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ESA'S ANNUAL SPACE ENVIRONMENT REPORT

Prepared by	ESA Space Debris Office
Document Type	LOG
Reference	GEN-DB-LOG-00288-OPS-SD
Issue/Revision	7.1
Date of Issue	12 September 2023
Status	Final

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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 subset 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 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 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 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 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**. In 2022, the launch traffic in all mass and type classes overtook historical rates not seen since the nineteen-eighties. 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].

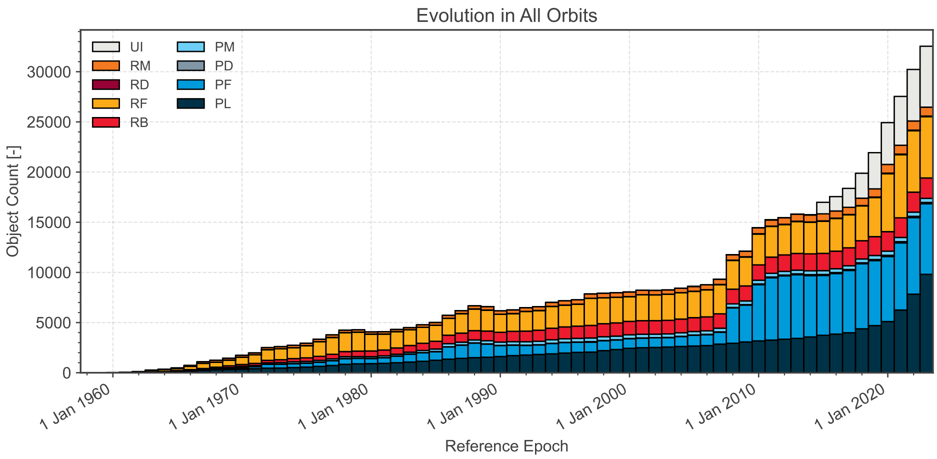


Figure 1: Evolution of number of objects in geocentric orbit by object class. Please consult Section 1.1 for the definitions.

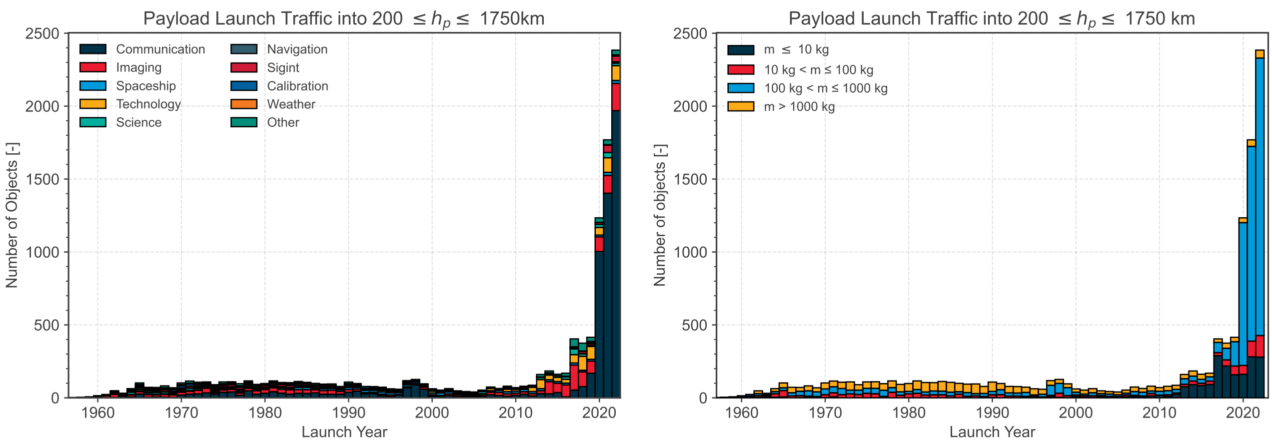


Figure 2: Evolution of the launch traffic near LEO_{IADC} per mission type (left) and mass category (right).

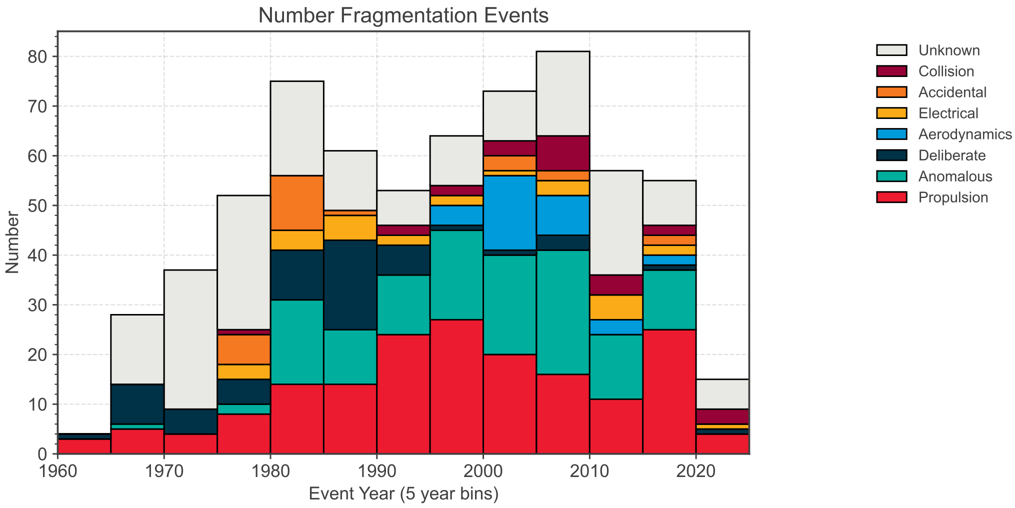


Figure 3: Historical trend of fragmentation events per event cause. The last bin covers until the year 2022.

On average over the last two decades, **11.2 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 **2.5** 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 re-use of a design 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. The increase in launch traffic and permanence of space debris events in Low Earth orbit leads **a significant conjunction risk** in the most congested Earth orbits. Detailed information is given in Section 3.5.

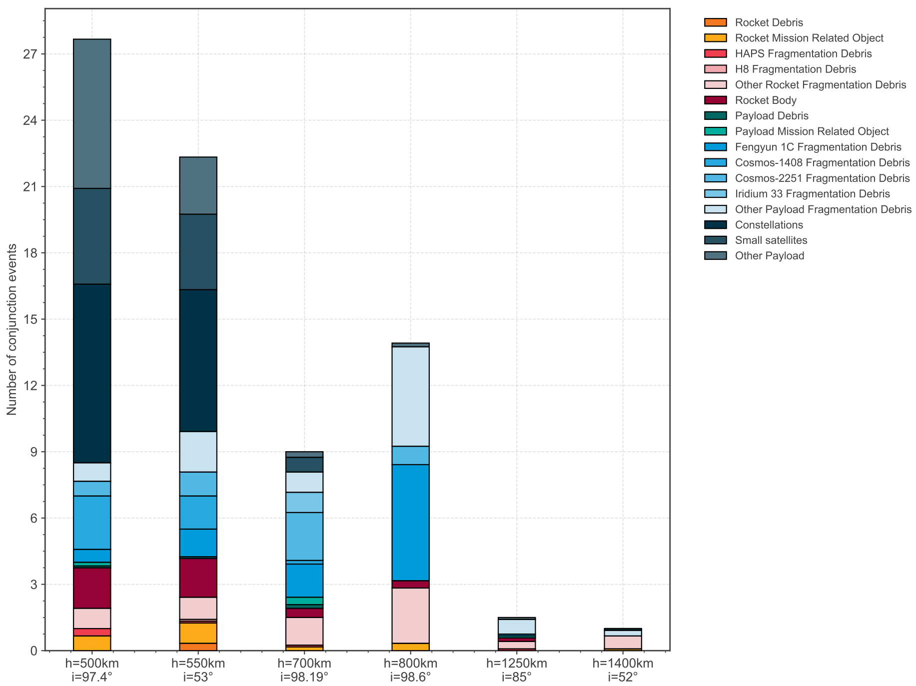


Figure 4: Conjunction events (i.e. events that could trigger an operator response but not necessarily an avoidance manoeuvre nor a collision) and corresponding chaser classification for a set of representative missions over 2022.

Around **93% of small payloads**, i.e. below 10.0 kg in mass, reaching the end of their mission during the last decade and injected into the LEO protected region operate in orbits that **naturally adhere to the space debris mitigation measures**. While this is a large fraction compared to higher mass categories, it still implies a growing contingent of small payloads in need of active means to dispose themselves from the LEO protected region. The **majority of larger payloads reaching the end of their mission** since 2010 did so in orbits where they **did not successfully remove themselves** from.

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 **space debris mitigation measures**, as shown in Fig. 6.4. 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 **85%** of all **rocket body mass** reaching end-of-life during the last decade does so in orbits that are estimated to **adhere** to the **space debris mitigation measures** on protecting **LEO** as shown in 6.6. A significant amount of this is due to **controlled re-entries** after launch, a practice which increased from 10% to over **40%** over the last decade.

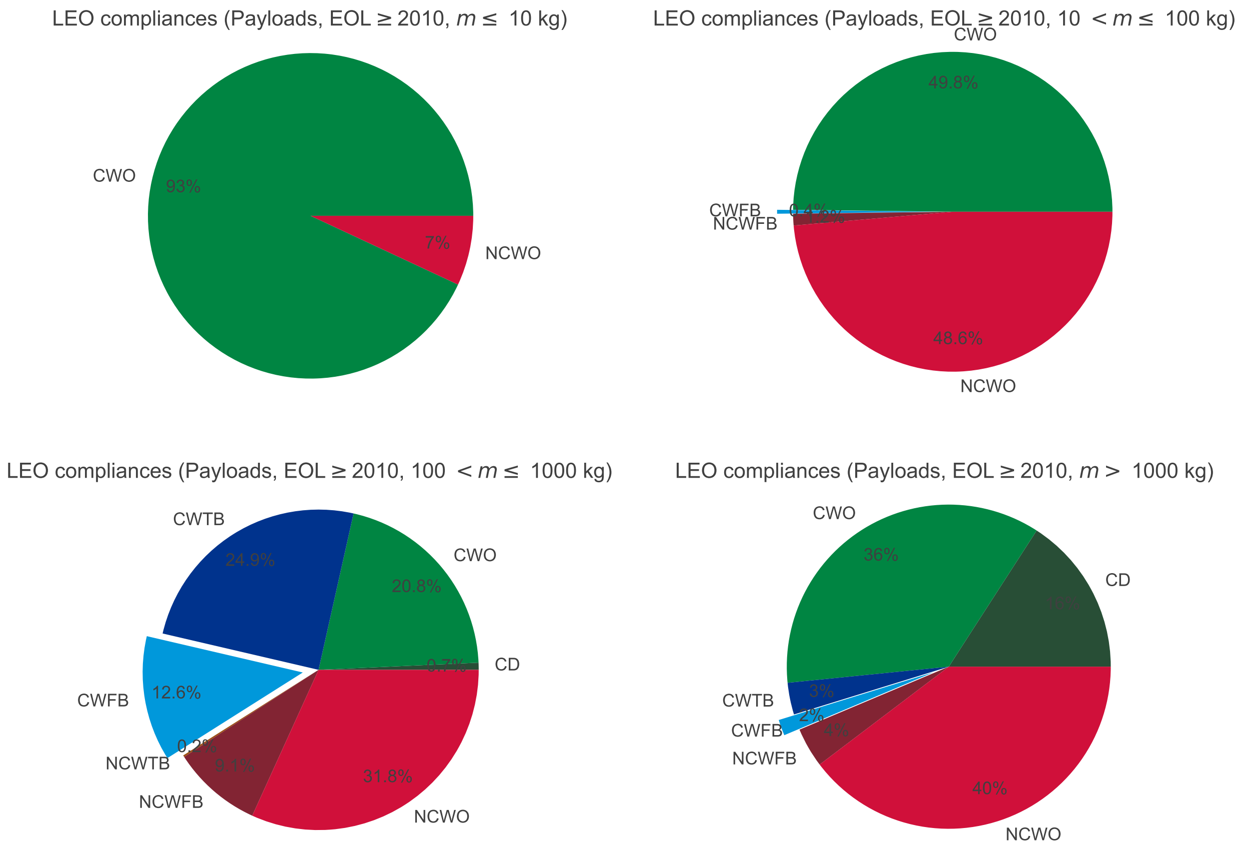
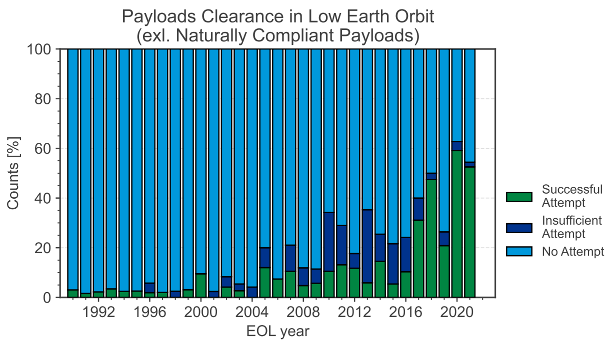
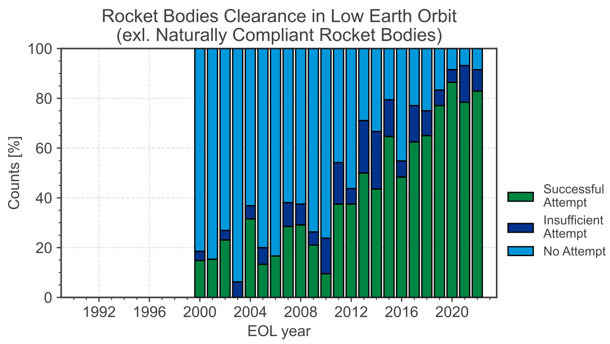


Figure 5: Breakdown of the 2010 decade of observed behavioural classes for payloads per mass category. Please consult Section 6.1 for the definitions.

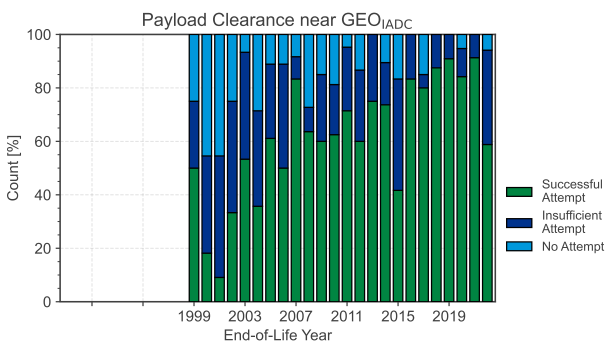
One of the core principles of the space debris mitigation guidelines is to remove objects from the LEO and GEO protected regions with a high success rate for those orbits where a natural disposal mechanism is absent [2]. In practice, a common target for this success rate set at 90% based on space traffic condition corresponding to first decade of the millennium and with as goal to slow down the rate of space debris creation. It is thus a valuable first step towards space sustainability, but will by itself no reduce the amount of debris in orbit, and will need to increase to near 100% in the near future. Between **20** and **50%** 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 space debris mitigation measures, with peaks in 2018 and 2020 respectively due to the de-orbiting of a constellation and a low amount of satellite reaching end of life in a non-compliant orbit. The difference in behaviour between constellation and non-constellation objects can be significant as shown in Fig. 6.3. Between **5%** and **40%**, again with peaks in 2018 and 2020 for the same reasons as before, do so **successfully** and a slight rising trend is noticeable. Between **40** and **90%** 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 space debris mitigation measures. Between **30%** and **80%** do so **successfully**, with the compliance trend linearly increasing. Between **40%** and **50%** of the **rocket bodies delivering payloads in or near the GEO protected region** during the last decade **are in compliance with space debris mitigation measures**. 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 **60%** and **90%** do so **successfully**, with the compliance trend asymptotically increasing, but some exceptions like 2015 and 2022.



(a) Relative clearance of LEO_{IADC} by payloads.



(b) Relative clearance of LEO_{IADC} by rocket bodies.



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

Figure 6: Trend of adherence to clearance of the protected region over time in terms of numbers, excluding naturally compliant objects.

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 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 constellations**. Other effects, such as a shift in usage of operational mission orbits in Low Earth Orbit as show in Fig. 2.20, are however independent of the category of the payload.

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

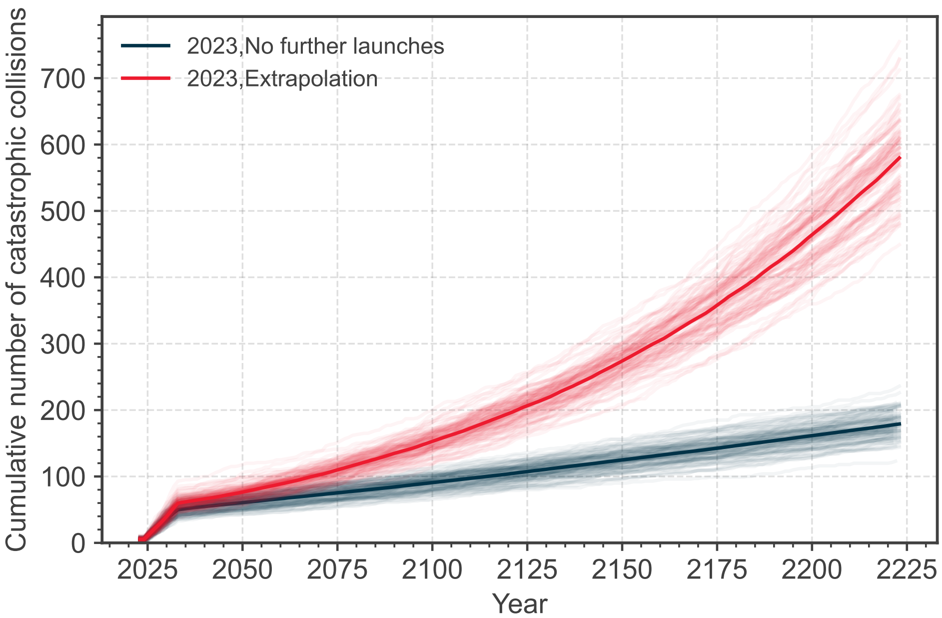


Figure 7: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

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 [3]. 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 [4] 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* [5] 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) [6].

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 [5].

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 21 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) [7]. 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 [8], which is used for data from 2019 onwards, and from the Union of Concerned Scientists (UCS) database [9], 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 man-made 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 [6]. In case of orbital lifetime predictions, the corresponding international standard is followed [10]. 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 [6] and the IADC space debris mitigation guidelines [2]. 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. 6.17. 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. 6.21), show the variability in disposal orbit strategies in the MEO region (Fig. 6.22), and focus on the space surveillance issues associated with the release of large amounts of Payloads by various services (Fig. 2.17). 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.

1.5. 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. 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:

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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.

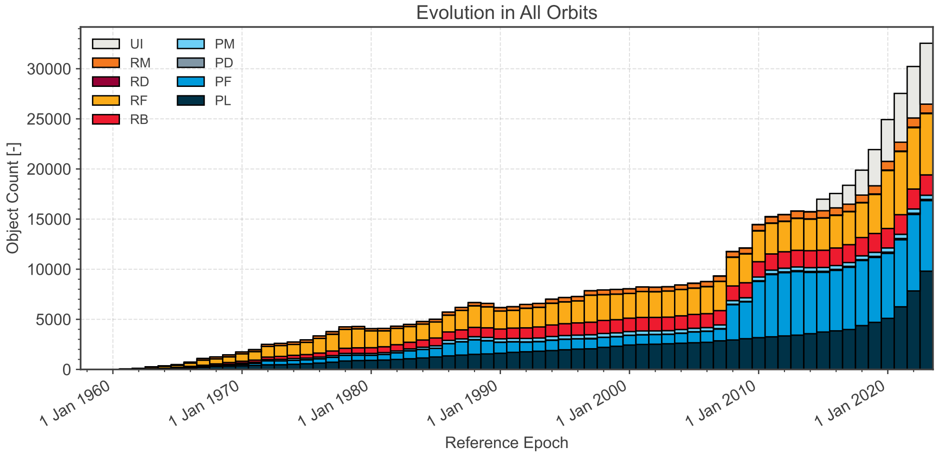
Concerning the LEO and GEO protected regions, the absolute and equivalent number of objects, mass, and area interfering with these regions are graphically represented. To obtain the equivalent object penetrating the protected regions, the physical property of the absolute object, i.e. count, mass, and 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.

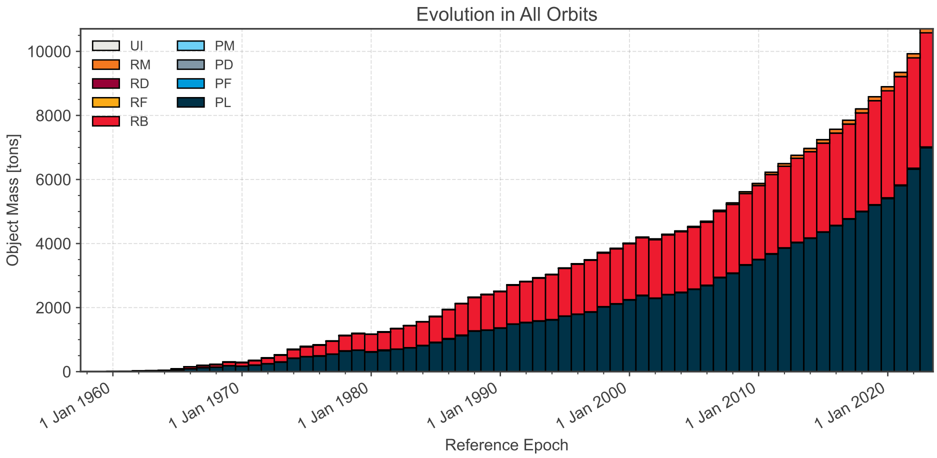
In all figures within Sections 2.1, 2.2, and 2.3, the environment parameters are presented as they are at the 1th of January of the indicated year. In all figures within Sections 2.5, 2.8, and 2.9, the environment parameters are presented as aggregated data within the indicated year. All data used to generate the analysis in this section is available online [7].

2.1. Overall Space Environment

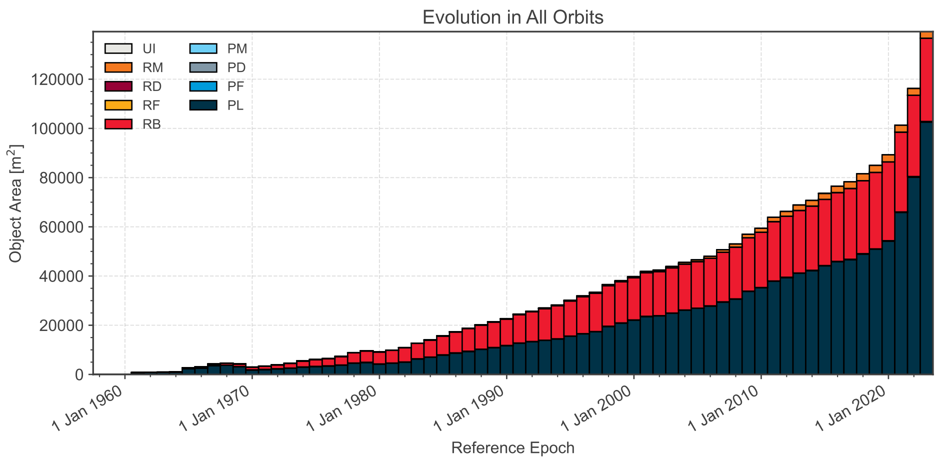
Figure 2.1 captures the evolution of the space environment in terms of number of objects, mass, and area in geocentric orbit by object class. This data is limited to catalogued and asserted objects, and hence at any given epoch limited to the capability of the space surveillance system in use at the time. A secondary effect hereof is that when new objects are detected due to increased sensor performance, they can generally not be traced back to an event or source and become classified as Unidentified. In Figures 2.2 the same data is presented by orbit class instead of object class. In Figures 2.3 the same data is presented in relation to the cumulative values for those properties in case they would not have been removed from orbit.



(a) Evolution of number of objects.

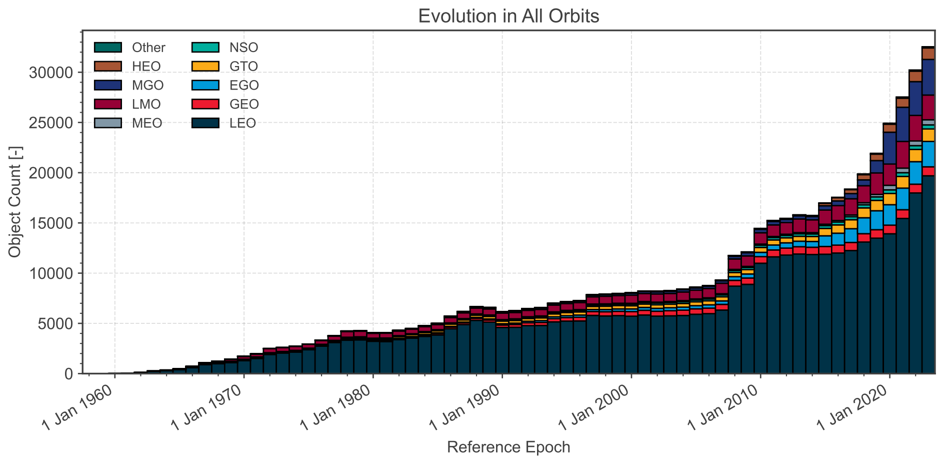


(b) Evolution of mass.

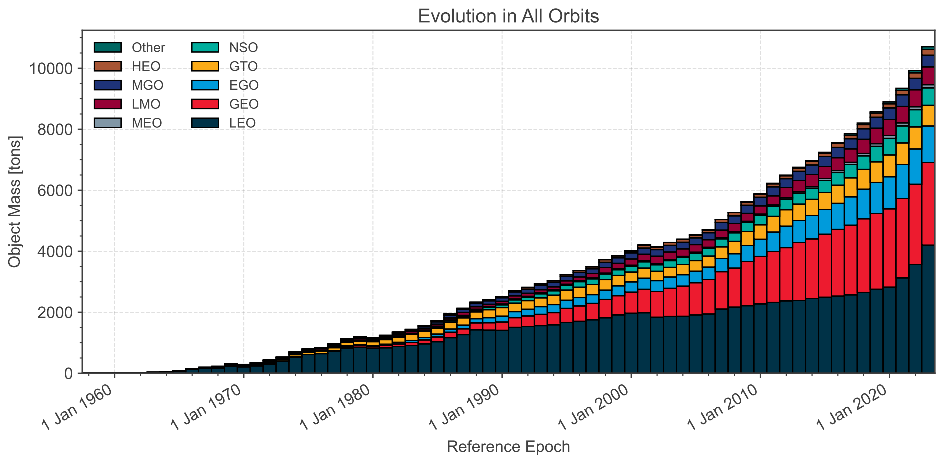


(c) Evolution of area.

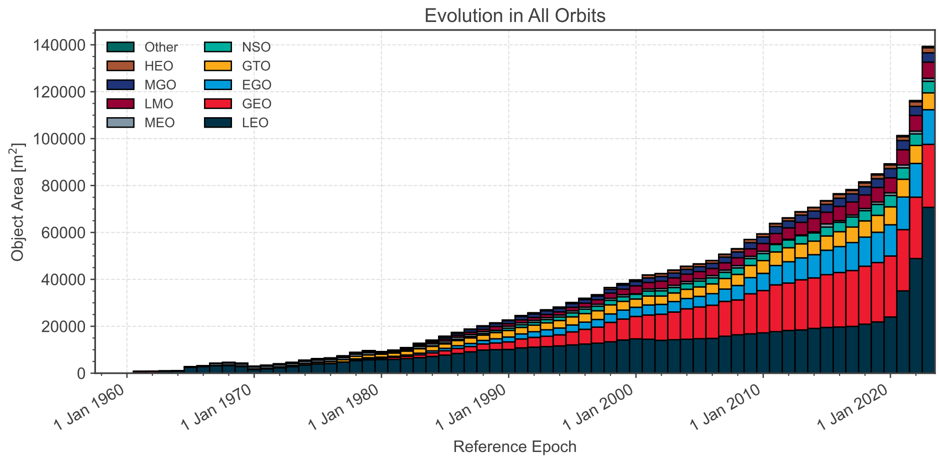
Figure 2.1: Evolution of number of objects, mass, and area in geocentric orbit by object class.



(a) Evolution of number of objects.

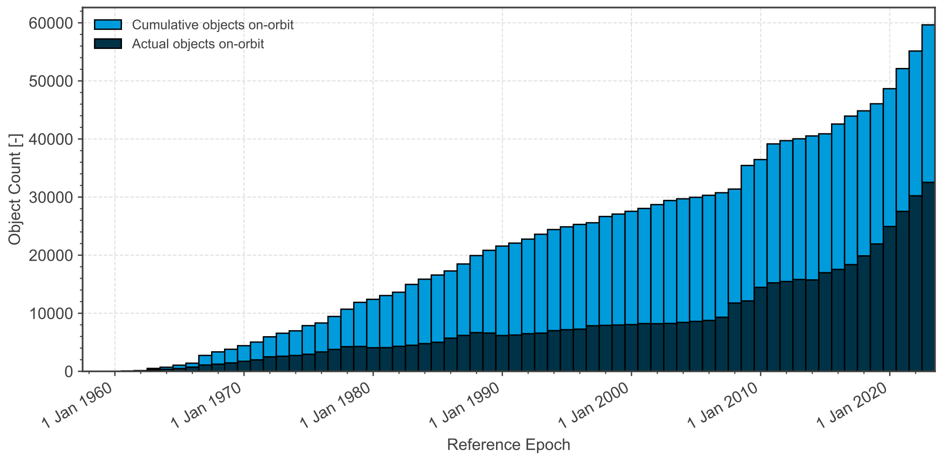


(b) Evolution of mass.

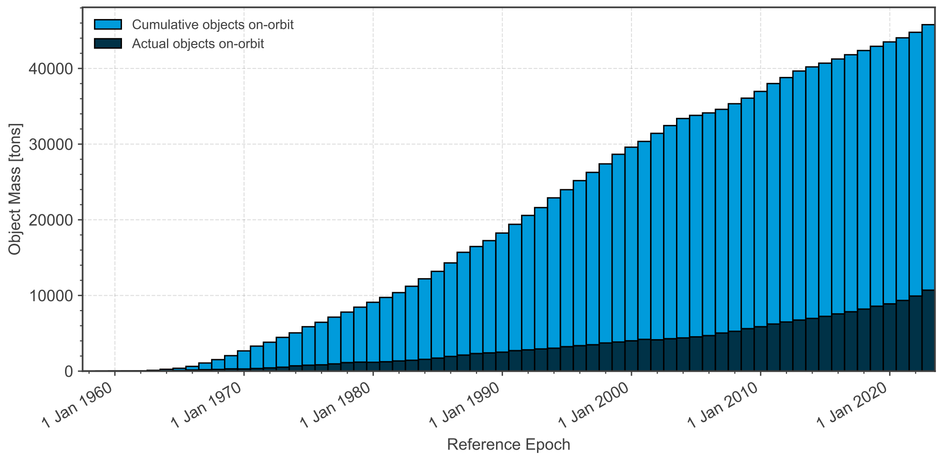


(c) Evolution of area.

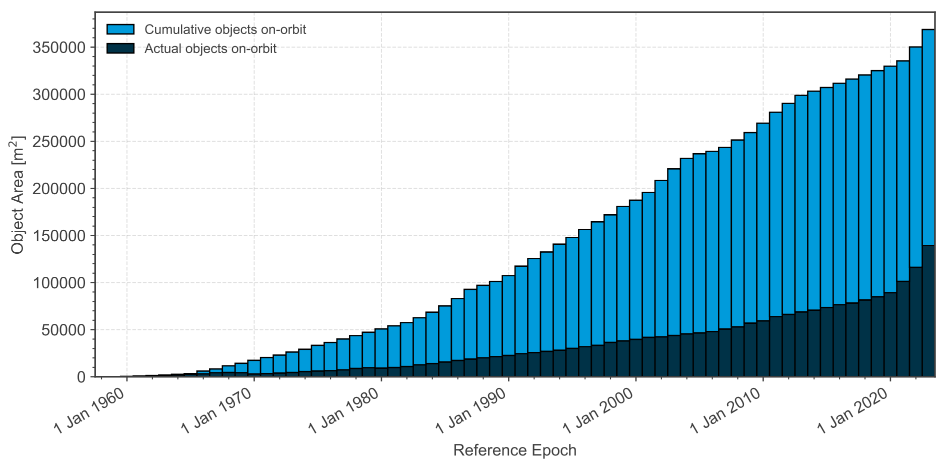
Figure 2.2: Evolution of number of objects, mass, and area in geocentric orbit by orbit class.



(a) Evolution of number of objects.



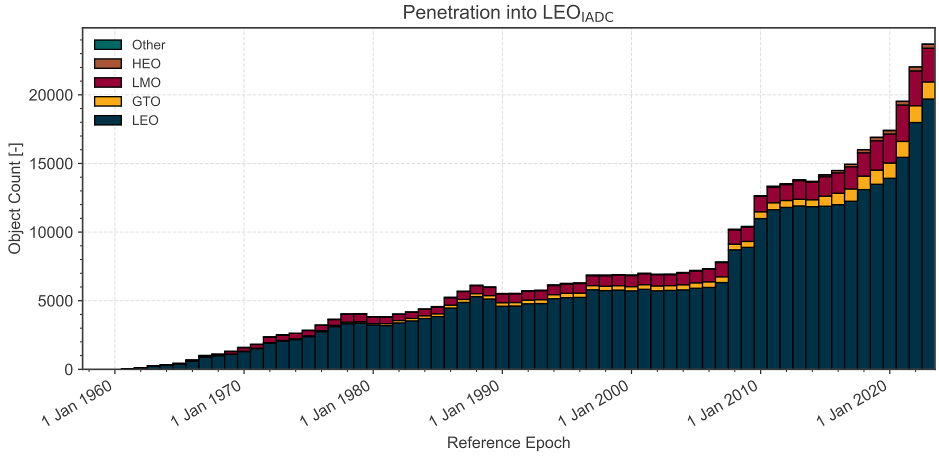
(b) Evolution of mass.



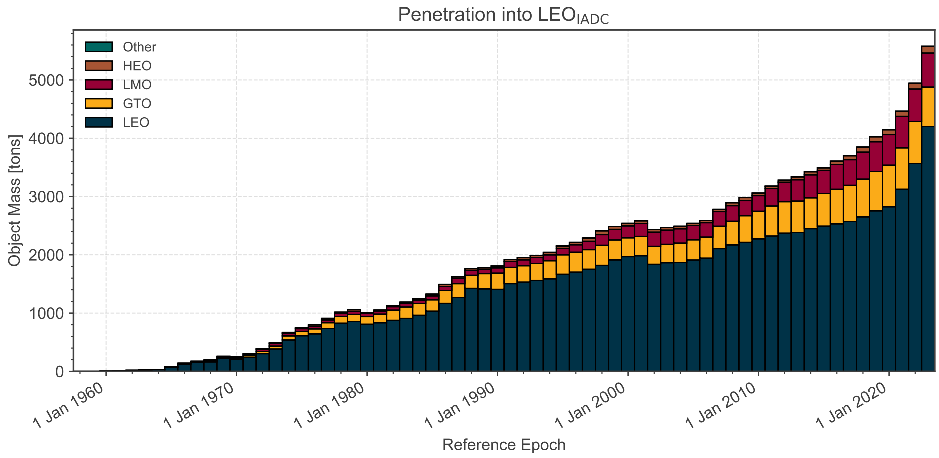
(c) Evolution of area.

Figure 2.3: Evolution of number of orbiting objects, mass, and area in geocentric orbit versus total number of objects.

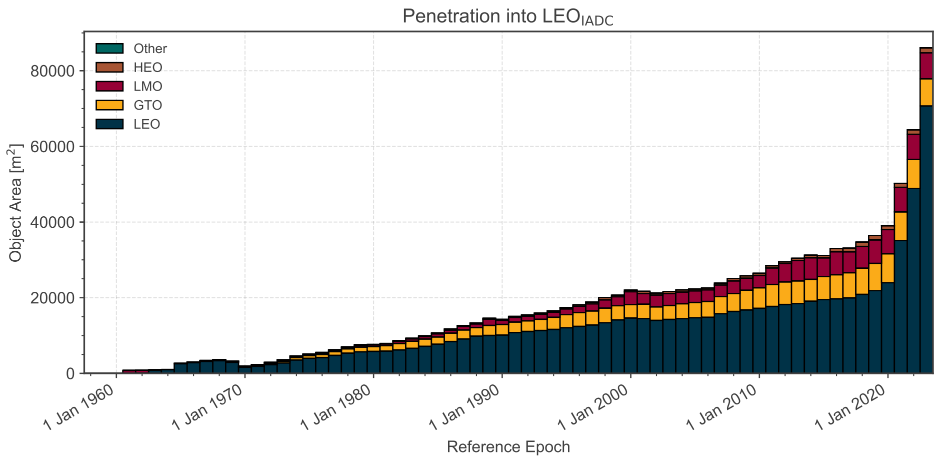
2.2. Evolution of Environment in LEO



(a) Evolution of absolute number of objects.

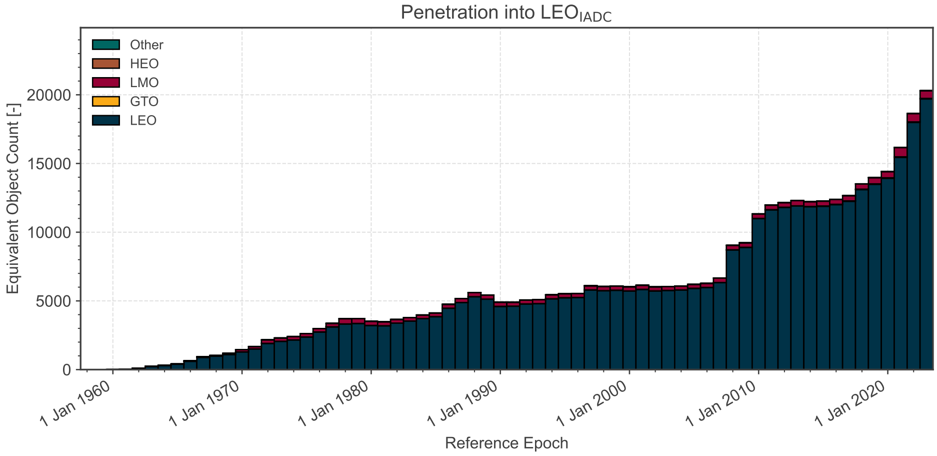


(b) Evolution of absolute mass.

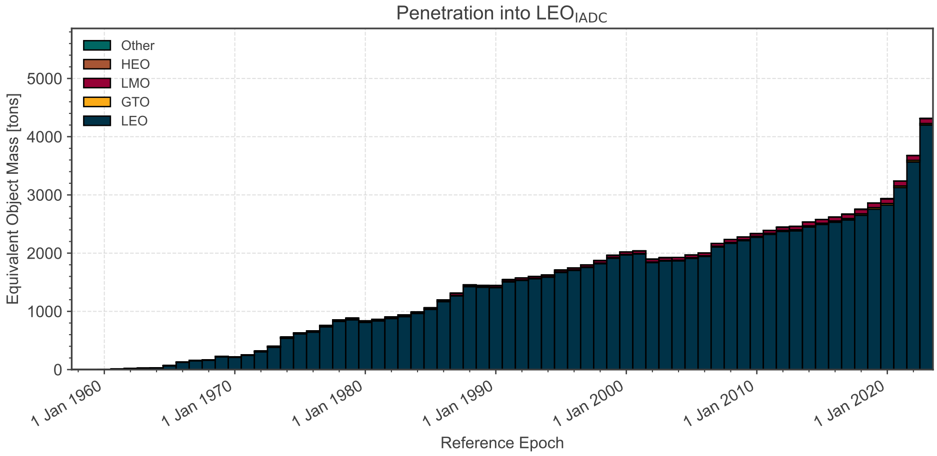


(c) Evolution of absolute area.

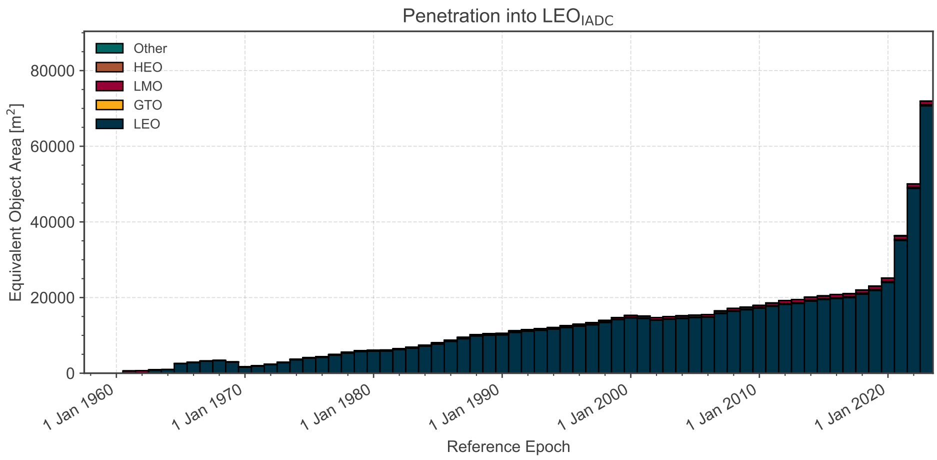
Figure 2.4: Evolution of absolute number of objects, mass and area residing in or penetrating LEO_{IADC}.



(a) Evolution of equivalent number of objects.



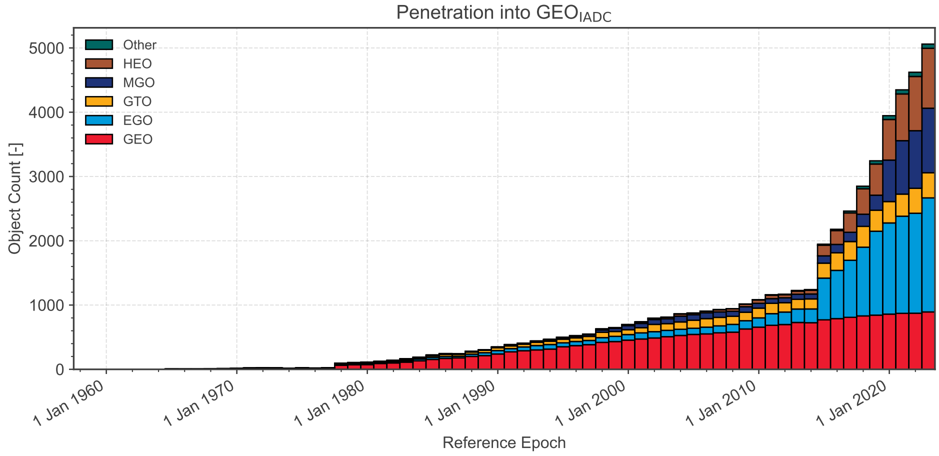
(b) Evolution of equivalent mass.



