherwise.

Space debris is defined as all artificial objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional [8].

Objects in the space environment can be categorised in two broad categories: The ones which can be traced back to a launch event and for which the nature can be identified, and the ones for which this is impossible. The later ones will be identified as *Unidentified*, whereas the former can be further categorised in:

- *Payloads*, space object designed to perform a specific function in space excluding launch functionality. This includes operational satellites as well as calibration objects.
- *Payload mission related objects*, space objects released as space debris which served a purpose for the functioning of a payload. Common examples include covers for optical instruments or astronaut tools.
- *Payload fragmentation debris*, space objects fragmented or unintentionally released from a payload as space debris for which their genesis can be traced back to a unique event. This class includes objects created when a payload explodes or when it collides with another object.
- *Payload debris*, space objects fragmented or unintentionally released from a payload as space debris for which the genesis is unclear but orbital or physical properties enable a correlation with a source.
- *Rocket body*, space object designed to perform launch related functionality; This includes the various orbital stages of launch vehicles, but not payloads which release smaller payloads themselves.
- *Rocket mission related objects*, space objects intentionally released as space debris which served a purpose for the function of a rocket body. Common examples include shrouds and engines.
- *Rocket fragmentation debris*, space objects fragmented or unintentionally released from a rocket body as

space debris for which their genesis can be traced back to a unique event. This class includes objects created when a launch vehicle explodes.

- *Rocket debris*, space objects fragmented or unintentionally released from a rocket body as space debris for which the genesis is unclear but orbital or physical properties enable a correlation with a source.

A *fragmentation* is thus loosely defined as an event on-orbit that creates space debris without purpose, including but not limited to collisions, explosive break-ups, and tear and wear. With this definition of a fragmentation event in mind, the distinction between mission related objects and fragmentations debris is clear. Objects that are classified as general payloads or rocket debris can be reclassified when more information becomes available. An overview of this object type classification and the abbreviations used in the rest of the document is given in Table 1.1.

The taxonomy of objects in the space environment can be done based on type as defined previously, but also via the orbital regime in which they reside. A *catalogued object* will refer to an object whose orbital elements are maintained for prolonged periods of time in a catalogue created by a space surveillance system. An *asserted object* will refer to an object which has not been reported by a space surveillance system but is known to exist in the space environment by design. Asserted objects include, for example, rocket bodies that perform a re-entry burn after inserting a payload into orbit prior to repeated detections by a space surveillance system. As such, catalogued and asserted objects are not mutually exclusive and neither one is strictly contained within the other. Further objects exists in the space environment that are not catalogued for prolonged periods of time, for example as unpredictable orbit motion prohibits the correlation of observations, and can neither be asserted from a design point of view. These objects are beyond the scope of this report.

Catalogued and asserted objects can be categorised in terms of their orbital elements for a given epoch. Orbital regimes in this report will be identified based on semi-major axis, eccentricity, inclination, perigee height and apogee height. The orbital regimes that shall be used are defined in Table 1.2. Two regions are often identified as so-called protected regions by international standards, guidelines, and national legislation; they are specifically defined in Table 1.3 and will be referred to as such. It is important to note that all these definitions are inherent to this document and can change between issues. In addition to the orbital regions defined in Table 1.2, the report also refers to *Sun-Synchronous orbits*, i.e. orbits for which the secular variation of the right ascension of the ascending node, due the Earth's oblateness, matches the Earth's rotation rate around the Sun. As a result, the orbital plane remains approximately fixed with respect to the Sun and a satellite in those orbits passes over a point on the Earth with the same local solar time and this makes Sun-Synchronous orbits particularly used for Earth Observation missions. This report will also make use of *Destination Orbits* for Payloads and Rocket Bodies. This single orbit per object is defined by an analyst to be representative for orbits used during its normal operations.

Table 1.1: Object Classifications.

Type	Description
PL	Payload
PF	Payload Fragmentation Debris
PD	Payload Debris
PM	Payload Mission Related Object
RB	Rocket Body
RF	Rocket Fragmentation Debris
RD	Rocket Debris
RM	Rocket Mission Related Object
UI	Unidentified

Table 1.2: Ranges defining each orbital class, with semi-major axis a, eccentricity e, inclination i, perigee height h_p and apogee height h_a. The units are km and degrees.

Orbit	Description	Definition		
GEO	Geostationary Orbit	$i \in [0, 25]$	$h_p \in [35586, 35986]$	$h_a \in [35586, 35986]$
IGO	Inclined Geosynchronous Orbit	$a \in [37948, 46380]$	$e \in [0.00, 0.25]$	$i \in [25, 180]$
EGO	Extended Geostationary Orbit	$a \in [37948, 46380]$	$e \in [0.00, 0.25]$	$i \in [0, 25]$
NSO	Navigation Satellites Orbit	$i \in [50, 70]$	$h_p \in [18100, 24300]$	$h_a \in [18100, 24300]$
GTO	GEO Transfer Orbit	$i \in [0, 90]$	$h_p \in [0, 2000]$	$h_a \in [31570, 40002]$
MEO	Medium Earth Orbit	$h_p \in [2000, 31570]$	$h_a \in [2000, 31570]$	
GHO	GEO-superGEO Crossing Orbits	$h_p \in [31570, 40002]$	$h_a > 40002$	
LEO	Low Earth Orbit	$h_p \in [0, 2000]$	$h_a \in [0, 2000]$	
HAO	High Altitude Earth Orbit	$h_p > 40002$	$h_a > 40002$	
MGO	MEO-GEO Crossing Orbits	$h_p \in [2000, 31570]$	$h_a \in [31570, 40002]$	
HEO	Highly Eccentric Earth Orbit	$h_p \in [0, 31570]$	$h_a > 40002$	
LMO	LEO-MEO Crossing Orbits	$h_p \in [0, 2000]$	$h_a \in [2000, 31570]$	
UFO	Undefined Orbit			
ESO	Escape Orbits			

Table 1.3: Ranges defining each protected region, with altitude h and declination δ. The units are km and degrees.

Orbit	Description	Definition	
LEO_{IADC}	IADC LEO Protected Region	$h \in [0, 2000]$	
GEO_{IADC}	IADC GEO Protected Region	$h \in [35586, 35986]$	$\delta \in [-15, 15]$

At various moments during the space age, payloads based on a limited amount of platforms have been deployed on-orbit with the intent to create a single larger system by operating in a coordinated manner. Well known examples include space segments of satellite navigation systems or systems dedicated to global data information coverage. Colloquially, such systems of payloads are known as *constellations*. For the purpose of this report, a constellation is understood as a set of at least 20 individual Payloads objects, released into orbits over more than 2 events and covering more than 1 year in time from first to last event, sharing the same objective as a combined system, and with the orbits in which they are deployed directly related to the systems' objective. A constellation is considered active, i.e. functional, as long as at least one of its constituting Payloads is functional. For the current analysis, constellations are identified only in LEO_{IADC} and MEO, resulting in a total of 26 constellations.

1.2. Data sources

Orbital information for catalogued objects is obtained from the USSTRATCOM Two-Line Elements data set, the Vimpel data set maintained by the JSC Vimpel Interstate Corporation and Keldysh Institute of Applied Mathematics (KIAM), and the Royal Aircraft Establishment (RAE) Tables of artificial satellites. Orbital information on asserted objects, as well as the justification for their assertion, is taken from the DISCOS Database (Database and Information System Characterising Objects in Space) [10]. Orbital information on catalogued and asserted objects are correlated among the various sources to avoid duplication.