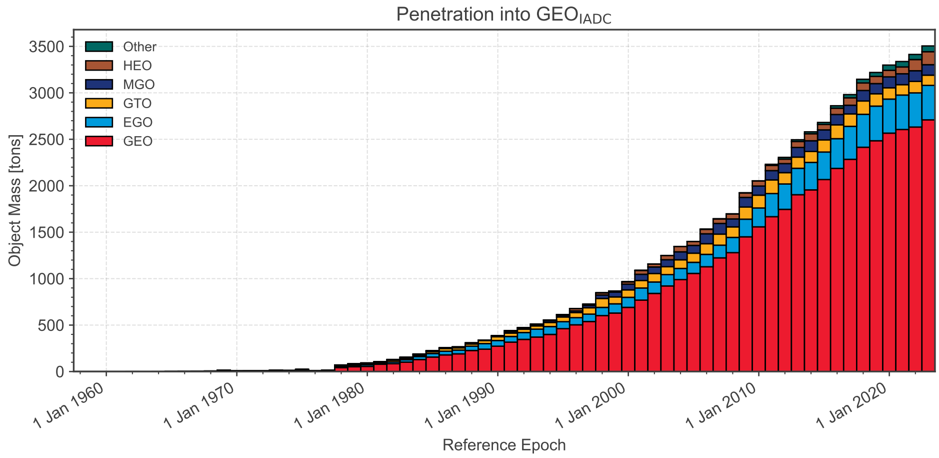
(c) Evolution of equivalent area.

Figure 2.5: Evolution of equivalent number of objects, mass and area residing in or penetrating LEO$_{IADC}$.

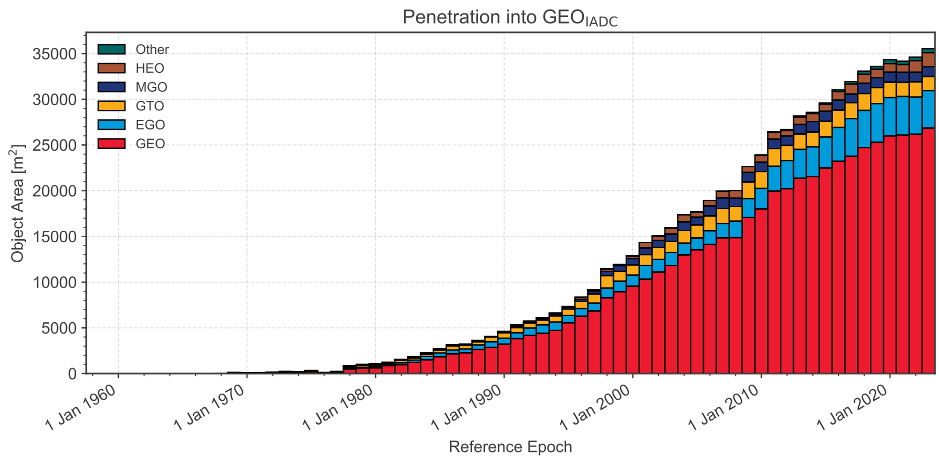
2.3. Evolution of Environment in GEO



(a) Evolution of absolute number of objects.

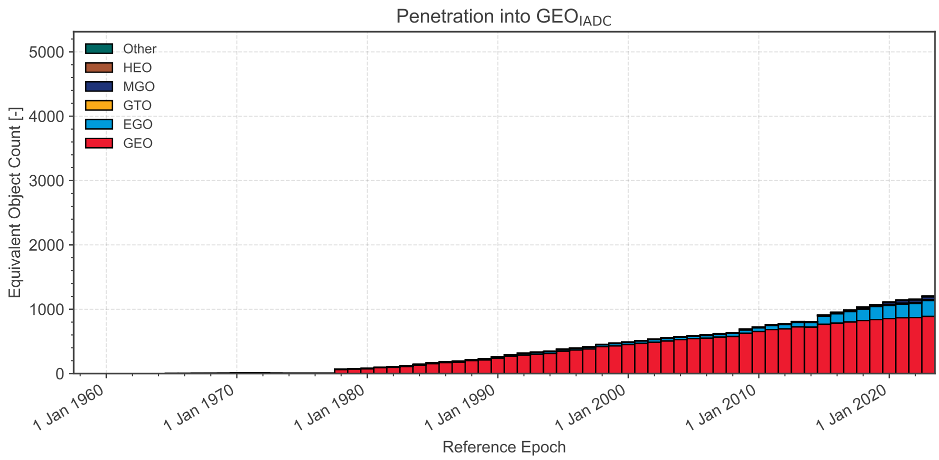


(b) Evolution of absolute mass.

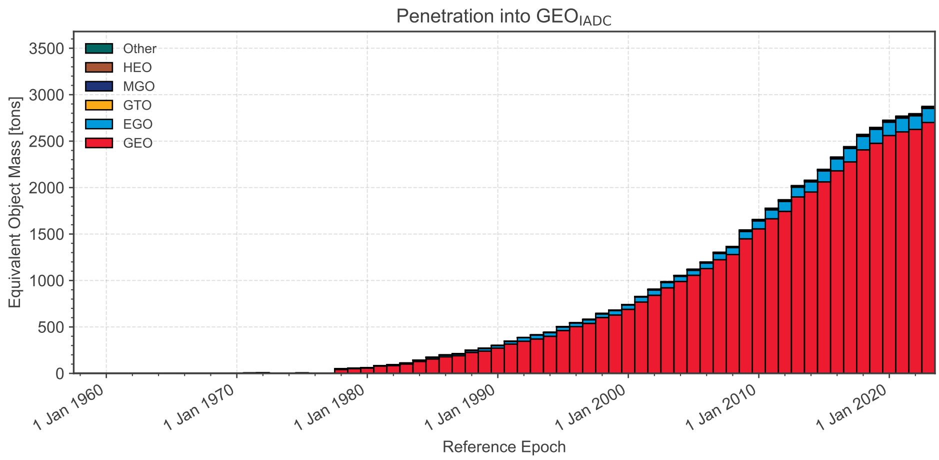


(c) Evolution of absolute area.

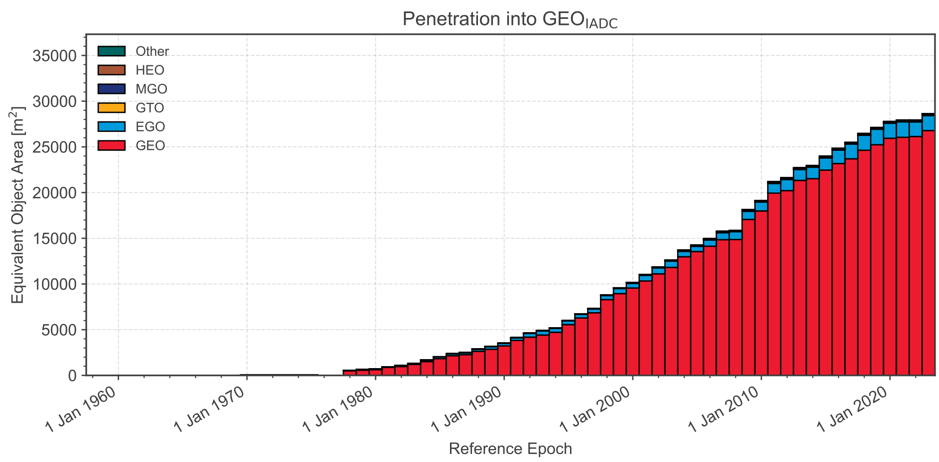
Figure 2.6: Evolution of absolute number of objects, mass and area residing in or penetrating GEO$_{IADC}$.



(a) Evolution of equivalent number of objects.



(b) Evolution of equivalent mass.



(c) Evolution of equivalent area.

Figure 2.7: Evolution of equivalent number of objects, mass and area residing in or penetrating GEO$_{IADC}$.

2.4. Non-catalogued and modelled objects

According to ESA's space debris environment model MASTER, at the reference epoch November 1st 2016, the estimated number of debris objects in orbit in the different size ranges is the following:

- 34.000 objects greater than 10 cm,
- 900.000 objects from 1 cm to 10 cm,
- 128 million objects from 1 mm to 1 cm.

The distribution of the number of objects as a function of their size is shown in Fig. 2.8: the plot shows the number of objects larger than the threshold size indicated in x-axis, considering space debris objects in all Earth orbits. Fig. 2.9 shows the density profiles with altitude corresponding to different minimum debris sizes (respectively 10 cm in dark blue and 1 cm in red), considering only the LEO region. The logarithmic scale is used in the y-axis to take into account the different orders of magnitude corresponding to the two populations.

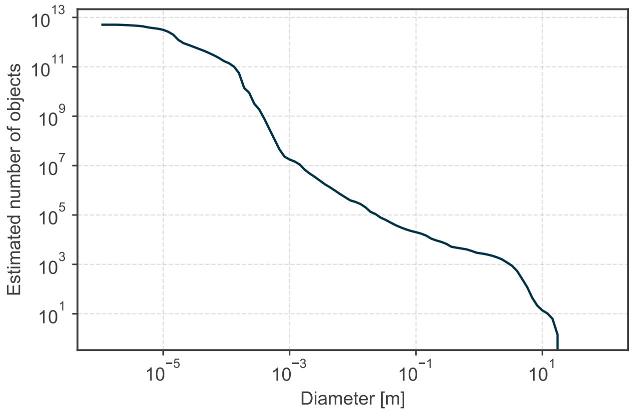


Figure 2.8: Estimated number of space debris objects as function of the object size in Earth orbit.

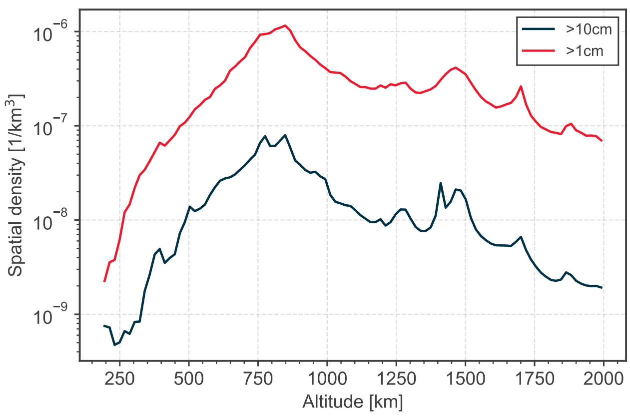


Figure 2.9: Density profiles in LEO for different space debris size ranges.

2.5. Usage of the Protected Regions

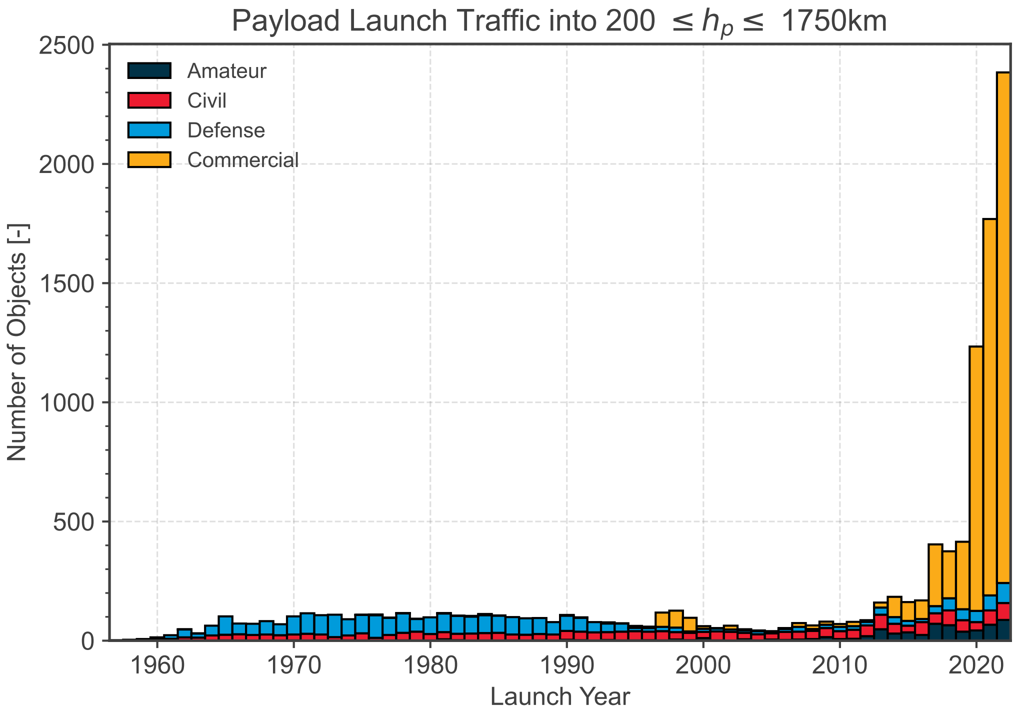
This section aims to provide an overview of the usage of the protected regions in terms of launch traffic as represented by object count and mass, given that the stability of the space environment is dependent on them.

From a historical point of view, the launch traffic of Payloads can be categorised in terms of the main funding source (Civil, Defence, Commercial, Amateur) or in terms of the main missions type (Communication, Imaging, Navigation, etc.). The Amateur category includes those Payloads associated by academic institutions when none of the other entities are the driving contributor. Payloads that are deployed from the International Space Station (ISS) are identified with a separate label as part of the launch traffic.

In case of Rocket Bodies, it is of importance which launcher family is generating the traffic to orbit, given that the adherence level to space debris mitigation guidelines correlates with this family identifier. These families are to be understood as major stable design versions of a launcher, e.g. covering performance improvements but not engine changes. New families can appear sporadically and in this report the most recent ones are identified. Earlier families of launchers are grouped under *Used earlier*.

Of increasing importance in a changing space traffic landscape are also the so-called *ride-share* launch opportunities, where a single launch vehicle carries a multitude of Payloads from different entities into orbit. For the purpose of this report, ride-share launches are defined as those launches that carry Payloads with at least three different mission domains and at least ten Payloads in total. A *mission domain* is defined by the combination of mission type, funding, and operator.

For Payload objects in LEO_{IADC}, it is instructive to analyse not only where they reside now, but also how the destination orbits that enable their operations evolve over time. In particular, as space debris mitigation measures focus on limiting orbital lifetimes, adoption of these practice leaves a noticeable imprint on the data. This imprint can distinctively visible as a function of the mission domain, in particular when distinguishing between constellation and non constellation objects.



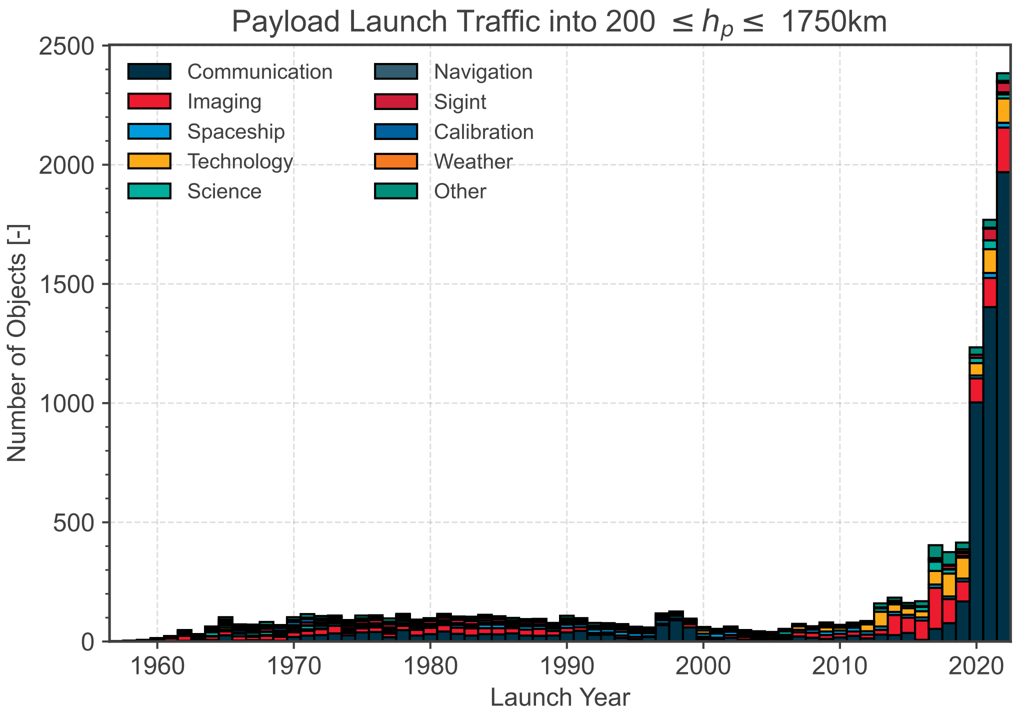


Figure 2.10: Evolution of the launch traffic near LEO_{IADC} per mission funding (top) and type (bottom).

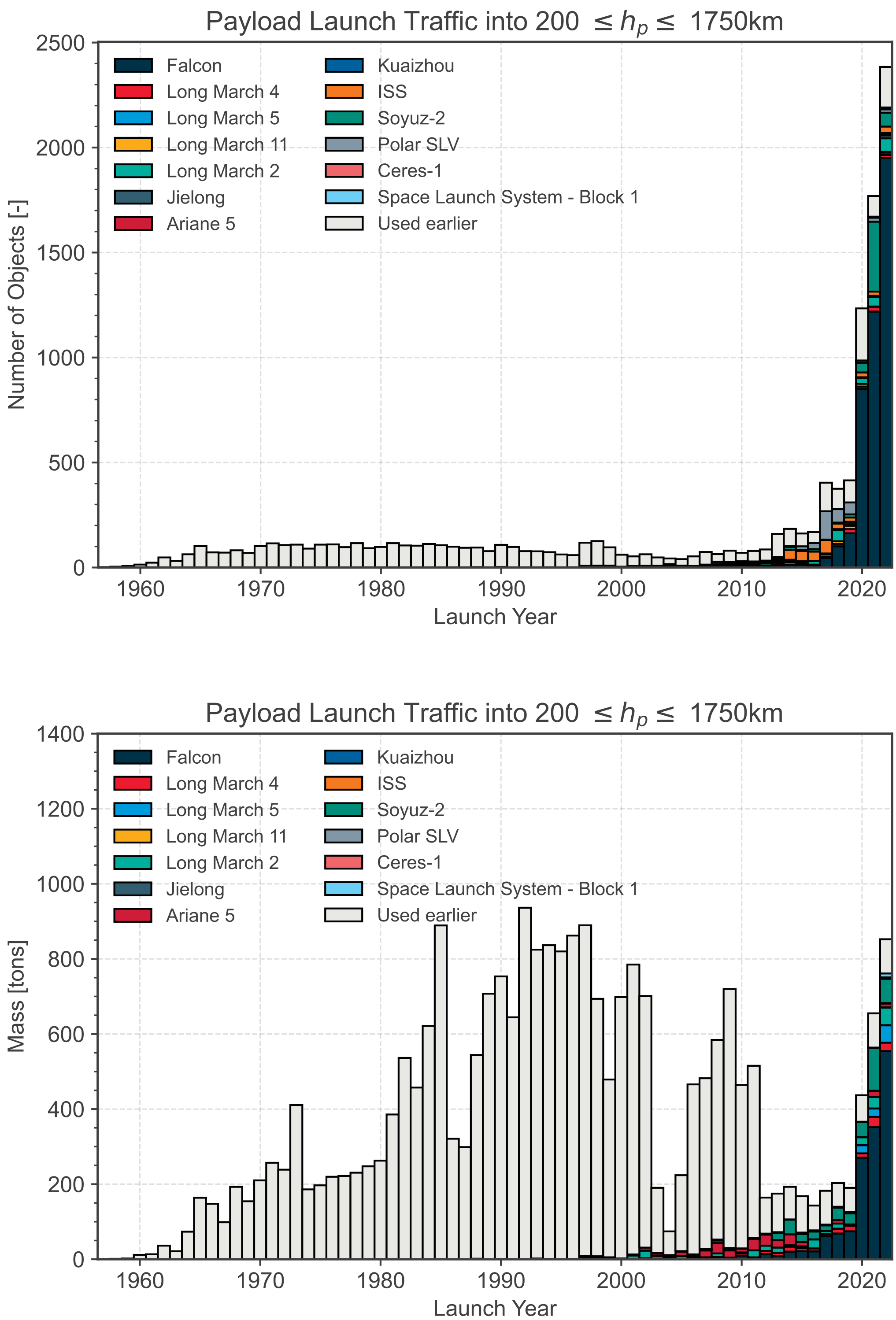
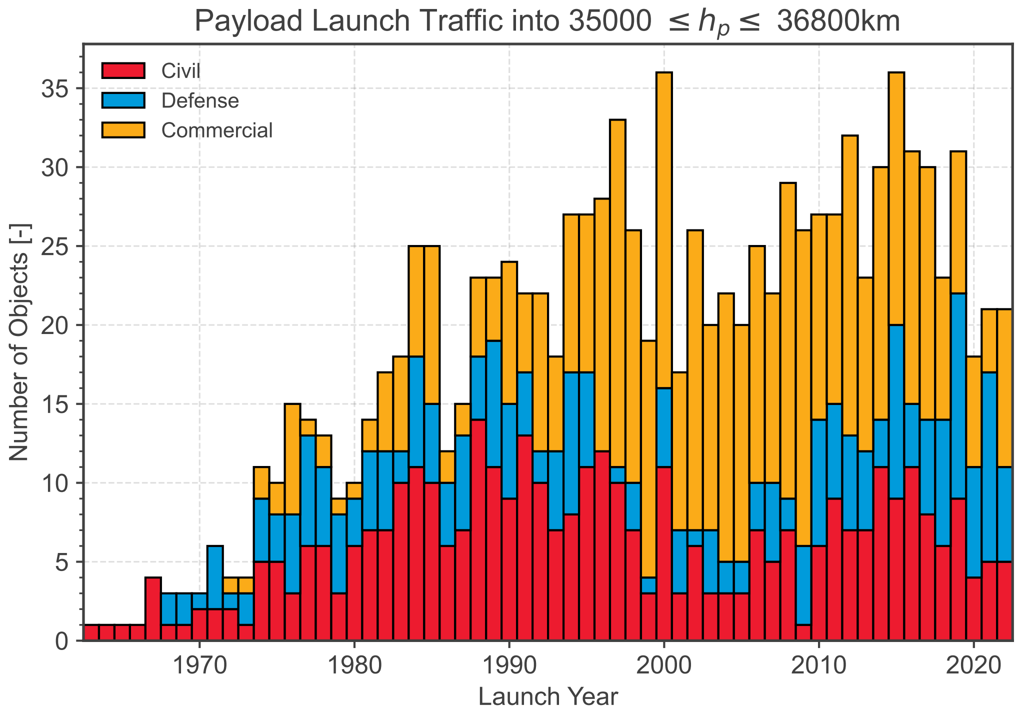


Figure 2.11: Evolution of the launch traffic near LEO_{IADC} per launcher family expressed in terms of number of objects (top) and mass (bottom).



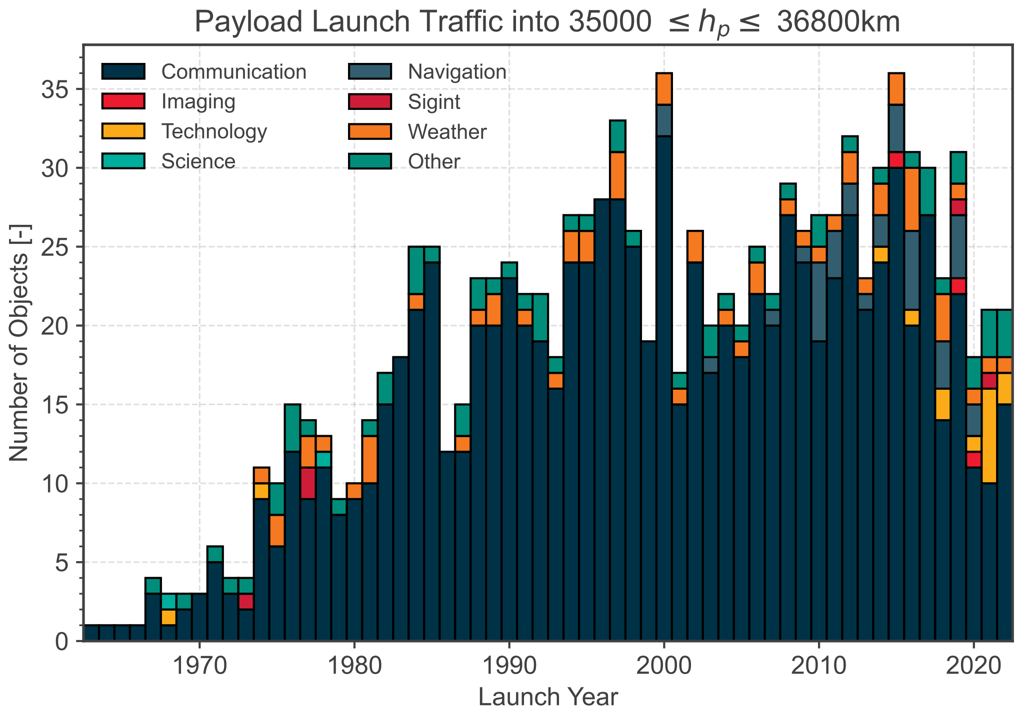
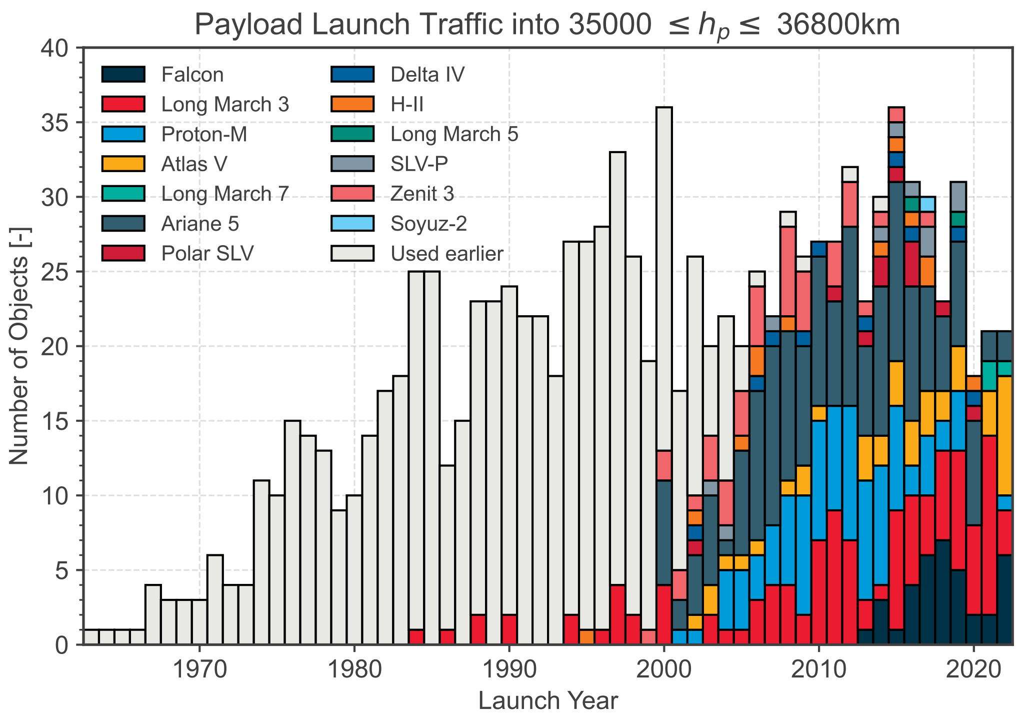


Figure 2.12: Evolution of the launch traffic near GEO_{IADC} per mission funding (top) and type (bottom).



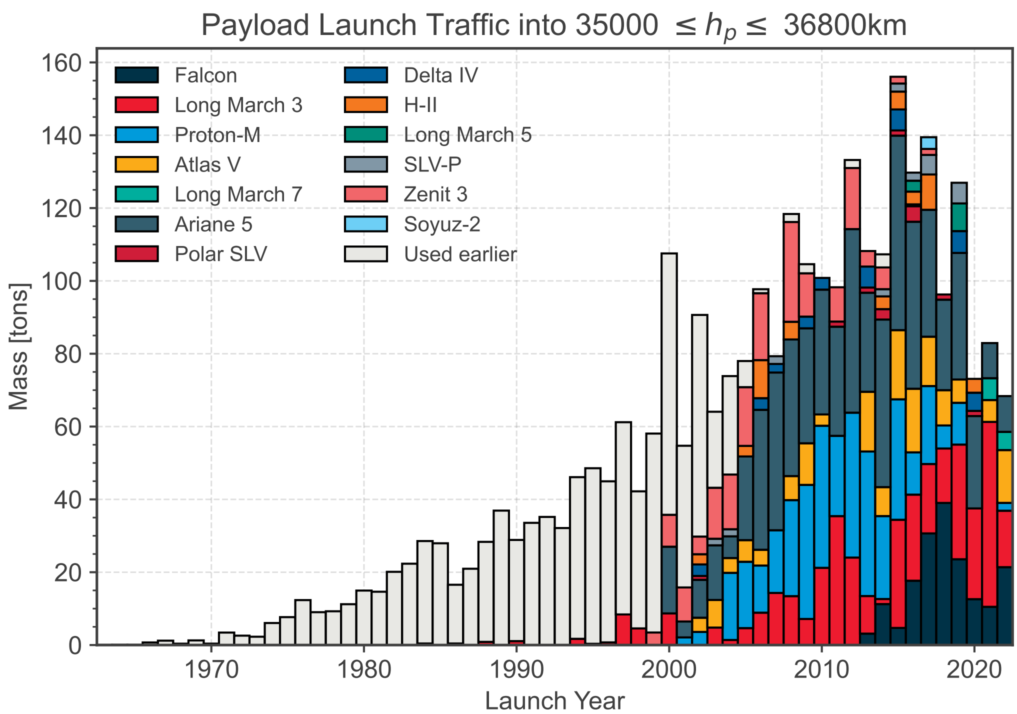
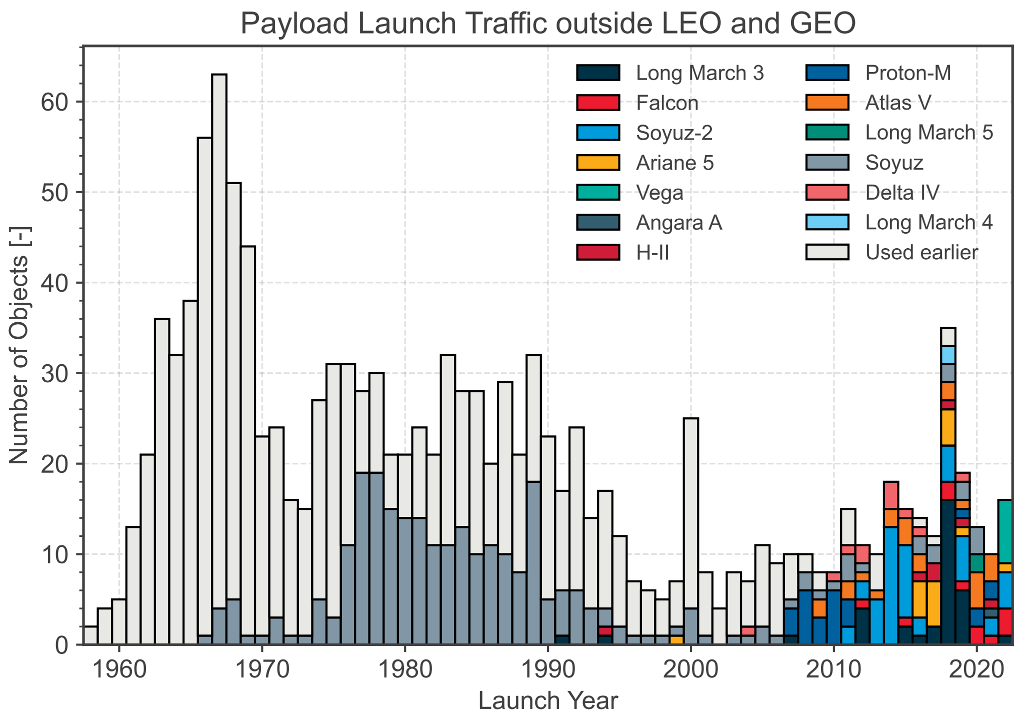


Figure 2.13: Evolution of the launch traffic near GEO_{IADC} per launcher family expressed in terms of number of objects (top) and mass (bottom).



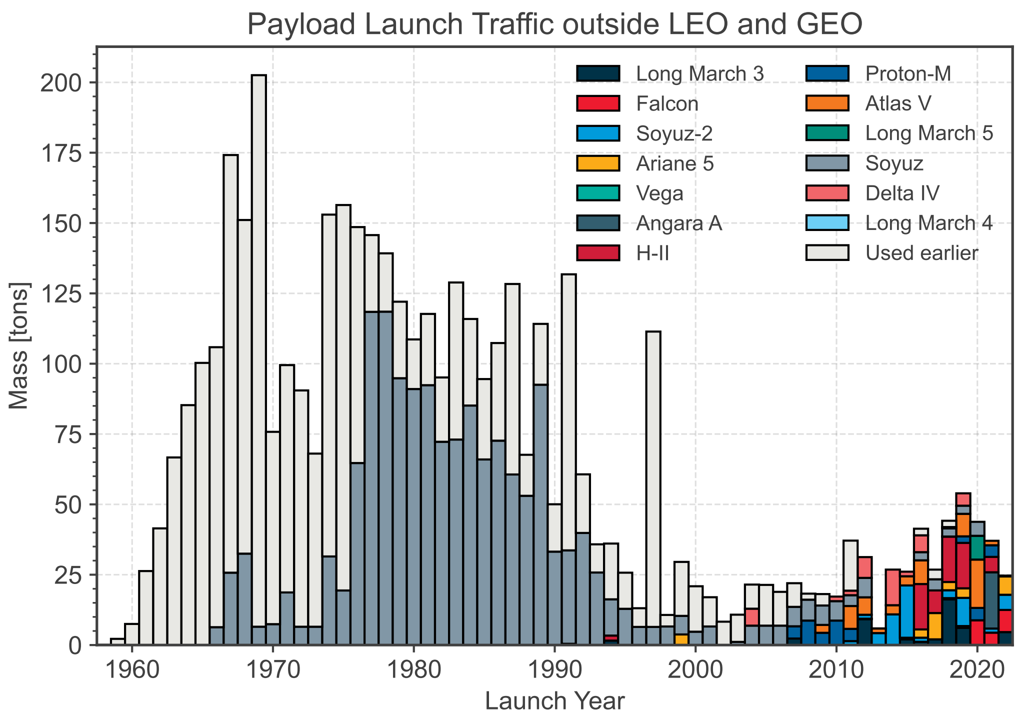


Figure 2.14: Evolution of the launch traffic outside LEO_{IADC} and GEO_{IADC} per launcher family expressed in terms of number of objects (top) and mass (bottom).

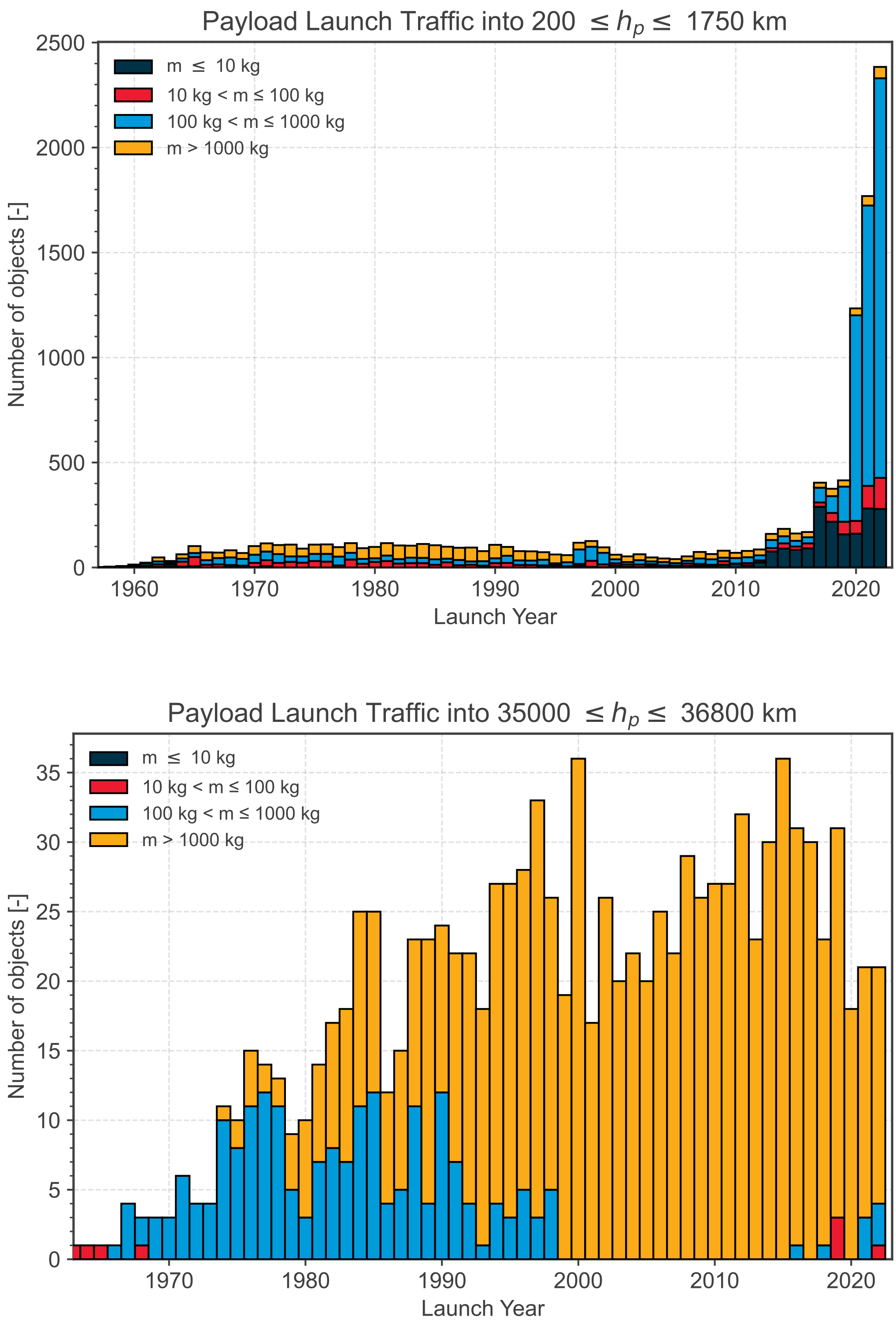
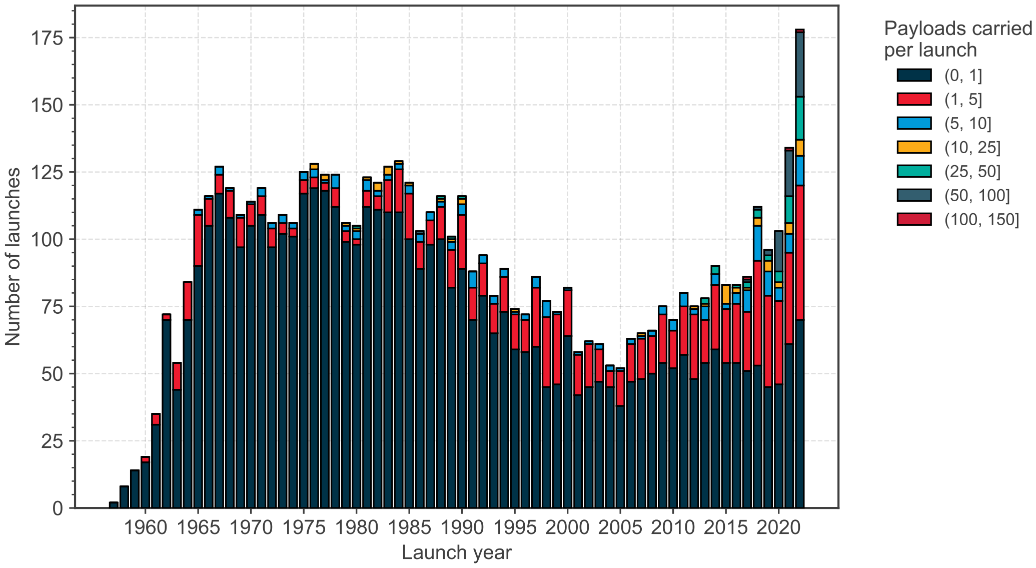
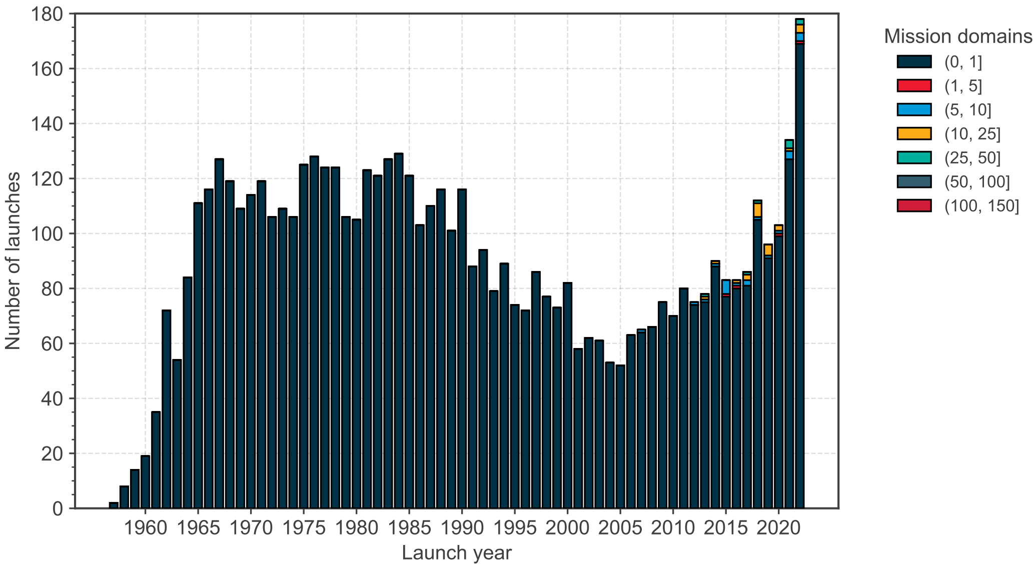


Figure 2.15: Evolution of the launch traffic per mass category in terms of number of objects in LEO_{IADC} (top) and GEO_{IADC} (bottom).