Physical properties for the objects, and the mission classification for Payloads, used in this report are taken from DISCOS. Shape properties such as area are derived from design values and not estimated from space surveillance systems, which implies that the debris and unidentified object types have no mass nor area indicated as part of this report. From the area and mass values so defined, the object area-to-mass ratio (A/m) is computed and it is used in the characterisation of Payloads (Section 2.7) and, more in general, for the propagation of the object trajectories for compliance analysis (Section 6) and in the simulation of the long-term evolution of the environment (Section 7.2). For orbital lifetime assessments, data derived from space surveillance systems can be used for these objects for the determination of the Ballistic Coefficient (BC), as explained in Section 6. Further information on the individual objects which is not directly physical in nature, e.g. ownership, is deliberately not reported on in this document.

The classification of whether a Payload is considered *active* is based on the data available at [11], which is used for data from 2019 onwards, and from the Union of Concerned Scientists (UCS) database [12], for earlier data since 2005. This classification by activity level is not used for the end-of-life analyses, where the activity of an object is instead estimated from space surveillance data.

1.3. Methodology

The first aim of this report is to describe the space environment based on observable facts. This takes the form of analysing trends in the various physical characteristics of the objects within the space environment, both covering the history since the beginning of the space age as well as a single year of analysis. The report focusses on the amount of mass, area, and object count passing through the different orbital regimes, with specific emphasis on the protected regions. Furthermore, the usage of the protected regions by payloads is documented.

Secondly, 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. The evolution of these metrics is described. Most internationally accepted space debris mitigation measures can be traced back to the following objectives:

- *The limitation of space debris released during normal operations;* i.e. in all operational orbit regimes, payloads and rocket bodies should be designed not to release space debris during normal operations. Where this is not feasible, any release of debris should be minimised in number, area and orbital lifetime.
- *The minimisation of the potential for on-orbit break-ups;* i.e. in all operational regimes one should minimise the potential for break-ups during operational phases, e.g. by thorough analysis of the failure trees, increase (sub)system reliability, etc., minimise the potential for post-mission break-ups resulting from stored energy, e.g. stored in tanks, batteries, flywheels, etc., and the avoidance of intentional destruction and other harmful activities, e.g. intentional break-ups should avoided at all cost but if need be they should be conducted at sufficiently low altitudes so that orbital fragments are short-lived.
- *Post mission disposal;* i.e. two protected regimes, Low Earth Orbit (LEO_{IADC}) and Geostationary Orbit (GEO_{IADC}), have been identified and should be cleared from permanent or (quasi-) periodic presence of non-functional artificial objects. Payloads or rocket bodies that are terminating their operational phases in other orbital regions should be manoeuvred to reduce their orbital lifetime, commensurate with LEO lifetime limitations, or relocated if they cause interference with highly utilised orbit regions.
- *Prevention of on-orbit collisions;* i.e. in developing the design and mission profile of a space object, a project should estimate and limit the probability of accidental collision with known objects during the payload or rocket body's orbital lifetime. If reliable orbital data is available, avoidance manoeuvres and co-ordination of launch windows may be considered if the collision risk is not considered negligible.

Even though the goals of the mitigation measures as identified above are intuitively clear, their technical implementation is less straightforward. The proposed metrics to observe adherence to these objectives are described in the corresponding sections and follow as close as possible [9]. In case of orbital lifetime predictions, the corresponding international standard is followed [13]. Details on the data gathered or methods used corresponding to results presented in the individual sections of in this report are covered in those sections.

Not all aspects of space debris mitigation can, currently, be reliably derived from observational data. For example a collision avoidance manoeuvre can look similar to an orbit control manoeuvre to maintain a specific ground-track. In the same way, the observed behaviour due to passivation of fluids at the end of life of a mission does not need to be different from the effects of an orbit control manoeuvre. The philosophy behind this document is to accept these limitations and not to risk over-interpreting the available data.