(a) Payloads



(b) Mission domains

Figure 2.16: Evolution of the launch traffic.

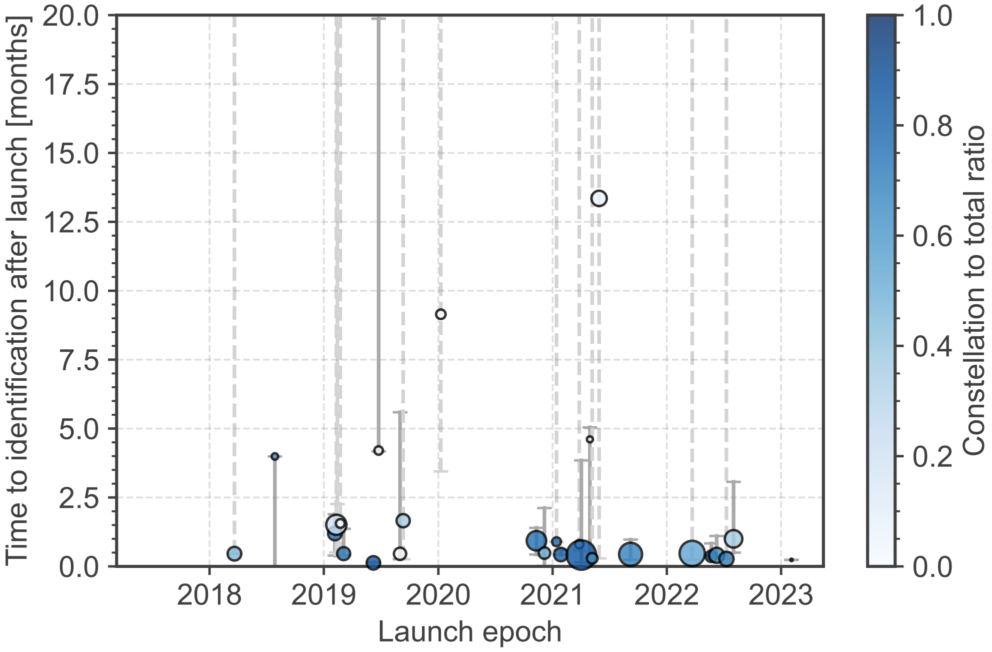
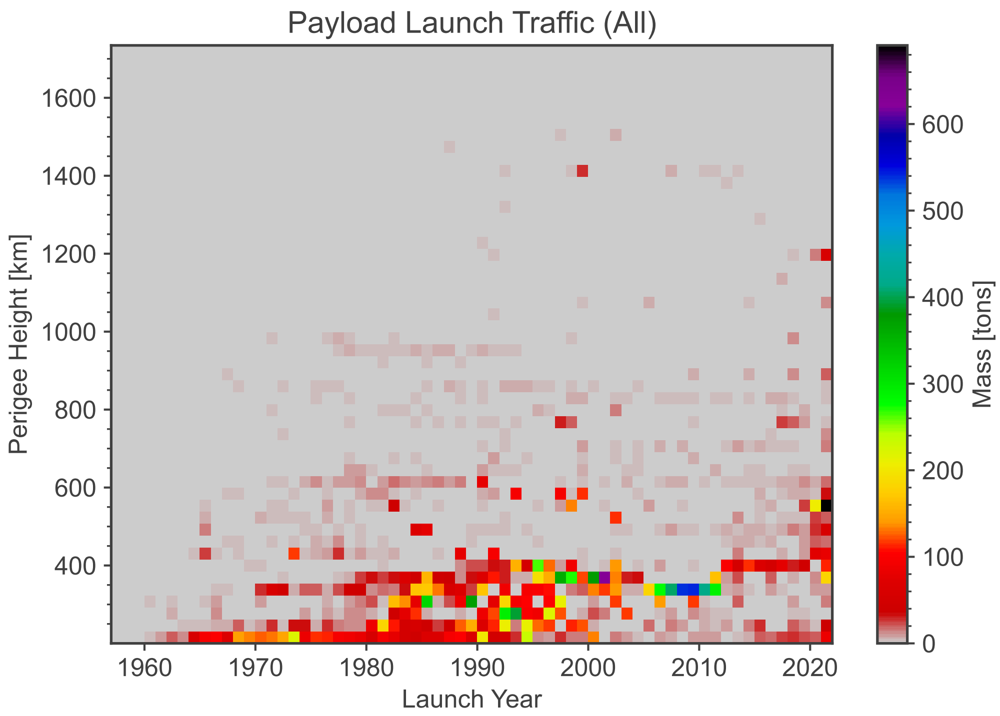
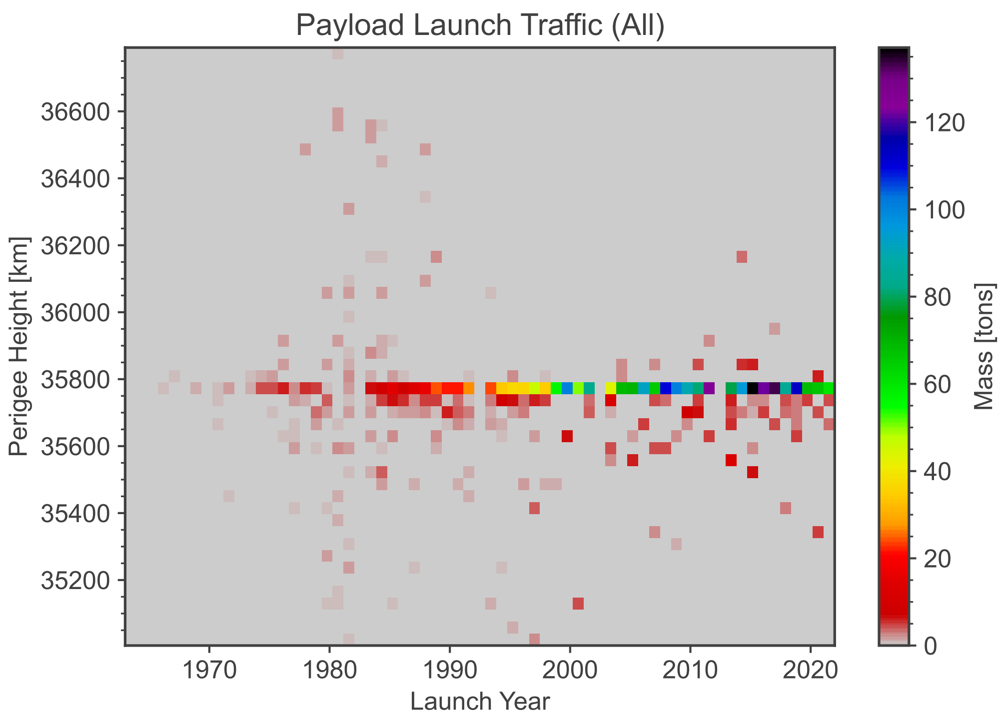


Figure 2.17: Identification rate for rideshare launches.

Unidentified Payload objects form a collision risk for active operators as potential avoidance scenarios cannot be coordinated effectively. In particular, ride-share launches can form an issue for timely identification by space surveillance networks when deployment is not coordinated with the operators on-board. Figure 2.17 plot represents the rate of identification for Payloads on ride-share launches since 2018, applying the definition introduced above. The x-axis indicates the launch epoch and the y-axis lists some of the crucial timings between launch and identification. Per ride-share launch event, the grey lines indicate the time interval between the epoch when 10% and 90% of the Payloads in the launch were identified with a cut-off after 12 months (some Payload might never be identified). If the 90% has not (yet) been reached, the interval is indicated with a dashed line. The location of the circular marker indicates the time when 50% of the Payloads are identified, the size is proportional to the total number of Payloads in the ride-share launch, and the colour indicates which fraction of the Payloads belong to a constellation. The latter makes a practical distinction in terms of amount of Payloads that can be coordinated with a space surveillance operators.

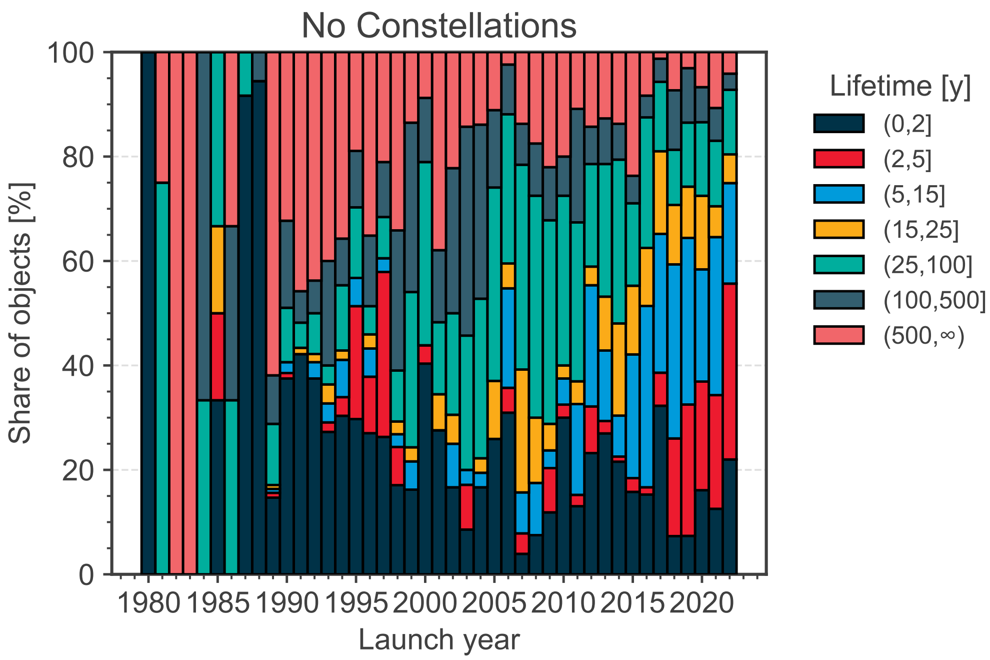


(a) LEO_{IADC}

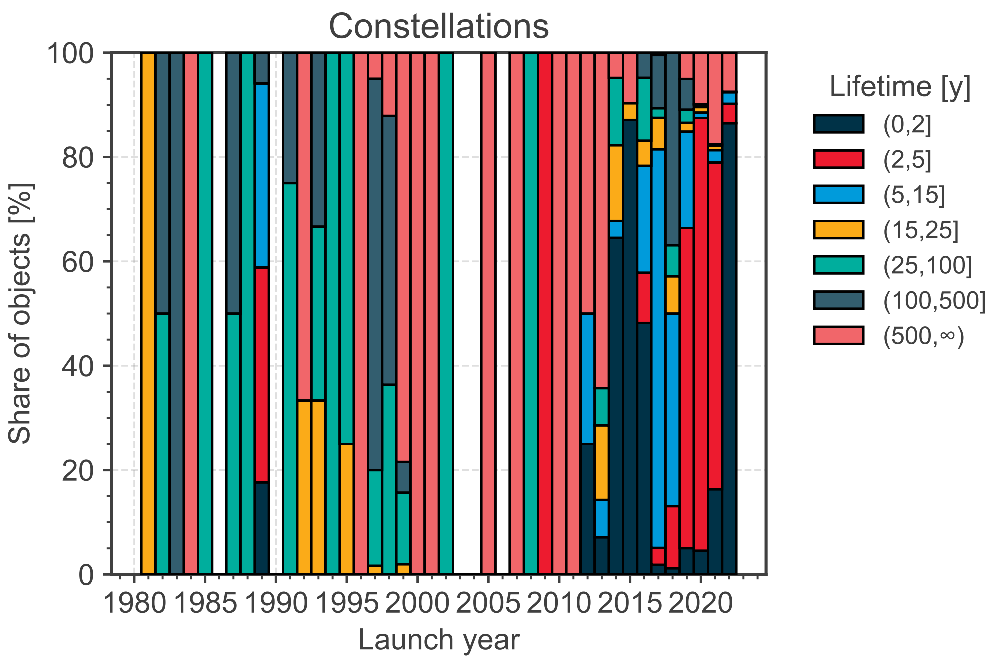


(b) GEO_{IADC}

Figure 2.18: Evolution of the launch traffic: mass injected.

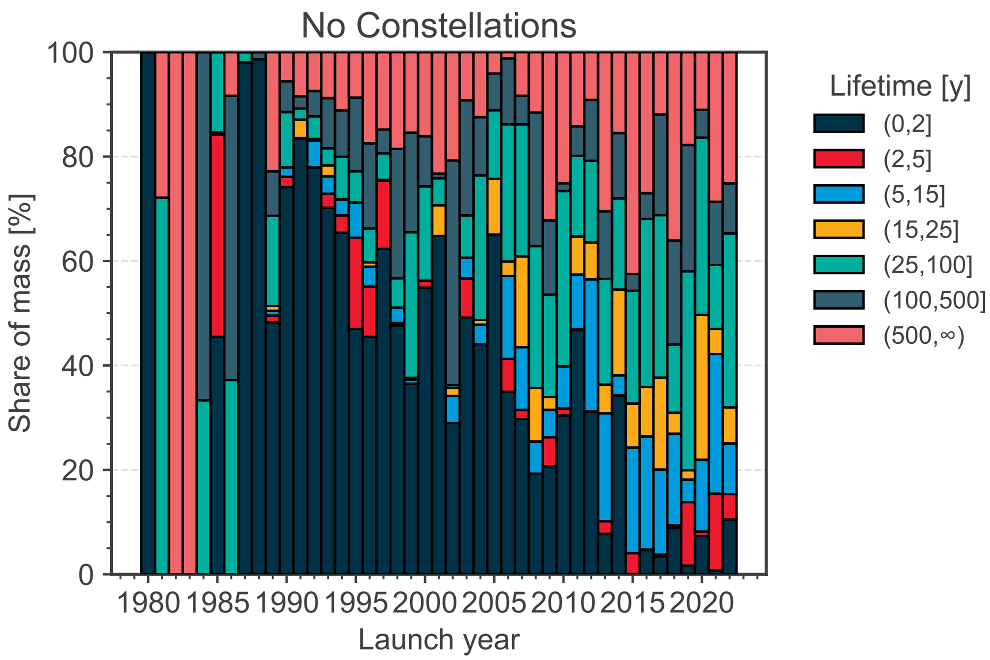


(a) Payload objects not belonging to constellations

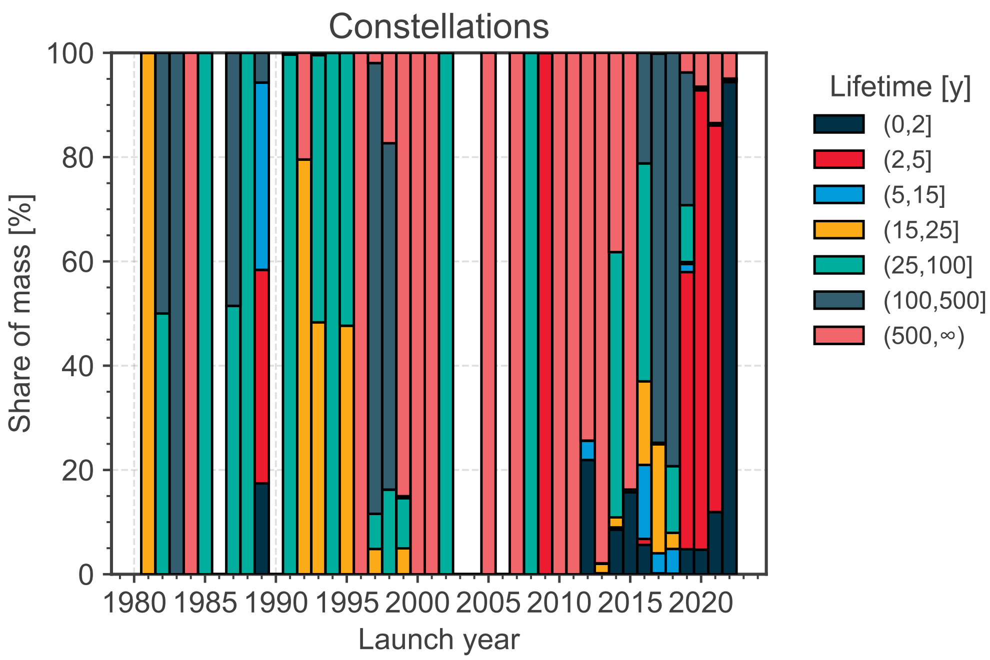


(b) Payload ojects belonging to constellations

Figure 2.19: Estimated lifetime for the Payload destination orbits by launch year: share of objects.



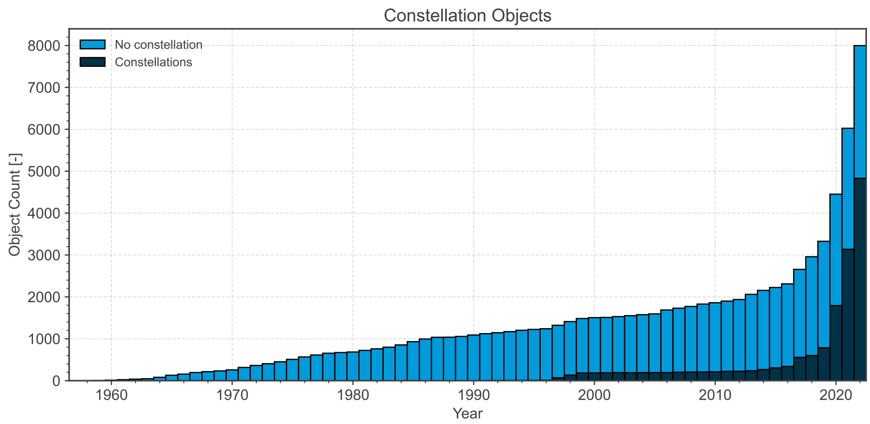
(a) Payload objects not belonging to constellations



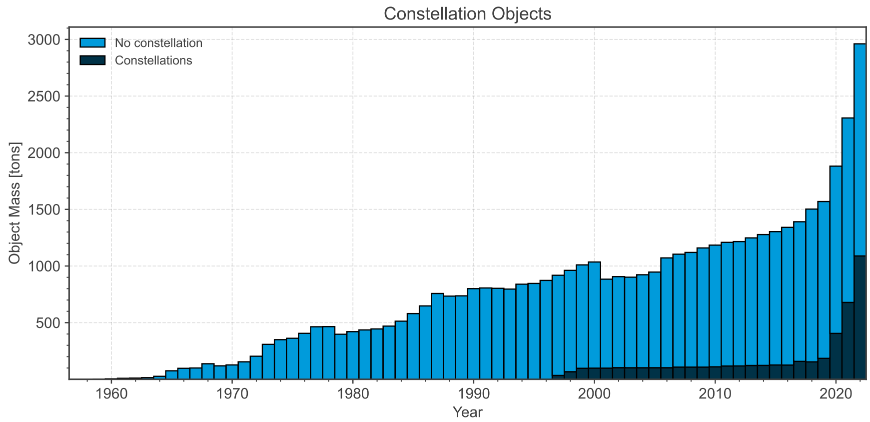
(b) Payload objects belonging to constellations

Figure 2.20: Estimated lifetime for the Payload destination orbits by launch year: share of mass.

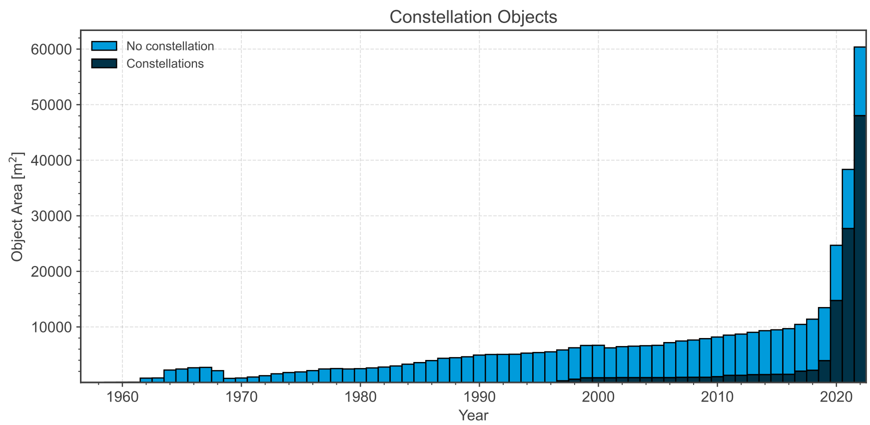
2.6. Constellations in the LEO protected region



(a) Evolution of number of objects.



(b) Evolution of mass.



(c) Evolution of area.

Figure 2.21: Evolution of number of objects, mass, and area in LEO_{IADC} distinguishing constellations and non-constellations payloads.

2.7. Active payloads in the LEO protected region

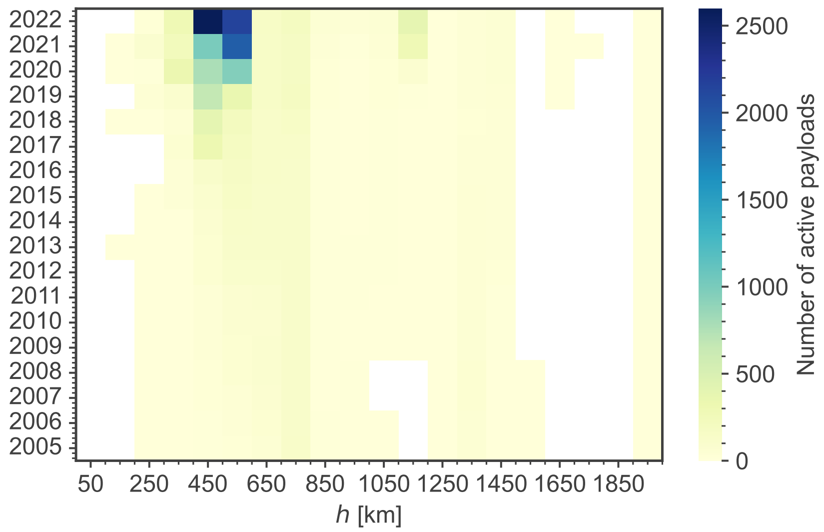


Figure 2.22: Distribution of active payloads in LEO by year and mean altitude.

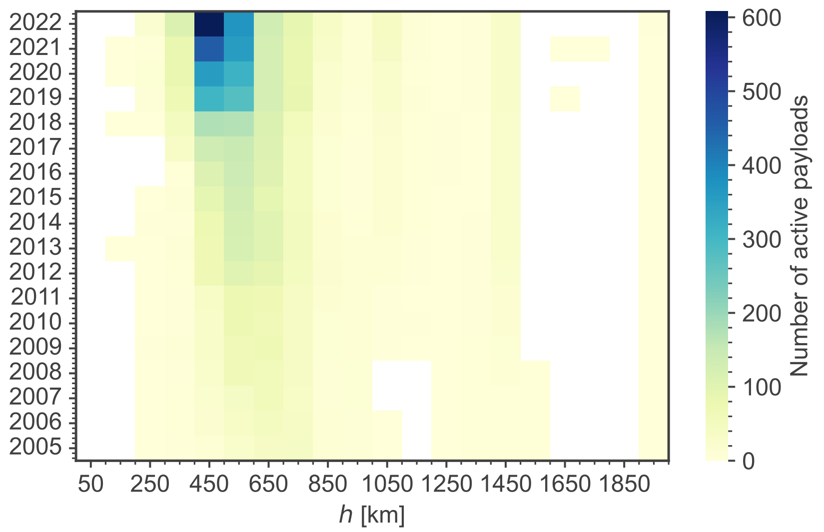


Figure 2.23: Distribution of active payloads not belonging to constellations in LEO by year and mean altitude.

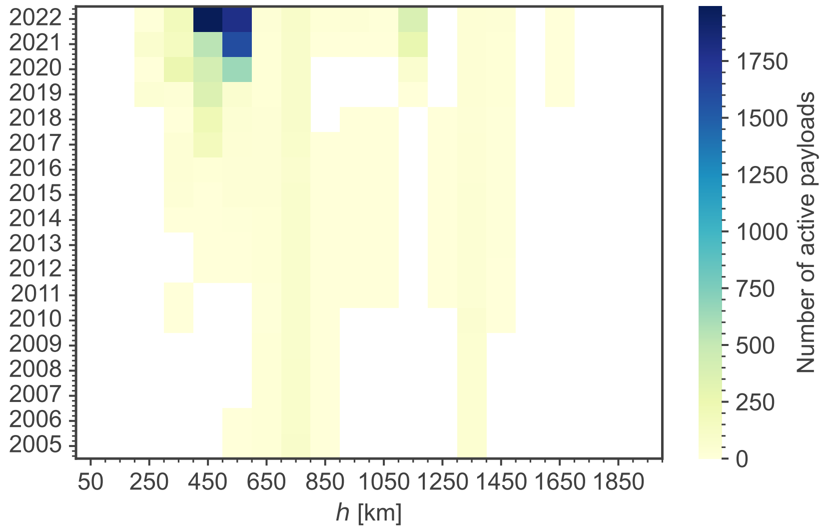


Figure 2.24: Distribution of active payloads belonging to constellations in LEO by year and mean altitude.

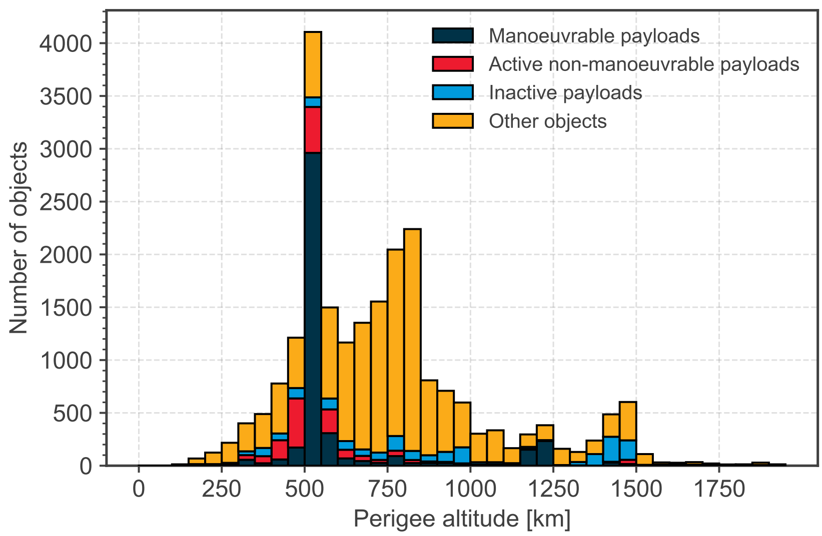


Figure 2.25: Number of manoeuvrable and active objects as a function of the perigee altitude.

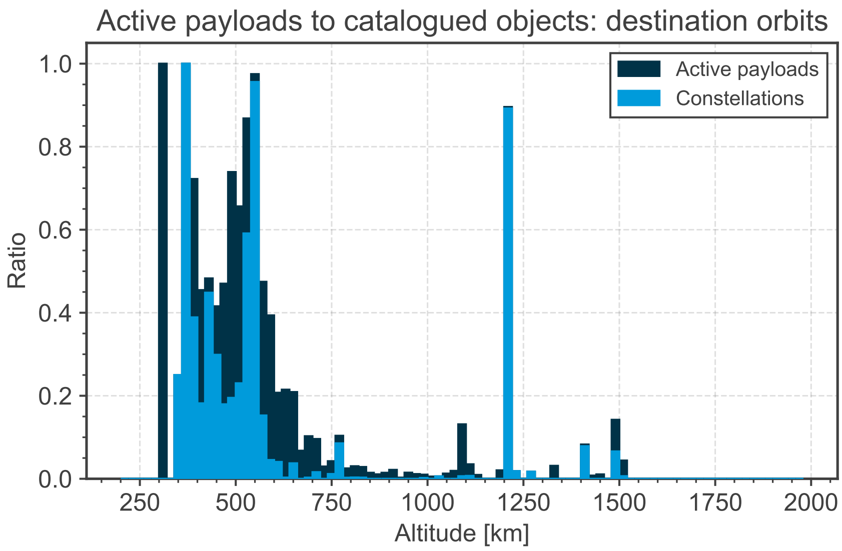


Figure 2.26: Ratio of active and constellation objects over the total number of catalogued objects.

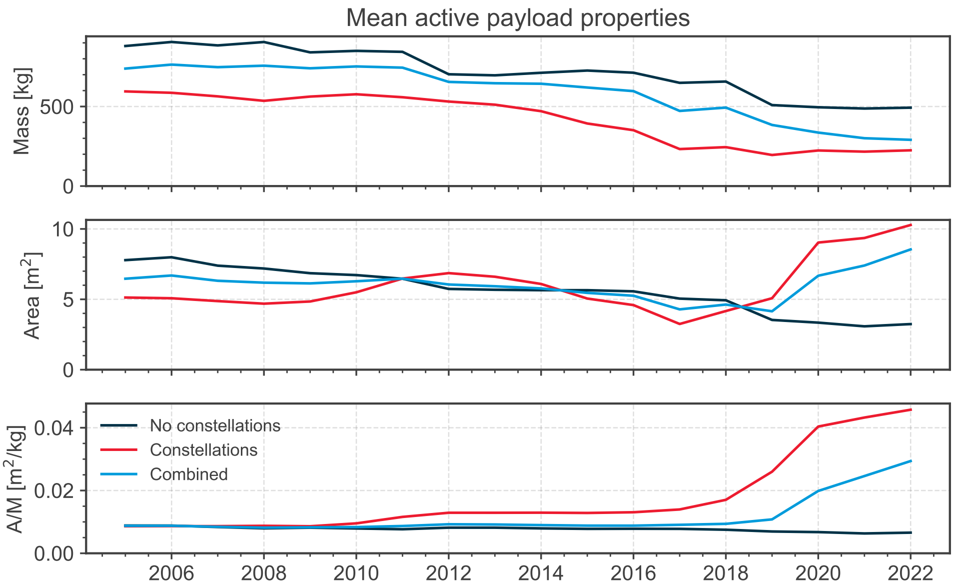
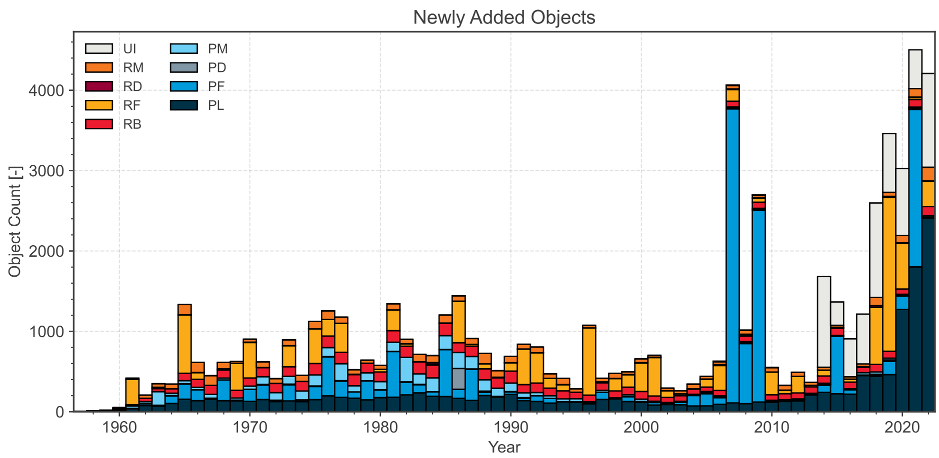
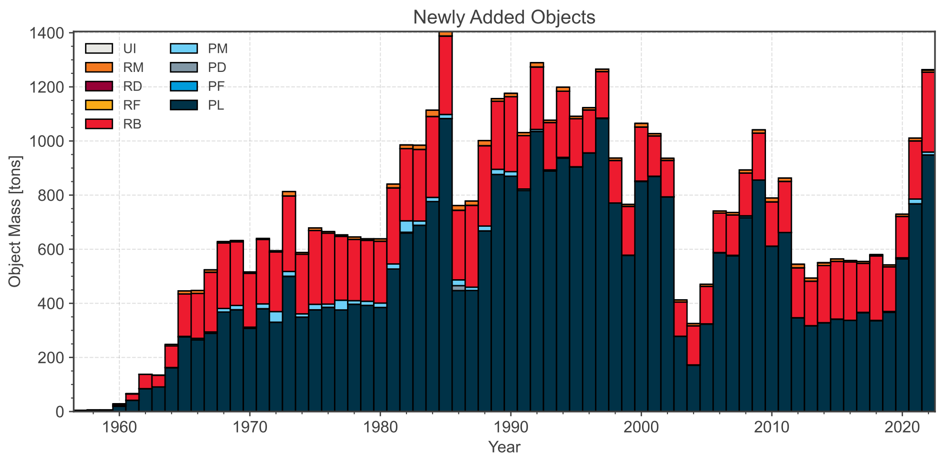


Figure 2.27: Payload parameters for active payloads in LEO over time.

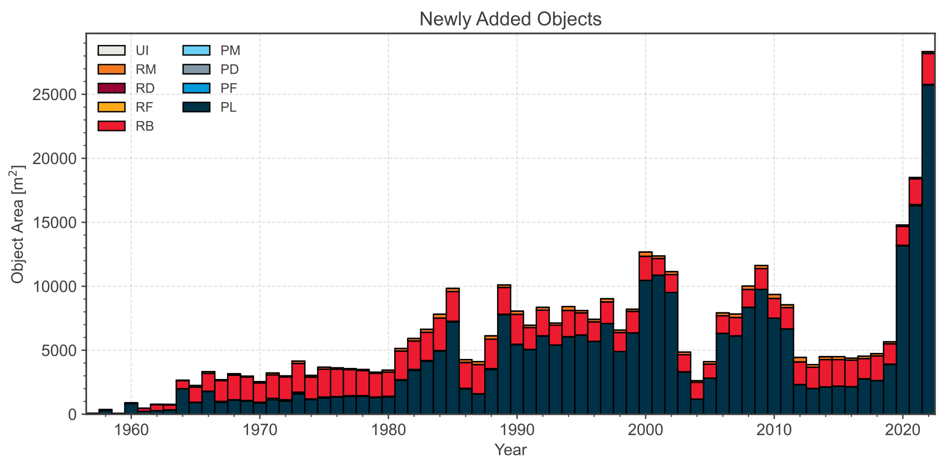
2.8. New Catalogued Objects in the Space Environment



(a) Evolution of newly added object by count.

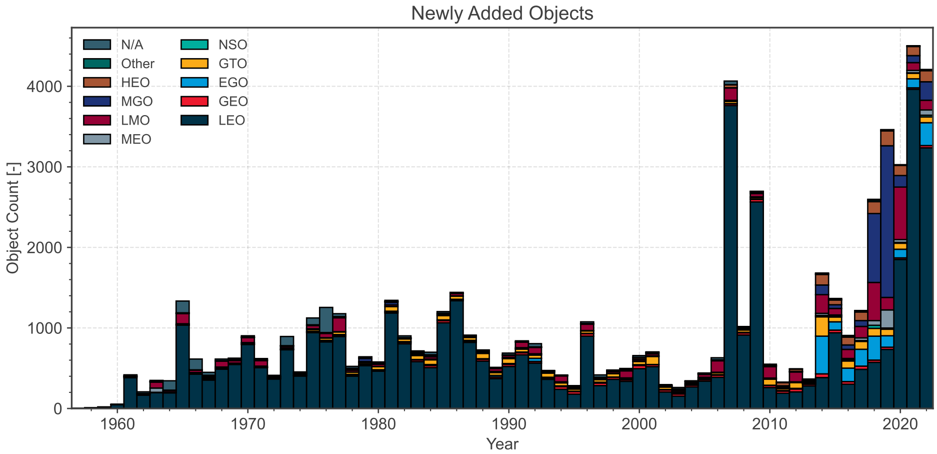


(b) Evolution of newly added mass.

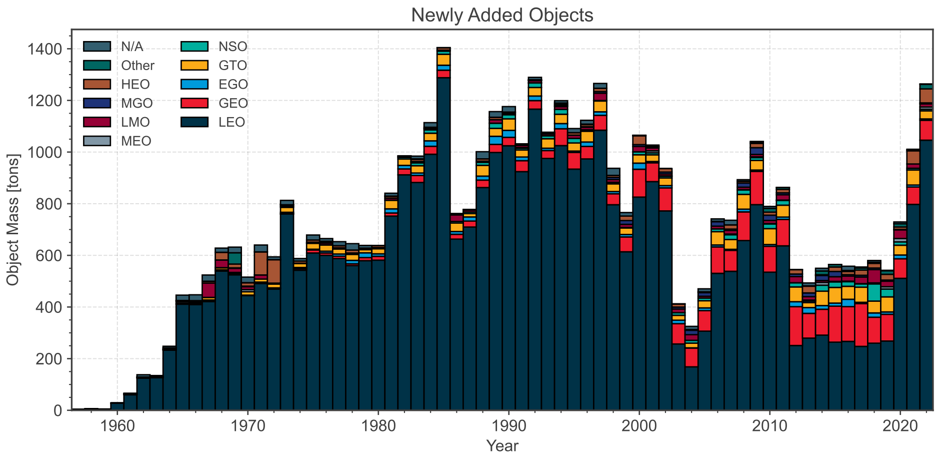


(c) Evolution of newly added area.

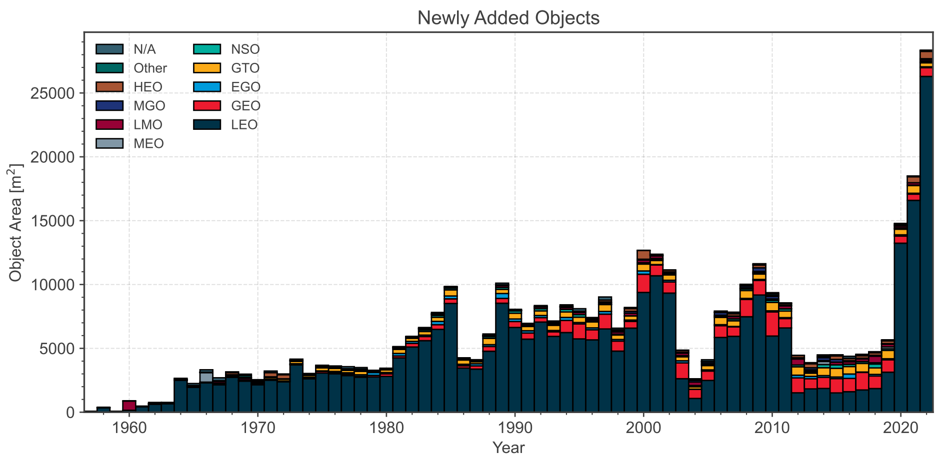
Figure 2.28: Evolution of newly added objects in each year by object type.



(a) Evolution of newly added object by count.



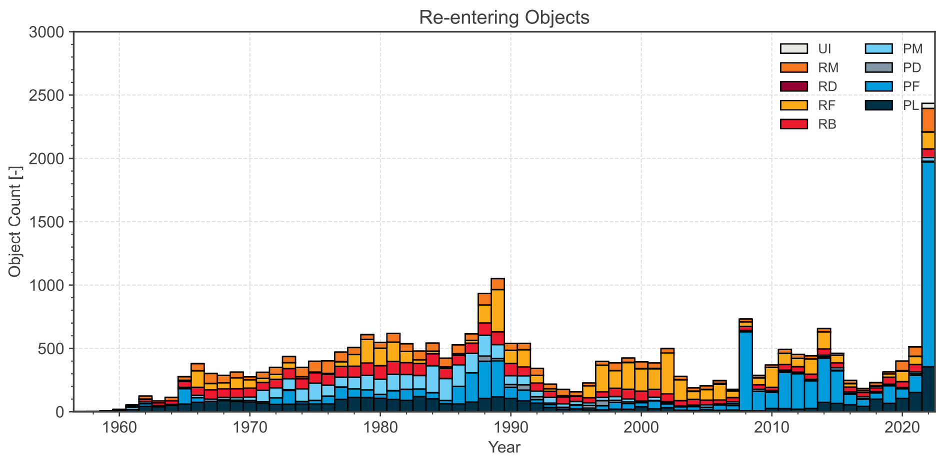
(b) Evolution of newly added mass.



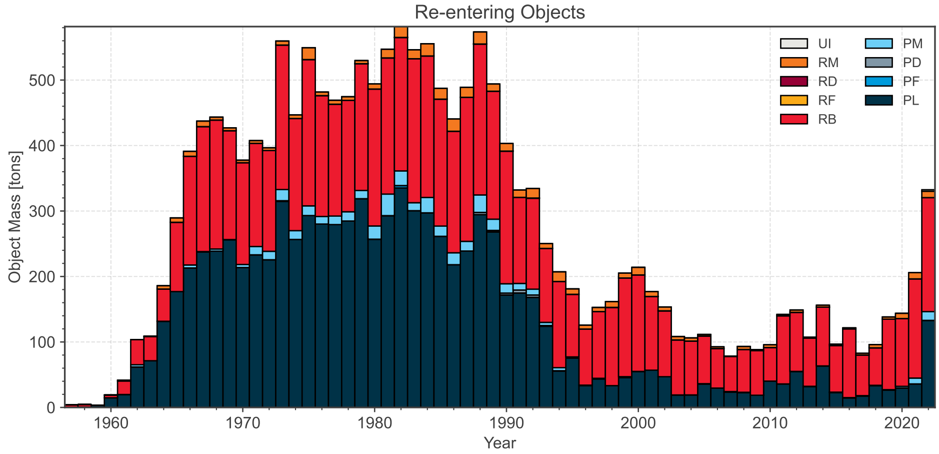
(c) Evolution of newly added area.

Figure 2.29: Evolution of newly added objects in each year by orbit type.

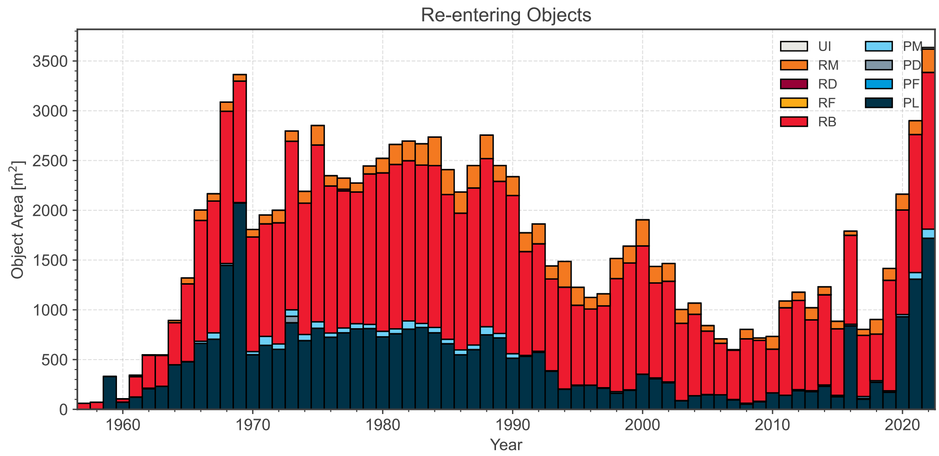
2.9. Objects Removed from the Space Environment



(a) Evolution of re-entered numbers.

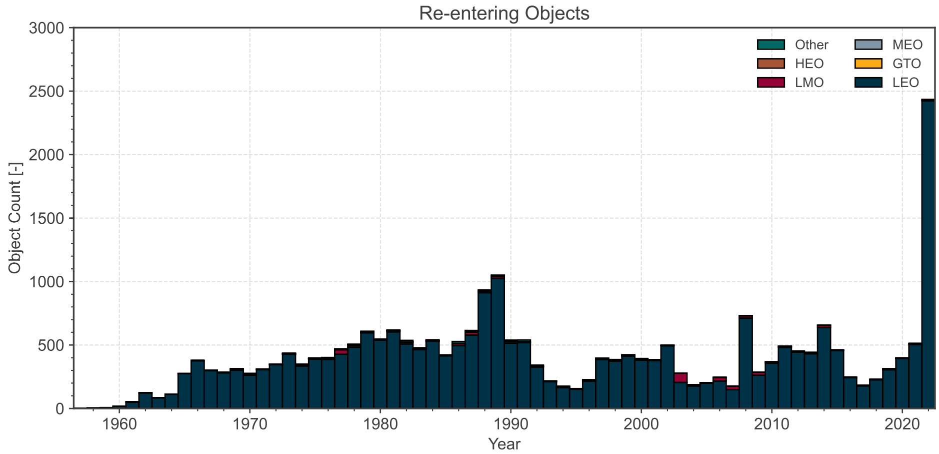


(b) Evolution of re-entered mass.

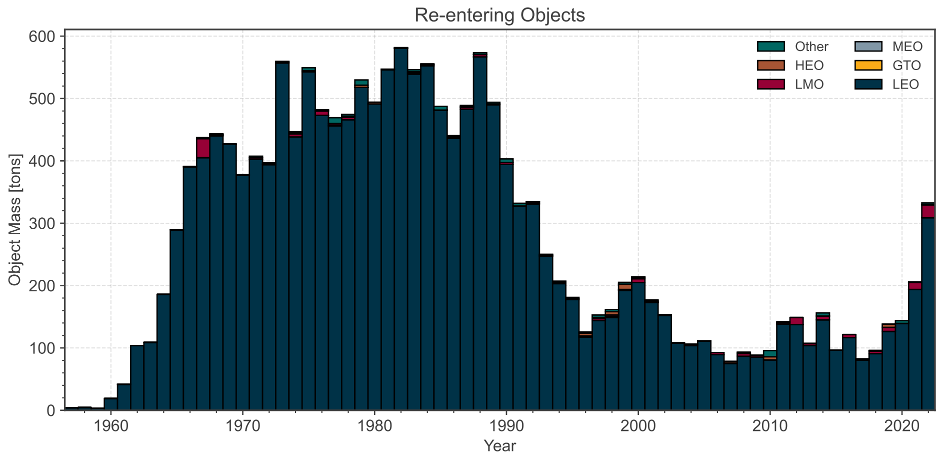


(c) Evolution of re-entered area.

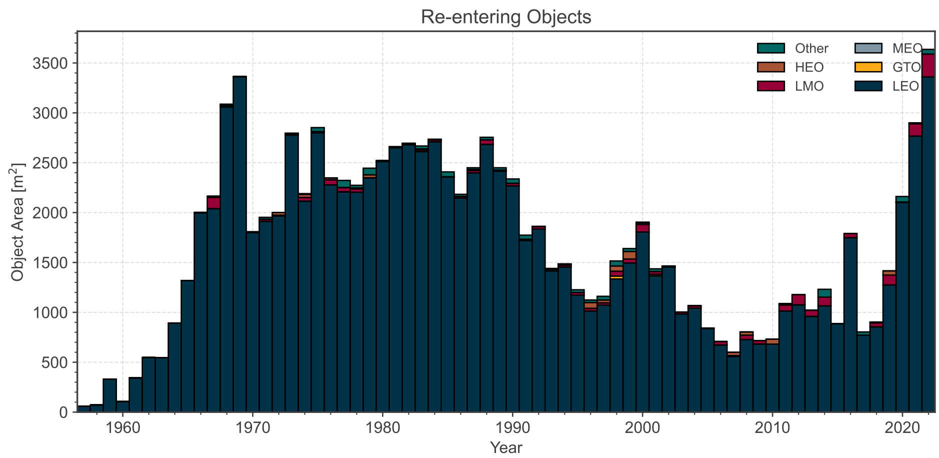
Figure 2.30: Evolution of re-entering objects in each year by object type without human spaceflight.



(a) Evolution of re-entered numbers.

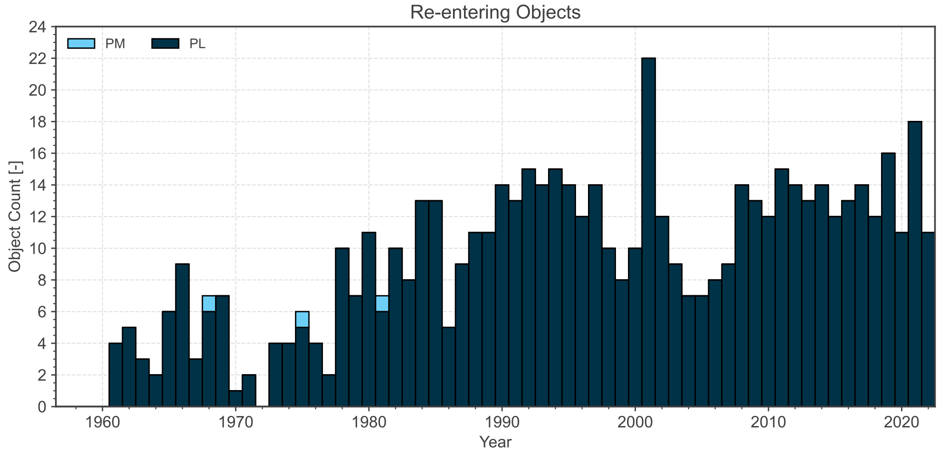


(b) Evolution of re-entered mass.

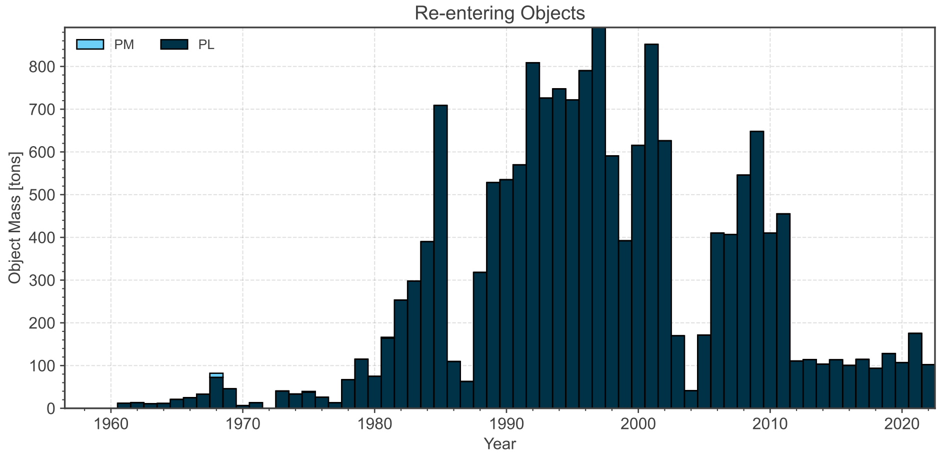


(c) Evolution of re-entered area.

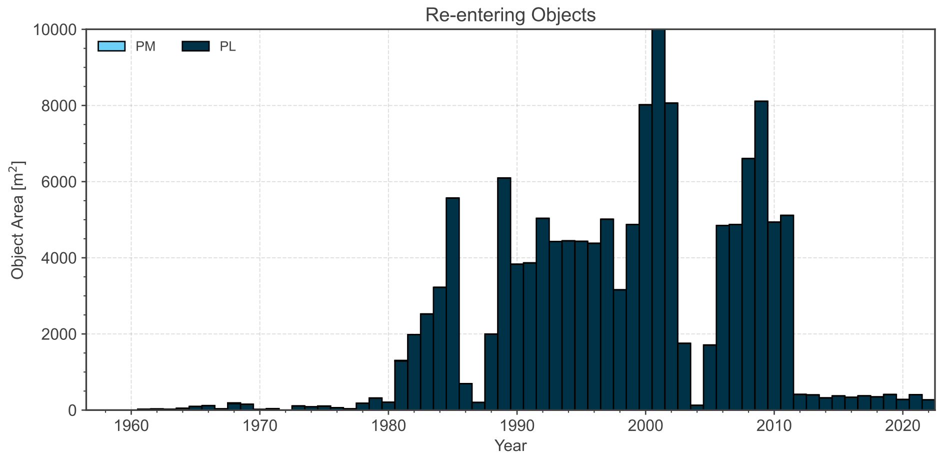
Figure 2.31: Evolution of re-entering objects in each year by orbit type without human spaceflight.



(a) Evolution of re-entered numbers.

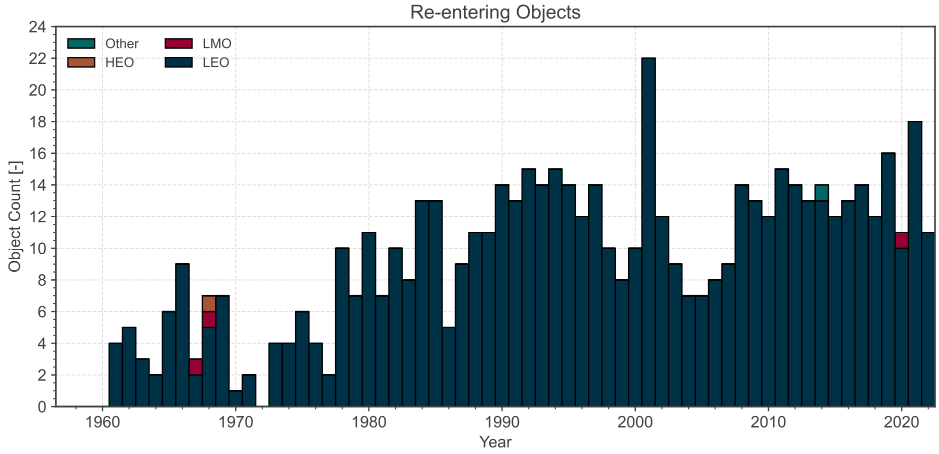


(b) Evolution of re-entered mass.

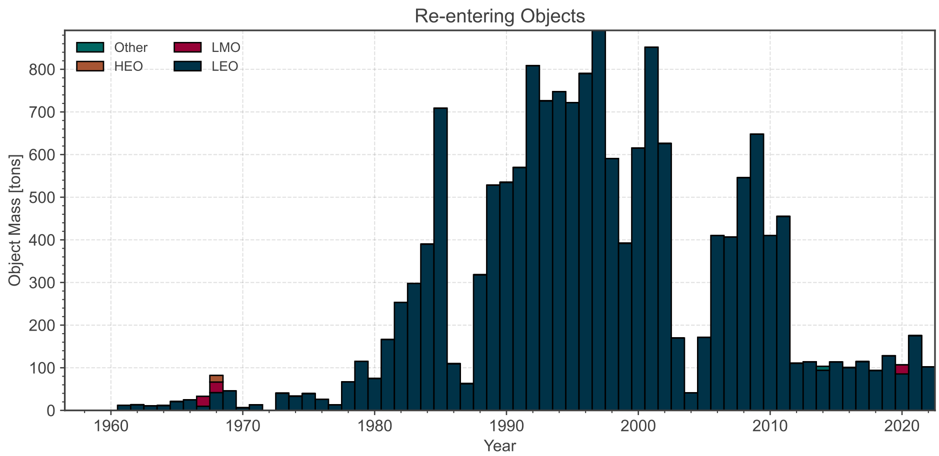


(c) Evolution of re-entered area.

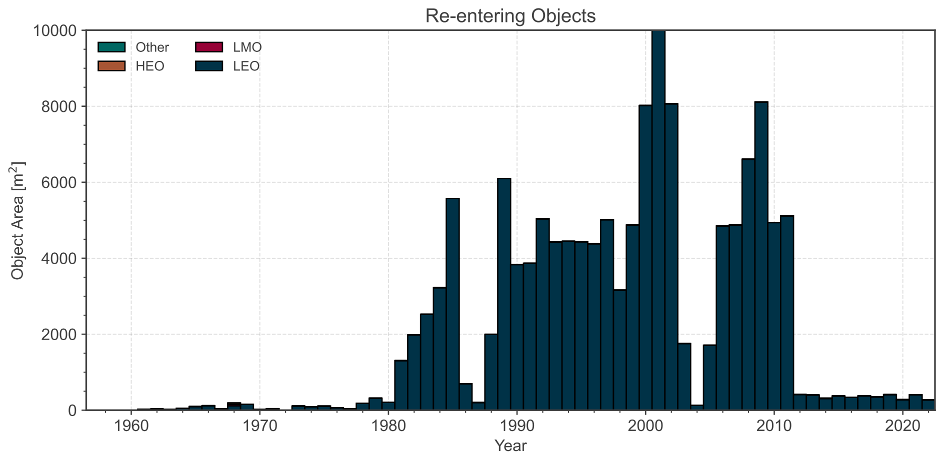
Figure 2.32: Evolution of re-entering human spaceflight objects in each year by object type.



(a) Evolution of re-entered numbers.

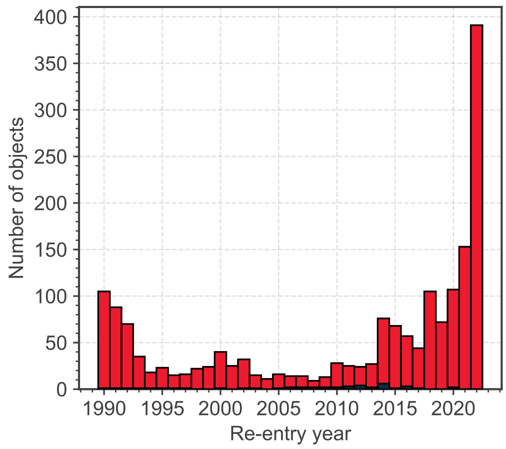


(b) Evolution of re-entered mass.

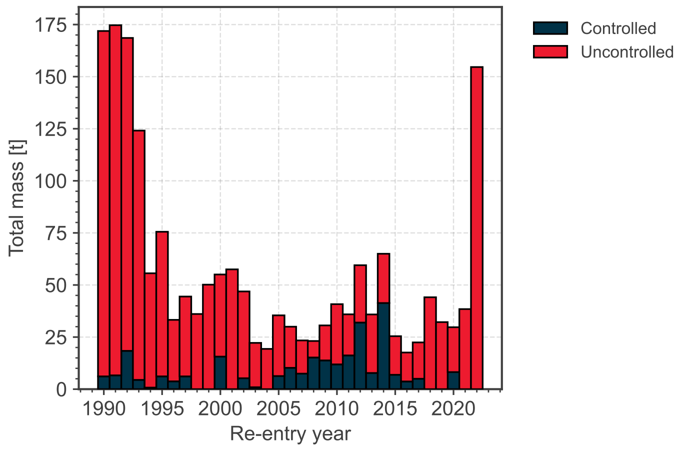


(c) Evolution of re-entered area.

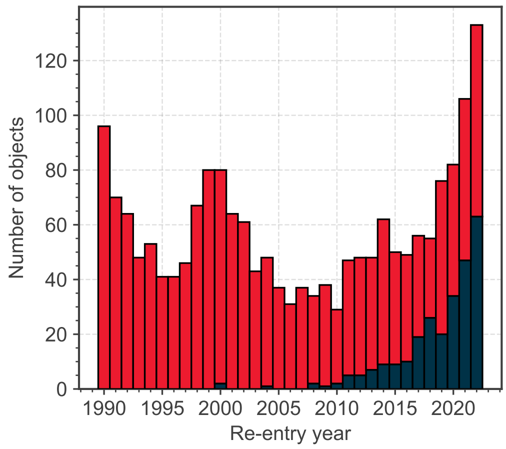
Figure 2.33: Evolution of re-entering human spaceflight objects by orbit type.



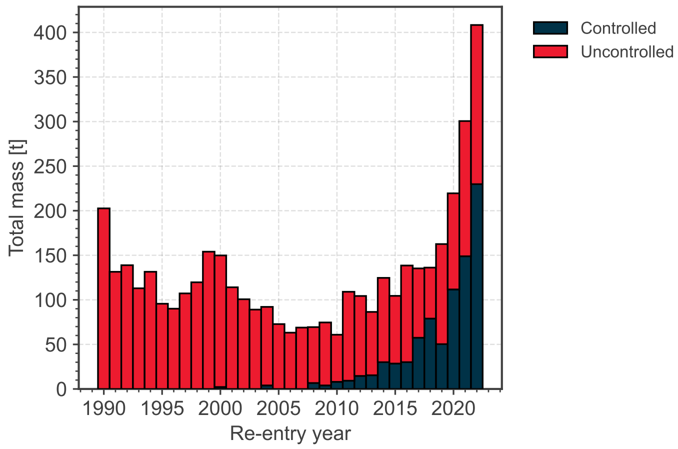
(a) Payloads: Count



(b) Payloads: Mass



(c) Rocket Bodies: Count



(d) Rocket Bodies: Mass

Figure 2.34: Controlled and uncontrolled re-entries for Payloads (top) and Rocket Bodies (bottom).

2.10. Nuclear Power Sources

Nuclear power sources (NPS) have been used in outer space as an efficient way of producing larger quantities of energy or heat, commonly implemented as small fission reactors or radioisotope thermoelectric generators. Since early during the space age such power systems were used in Earth orbit but they have been largely phased out after the 80íes due to safety concerns. The notable exception is the use of NPSs for interplanetary Payloads and planetary exploration.

The safety concerns related to NPSs in Earth orbit related to risks implied when they would re-enter the atmosphere and break-up. To mitigate this risk, the reactor cores were generally injected into orbits with long orbital lifetimes after the end of operations of the Payload. There are 61 objects related to NPSs known to have entered Earth orbit, out of which 3 are asserted but not catalogued. A total of 3 out of those 61 have re-entered, and the orbital distribution on the remainder is presented in Figure 2.35.

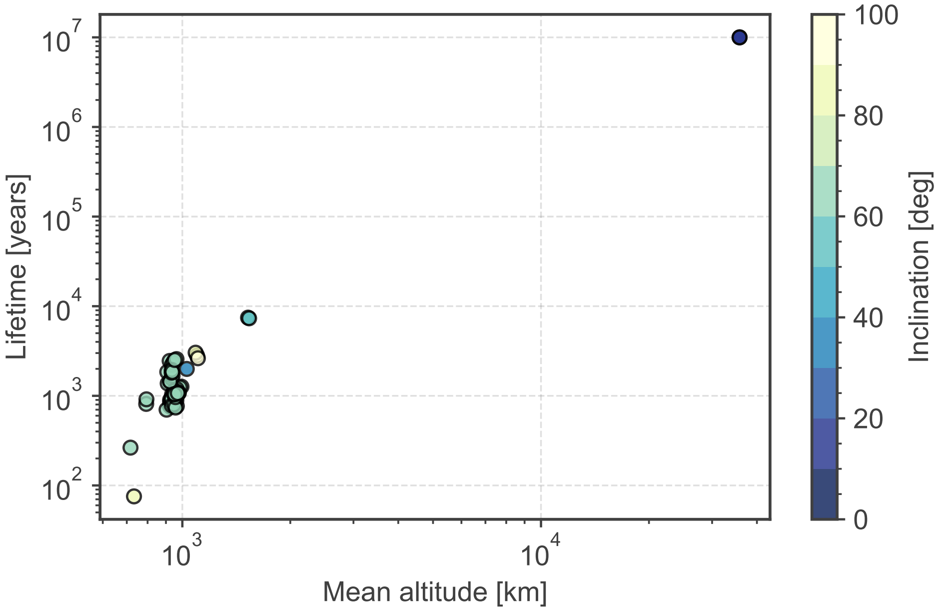


Figure 2.35: Distribution of space objects with nuclear power sources with mean altitude, orbital lifetime, and inclination.

2.11. Registration of Objects Launched in Outer Space

The United Nations Register of Objects Launched into Outer Space [11] and its implementation was established as consequence of the Convention on Registration of Objects Launched into Outer Space [12]. State parties to the treaty are required to establish their own national registries and provide information on their space objects, which in turn creates transparency on space operations. The increasing amount of launching states of time serves as a reminder for the need to coordinate space debris mitigation measures across all those actors, as one failure to do so will affect many others. Notwithstanding the increase in actors, positive trends are the retro-active registration of objects and the reducing time between launch and registration.

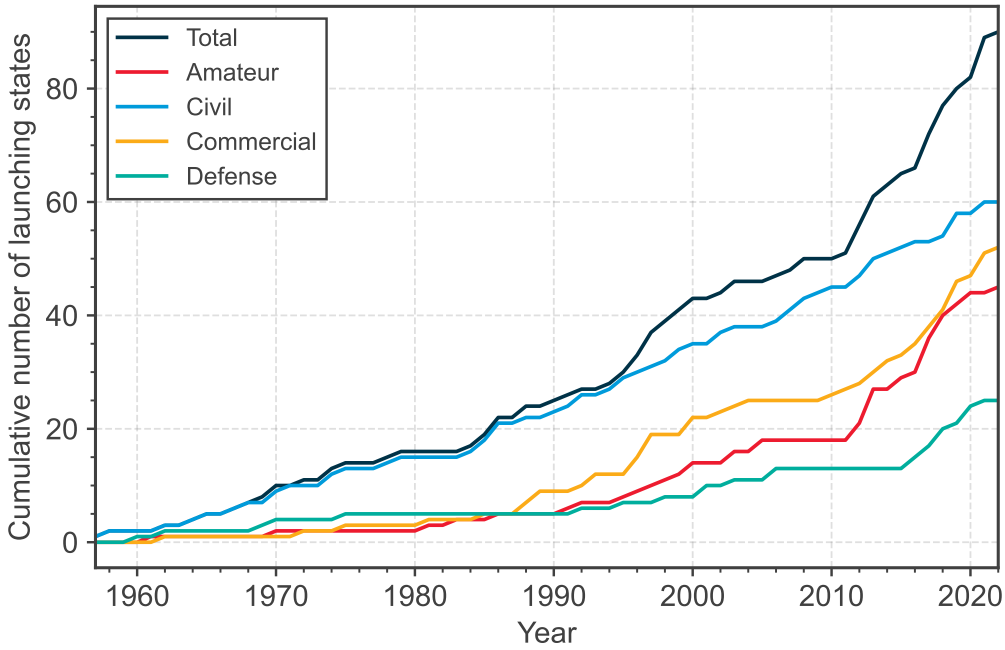


Figure 2.36: Launching states with at least one registered space object over time by category.

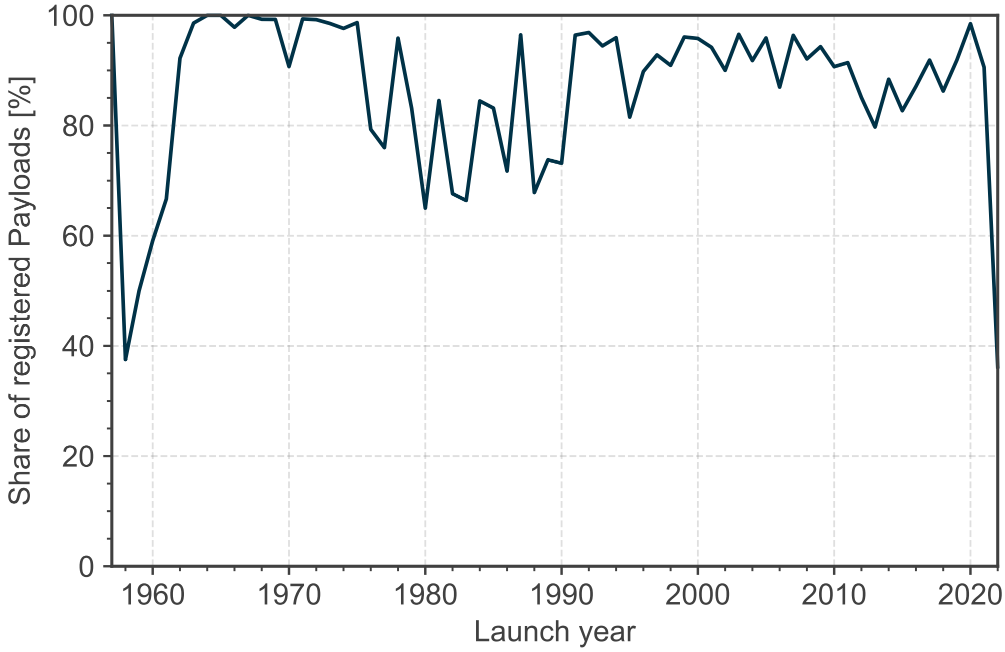


Figure 2.37: Share of registered payloads over the total of launched payloads by launch year.

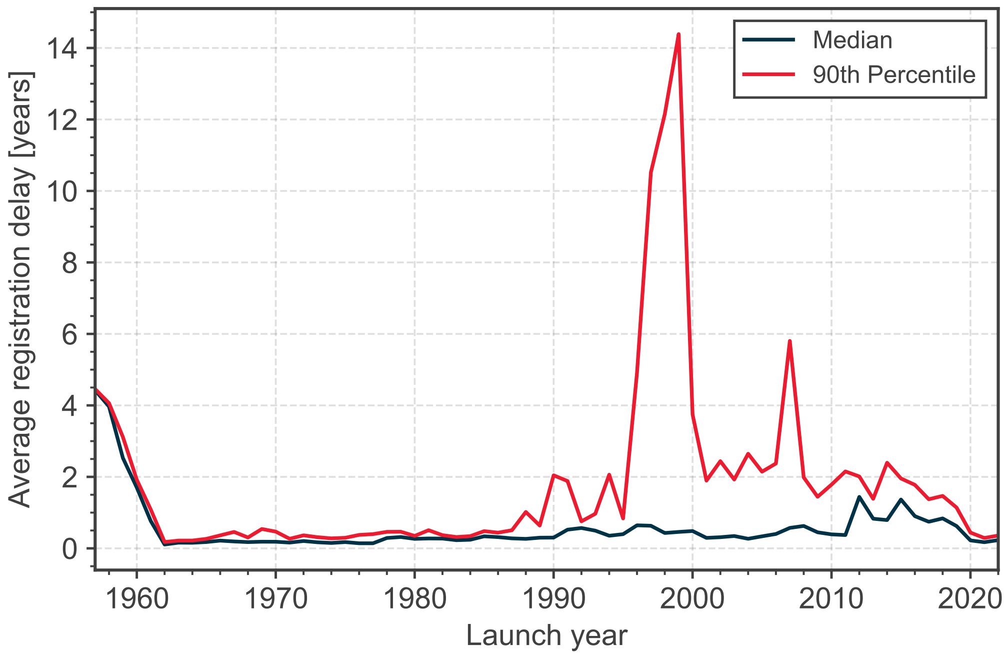


Figure 2.38: Delay between launch and registration by launch year.

3. ENVIRONMENTAL STATUS 2022

In this section, the status of the environment as of end of 2022 is listed and illustrated.

Table 3.1: Number of objects orbiting Earth. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	7889	6772	114	232	948	2782	22	609	326	19694
GEO	786	3	3	7	66	0	0	0	28	893
EGO	496	1	1	49	191	90	3	3	1689	2523
GTO	54	26	1	11	239	206	13	54	639	1243
NSO	278	0	0	1	95	0	0	2	29	405
MEO	72	0	5	52	22	38	1	3	318	511
LMO	85	145	6	49	237	713	19	219	988	2461
MGO	67	70	1	2	176	2167	4	0	1057	3544
HEO	37	16	0	1	52	111	0	0	927	1144
Other	42	0	0	5	6	0	0	0	69	122
Total	9806	7033	131	409	2032	6107	62	890	6070	32540

Table 3.2: Absolute and equivalent number of objects intersecting with the protected regions.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
both (abs)	19	18	1	1	75	131	0	18	327	590
LEO_{IADC} (abs)	8043	6959	121	293	1461	3760	54	882	2125	23698
LEO_{IADC} (eqv)	7921	6862	118	244	1000	2989	26	644	501	20306
GEO_{IADC} (abs)	952	59	5	50	307	802	2	20	2863	5060
GEO_{IADC} (eqv)	826	5	3	18	104	38	1	1	210	1206
none (abs)	830	33	6	67	339	1676	6	6	1409	4372

Table 3.3: Mass in tons orbiting Earth. Objects of unknown mass do not contribute to the figures presented. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	2767.1	0.2	0.0	10.8	1411.3	0.0	0.0	10.9	0.0	4200.4
GEO	2571.3	0.0	0.0	1.0	136.6	0.0	0.0	0.0	0.0	2709.0
EGO	834.8	0.0	0.0	4.9	358.3	0.0	0.0	0.2	0.0	1198.3
GTO	95.1	0.0	0.0	1.0	556.9	0.0	0.0	25.1	0.0	678.2
NSO	358.0	0.0	0.0	0.4	212.5	0.0	0.0	0.0	0.0	570.8
MEO	70.2	0.0	0.0	0.3	31.7	0.0	0.0	2.0	0.0	104.2
LMO	63.8	0.0	0.0	8.4	425.2	0.0	0.0	86.7	0.0	584.1
MGO	92.5	0.0	0.0	1.9	288.9	0.0	0.0	0.0	0.0	383.3
HEO	65.0	0.0	0.0	0.1	123.8	0.0	0.0	0.0	0.0	188.9
Other	70.4	0.0	0.0	0.1	17.5	0.0	0.0	0.0	0.0	88.0
Total	6988.2	0.2	0.0	28.9	3562.9	0.0	0.0	124.9	0.0	10705.1

Table 3.4: Absolute and equivalent mass in tons intersecting with the protected regions.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
both (abs)	24.6	0.0	0.0	0.1	167.7	0.0	0.0	6.1	0.0	198.5
LEO_{IADC} (abs)	2944.4	0.2	0.0	20.3	2492.5	0.0	0.0	122.7	0.0	5580.2
LEO_{IADC} (eqv)	2791.7	0.2	0.0	13.5	1486.8	0.0	0.0	21.5	0.0	4313.8
GEO_{IADC} (abs)	2890.1	0.0	0.0	6.4	601.8	0.0	0.0	6.3	0.0	3504.7
GEO_{IADC} (eqv)	2663.1	0.0	0.0	2.1	208.5	0.0	0.0	0.4	0.0	2874.2
none (abs)	1178.2	0.0	0.0	2.2	636.3	0.0	0.0	2.0	0.0	1818.8

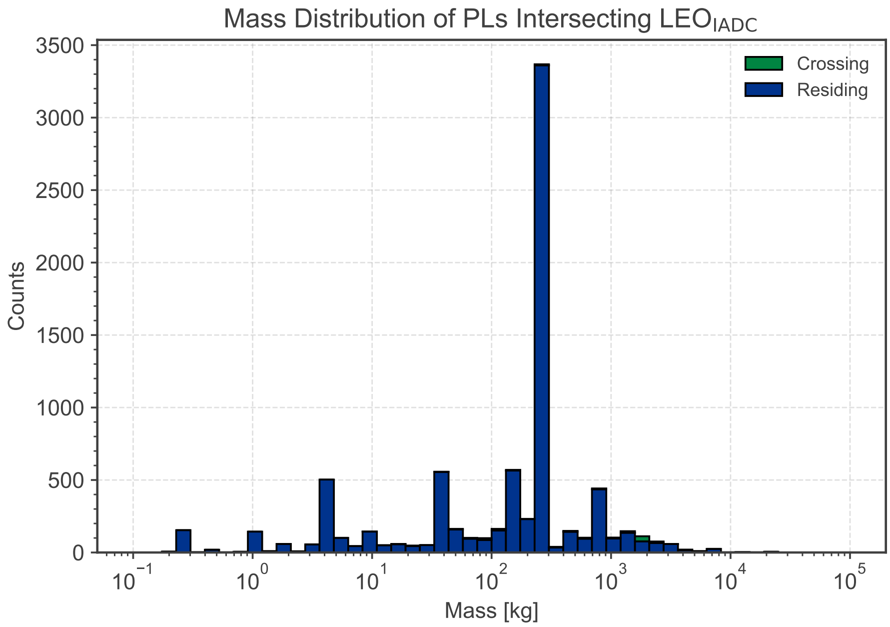
Table 3.5: Area in m^2 orbiting Earth. Objects of unknown area do not contribute to the figures presented. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	58891.4	0.5	0.0	73.3	11424.6	2.6	0.0	312.1	0.0	70704.5
GEO	25343.2	0.0	23.6	8.4	1486.5	0.0	0.0	0.0	0.0	26861.7
EGO	10798.9	0.0	0.6	37.0	3927.9	0.0	0.0	1.3	0.0	14765.8
GTO	734.3	0.0	0.0	8.9	5654.9	0.0	0.0	774.9	0.0	7173.0
NSO	3057.8	0.0	0.0	0.8	1875.9	0.0	0.0	0.0	0.0	4934.4
MEO	976.7	0.0	0.0	11.2	307.6	0.0	0.0	15.3	0.0	1310.8
LMO	633.0	0.0	0.0	25.2	4642.8	0.6	0.0	1569.5	0.0	6871.1
MGO	854.0	0.0	0.0	14.5	3089.8	0.0	0.0	0.0	0.0	3958.3
HEO	875.4	0.0	0.0	0.1	1270.0	0.0	0.0	0.0	0.0	2145.6
Other	453.7	0.0	0.0	0.5	157.8	0.0	0.0	0.0	0.0	612.0
Total	102618.3	0.5	24.2	180.0	33837.8	3.2	0.0	2673.1	0.0	139337.1

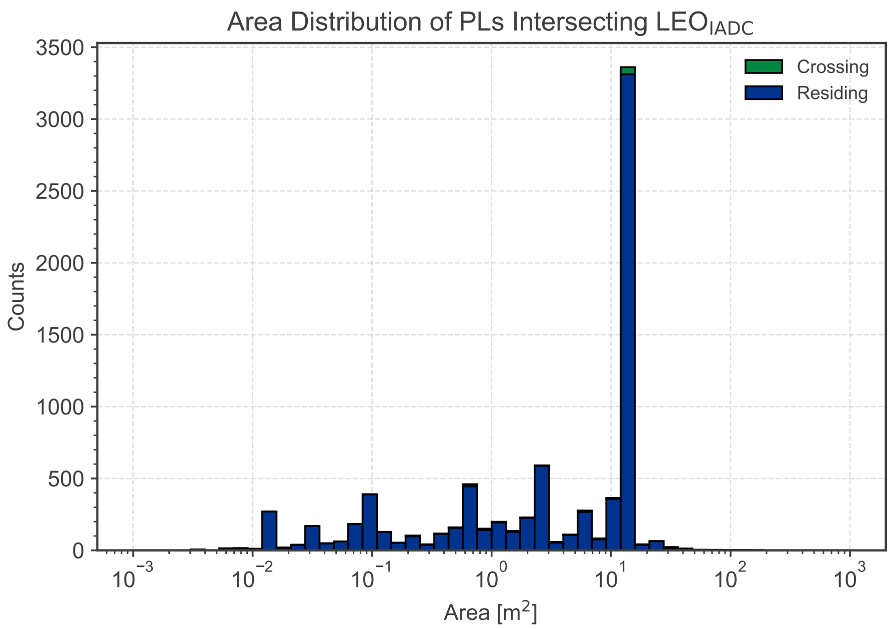
Table 3.6: Absolute and equivalent area in m^2 intersecting with the protected regions.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
both (abs)	197.0	0.0	0.0	0.1	1958.2	0.0	0.0	343.0	0.0	2498.3
LEO_{IADC} (abs)	60524.2	0.5	0.0	107.5	22787.8	3.2	0.0	2656.6	0.0	86079.7
LEO_{IADC} (eqv)	59056.4	0.5	0.0	81.6	12257.3	2.7	0.0	521.8	0.0	71920.2
GEO_{IADC} (abs)	28652.5	0.0	23.6	52.1	6471.9	0.0	0.0	344.3	0.0	35544.3
GEO_{IADC} (eqv)	26304.4	0.0	23.6	17.8	2273.3	0.0	0.0	22.6	0.0	28641.7
none (abs)	13638.6	0.0	0.6	20.6	6536.4	0.0	0.0	15.3	0.0	20211.4

3.1. Status of the Environment in LEO

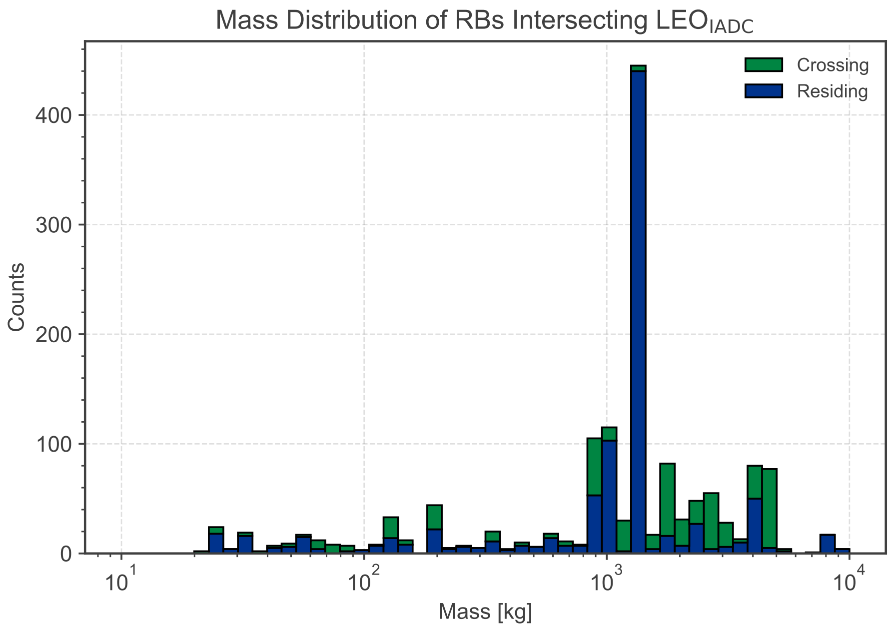


(a) Mass histogram of payloads in LEO.

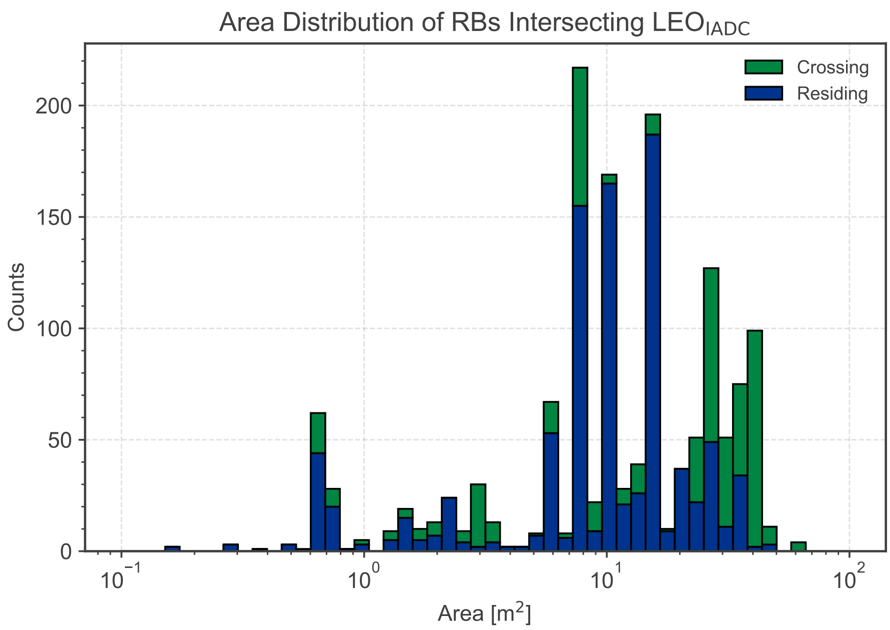


(b) Area histogram of payloads in LEO.

Figure 3.1: Distribution of mass and area of payloads in LEO.