Thirdly, metrics are identified to estimate the impact of global space activities on the space environment. Historically, such metrics have often been formulated in terms of the outcomes of long-term, i.e. centuries, space environment evolution models that serve to extrapolate a set of space traffic condition into the future and derive the expected amount of space debris and collision events. As of recent, also the establishment of dedicated risk metrics for the purpose of impact assessments has become more commonplace. Both metrics are included in this report.

1.4. Notable changes

1.4.1. Edition 4

Significant changes have taken place when it comes to the usage of the space environment since the first issue of this report in 2016. As can be observed in Section 2, there has been a significant increase in the ability of space surveillance networks to reliably catalogue objects in orbits near the Geostationary Orbit, and launch traffic to Low Earth Orbit increased to previously unseen levels. With the improvements in capabilities of observation systems and the rapid miniaturisation and innovation for space system designs, it is likely that those developments will continue in the future.

As a consequence, also international documents dealing with space debris mitigation have been updated in 2019, with most notably the ISO space debris mitigation requirements [9] and the IADC space debris mitigation guidelines [14]. This is also reflected in the content of this report by means of some noticeable changes. Prior to edition 4, attempts to relocate Payloads above Low Earth Orbit were seen as a positive space debris mitigation effort, even though this was not endorsed by the IADC space debris mitigation guidelines. This is no longer the case. Furthermore, given the uncertainties associated with orbital lifetime predictions, the thresholds used to categorise Payload or Rocket Body as (non-)compliant w.r.t. space debris mitigation guidelines are now addressed stochastically for those cases near the threshold.

A major event visible in this edition of the report is the de-orbiting of a telecommunication constellation in Low Earth Orbit which started in 2018. Just as the insertion of this constellation is visible in the launch traffic increase, it now stands out as an increase in successful post mission de-orbiting when it comes to compliance to the guidelines. Furthermore, with the coming into operations of a newer generation of launchers, the release of mission related objects as part of their operations is going down. However, releasing large mission related objects altogether is unfortunately not a relic of the past (yet).

1.4.2. Edition 5

Starting with edition 5 of this report, an increased emphasis is put on the consequence of the global level of adherence to space debris mitigation guidelines. To capture these consequences in relation to the dynamic evolution of the actors in orbit and measures to achieve space debris mitigation, it became necessary to estimate automatically the average properties of objects and the orbital usage alike. Based on these properties, short-term consequences such as the risk of collision faced by operators in the LEO protected region as well as the long term risk of triggering the Kessler syndrome in the LEO protected region can be estimated.

Notable events visible in this edition of the report are the completion of the de-orbiting of a telecommunication constellation from Low Earth orbit in 2019 and the start of on-orbit deployment of two new ones during 2020. To a certain extent, 2020 marks the beginning of a new era in spaceflight with the maturation of large and medium-sized constellations being deployed on orbit and the availability on ground of the derived service, the increased use of so-called ride-share missions, and the continuation of miniaturisation of space system. This is in contrast with the period between the mid 1990'ies and ending mid 2010's, which saw the slow but steady roll-out and demonstration of the new technologies that are becoming commonplace today.

The start of solar cycle 25 marks a change for the regularly updated orbital lifetimes used in this report. The change in cycle behaviour has an impact on the estimated compliance rates as show in Fig. 6.34. In the uncertainty analysis, the values for the last year are affected by the low number of cases for Rocket Bodies due to the increased usage for controlled re-entry as disposal strategy. This is not an issue, as Payload data is accounted for with one year delay, and the uncertainties have generally a limited impact in this case.

1.4.3. Edition 6

The space environment continued to change rapidly in 2021 with the accelerated deployment of large constellations in LEO_{IADC}, increasing demand for the deployment of small Payloads, but reduction of launch traffic to GEO_{IADC}. For the first time, launching more than one payload per launch has become the most common way of getting into orbit. To put this into perspective, the analyses introduced in Edition 5 of this report were extended to cover different epochs from the recent space age, i.e. addressing how collision avoidance risk has evolved (Fig. 3.12) and what would be the outcome of extrapolating various long-term evolution scenarios (Fig. 7.5-7.6). The combination of changing launch traffic patterns in general, and the dichotomy between constellation-related objects and other intact objects specifically, has a noticeable impact on both short and long-term risk indicators.