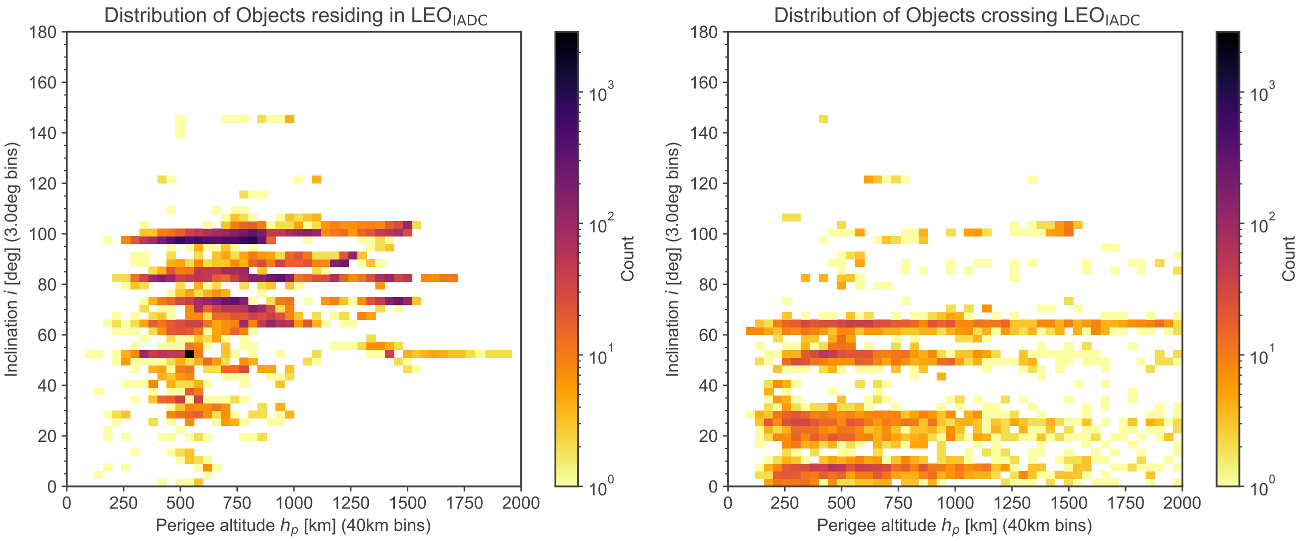


(a) Mass histogram of rocket bodies in LEO.



(b) Area histogram of rocket bodies in LEO.

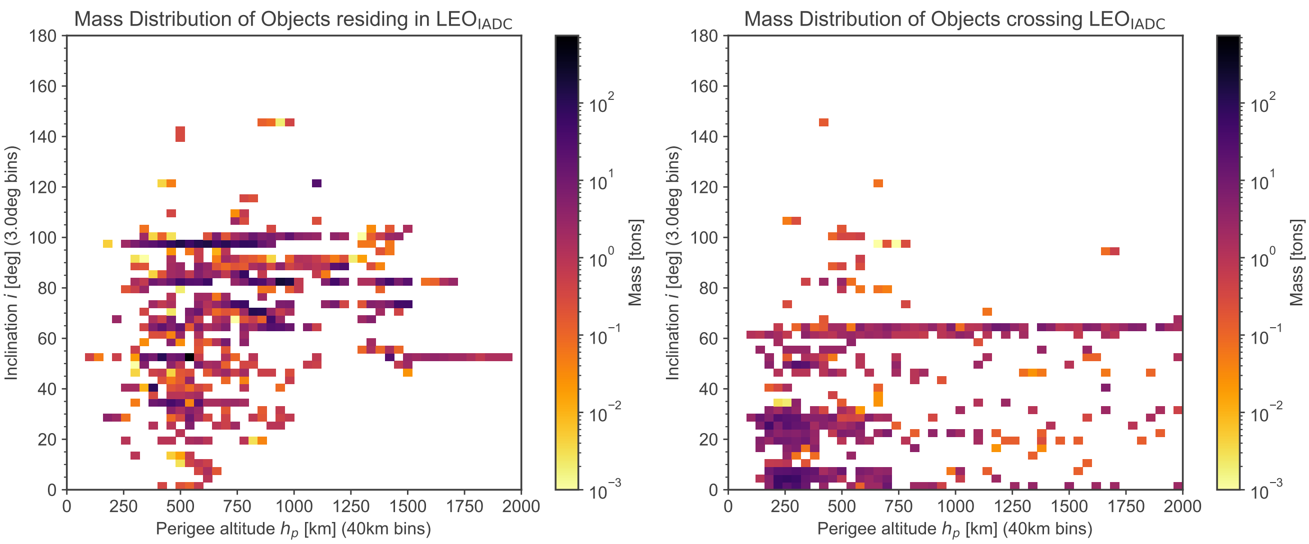
Figure 3.2: Distribution of mass and area of rocket bodies in LEO.



(a) Distribution of objects residing in LEO.

(b) Distribution of objects crossing LEO.

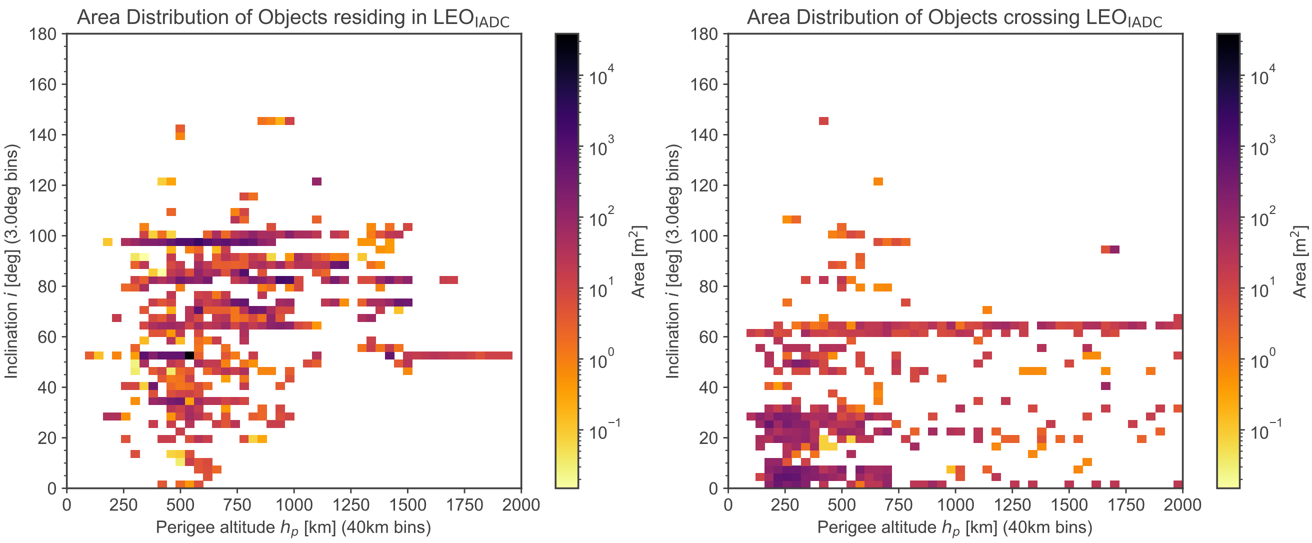
Figure 3.3: Distribution of number of objects in LEO as a function of inclination and perigee altitude.



(a) Mass distribution of objects residing in LEO.

(b) Mass distribution of objects crossing LEO.

Figure 3.4: Distribution of mass in LEO as a function of inclination and perigee altitude.



(a) Area distribution of objects residing in LEO.

(b) Area distribution of objects crossing LEO.

Figure 3.5: Distribution of area in LEO as a function of inclination and perigee altitude.

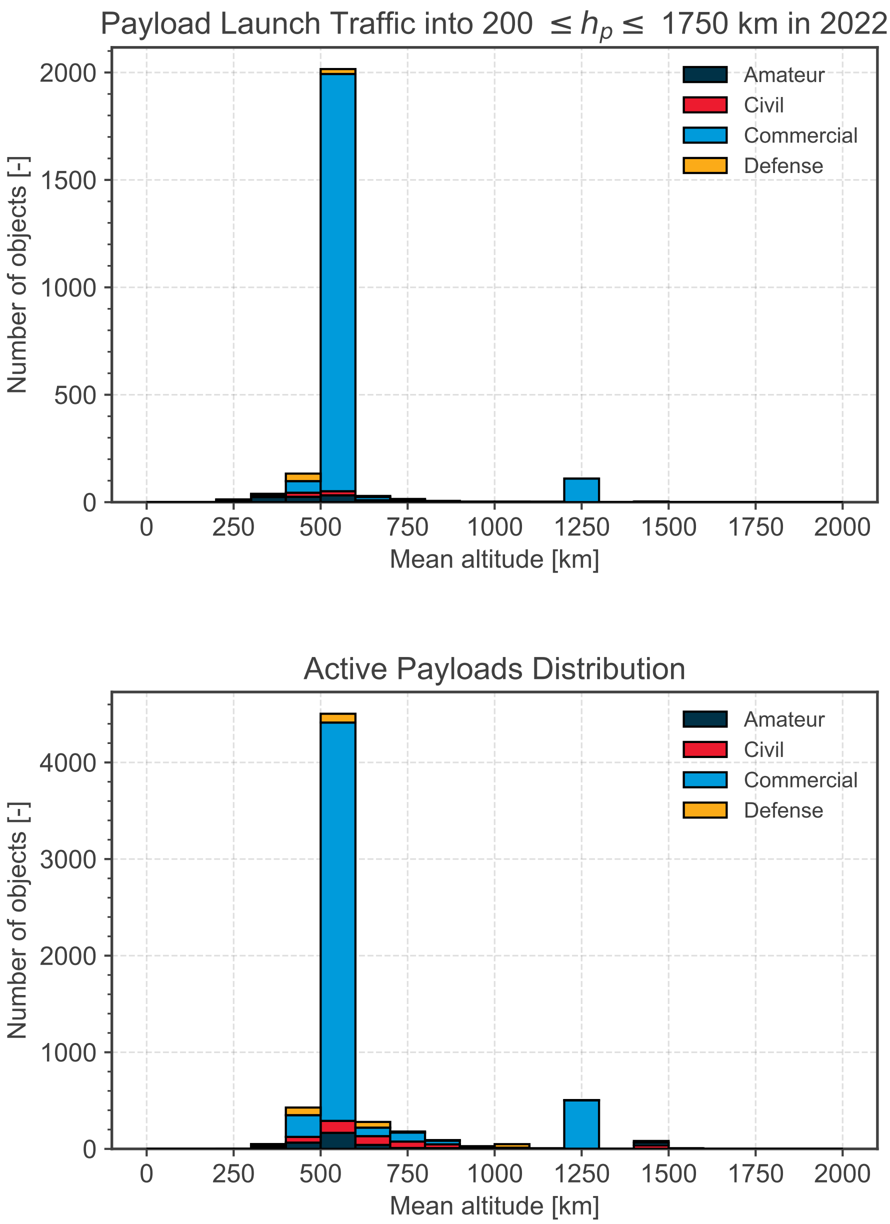


Figure 3.6: Launch traffic in 2022 (top) and distribution of active payloads (bottom) in LEO_{IADC} by mean altitude.

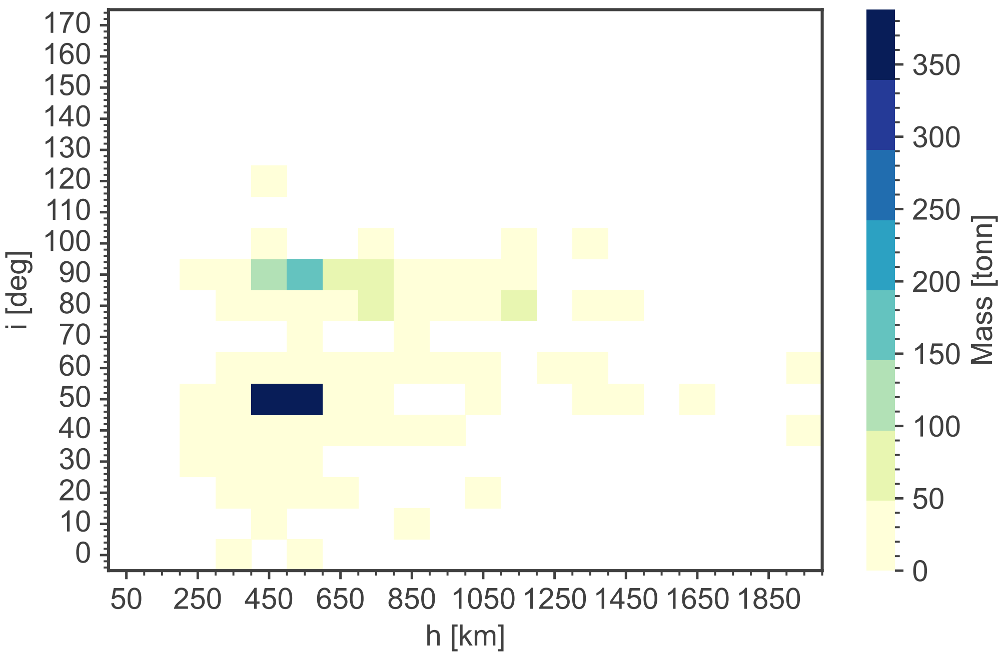
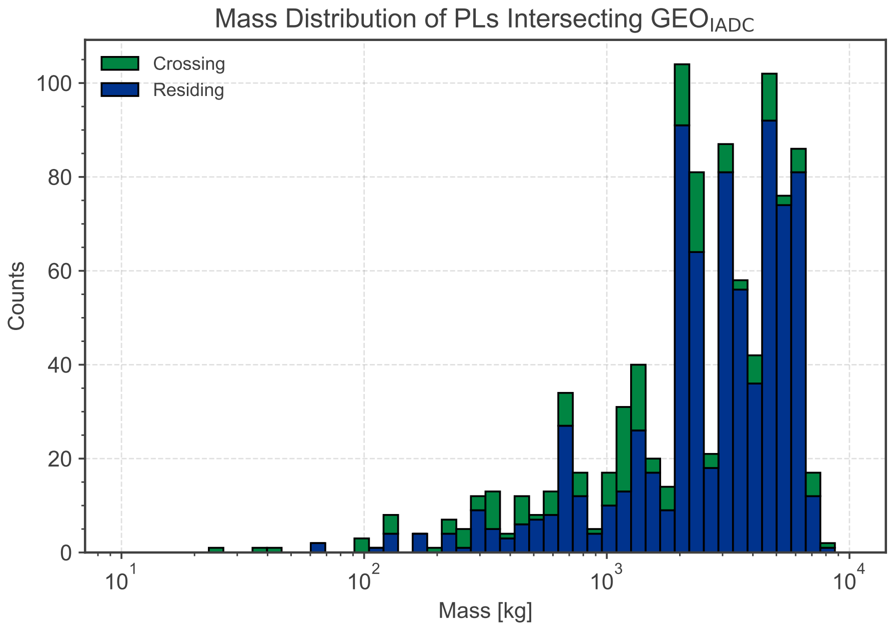
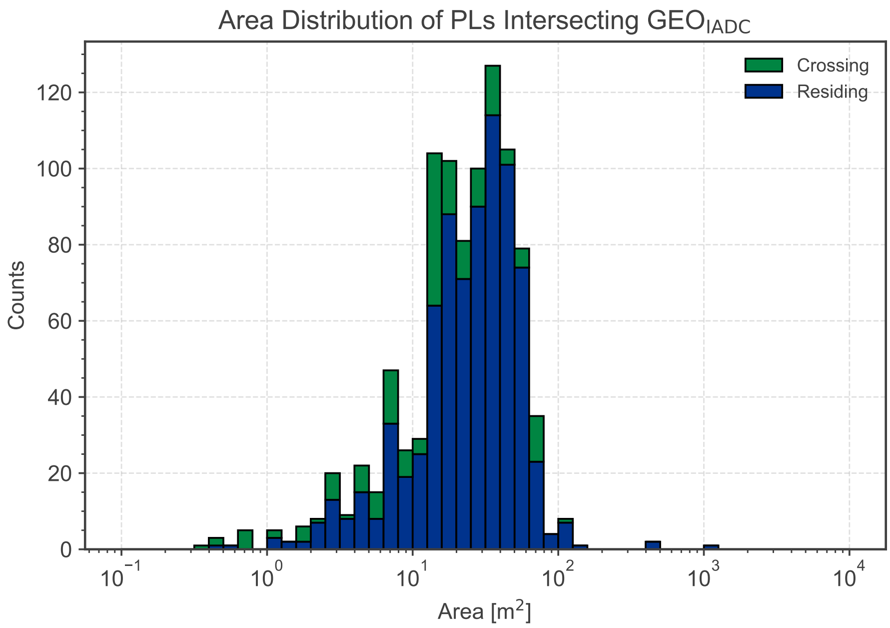


Figure 3.7: Distribution of active payloads in LEO by mean altitude and inclination.

3.2. Status of the Environment in GEO

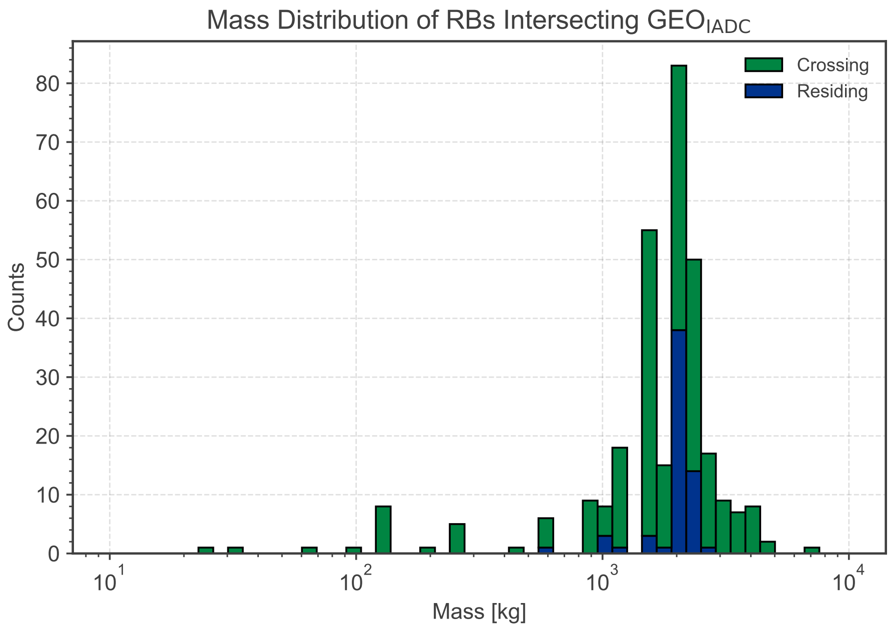


(a) Mass histogram of payloads in GEO.

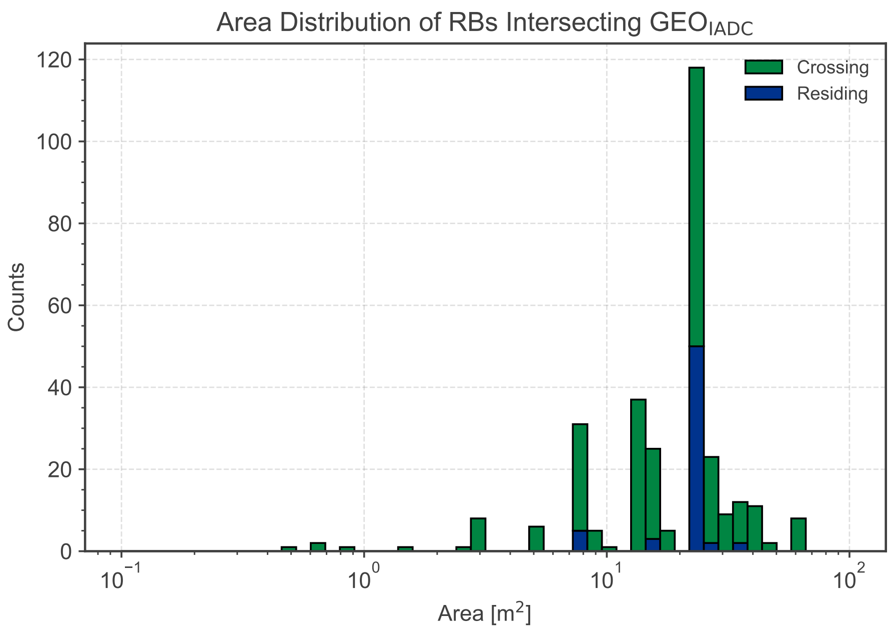


(b) Area histogram of payloads in GEO.

Figure 3.8: Distribution of mass and area of payloads in GEO.



(a) Mass histogram of rocket bodies in GEO.



(b) Area histogram of rocket bodies in GEO.

Figure 3.9: Distribution of mass and area of rocket bodies in GEO.

3.3. Fragmentations in 2022

In Table 3.7 all established fragmentation events of the year 2022 are shown. For a description of the event categories, please consult Section 5. In case no credible source is available on the amount of Asserted Objects associated with a fragmentation event, it is indicated with None. Those Asserted Object are reported by space surveillance networks which can have variable detection limits. A more in-depth overview of the consequences of those events can be accessed online [13].

Table 3.7: Fragmentation events in 2022.

Event epoch	Object type	Mass [kg]	Catalogued objects	Asserted objects	Orbit	Event cause
2022-04-15	Rocket Mission Related Object	55	1	19	LMO	Propulsion
2022-07-03	Rocket Mission Related Object	200	6	52	LEO	Small Impactor
2022-11-12	Rocket Body	1850	331		LEO	Propulsion
2022-11-17	Rocket Mission Related Object	100	37	50	LEO	Unknown
Total		2205	375			

3.4. Changes to the Environment in 2022

In this section, the change to the environment during 2022 is listed. The last state of the year is used to classify the object orbit. If no state is available, a destination orbit defined by an analyst is used instead.

Table 3.8: Number of newly added objects orbiting Earth. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	2359	0	9	17	86	315	0	168	282	3236
GEO	22	0	1	0	0	0	0	0	5	28
EGO	3	0	0	0	2	0	1	0	278	284
GTO	3	0	0	0	7	0	0	2	59	71
NSO	3	0	0	0	3	0	0	0	16	22
MEO	9	0	0	0	2	0	0	0	54	65
LMO	1	0	0	0	3	1	0	0	116	121
MGO	0	0	0	0	2	0	0	0	227	229
HEO	7	0	0	0	7	0	0	0	124	138
Other	2	0	0	0	1	0	0	0	6	9
N/A	3	0	0	0	0	3	0	0	0	6
Total	2409	0	10	17	113	316	1	170	1167	4203

Table 3.9: Absolute and equivalent number of newly added objects intersecting with the protected regions.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
both (abs)	4	0	0	0	6	0	0	1	27	38
LEO_{IADC} (abs)	2367	0	9	17	104	316	0	170	468	3451
LEO_{IADC} (eqv)	2360	0	9	17	87	315	0	168	293	3249
GEO_{IADC} (abs)	30	0	1	0	6	0	1	1	457	496
GEO_{IADC} (eqv)	22	0	1	0	0	0	1	0	30	54
none (abs)	16	0	0	0	9	0	0	0	269	294

Table 3.10: Newly added mass in tons orbiting Earth. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	816.1	0.0	0.0	10.5	210.7	0.0	0.0	6.4	2.3	1046.0
GEO	77.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	77.1
EGO	1.0	0.0	0.0	0.0	4.2	0.0	0.0	0.0	0.0	5.2
GTO	8.3	0.0	0.0	0.0	21.9	0.0	0.0	0.9	0.0	31.1
NSO	3.4	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	6.4
MEO	3.7	0.0	0.0	0.0	4.9	0.0	0.0	0.0	0.0	8.6
LMO	2.0	0.0	0.0	0.0	9.9	0.0	0.0	0.0	0.0	11.9
MGO	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	4.0
HEO	24.9	0.0	0.0	0.0	29.3	0.0	0.0	0.0	0.0	54.2
Other	10.4	0.0	0.0	0.0	7.3	0.0	0.0	0.0	0.0	17.7
N/A	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6
Total	946.9	0.0	0.0	10.5	295.3	0.0	0.0	7.3	2.3	1262.3

Table 3.11: Absolute and equivalent newly added mass in tons intersecting with the protected regions.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
both (abs)	14.5	0.0	0.0	0.0	29.5	0.0	0.0	0.4	0.0	44.4
LEO_{IADC} (abs)	841.7	0.0	0.0	10.5	279.1	0.0	0.0	7.3	2.3	1140.9
LEO_{IADC} (eqv)	817.3	0.0	0.0	10.5	214.5	0.0	0.0	6.5	2.3	1051.1
GEO_{IADC} (abs)	111.6	0.0	0.0	0.0	29.5	0.0	0.0	0.4	0.0	141.5
GEO_{IADC} (eqv)	77.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	77.7
none (abs)	8.1	0.0	0.0	0.0	16.1	0.0	0.0	0.0	0.0	24.3

Table 3.12: Newly added area in m^2 orbiting Earth. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	24562.5	0.0	0.0	67.5	1571.7	0.0	0.0	77.7	16.3	26295.6
GEO	689.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	689.9
EGO	6.2	0.0	0.0	0.0	58.3	0.0	0.0	0.0	0.0	64.5
GTO	48.0	0.0	0.0	0.0	207.5	0.0	0.0	54.8	0.0	310.2
NSO	15.6	0.0	0.0	0.0	25.1	0.0	0.0	0.0	0.0	40.7
MEO	55.1	0.0	0.0	0.0	42.2	0.0	0.0	0.0	0.0	97.3
LMO	14.3	0.0	0.0	0.0	107.5	0.6	0.0	0.0	0.0	122.4
MGO	0.0	0.0	0.0	0.0	64.5	0.0	0.0	0.0	0.0	64.5
HEO	296.6	0.0	0.0	0.0	275.3	0.0	0.0	0.0	0.0	571.9
Other	13.5	0.0	0.0	0.0	60.9	0.0	0.0	0.0	0.0	74.4
N/A	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0
Total	25701.7	0.0	0.0	67.5	2412.9	0.6	0.0	132.5	16.3	28331.4

Table 3.13: Absolute and equivalent newly added area in m^2 intersecting with the protected regions.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
both (abs)	33.1	0.0	0.0	0.0	262.5	0.0	0.0	27.4	0.0	323.0
LEO_{IADC} (abs)	24672.6	0.0	0.0	67.5	2222.9	0.6	0.0	132.5	16.3	27112.3
LEO_{IADC} (eqv)	24571.0	0.0	0.0	67.5	1612.1	0.1	0.0	80.0	16.3	26346.9
GEO_{IADC} (abs)	985.1	0.0	0.0	0.0	262.5	0.0	0.0	27.4	0.0	1275.0
GEO_{IADC} (eqv)	693.0	0.0	0.0	0.0	0.8	0.0	0.0	1.1	0.0	694.9
none (abs)	77.0	0.0	0.0	0.0	190.0	0.0	0.0	0.0	0.0	267.1

Table 3.14: Number of re-entered objects. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	354	1615	6	28	61	134	1	185	40	2424
LMO	0	1	0	1	6	0	0	0	0	8
Other	2	0	0	0	1	0	0	0	0	3
N/A	1	1	1	0	1	0	0	0	0	4
Total	356	1616	6	29	68	134	1	185	40	2435

Table 3.15: Re-entered mass in tons. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	133.0	0.0	0.0	13.3	150.6	0.0	0.0	9.7	2.3	308.9
LMO	0.0	0.0	0.0	0.0	20.6	0.0	0.0	0.0	0.0	20.6
Other	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	3.0
N/A	2.3	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	3.9
Total	133.0	0.0	0.0	13.3	174.2	0.0	0.0	9.7	2.3	332.5

Table 3.16: Re-entered area in m^2. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	1719.4	0.0	0.0	91.0	1299.3	0.0	0.0	234.2	16.3	3360.2
LMO	0.0	0.0	0.0	0.0	229.5	0.0	0.0	0.0	0.0	229.5
Other	0.2	0.0	0.0	0.0	46.4	0.0	0.0	0.0	0.0	46.6
N/A	14.1	0.0	0.0	0.0	14.5	0.0	0.0	0.0	0.0	28.6
Total	1719.6	0.0	0.0	91.0	1575.2	0.0	0.0	234.2	16.3	3636.3

3.5. Conjunction statistics in LEO in 2022

This section aims to provide an assessment of the short-term risk related to space debris, quantified in terms of the number of conjunctions expected in different orbital regions, distinguishing also the type of secondary object involved in the conjunction. For the purpose of this report, a *conjunction* is understood as a geometric close approach between two objects, irrespective of their activity status, triggering an operator analysis but not necessarily an avoidance manoeuvre nor implying a collision.

The first step of the analysis is to define some representative *target* (or primary) objects in the conjunctions. The physical characteristics of the objects are derived from the average parameters of active payloads in LEO_{IADC}, reported in Fig. 2.27. In particular, a mass value of 355 kg and a cross-sectional area of 6 m^2 were used for the analysis based on the averages for 2020 and applied also to 2022 considering the consistent trend in the properties shown in Fig. 2.27. For what concerns the orbital parameters of the targets, two approaches are used here. The first set of representative targets is defined by looking at the distribution of active payloads in LEO_{IADC} in semi-major axis and inclination as shown in Fig. 3.7, and a total of seven targets were defined for this analysis. The second approach is to define a set of targets in the Sun-Synchronous region; in particular, seven targets are defined to cover the region between 400 and 1000 km in altitude. In both cases, twelve values of the initial longitude of ascending nodes are considered and the results presented in the following are the mean across the simulated cases for each target.

In both cases, the trajectory of the targets is propagated for one year (from 1st January 2022 to 31st December 2022) and for each day of the year an analysis is run to detect potential conjunctions with catalogued objects, by using ESA CRASS (Collision Risk ASsessment Software) [14]. For the analysis shown here, General Perturbations (GP) data is retrieved to define the orbits of the secondary objects involved in the conjunctions [15]. The data in DISCOS is used to further characterise the secondary object, for example in terms of its size and its category. In addition to the object categories defined in Section 1.1, the following subcategories are introduced:

- *Payloads* is further distinguished in:
  - *Constellation objects*, payloads belonging to a constellation,
  - *Small satellites*, payloads with a mass smaller than 15 kg,
  - *Other Payloads*, all the other payloads.
- *Payload fragmentation debris*, four subcategories were defined to collect objects belonging to the fragmentation events with the highest number of catalogued objects.
  - *Fengyun 1C Fragmentation Debris*, objects generated by the fragmentation of Fengyun 1C (1999-25A), with mass 958.0, on the 11/01/2007 at an altitude between 843.3 and 863.3 km and inclination of 98.6 degrees.
  - *Cosmos-2251 Fragmentation Debris*, objects generated by the fragmentation of Cosmos-2251 (1993-36A), with mass 892.0, on the 10/02/2009 at an altitude between 776.1 and 791.1 km and inclination of 86.4 degrees.
  - *Iridium 33 Fragmentation Debris*, objects generated by the fragmentation of Iridium 33 (1997-51C), with mass 661.0, on the 10/02/2009 at an altitude between 776.2 and 779.4 km and inclination of 86.4 degrees.
  - *Cosmos-1408 Fragmentation Debris*, objects generated by the fragmentation of Cosmos-1408 (1982-92A), with mass 2180.4, on the 15/11/2021 at an altitude between 465.0 and 490.5 km and inclination of 82.6 degrees.

- *Other Payload fragmentation debris*, all the other payload fragmentation debris.

- *Rocket fragmentation debris*, four subcategories were defined to collect objects belonging to the fragmentation events with the highest number of catalogued objects.

  - *Centaur-5 SEC Fragmentation Debris*, objects generated by the fragmentation of Centaur-5 SEC (2018-79B), with mass 2020.0, on the 06/04/2019 at an altitude between 8526.3 and 35092.8 km and inclination of 12.0 degrees.

  - *HAPS Fragmentation Debris*, objects generated by the fragmentation of HAPS (1994-29B), with mass 96.1, on the 03/06/1996 at an altitude between 584.1 and 818.9 km and inclination of 82.0 degrees.

  - *Centaur-5 SEC Fragmentation Debris*, objects generated by the fragmentation of Centaur-5 SEC (2009-47B), with mass 2020.0, on the 25/03/2019 at an altitude between 6673.4 and 34706.6 km and inclination of 23.3 degrees.

  - *Other Rocket fragmentation debris*, all the other rocket fragmentation debris.

Additional information on the fragmentation events can be found in ESA Fragmentation Database [13].

For each conjunction, the encounter geometry (i.e. the relative orientation of the orbits and time of closest approach) is retrieved from CRASS, whereas the computation of the collision probability is performed using Alfriend-Akella's method [16]. The values of positional uncertainty required for the collision probability calculation are obtained with the methodology in [17], where the covariance for an object is dependent on its size, orbit (i.e. perigee altitude, eccentricity, inclination) and time between the assessment and the Time of Close Approach (TCA).

In the results in the following, the conjunctions are grouped in *events*, where an event is defined by a pair of primary and secondary object and a given TCA. The number of conjunction events with collision probability above 10^{-6} within three days to TCA is shown in Fig. 3.10 and Fig. 3.11, which refer, respectively, to targets defined based on the distribution of payload objects and to targets defined along the Sun-Synchronous region. The threshold at 10^{-6} is usually well below the reaction threshold for payloads in LEO_{IADC} (i.e. the events in Fig. 3.10 and Fig. 3.11 will not all results in collision avoidance manoeuvres), but this threshold could be already representative of events where increased monitoring of the conjunction is activated.

In addition to the yearly statistics, the analysis has been systematically repeated yearly since 2015. This shows, particularly in the lower LEO_{IADC} regime, the increase of conjunction events that require coordination between active operators due to the change in space traffic, whereas higher orbits remain dominated by space debris related events.

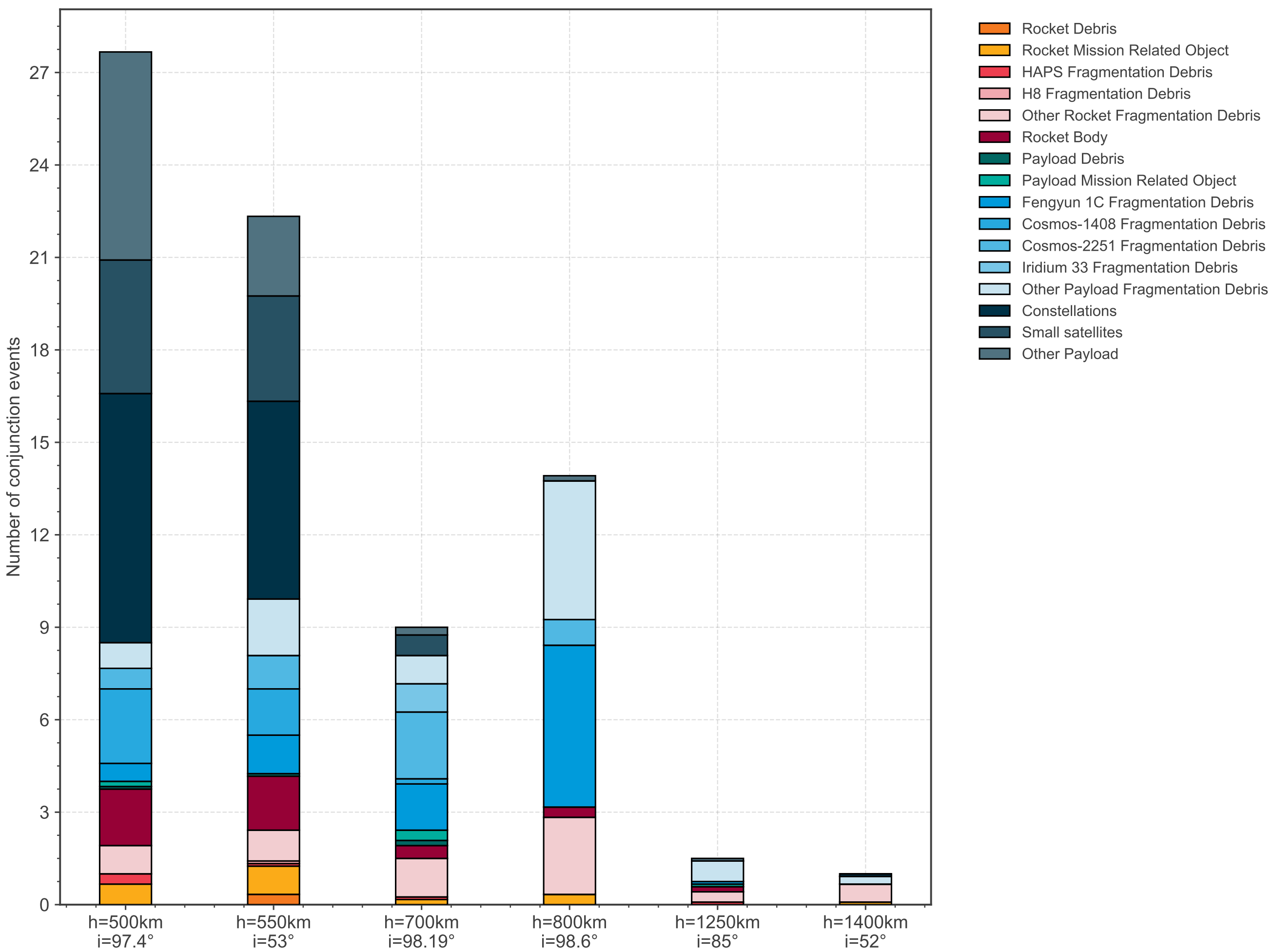


Figure 3.10: Conjunction events, and corresponding chaser classification, for a set of representative targets over 2022.

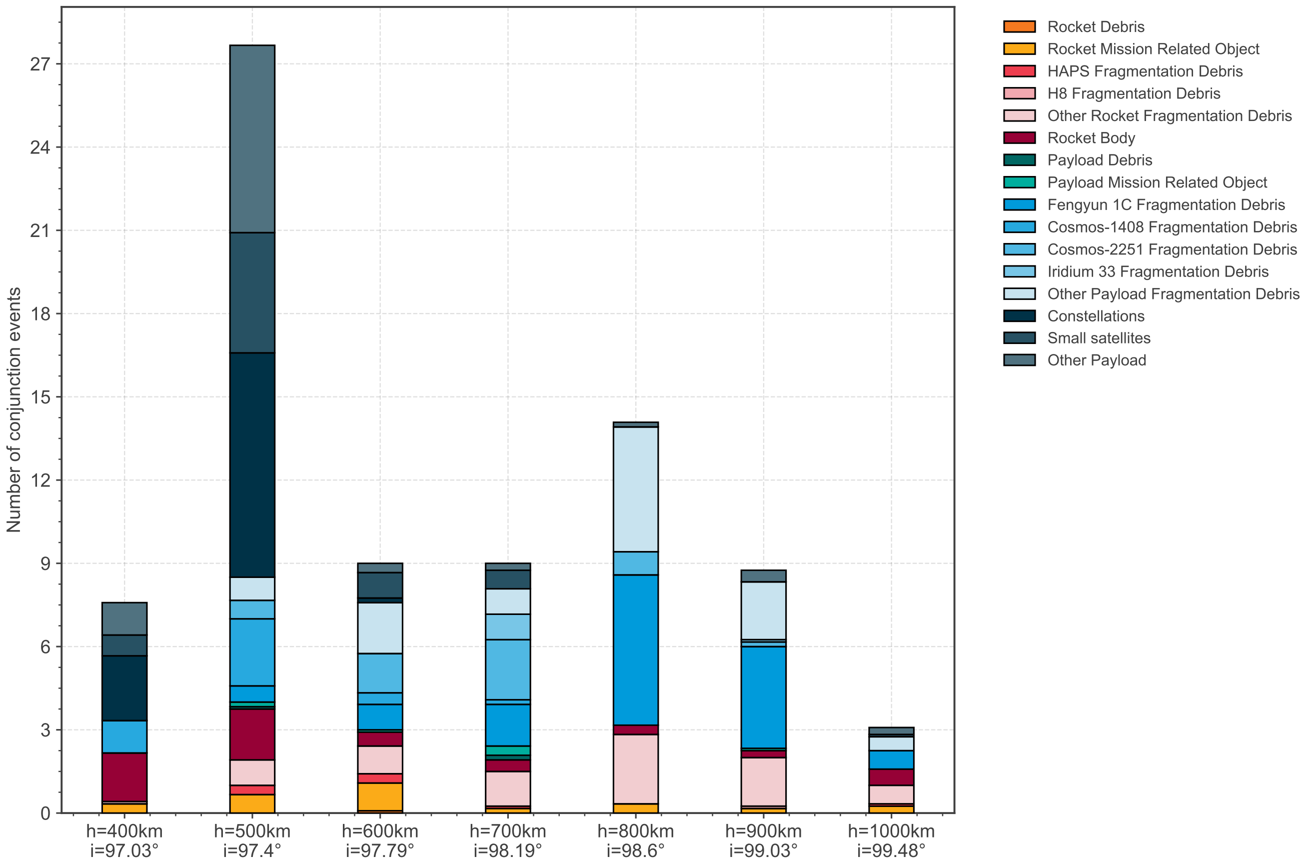


Figure 3.11: Conjunction events, and chaser classification, for a set of representative targets in Sun-synchronous orbits over 2022.

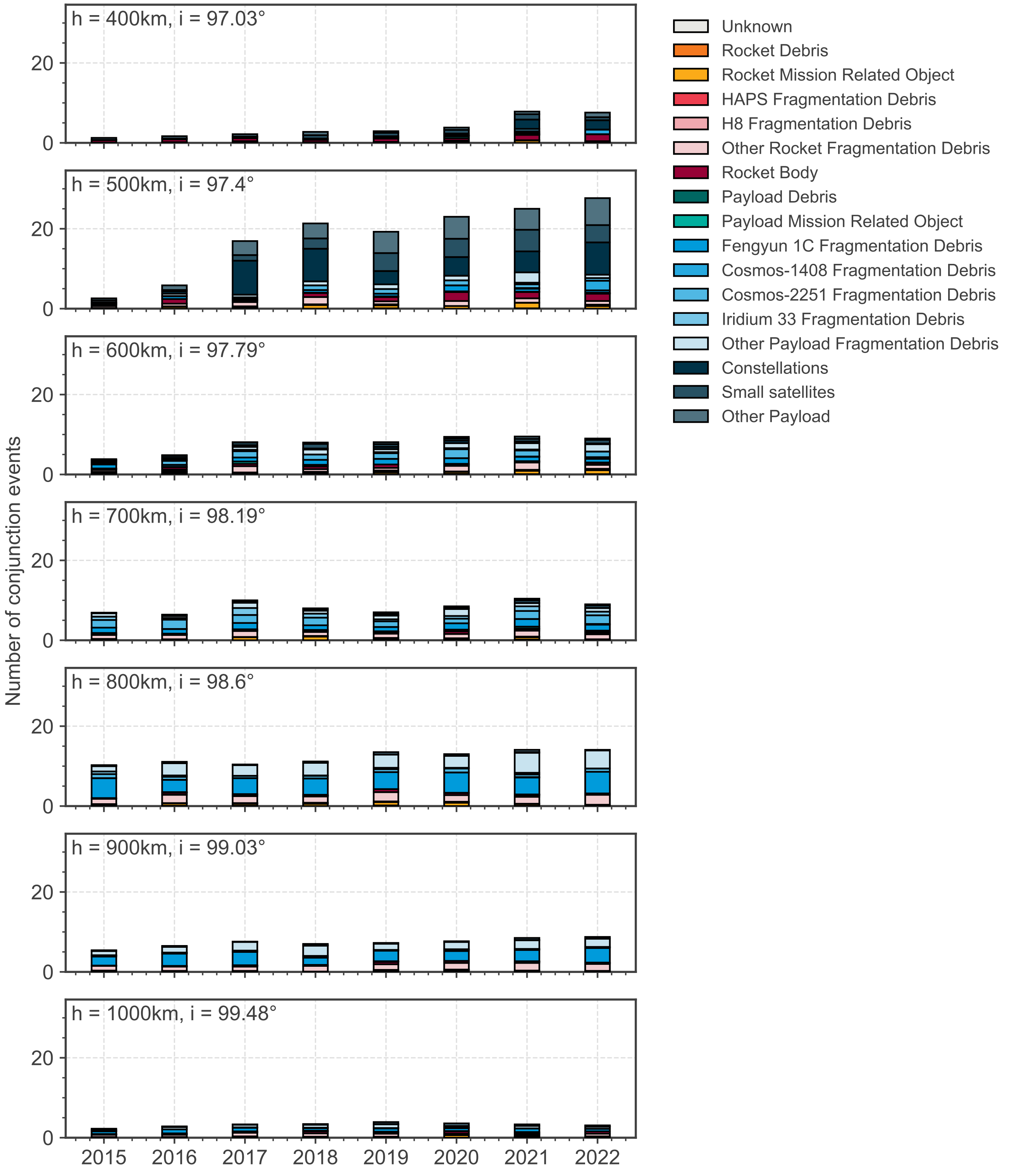


Figure 3.12: Conjunction events, and chaser classification, for a set of representative targets in Sun-synchronous orbits over multiple years.