With the increased awareness of space sustainability in the community at large, a new emphasis is placed on space debris mitigation aspects that were previously less noticeable or are gaining in prominence. As such, new analyses have been added to this version of the report to highlight the risks posed by Rocket Bodies crossing the GEO_{IADC} Protected Region (Fig. 6.38), show the variability in disposal orbit strategies in the MEO region (Fig. 6.39), and focus on the space surveillance issues associated with the release of large amounts of Payloads by various services (Fig. 2.21). In addition, a review of the United Nation Register of Objects Launched into Outer Space is added to show the diversification of space actors (Section 2.11).

1.4.4. Edition 7

The accelerated use of space over the last years continued unabated in 2022, leading to launch and re-entry traffic rates to see new records and challenges in keeping accurate track of the state of the environment. The metrics presented in this report were further refined to give an overview of the impacts on space debris mitigation aspects, and to prepare for the trend in calling for stricter guidelines. Notably, forecasting methodologies have been updated and a greater emphasis on understanding the space debris environment at smaller length scales has been introduced. Furthermore, it is worth mentioning that the observed spike in 2022 concerning re-entering space debris is due to the Kosmos 1408 anti-satellite missile test.

1.4.5. Edition 8

In 2023, the space environment continued to experience substantial growth, with launch traffic once again reaching record levels. In LEO_{IADC}, large constellations, which have outpaced other payloads not only in number but also mass and area, now drive many of the global statistics. While this is leading to increased congestion and challenges for space traffic coordination in certain orbits, it is also accompanied by an increased usage of controlled re-entry as a disposal strategy for rocket bodies and new levels of compliance with space debris mitigation guidelines.

In this edition of the report, methodologies for modelling the future evolution of the space environment have been further refined, specifically for forecasting the growing contribution from constellations, leading to new and updated results for the analysed years 2022 and 2023. It should be noted that current levels of compliance still result in an unsustainable environment in the long-term. Consequently, there is a growing trend advocating for stricter guidelines, with new measures introduced in 2023 as a part of ESA's Zero Debris Policy and updated Space Debris Mitigation Standard [3]. These developments imply that notable changes may be anticipated in the next edition of this report in terms of methodologies and assessed thresholds, reflecting ongoing efforts to address the challenges of space sustainability.

1.4.6. Edition 9

While the exponential growth in the number of new payloads slowed in 2024, the number of launches continued to rise, setting new records for both the mass and size of objects sent into Low Earth Orbit. With new launches targeting lower altitudes, high levels of solar activity, and an increasing (but insufficient) rate of willingness to limit orbital lifetime, this trend is reflected in re-entries, with new records also in the mass and size of re-entering objects. However, fragmentation events remain a persistent issue, continuing to pollute the space environment. Related to this, 2024 saw an increase in the number of space objects with unidentified object class (Figures 2.1, 2.32). It can be seen from Figures 2.6 and 2.33 that these mostly affect the GEO regime, and are likely associated to fragmentation events that occurred in the vicinity of this region (Table 3.7). Further work to correlate unidentified objects to these events may see a reduction in this object class in future editions as they are assigned to known object classes (such as Payload or Rocket Fragmentation Debris).