4. INTENTIONAL OBJECT RELEASE

A major part of the space debris mitigation measures are dedicated to the avoidance of intentionally releasing space debris as part of the mission of a rocket body or payload. This type of mission related objects can generally be sub-categorised into functional parts that are designed to be released after they are no longer required, e.g. covers protecting instruments during launch, or combustion related products that support the main mission, e.g. slag from solid rocket motors, or pyrotechnics. Objects from both subcategories can generally be avoided by design changes on the rocket bodies or payloads. For example, camera covers can be opened and folded away instead, or pyrotechnically expelled and solid rocket motor slag can be avoided by using on-board chemical or electrical propulsion systems. Small, i.e. sub millimetre, combustion related particles do contribute to the space debris environment but are not considered a threat. Most pyrotechnic devices fall under this case.

In this section, the evolution in terms of occurrence of this type of space debris is illustrated.

4.1. Mission Related Objects

As metric for the adherence to space debris mitigations guidelines, the release of catalogued mission related objects can be used. For every single payload and rocket body, the amount of released and catalogued mission related objects are counted. Furthermore, the fraction of payloads and rocket bodies releasing mission related objects to the total amount of payloads and rocket bodies launched in given year is presented.

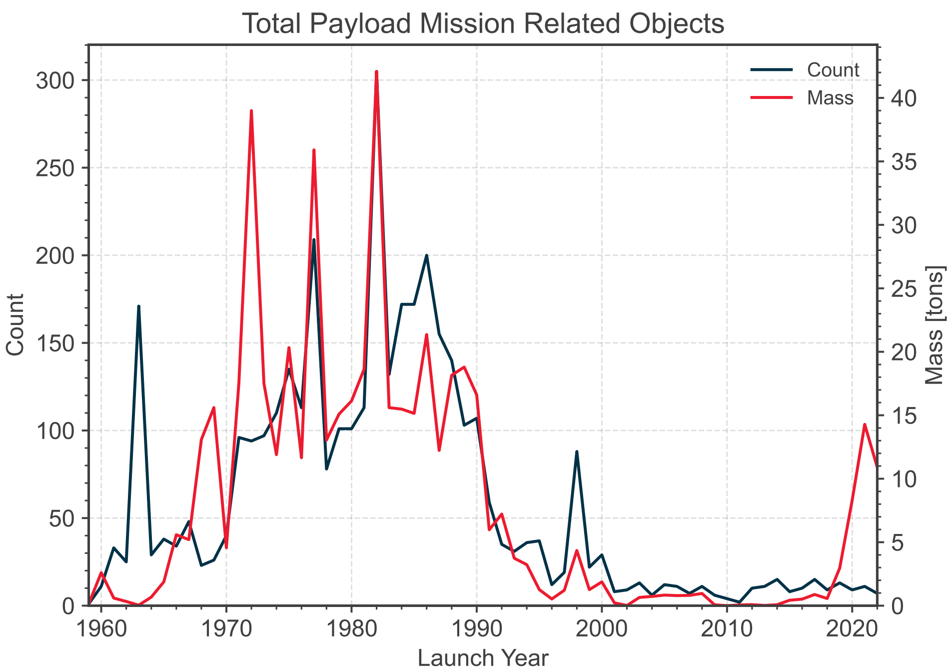


Figure 4.1: Total number and mass of catalogued mission related objects released from payloads.

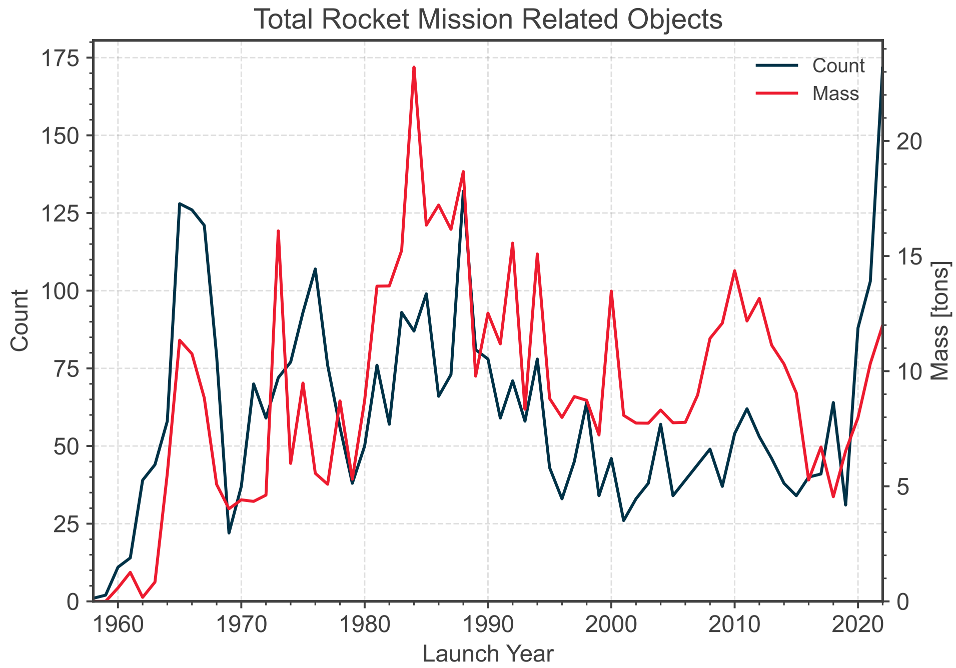


Figure 4.2: Total number and mass of catalogued mission related objects released from rocket bodies.

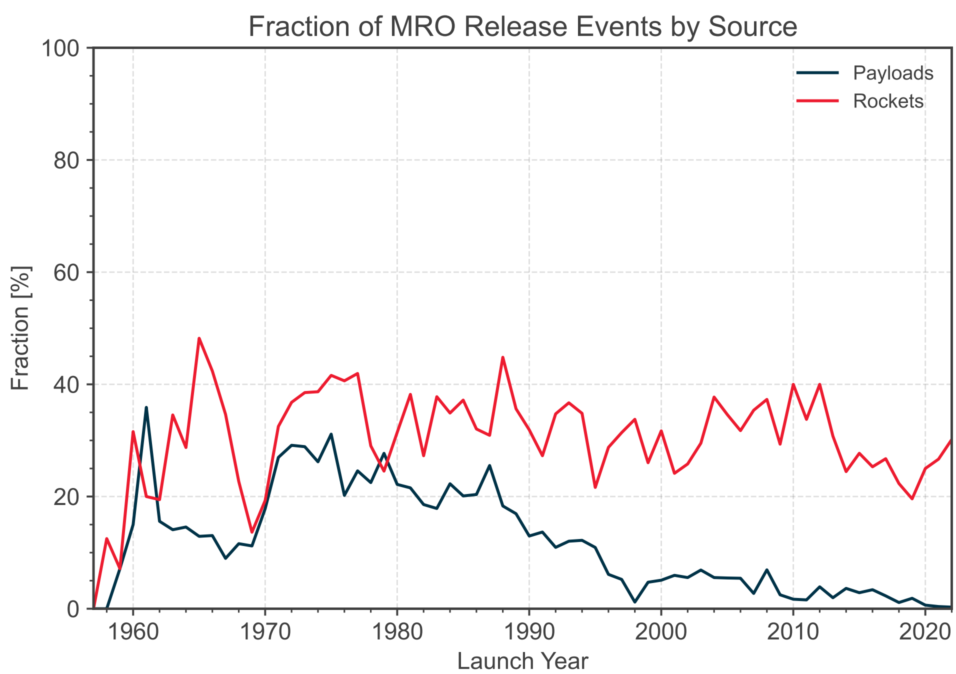


Figure 4.3: Fraction of mission related objects releases per year w.r.t. the total amount of payloads and rocket bodies injected into the space environment during that year.

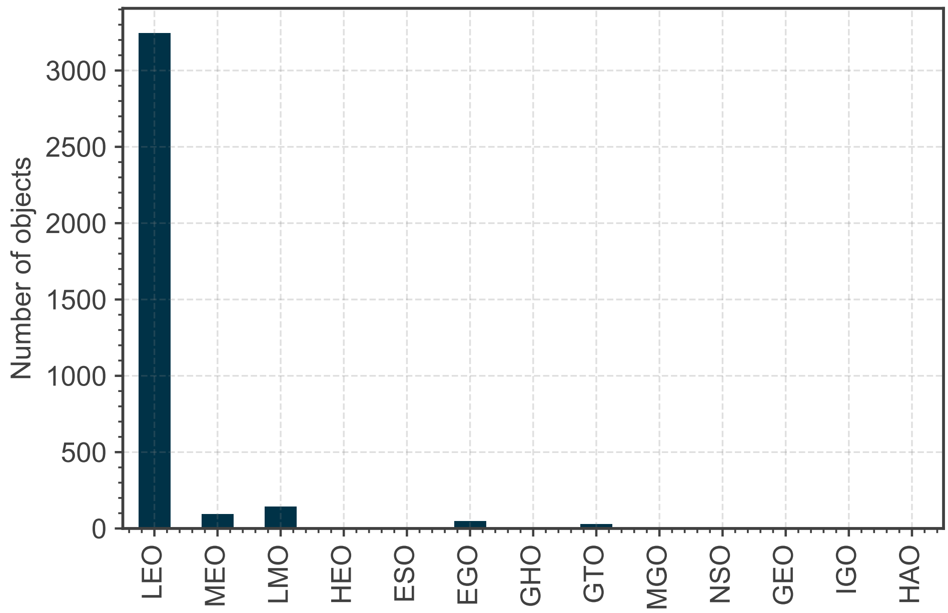


Figure 4.4: Distribution of release orbits for Payload Mission Related Objects since the start of the space age.

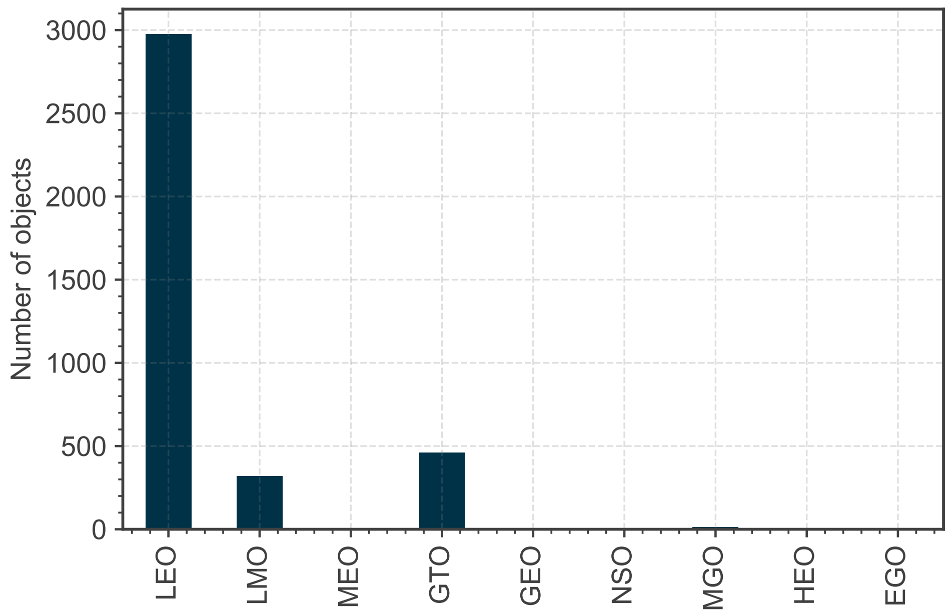


Figure 4.5: Distribution of release orbits for Rocket Body Mission Related Objects since the start of the space age.

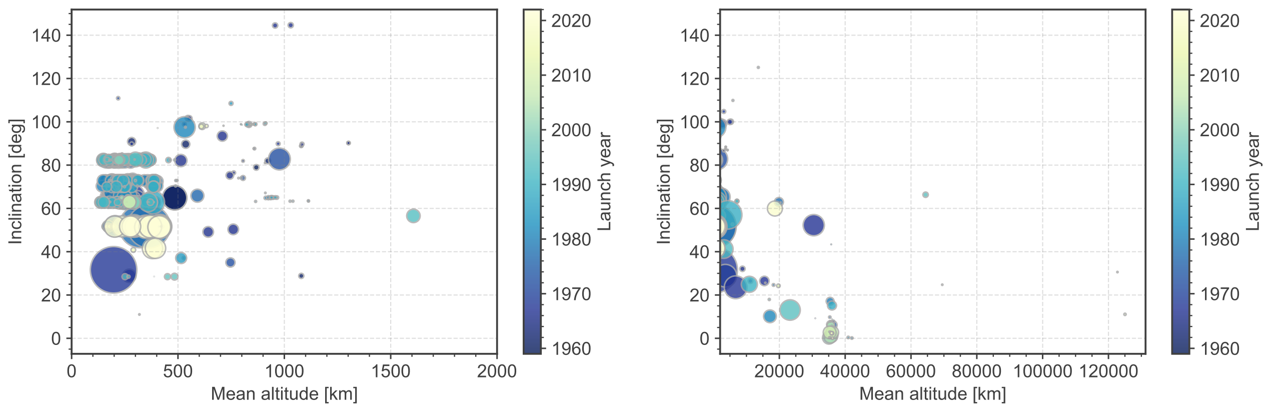


Figure 4.6: Distribution of release orbits for Payload Mission Related Objects in LEO (left) and outside LEO (right). The size of the marker is proportional to the object mass.

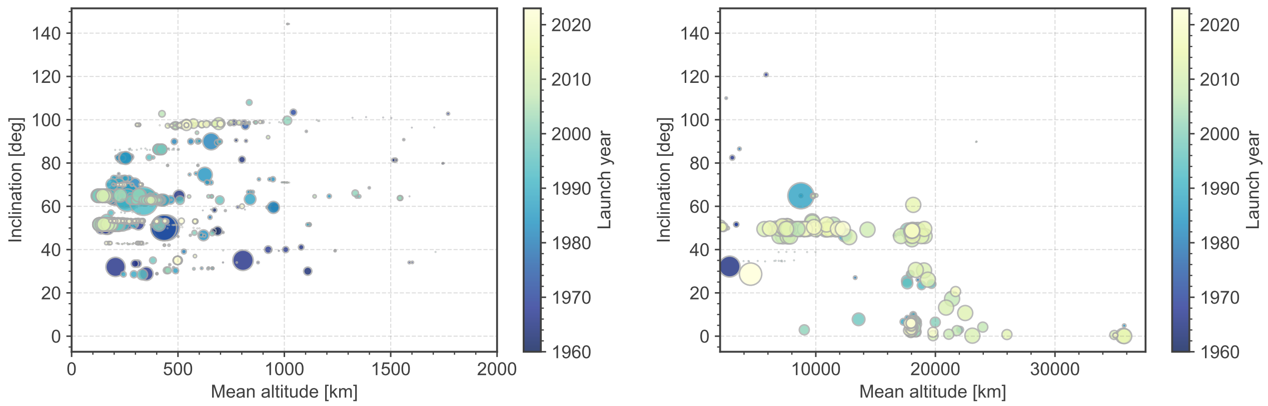


Figure 4.7: Distribution of release orbits for Rocket Body Mission Related Objects in LEO (left) and outside LEO (right). The size of the marker is proportional to the object mass.

4.2. Solid Rocket Motor Firings

As a metric of the adherence to space debris mitigations guidelines the amount of solid rocket motor firings for asserted objects can be used. The propellant mass associated with each firing is given versus the date of the firing. Not all solid rocket motor firings are equally damaging for the space environment, i.e. solid rocket motor fuels which do not create large slag particles have been developed. However, such an identification is not made in this section.

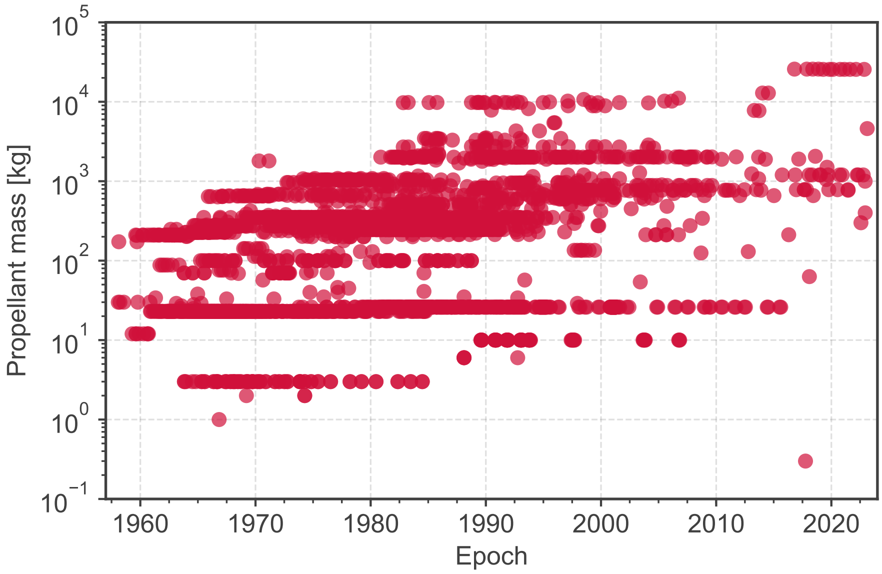


Figure 4.8: Evolution solid rocket motor firings.

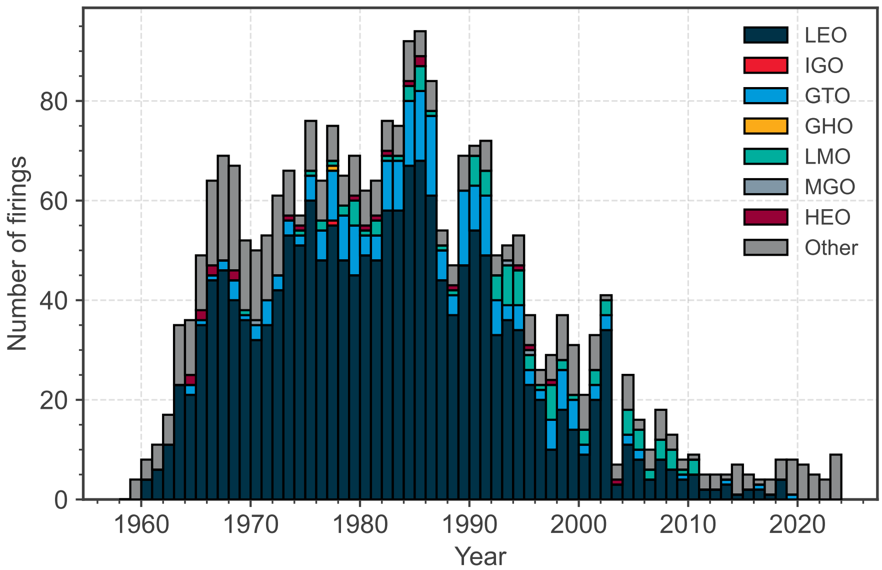


Figure 4.9: Evolution solid rocket motor firings by orbit type.

5. FRAGMENTATION HISTORY

Since the beginning of the space age until the end of 2022, there have been 643 confirmed on-orbit fragmentation events. In Figure 5.2, the historical trend of the amount of fragmentation events per year is shown, as a function of the event date and the launch date, respectively. Fragmentation events are currently being categorised in main and sub-classes according to the assessed break-up cause. In the first list of classes, the break-up cause is fairly well known:

Accidental: Subsystems that showed design flaws ultimately leading to breakups in some cases. This includes, for example, the breakup of Hitomi (Astro-H) in 2016 or the sub-class of Oko satellites.

Cosmos 862 Class (Explosive Charge): The Oko missile early warning satellites were launched into Molniya orbits. Each satellite carried an explosive charge in order to destroy it in case of a malfunction. Reportedly, the control of this mechanism was unreliable.

Aerodynamics: A breakup most often caused by an overpressure due to atmospheric drag.

Collision: There have been several collisions observed between objects. A sub-class are so-called small impactors.

Small Impactor: Caused by a collision, but without explicit evidence for an impactor. Changes in the angular momentum, attitude and subsystem failures are, however, indirect indications of an impact.

Deliberate: All intentional breakup events.

ASAT: Anti-satellite tests.

Cosmos 2031 Class: The Orlets reconnaissance satellites were introduced in 1989 and employed detonation as a standard procedure after the nominal mission.

Payload Recovery Failure: Some satellites were designed such that they exploded as soon as a non-nominal re-entry was detected.

RORSAT Reactor Core Ejection Class: Between 1980 and 1988, the Soviet Union re-orbited their Radar Ocean Reconnaissance Satellites (RORSAT) after a successful mission to a sufficiently high orbit around 900 km altitude. The manoeuvre was followed by a reactor core ejection, which resulted in an opening of the primary coolant loop (Sodium-Potassium or NaK alloy) and an associated release of NaK droplets.

Electrical: Most of the events in this category occurred due to an overcharging and subsequent explosion of batteries. A sub-class is defined based on the satellite bus.

Battery: Battery-related explosions may occur due to over-charging, over-temperature, short-circuits, over-discharging, structural issues or damage, in each cases leading to a thermal run-away and subsequent breakup.

DMSP/NOAA Class: Based on the Television and InfraRed Observation Satellite (TIROS-N) satellite bus, some of the satellites in this series suffered from battery explosions.

Propulsion: Stored energy for non-passivated propulsion-related subsystems might lead to an explosion, for example due to thermal stress. Several sub-classes are defined for rocket stages that showed repeated breakup events.

Ariane Upper Stage: Breakups for the H8 and H10 cryogenic stages were observed, most likely due to overpressure and subsequent bulkhead rupture. Passivation was introduced in 1990.

Briz-M: The fourth stage of the Proton rocket which is used to insert satellites into higher orbits.

Delta Upper Stage: There were several events for Delta second stages due to residual propellants until depletion burns were introduced in 1981.

Proton Ullage Motor: The Blok D/DM upper stages of the Proton rocket used two ullage motors to support the main engine. They were released as the main engine performed its final burn.

Titan Transtage: The upper stage of the Titan 3A rocket used a hypergolic fuel oxidizer combination.

Tsyklon Upper Stage: The third stage of the Tsyklon-3 launcher used a hypergolic fuel oxidizer combination.

Zenit-2 Upper Stage: The second stage of the Zenit 2 launcher used an RP-1/Liquid oxygen propellant.

A second list of classes relates to break-ups where the cause has not been well established. Events or sub-classes within these classes could be reclassified in the future:

Anomalous: Defined as the unplanned separation, usually at low velocity, of one or more detectable objects from a satellite that remains essentially intact. This may include debris shedding due to material deterioration, which includes insulation material or solar panels all of which have been observed from ground in the past. Events with sufficient evidence for an impact of debris or micrometeroids are classified under Small Impactor. Sub-classes for anomalous events are defined, as soon as events occur multiple times for the same spacecraft or bus type.

Cosmos-3 Class: Soviet/Russian launcher for small satellites.

Delta 4 Class: Events with several catalogued objects for the Delta Cryogenic Second Stages (DCSS).

ERS/SPOT Class: Both the ERS-1 and -2 satellites, as well as the SPOT-4 satellite had confirmed anomalies and fragments were catalogued.

Meteor Class: Russian meteorological satellite family.

Scout Class: Refers to the Altair upper stage of the Scout rocket family.

TOPAZ Leakage Class: There are two known events for TOPAZ satellites where NaK droplets have been observed in the vicinity of the parent object presumably due to leakage [18].

Transit Class: Satellites of the U.S. Navy's first satellite navigation system operational between 1964 and 1996.

Vostok Class: Refers to the upper stage of the Vostok rocket (Blok E).

Assumed: Introduced for the MASTER model. Currently the only assumed events are in the GEO region, backed by information obtained during survey campaigns [19].

Unconfirmed: A provisional status until an event is confirmed and classified accordingly.

Unknown: Is assigned whenever there is lacking evidence to support a more specific classification.

Cosmos 699 Class (EORSAT): For many of the ELINT Ocean Reconnaissance Satellites (EORSAT) a breakup was observed during the orbital decay.

H-IIA Class: The second stage of the H-IIA launcher used a cryogenic propellant.

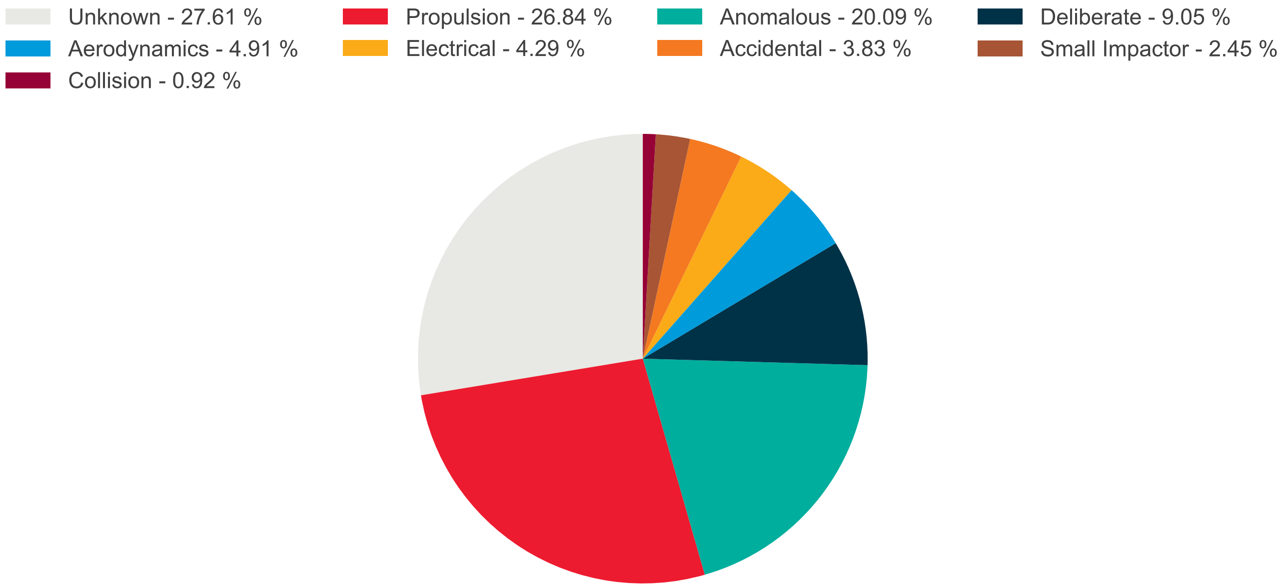
L-14B Class: The third stage of the Long March 4B (CZ-4B) launcher used a hypergolic propellant.

5.1. All fragmentation events

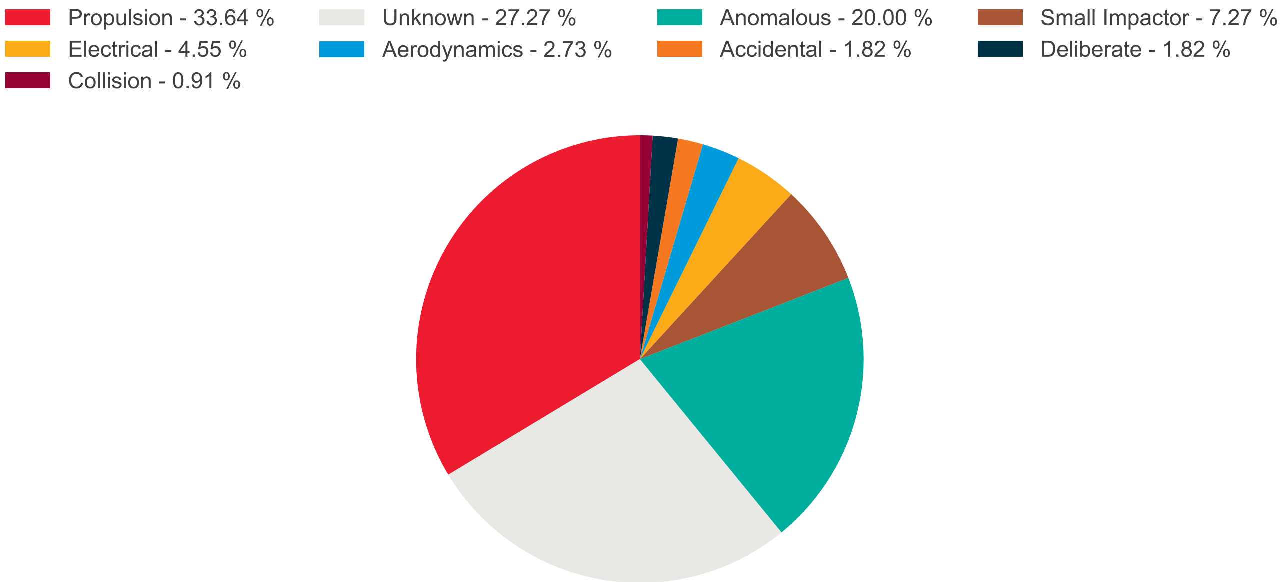
A summary of the statistics on the recorded fragmentation events is reported in Table 5.1, where *Assumed* and *Unconfirmed* were excluded from the aggregation. A breakdown of the observed fragmentation events grouped by the main classes in terms of frequency and resulting catalogued debris is given in Figure 5.3 and Figure 5.4, respectively.

Table 5.1: Statistics on fragmentation events.

	All history	**Last 20 years**
Number of events	643	239
Non-deliberate events per year	9.5	11.3
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 10 years	2.7	2.1
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 25 years	1.8	1.5
Mean time (years) between launch and fragmentation	5.5	10.3
Median time (years) between launch and fragmentation	1.0	6.8

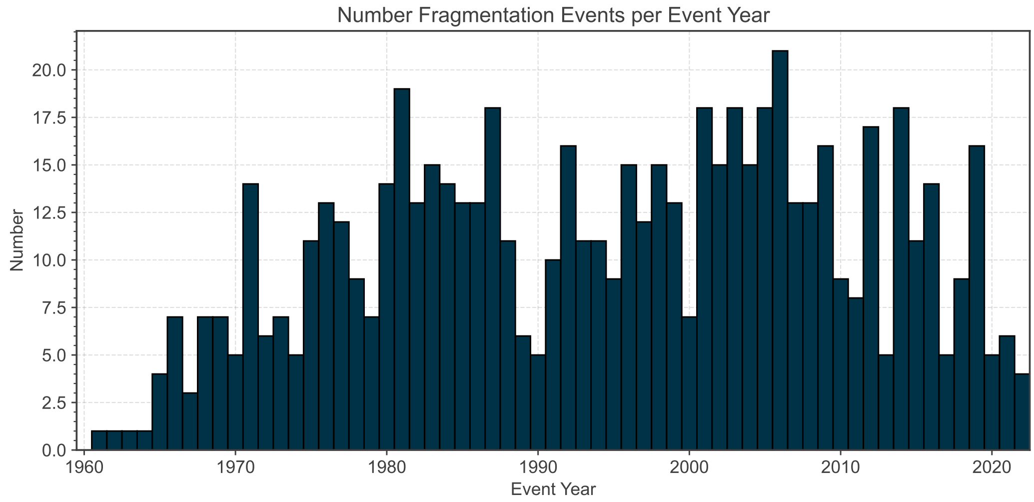


(a) Whole history.

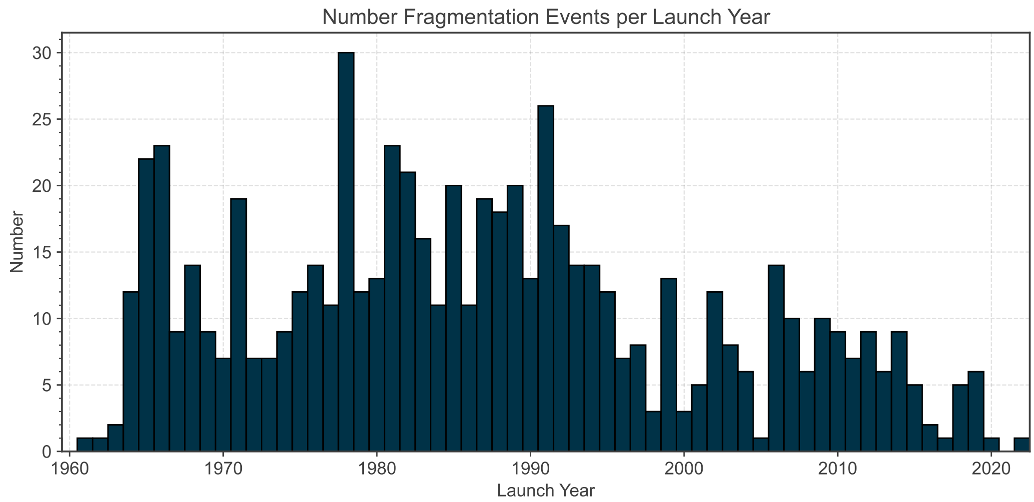


(b) Last 10 years.

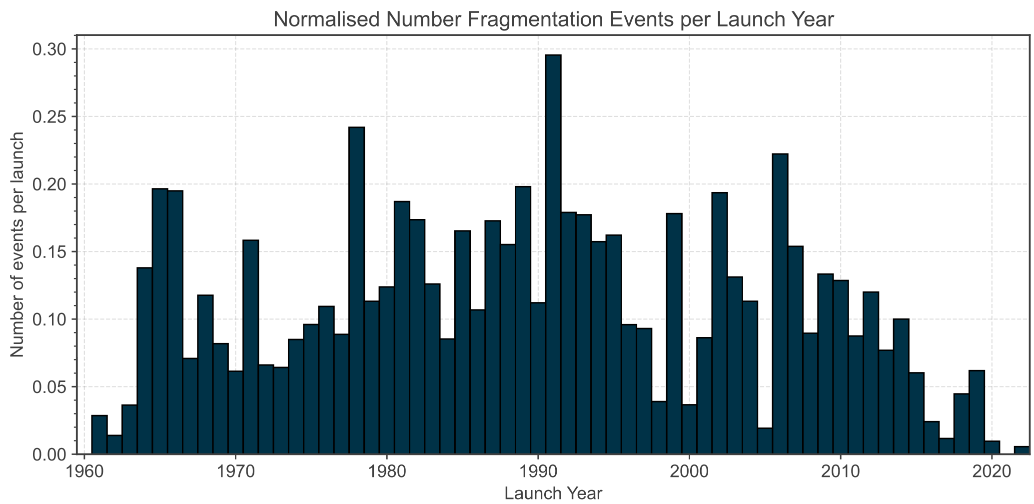
Figure 5.1: Event causes and their relative share for all past fragmentation events.



(a) Number of fragmentation events per event year.

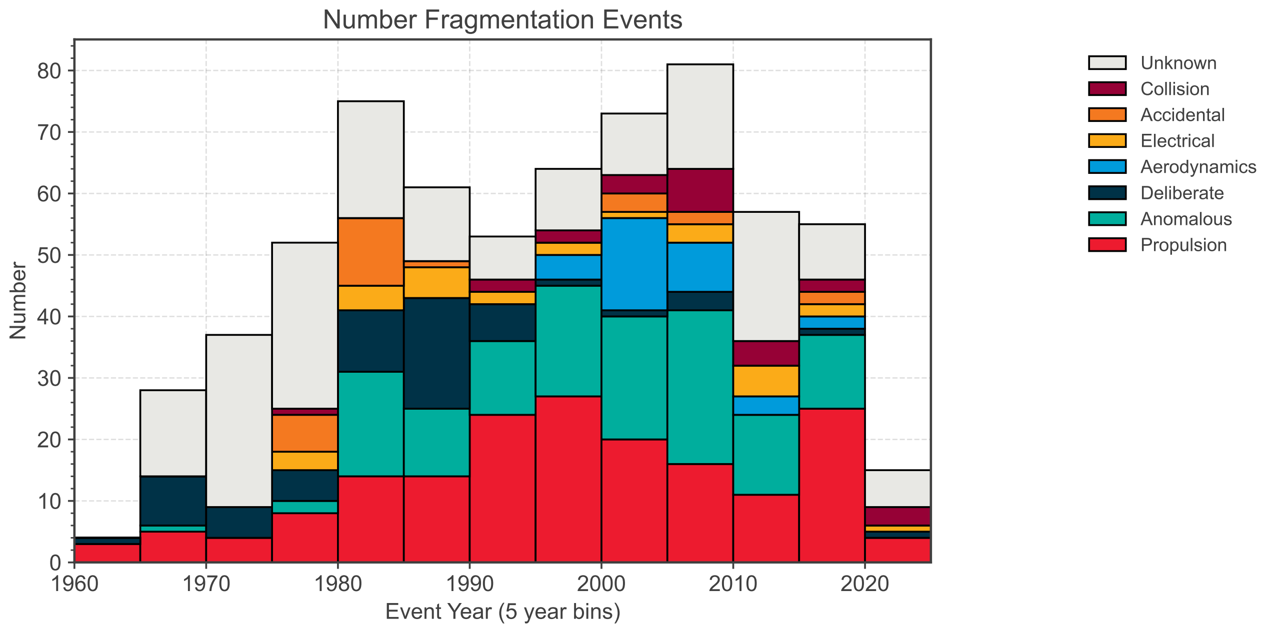


(b) Number of fragmentation events per launch year.

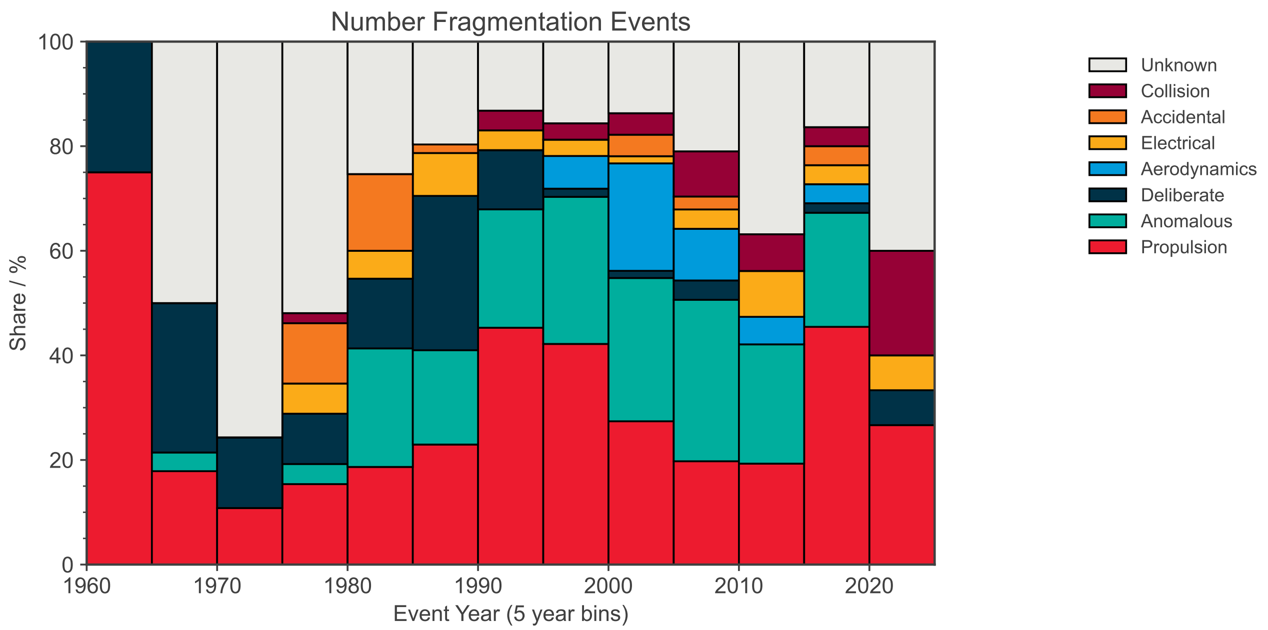


(c) Number of fragmentation events per launch year normalised by the number of launches in that year.

Figure 5.2: Historical trend of fragmentation events.

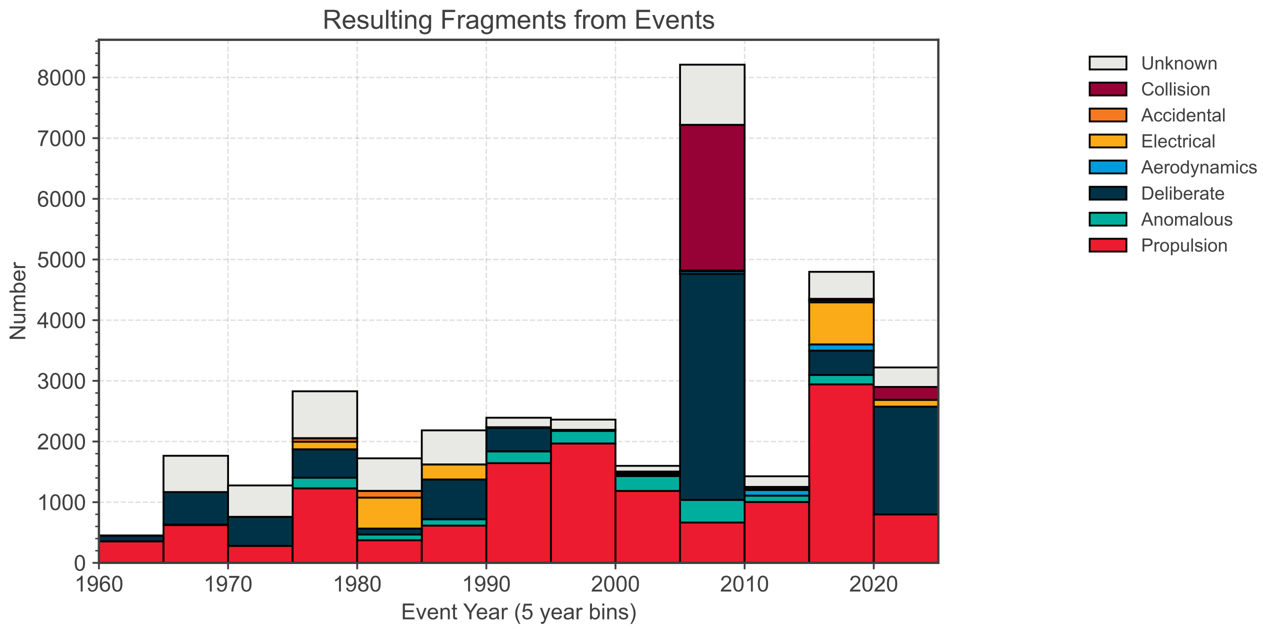


(a) Absolute number of fragmentation events per event cause.

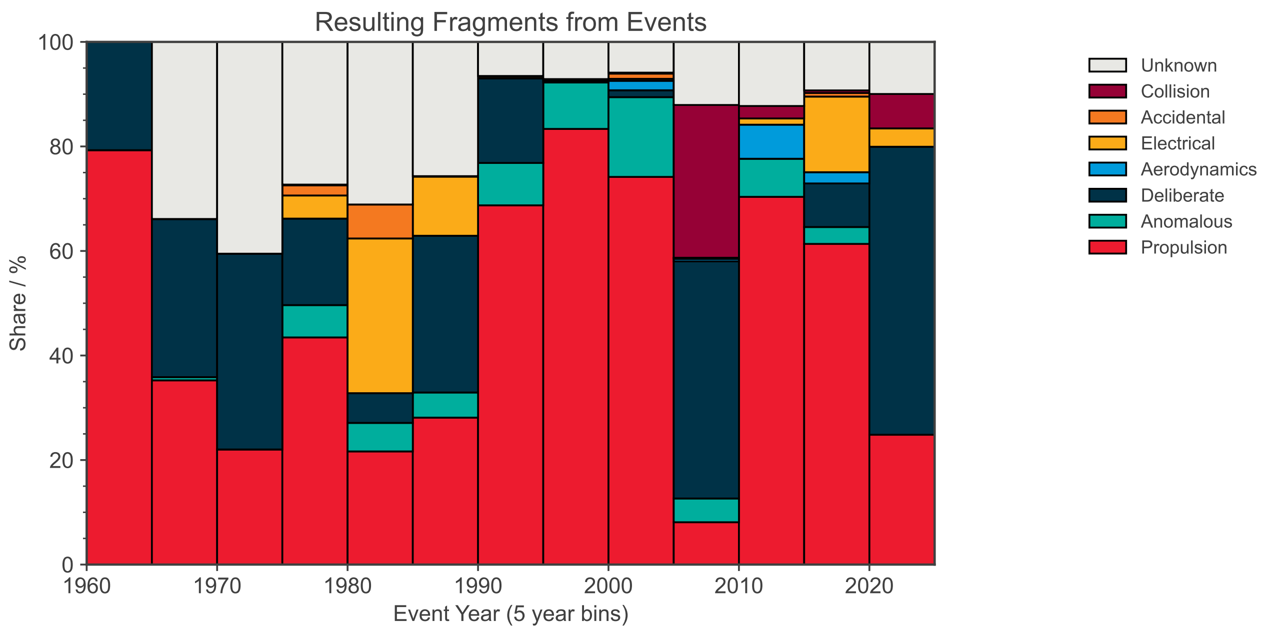


(b) Relative number of fragmentation events per event cause.

Figure 5.3: Historical trend of fragmentation events per event cause.



(a) Absolute number of resulting fragments per event cause.



(b) Relative number of resulting fragments per event cause.

Figure 5.4: Historical trend of numbers of fragments produced by fragmentation events.

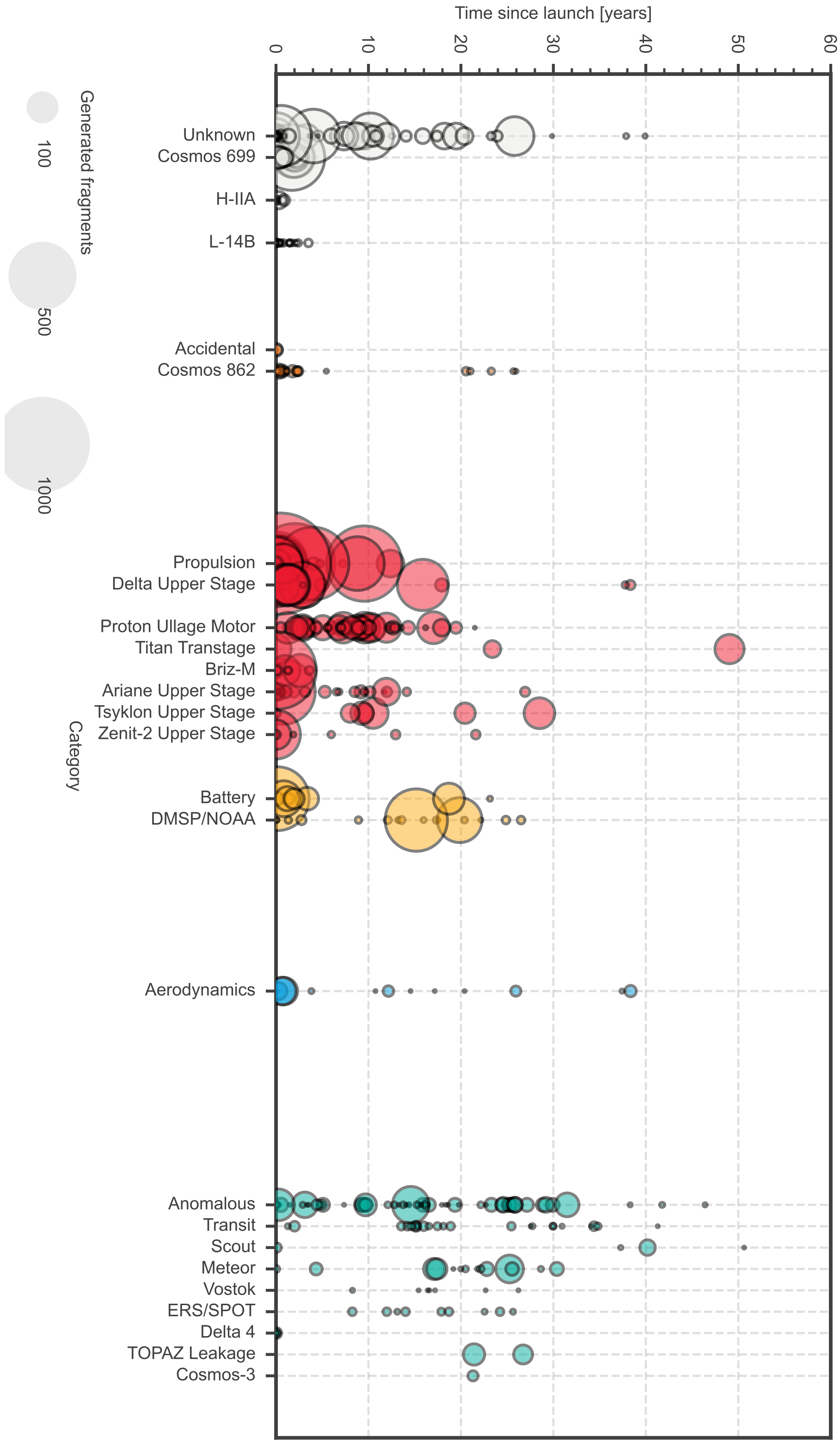


Figure 5.5: Elapsed time between fragmentation and launch by category. The bubble size indicates the number of generated fragments.

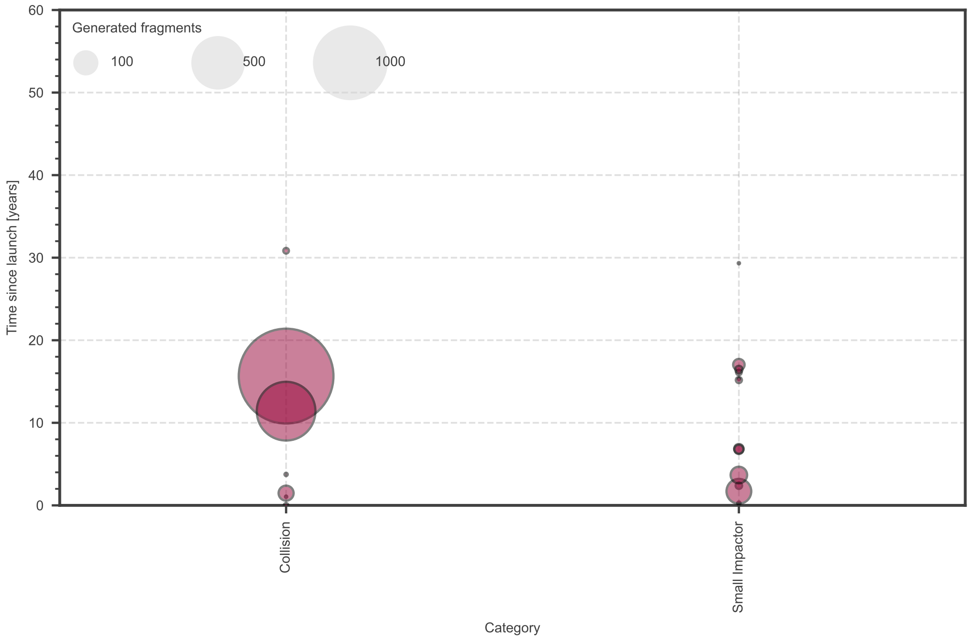


Figure 5.6: Elapsed time between fragmentation and launch for collision events. The bubble size indicates the number of generated fragments.

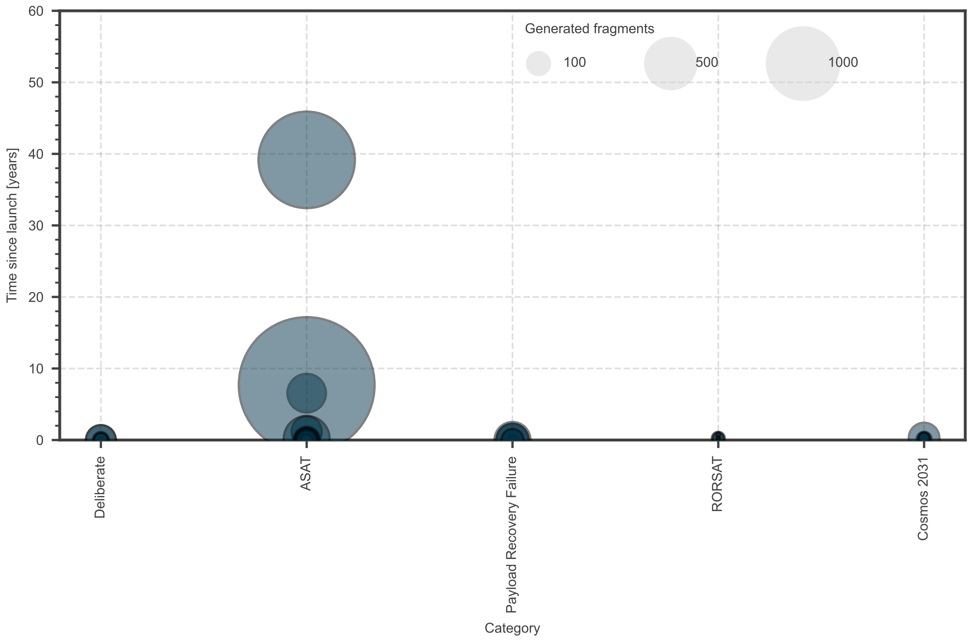


Figure 5.7: Elapsed time between fragmentation and launch for deliberate events. The bubble size indicates the number of generated fragments.

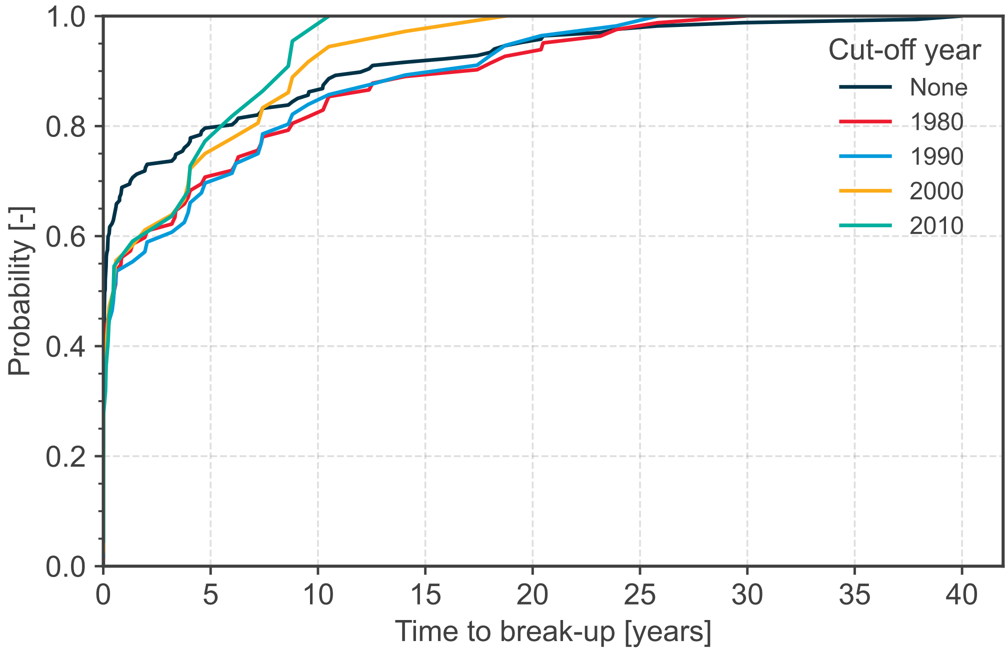


Figure 5.8: Cumulative distribution function (CDF) for the elapsed time between fragmentation and launch for non-system related fragmentation events, with different cut-off values on the launch year.

5.2. Non-system related fragmentation events

As also described when introducing the classes for fragmentation events, not all events are similar in nature and hence the consequences on the environment and for mitigation measures can vary. In particular, events caused by a technical flaw in the design of a (sub-)system that is re-used for many Rocket Bodies or Payload platforms, so-called *system related* events as for battery-related classes, are not representative for the space environment as a whole and need targeted counter measures, e.g. it as was done for certain launch vehicle related classes. To understand the likelihood of fragmentation events occurring in the environment as single stochastic events, i.e. a background risk for any intact space object, it is instructive to analyses the non-system related fragmentation events in isolation. In this sense, we can group the data from the fragmentation classes Unknown, Accidental, Propulsion, Electrical, Battery, excluding their sub-classes.

A relation between the time to a fragmentation event and the launch epoch can be observed for non-system related classes in Fig. 5.8. A causal relationship with the orbital region in which these object resided at the time of the fragmentation event could not be derived, as shown in Fig. 5.9. The derived statistics for the non-system related fragmentations are significantly lower than those for the entire population as observed in the previous sub-section, and reported in Table 5.2. Based on the recent trend analysis, a value of 18 years is adopted as time limit after which the explosion probability for a recently launched space object, due to non-systematic design flaws, can be considered as effectively 0.

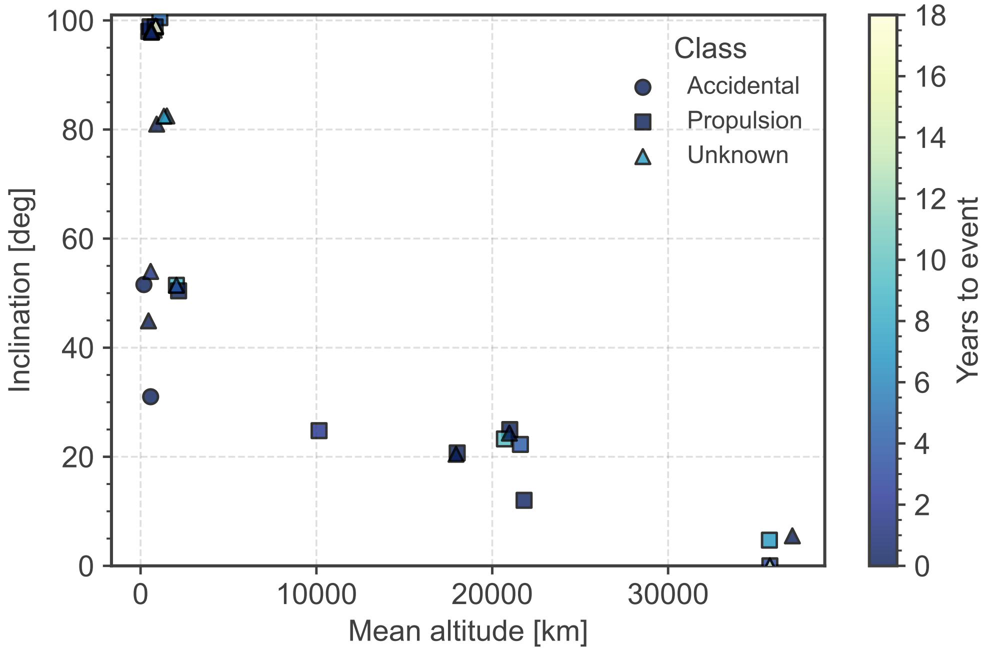


Figure 5.9: Distribution of non-system related fragmentation events in mean altitude, inclination, and time to fragmentation.

Table 5.2: Statistics on non-system related fragmentation events.

	All history	**Last 18 years**
Number of events	169	46
Non-deliberate events per year	2.7	2.4
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 10 years	0.7	0.4
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 25 years	0.5	0.3
Mean time (years) between launch and fragmentation	5.4	9.7
Median time (years) between launch and fragmentation	1.3	4.2

6. END-OF-LIFE OPERATIONS HISTORY

Post mission disposal mitigation measures are specifically aimed at reducing the long term interference an object in the space environment could have on the two protected regions, LEO_{IADC} and GEO_{IADC}. These mitigation measures are associated with time criteria, i.e. so-called orbital lifetimes or clearance of orbital regions, and hence require evaluating the long term evolution of orbits. For both protected regions, different mitigation measures imply different end-of life operations. The reported years for payload clearance of LEO_{IADC} goes up to 2021, for rocket body clearance of LEO_{IADC} goes up to 2022, and for payload clearance of GEO_{IADC} goes up to 2022.

6.1. End-Of-Life Operations in Low Earth Orbit

Due to the presence of atmospheric drag in the lower levels of the LEO region, a natural cleansing of space debris from these regions occurs. A payload or rocket body operating in the LEO Protected region, with either a permanent or periodic presence, shall limit its post-mission presence in the LEO Protected region to a maximum of 25 years from the end of mission [6]. This limit by itself will not lead to a long-term reduction in the amount of space debris, as will be show in Section 7.2, but is an important step towards limiting the space debris growth rate in LEO_{IADC} [2]. The mitigation measure itself, i.e. the so-called *25-year rule*, does not indicate how it has to be achieved, but various standards provide an order of preference for various methodologies, i.e. controlled re-entry, accelerated natural orbital decay, etc.

For catalogued objects, the orbital activity of a payload or rocket body can be derived and the orbital lifetime estimated. This method is preferred over direct investigation, intelligence, of communication with the owners of a payload or a rocket body, which could increase the accuracy of the prediction, but it might be unbalanced as the request for such data might not be answered nor can all owners be clearly identified and approached. As some rocket bodies have been found to perform direct re-entries before they can be considered catalogued objects, additional asserted objects are used as to make sure that such positive cases are correctly considered in the resulting statistics. The methodology to determine the end of the operational phase of an object in LEO employed here is described in depth in [20].

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

The boundaries between having an orbital control capacity or not is not always clearly defined by the underlying technology. This is because the effects observed by the space surveillance system may not be reliably discerned in all cases. Impulsive manoeuvres, multi-revolutions use of electrical propulsion, and large drag sail deployments are reliably picked up and hence objects exhibiting those features are categorised as having OCC.

On the other hand, smaller orbital changes, such as drag sailing, where the change in ballistic coefficient is smaller than the error margin or the orbit determination capacity of the space surveillance system, are not picked up. However, the most important metric w.r.t. the implementation is to remove an object from LEO_{IADC} within 25 years, or shortly thereafter, which is measured independently of the OCC categorisation.

In order to estimate the orbital lifetime of an object after reaching its end of life, the general processes as laid out in standard [10] are followed. To apply these processes to all catalogued objects, a Ballistic Coefficient (BC) needs to be estimated for each of them. The BC estimation is based on least root-mean-square orbit fitting during the longest periods free from estimated manoeuvres, generally after end of life is reached in case of OCC classified objects. In case this can't be achieved, the BC is defined based in the available physical properties in DISCOS. The estimated BC is used to extrapolate the last recorded orbital state in 2022 until re-entry in combination with a long term space weather forecast [21]. The used values and obtained results are stored in DISCOS and distributed on request [7]. The process itself is subject to a significant amount of stochastic assumptions which are described in [22]. Hence, the reported orbital lifetimes are procedurally defined and need to be understood as a *current* best-estimate that can vary between different versions of this report, as discussed in Section 6.1.3.

In case of payload objects, at least one calendar year without orbit control actions needs to pass for an object to be classified as reaching end-of-life unless it performs a controlled re-entry. This is done to mitigate the implications of the detection algorithm described above, and to avoid a potentially large amount of reclassifications in subsequent editions of this report as some operators implement less frequent actions near the end-of-life. In practice, this means that the reported years for the payload clearance of LEO_{IADC} goes up to 2021 instead of 2022.

It is important to note that for this report, where conformance to a time-limitation guidelines is to be evaluated, the categorisation of each object becomes fixed after 25 years. Unpredicted events, such as increased solar activities or missions which actively remove large pieces of space debris, will thus be accounted for only when they materialise.

Relocations from LEO_{IADC} into orbits with a perigee altitude above 2000 kilometres are no longer viable end-of-life debris mitigation practices [6]. While such relocations where relatively rare for Payload objects and only a minor historical entry in the dataset of this section, they have been more commonly used to raise the perigee of Rocket Bodies when, e.g. eccentric destination orbits such as GTO were targeted.

Human spaceflight (HS) related missions are analysed separately, as they skew results in terms of mass and count affected. These missions include crew vehicles as well as cargo payloads, but not the rocket bodies that bring them into orbit. Throughout this section, *Stage* is used as synonym for *Rocket Body*. The end-of-life behaviour of space objects can be categorised in seven behavioural classes to illustrate disposal success rates:

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

In summary, clearance of the LEO protected region by payloads and rocket bodies will be presented as *Naturally Compliant* if injected into an orbit that fulfils the 25-year lifetime measure, *Successful Attempt* when compliant after an attempt to reduce its orbital lifetime, *Insufficient Attempt* when not compliant but having attempted to reduce its orbital lifetime or *No Attempt* when not compliant with no attempt at all.

6.1.1. Evolution of compliance shares

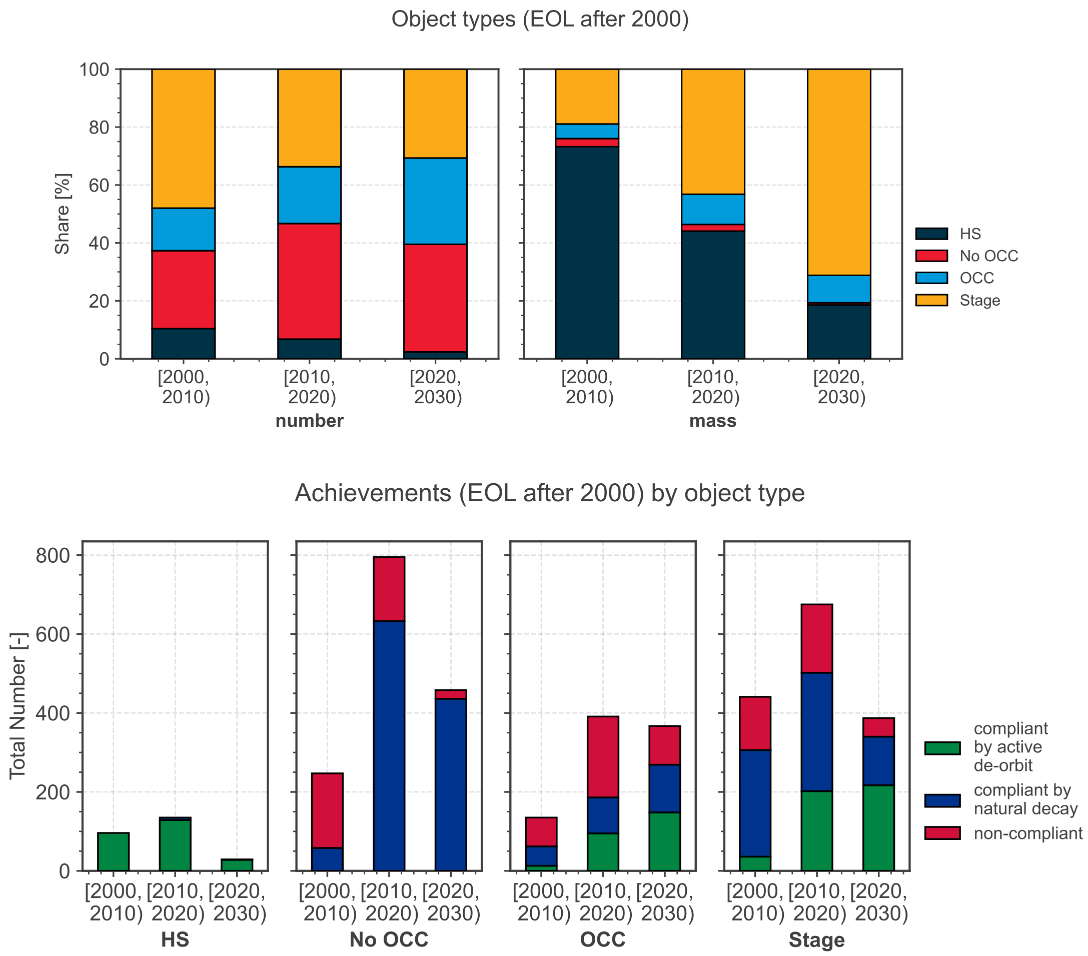


Figure 6.1: Share of payloads and rocket bodies in terms of mass and number (top) and compliance in terms of clearing the LEO protected region (bottom). The reported years for payload clearance of LEO_{IADC} goes up to 2021, for rocket body clearance of LEO_{IADC} goes up to 2022.

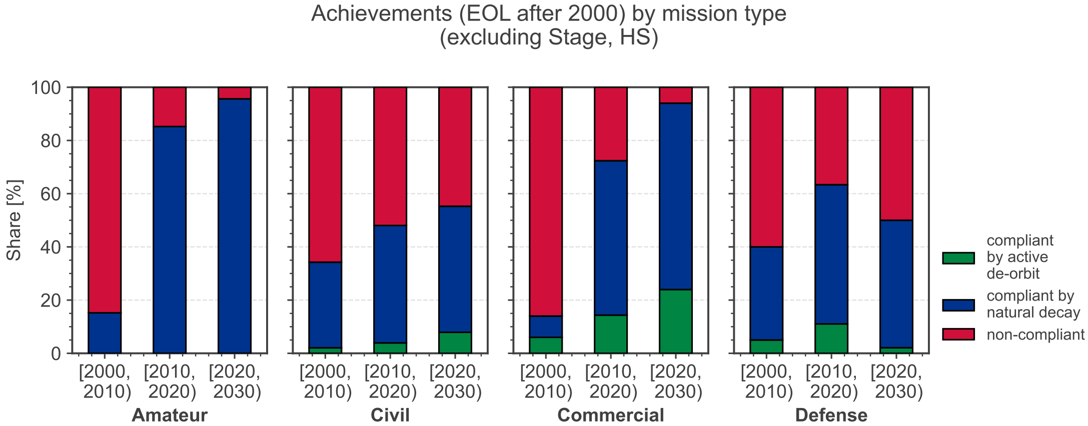


Figure 6.2: Share of compliance in terms of clearing the LEO protected region by mission type.

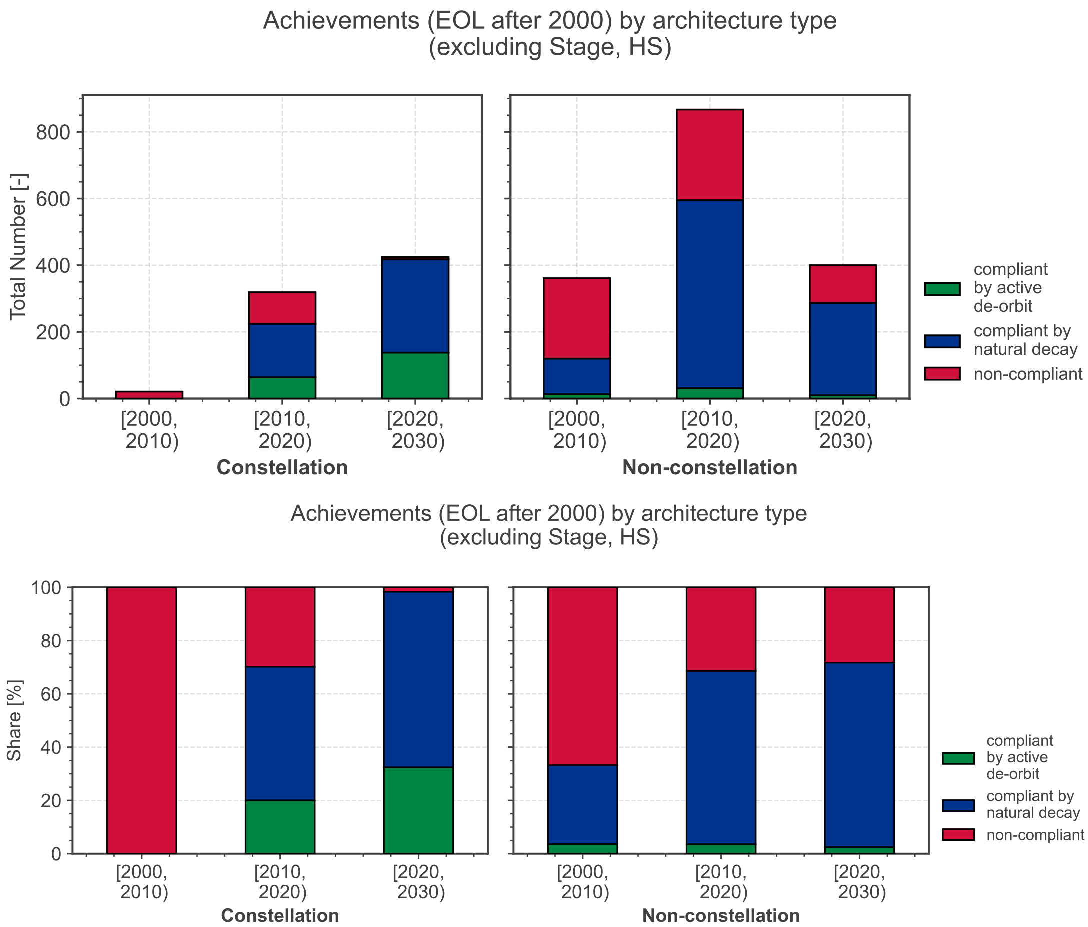
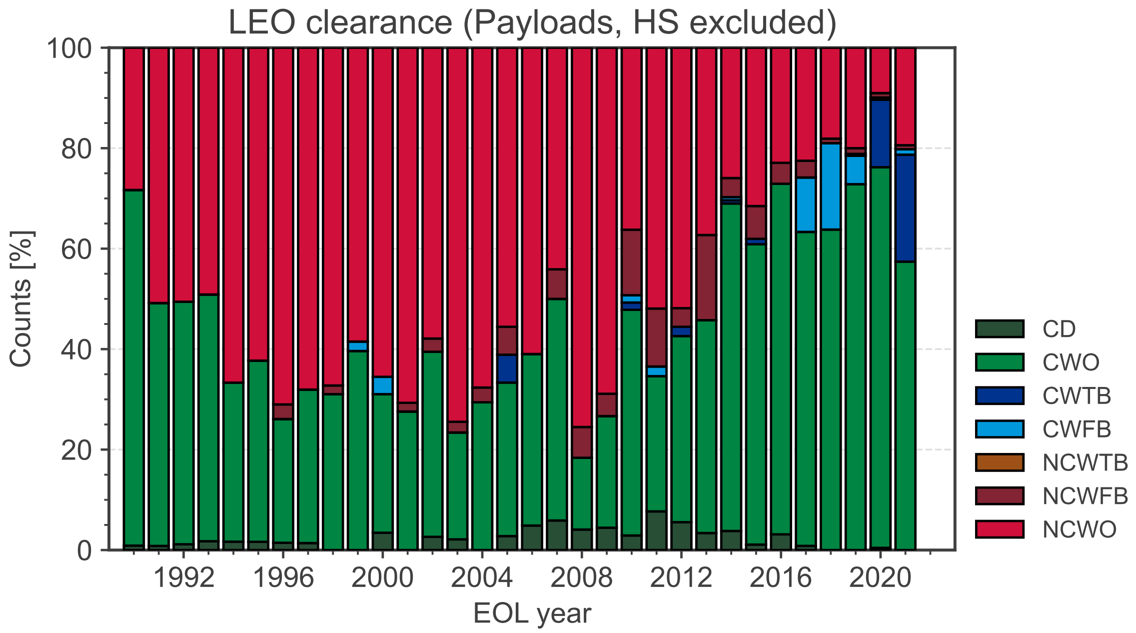


Figure 6.3: Compliance in terms of clearing the LEO protected region for constellation and non-constellation objects, in absolute numbers and in relative share.



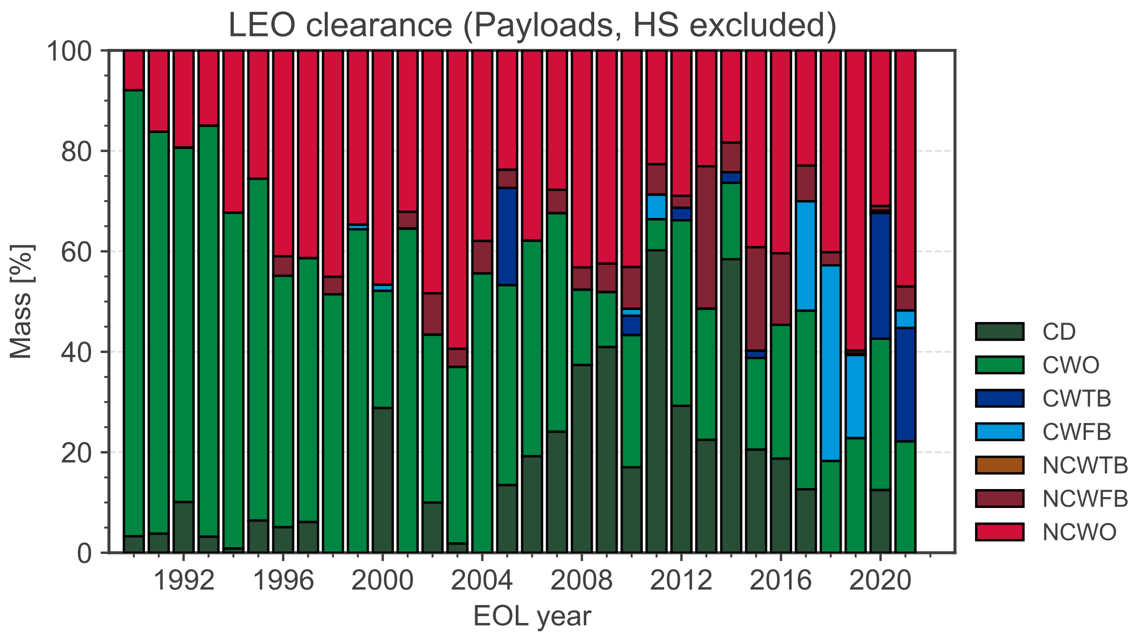
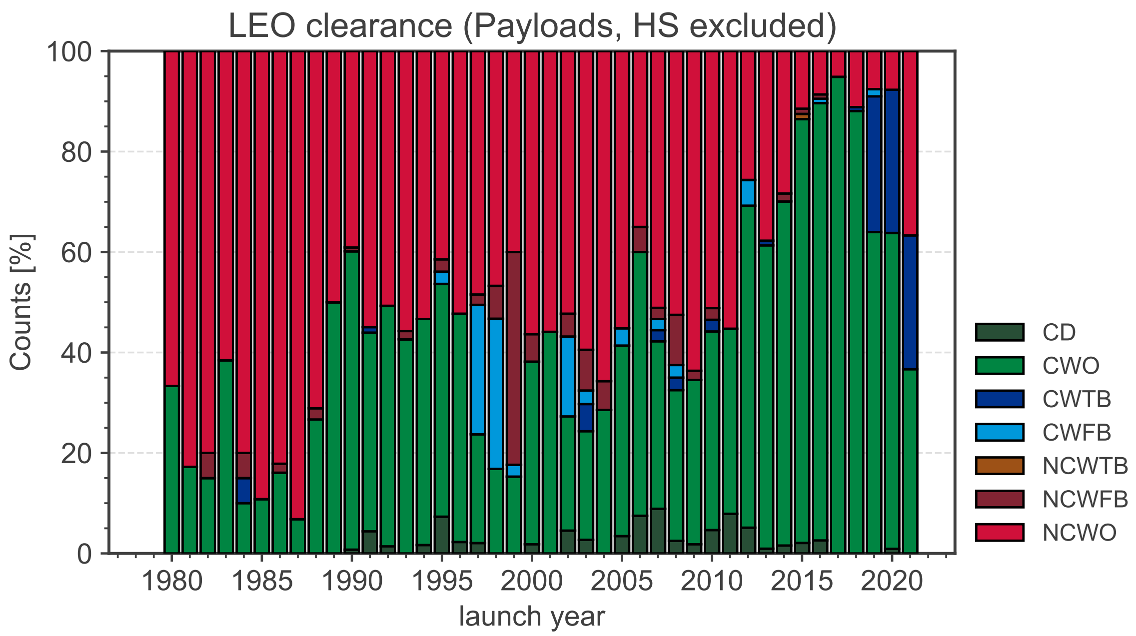


Figure 6.4: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for payloads in LEO, excluding objects associated with human spaceflight by end-of-life year.



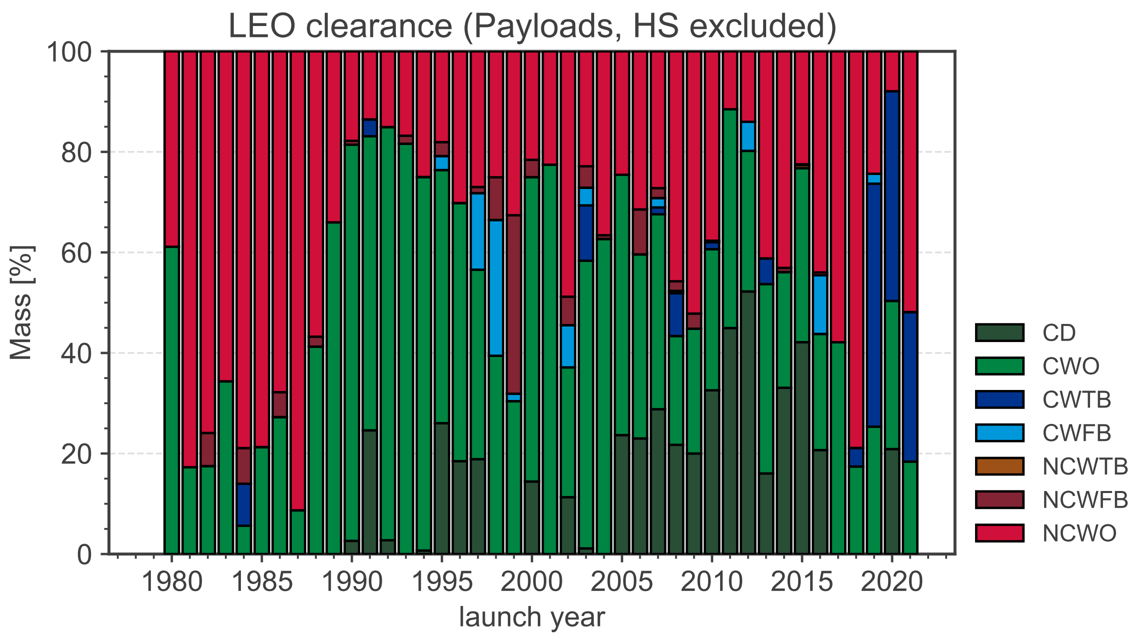
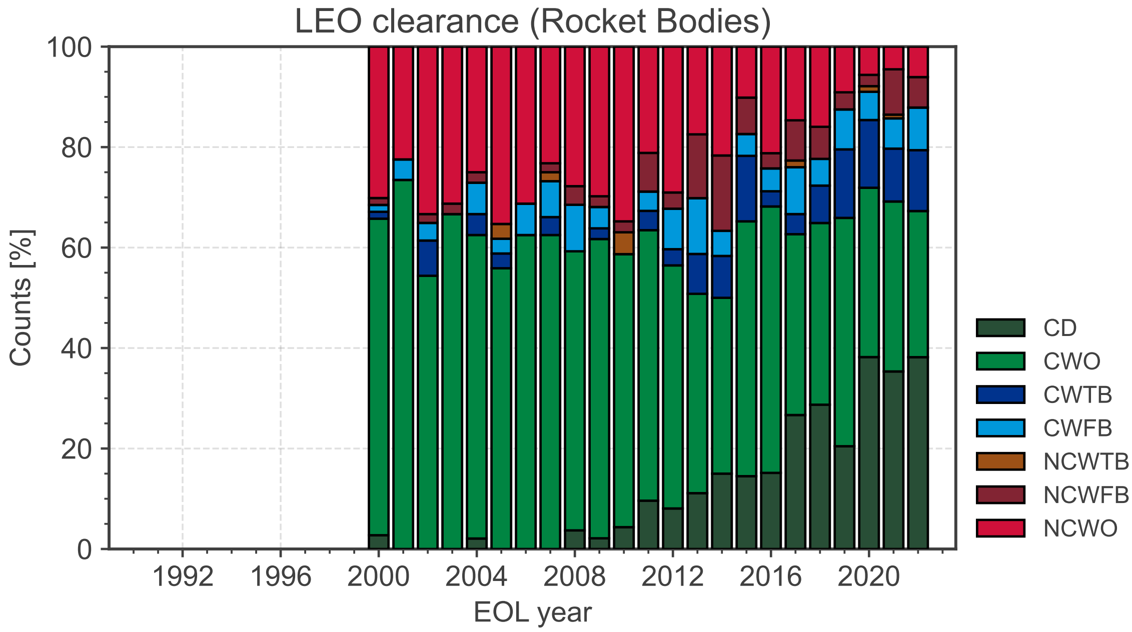


Figure 6.5: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for payloads in LEO, excluding objects associated with human spaceflight by launch year.