This edition of the report contains three main updates. The first, is the release of the MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) 2024 population, which reveals that the density of active payloads is approaching that of space debris in heavily populated altitude bands for the first time. Secondly, 2024 marks the first full year for which the ESA Space Debris Mitigation Standard [3] became applicable to ESA projects. As such, new analyses have been added to this version of the report to highlight global compliance to the 5-year post-mission lifetime limit, in addition to the 25-year limit used in previous editions. This change required the methodology for calculating the orbital lifetimes to be updated to account for solar activity variation, with the lifetime now calculated probabilistically over a full 11-year solar cycle to ensure robust compliance assessment. The difference in compliance between these two thresholds can be seen to be on the order of 10%, indicating that global adherence to stricter guidelines is attainable for ensuring the long-term sustainability of space activities. Finally, a target environment, or *orbital sustainability threshold*, was introduced to facilitate a transparent evaluation of global steps towards space sustainability. Extrapolating current trends, the level of risk of fragmentation and collision associated with the space environment (encapsulated in a single environment index) is predicted to be 4 times higher than this acceptable threshold for long-term sustainability.

1.5. Acknowledgements

The authors take the opportunity to thank the team at the European Space Agency's Space Debris Office for providing technical support and all data quality work, in particular Álvaro Arroyo Parejo. Furthermore, we thank the international space debris community at large for the received comments and suggestions for improvements.

1.6. Disclaimer

The analysis presented in this document is derived from a continuously evolving database. Mistakes can unavoidably happen during the preparation process and we are thus ready to take feedback. If you detect any error or if you have any comment or question please contact:

Emma Stevenson
European Space Agency
Space Debris Office (OPS-SD)
Keplerlaan 1
2201 AZ Noordwijk, Netherlands
emma.stevenson@esa.int

Francesca Letizia
European Space Agency
Independent Safety Office (TEC-QI)
Keplerlaan 1
2201 AZ Noordwijk, Netherlands
francesca.letizia@esa.int

Stijn Lemmens
European Space Agency
Space Debris Office (OPS-SD)
Keplerlaan 1
2201 AZ Noordwijk, Netherlands
stijn.lemmens@esa.int

2. SPACE ENVIRONMENTAL HISTORY IN NUMBERS

This section reports on the evolution of the space environment since the beginning of the space age. The evolution of catalogued objects in orbit is graphically represented for count, mass, and area. This data is further subdivided based on object and orbit classification. A catalogued object is only taken into account for a given year if it appeared in a space surveillance system during that year. This implies that reported evolutions do scale with the quality of the space surveillance systems at a given epoch. In case of the evolution of payloads and rocket bodies the reported numbers are close to values one would obtain when only considering asserted objects. In all other object classifications the amount of catalogued objects are almost certainly an underestimation and hence lower limit for the true space environment.

Concerning the LEO and GEO protected regions, the absolute and equivalent number of objects, mass, and area interfering with these regions are graphically represented. To obtain the equivalent object penetrating the protected regions, the physical property of the absolute object, i.e. count, mass, and area, is multiplied with an equivalence factor. This factor is computed as the ratio of the time spent in the protected region per orbit to the orbital period for each orbit. This indicates per orbital class how many objects are interfering with the protected regions without being permanently present. Even though the LEO and GEO regions are defined as protected regions as a whole, most of the traffic takes place in narrow bands.

The evolution of the catalogued and asserted objects appearing in or re-entering the Earth atmosphere from the space environment is graphically represented for count, mass, and area. This data is further subdivided based on object and orbit classification. In case of incomplete orbital data, the orbit classification may be affected. This is the case, for example, of a group of objects for which the last available orbital data is such to classify them as MEO, but the re-entry epochs are several months later. Objects that are both asserted and catalogued are only counted once for a given year. In case of minor inconsistencies between the asserted and catalogued object information for the same object, the 'N/A' tag is applied. Objects associated with human spaceflight include crew vehicles or parts thereof as well as payloads dedicated to cargo transfer, but not the rocket bodies associated to these missions. For the vast majority of cases, there is no reliable mass or area estimate for objects in the Debris or Unidentified categories and hence they are equated to 0.

In all figures within Sections 2.1, 2.2, and 2.3, the environment parameters are presented as they are at the 1st of January of the indicated year. In all figures within Sections 2.5, 2.8, and 2.9, the environment parameters are presented as aggregated data within the indicated year. All data used to generate the analysis in this section is available online [10].