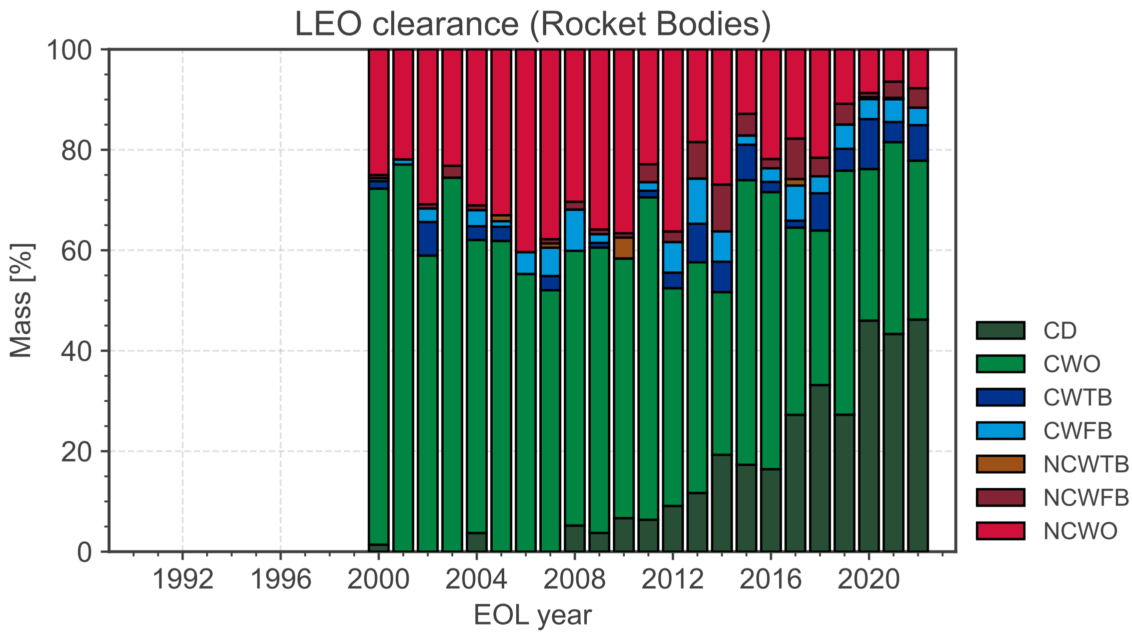
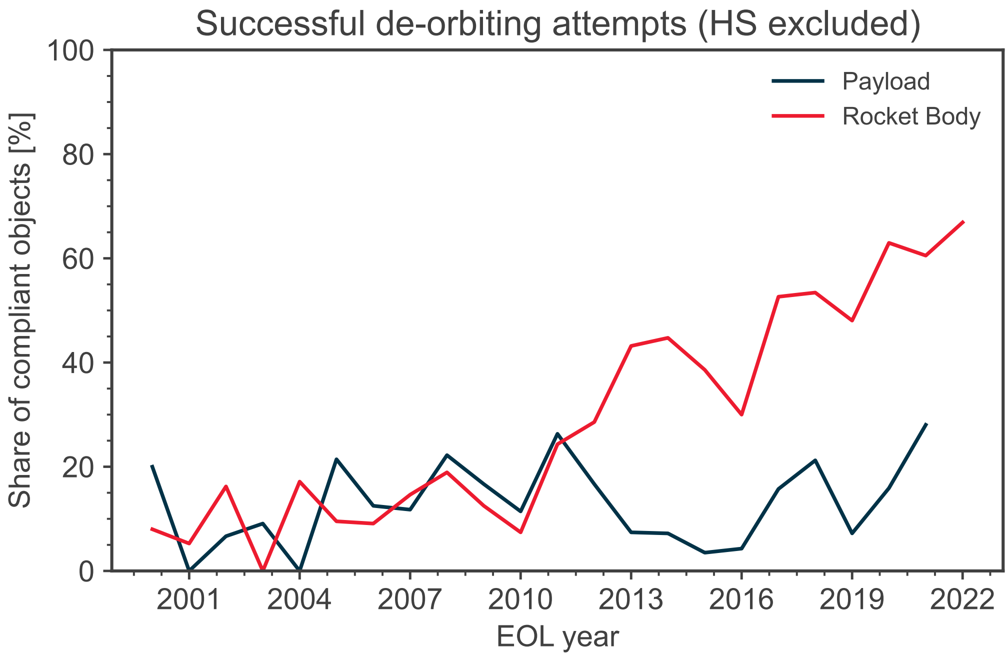


Figure 6.6: Relative share of disposal behaviour classes over time in terms of number (top) and mass (bottom) for Rocket Bodies in LEO by end-of-life, i.e. launch year.



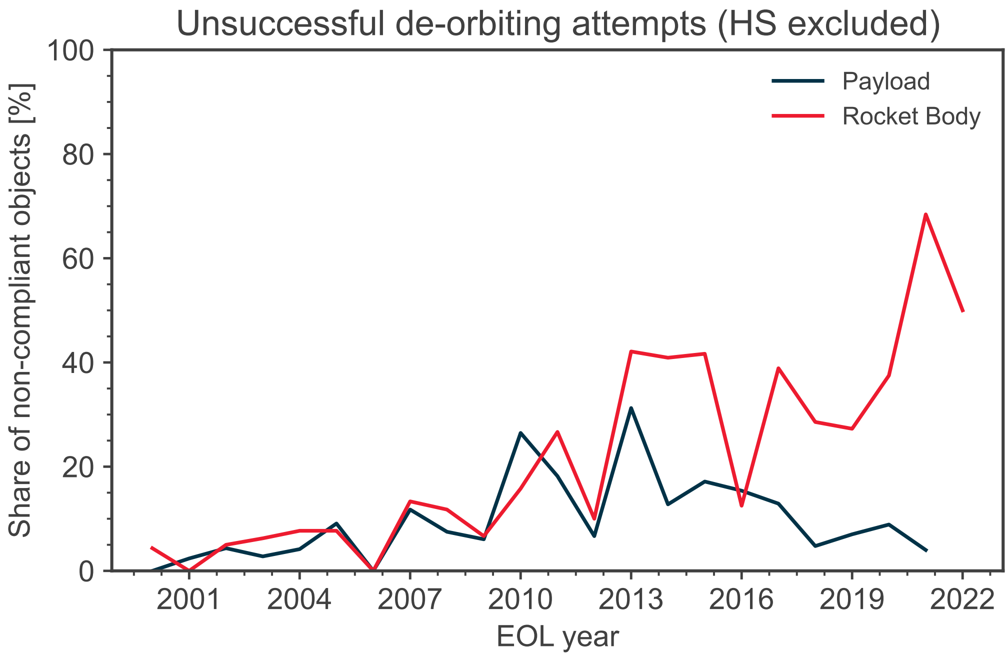
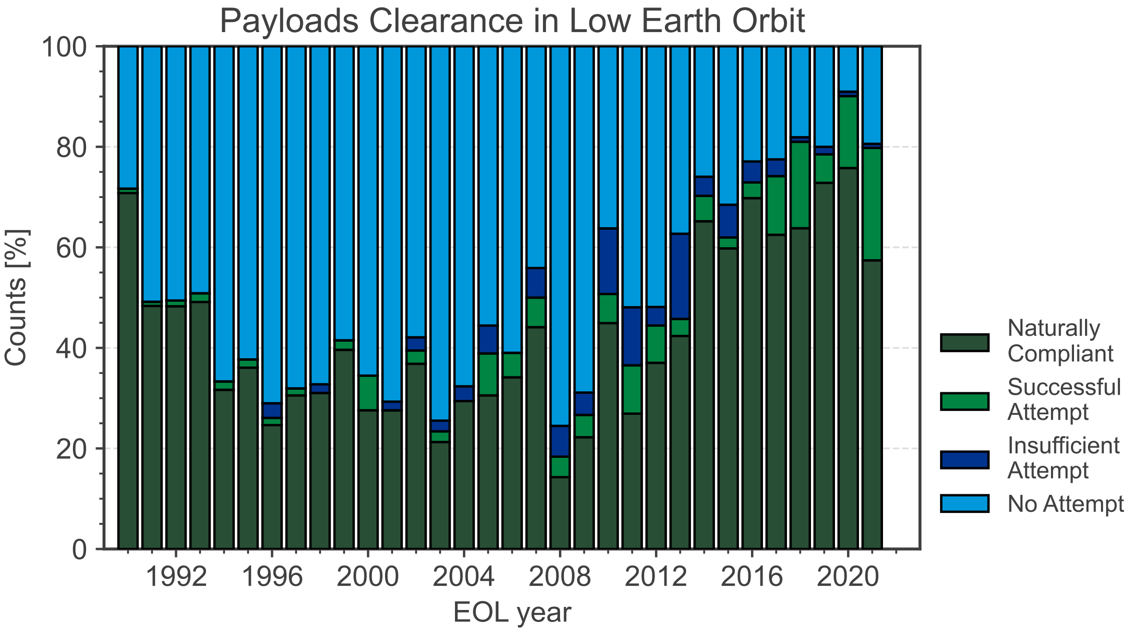
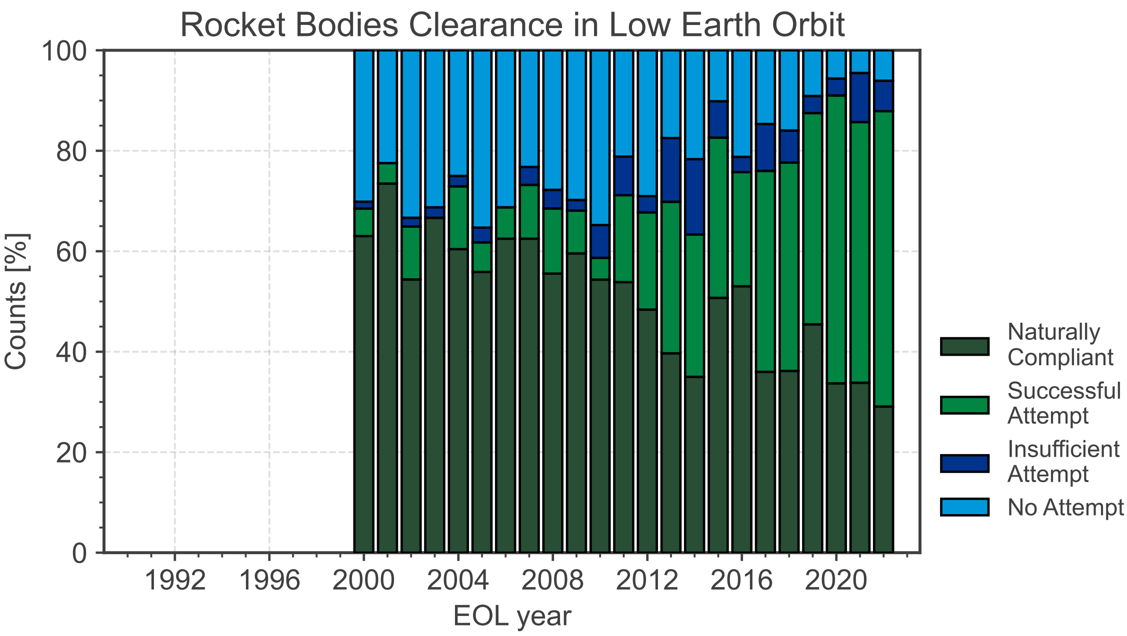


Figure 6.7: Relative shares of success w.r.t. compliance (top) and non-compliance (bottom) over time, excluding objects associated with human spaceflight.

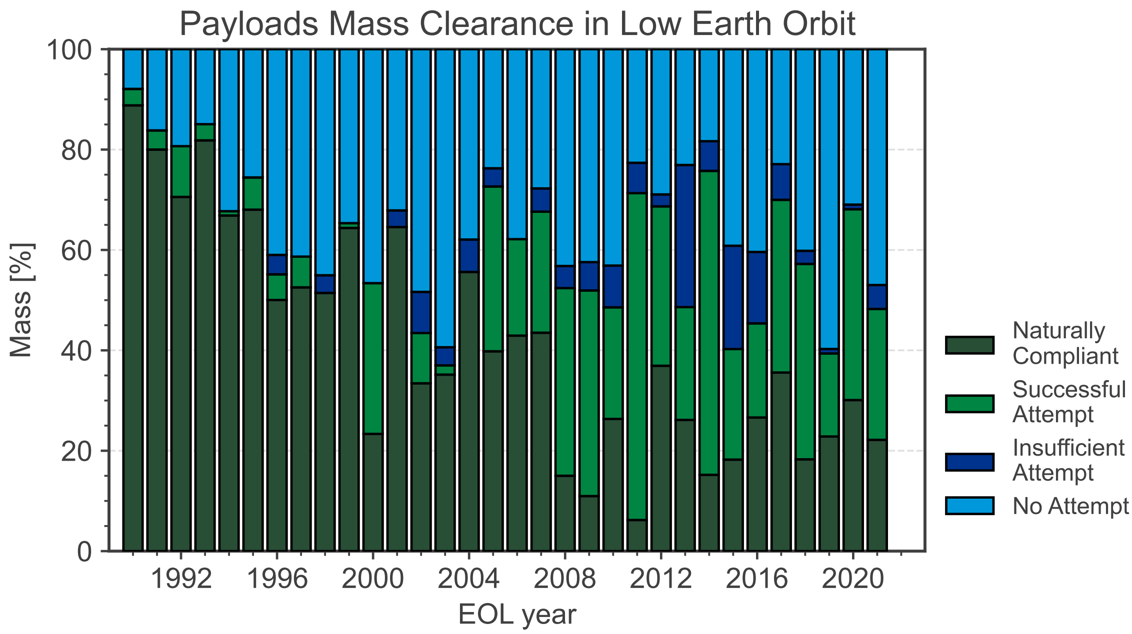


(a) Relative clearance of LEO_{IADC} by payloads.

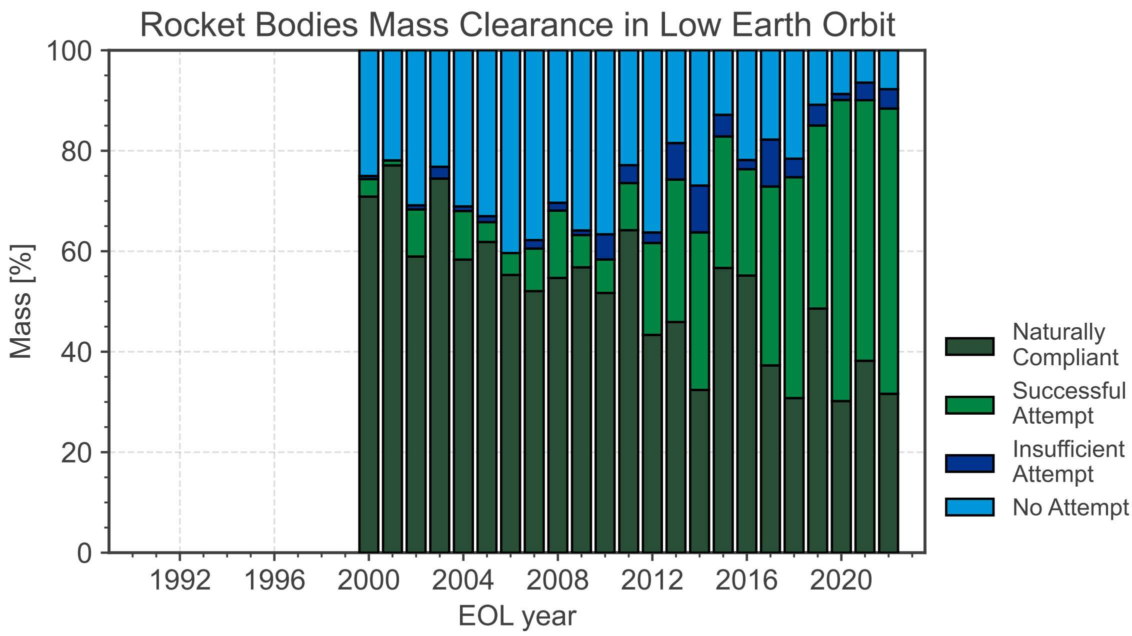


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.8: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers.

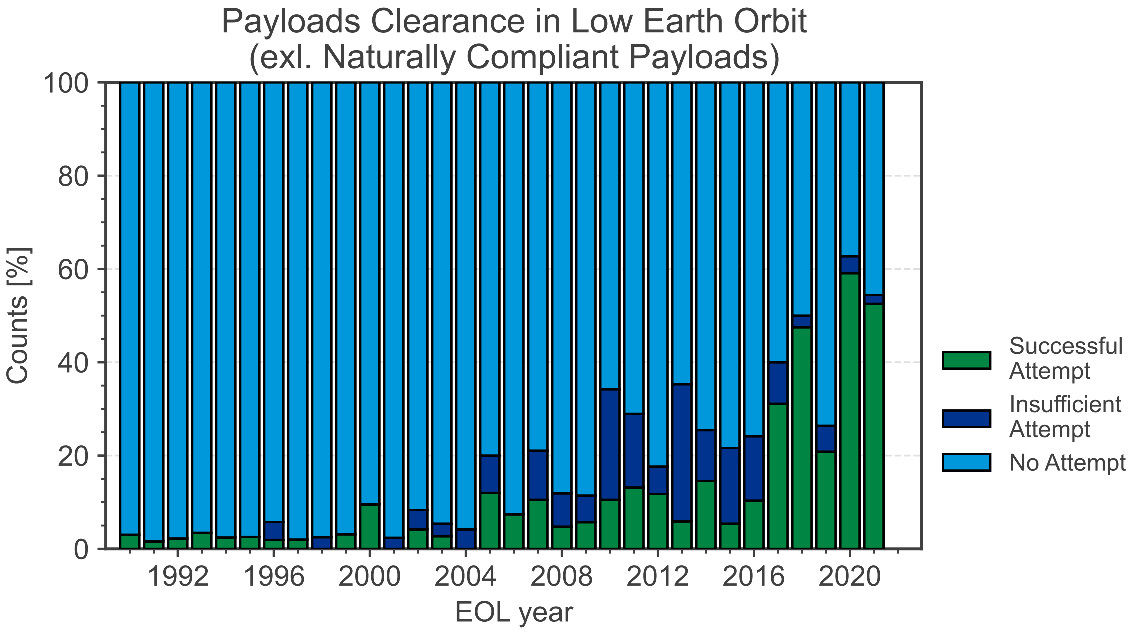


(a) Relative clearance of LEO_{IADC} by payloads.

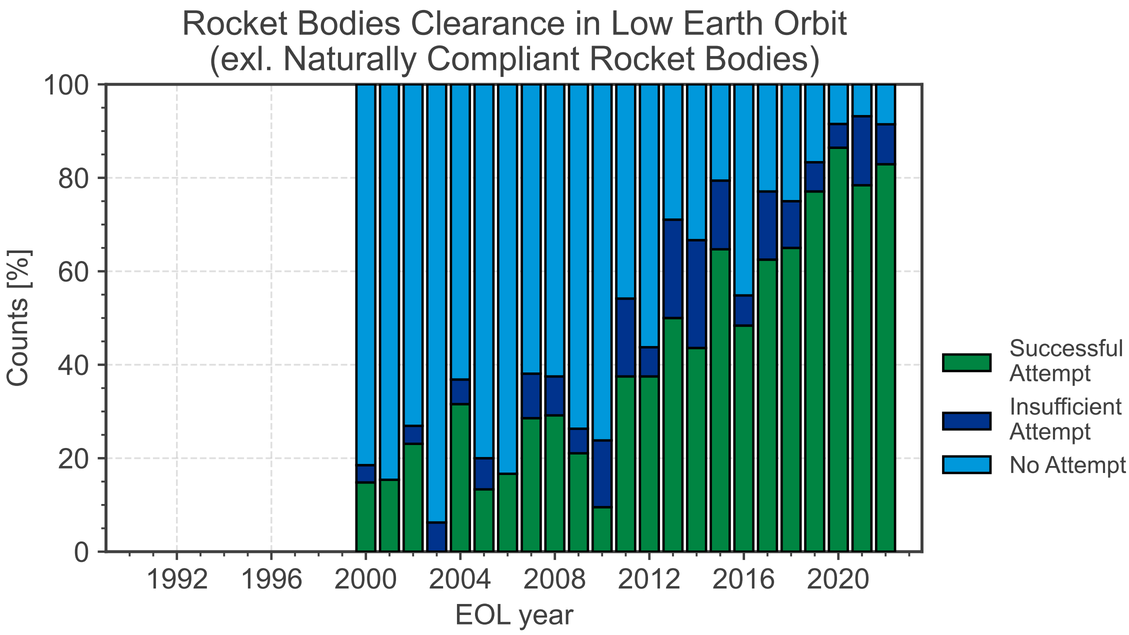


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.9: Trend of adherence to clearance of LEO_{IADC} over time in terms of mass.

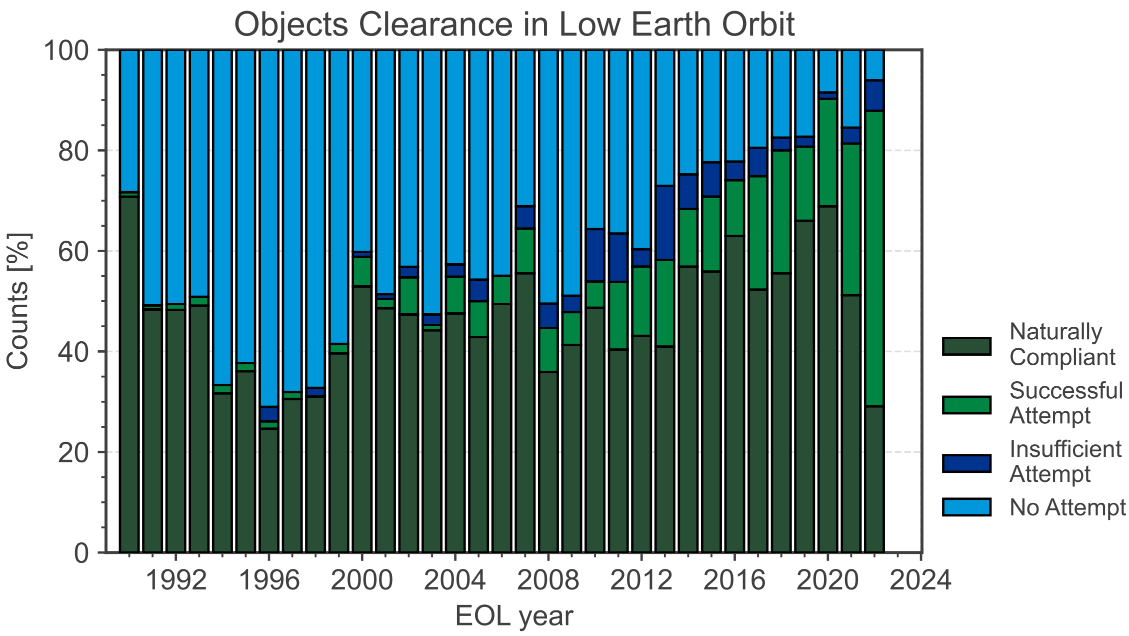


(a) Relative clearance of LEO_{IADC} by payloads.

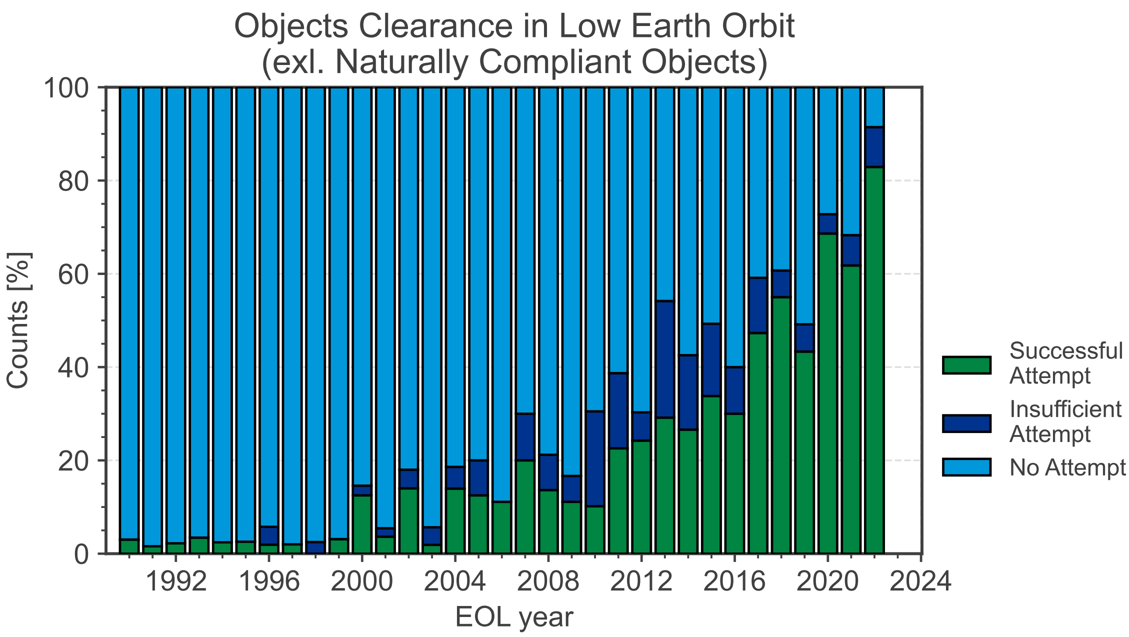


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.10: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, excluding naturally compliant objects.



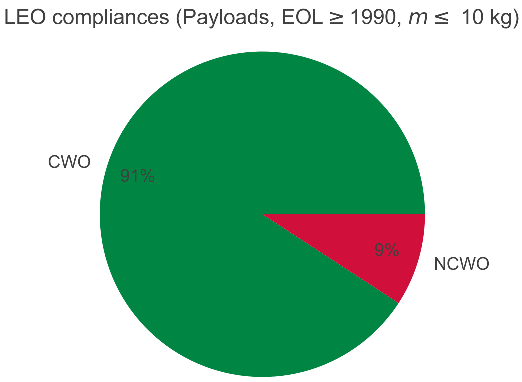
(a) Relative clearance of LEO_{IADC}.



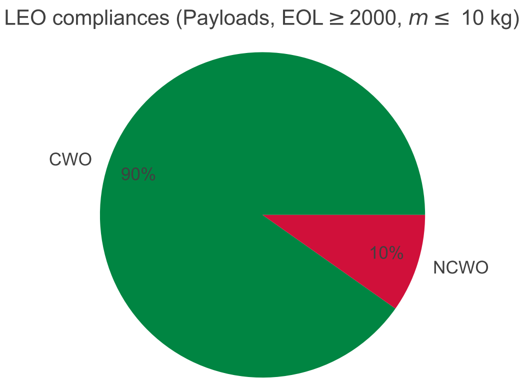
(b) Relative clearance of LEO_{IADC} excluding naturally compliant objects.

Figure 6.11: Trend of adherence to clearance of LEO_{IADC} over time in terms of numbers, considering payloads and rocket bodies together.

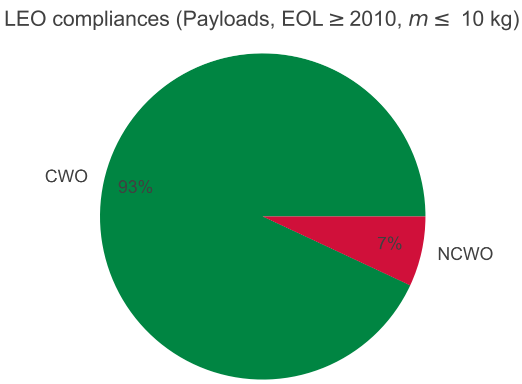
6.1.2. Evolution of behavioural classes per mass breakdown



(a) 1990

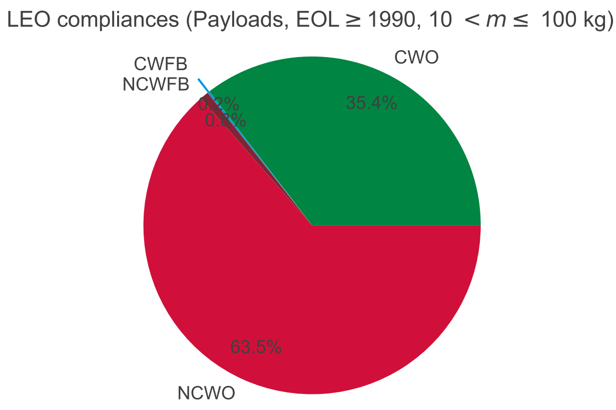


(b) 2000

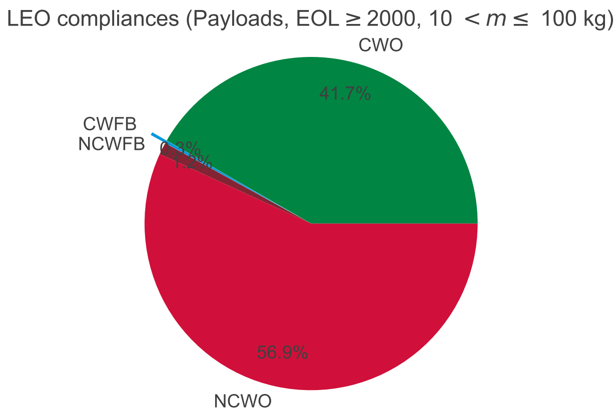


(c) 2010

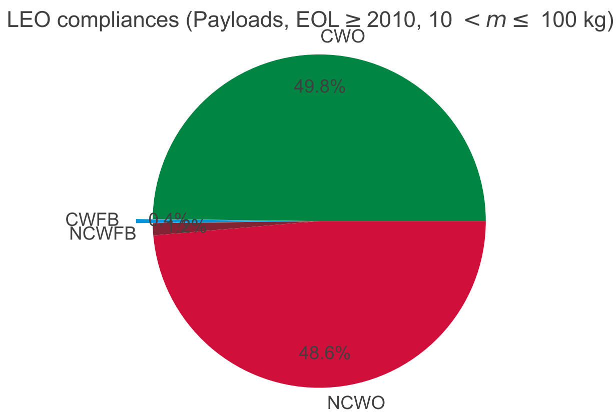
Figure 6.12: Breakdown per decade of observed behavioural classes for payloads with a mass below 10.0 kg.



(a) 1990

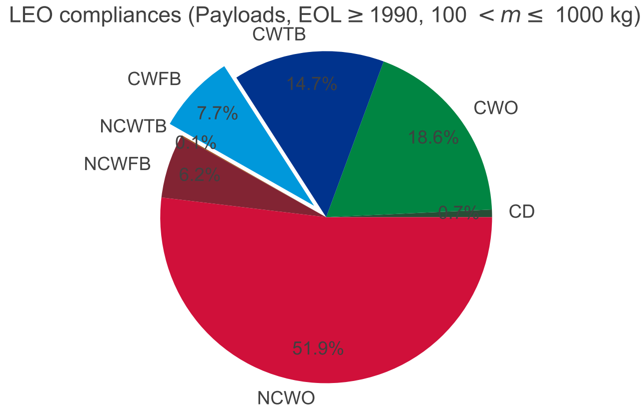


(b) 2000

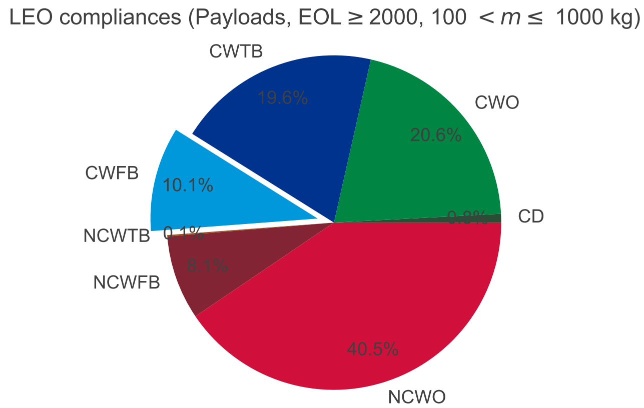


(c) 2010

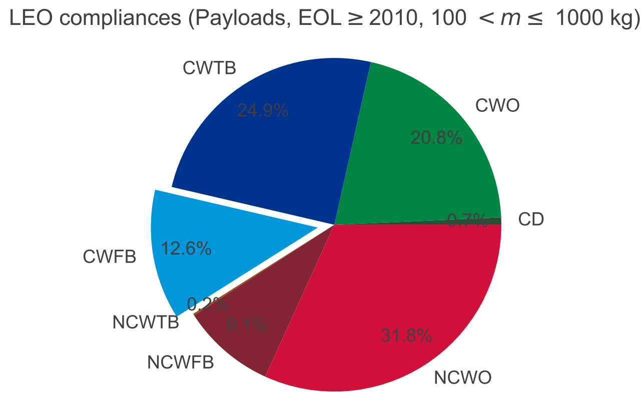
Figure 6.13: Breakdown per decade of observed behavioural classes for payloads with a mass between 10.0 and 100.0 kg.



(a) 1990

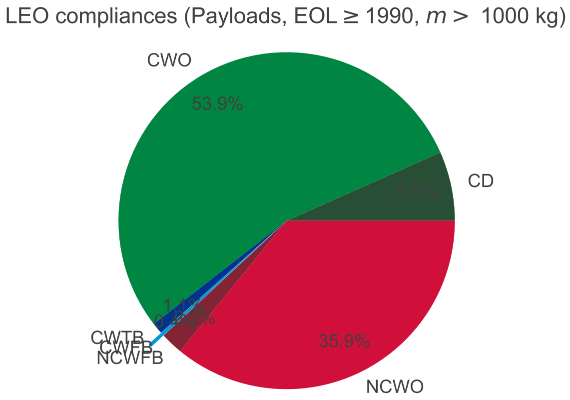


(b) 2000

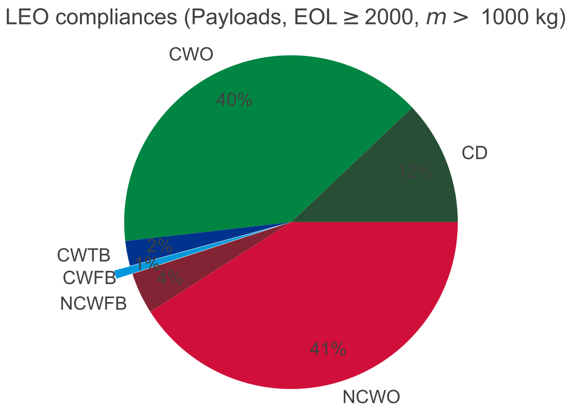


(c) 2010

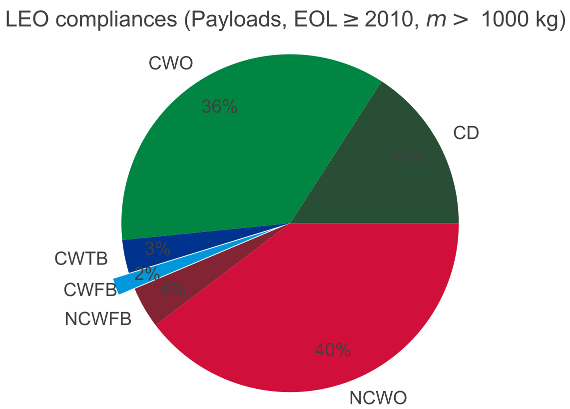
Figure 6.14: Breakdown per decade of observed behavioural classes for payloads with a mass between 100.0 and 1000.0 kg.



(a) 1990



(b) 2000



(c) 2010

Figure 6.15: Breakdown per decade of observed behavioural classes for payloads with a mass above 1000.0 kg.

6.1.3. Robustness of the evaluation of compliance shares in LEO

In order to evaluate the robustness of the compliance classification presented in this chapter, two additional analyses are presented.

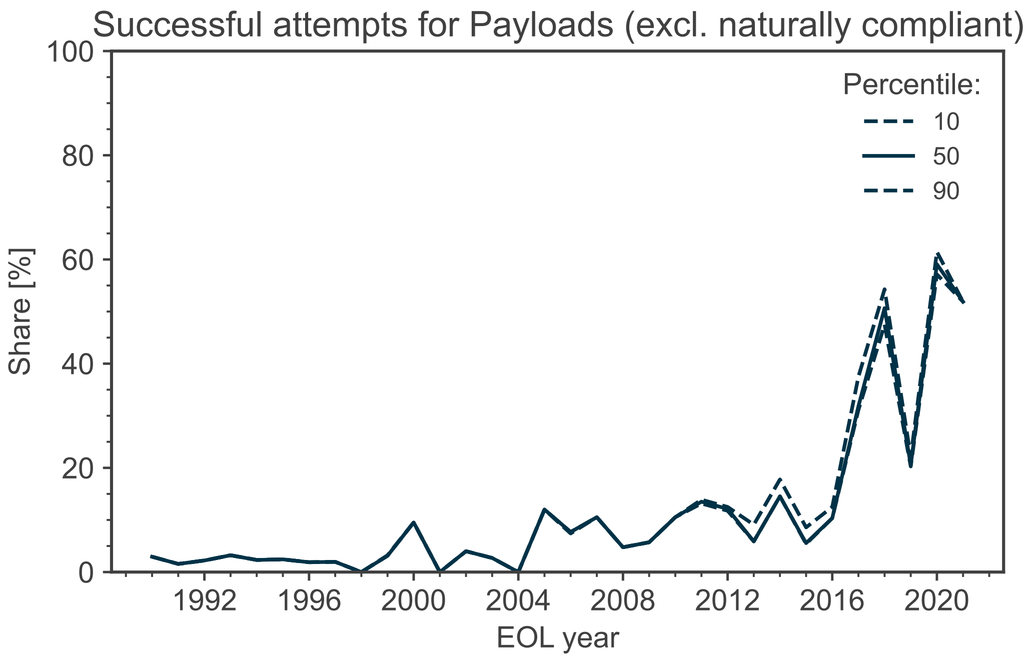
First, as mentioned, the classification of the compliance is based on the computation of orbital lifetimes, which are affected by several sources of uncertainty, such as the estimation of the ballistic coefficient and the adopted prediction for the solar and geomagnetic activity [22]. For this reason, a Monte Carlo (MC) approach was adopted to derive the distribution of the computed lifetime values for objects for which either the destination orbit or the latest orbit in the 2022 has an eccentricity > 0.1 or a nominal orbital lifetime between 20 and 50 years.

A minimum number of 500 MC runs is performed for the evaluation of the orbital lifetime of each reference orbit, changing the value of ballistic coefficient for each run. In particular, in the current stage, the ballistic coefficient is drawn from a uniform distribution between -40% and +40% of the nominal value defined by the process described at the beginning of this Section. In the next editions, we plan to consider also the variability in the space weather predictions.

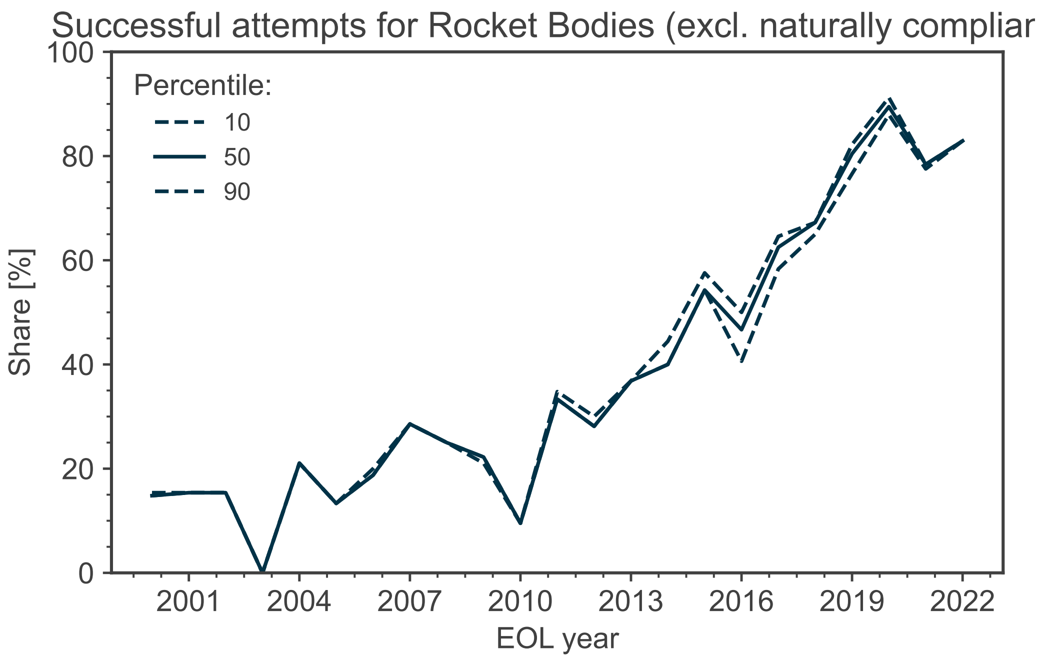
A statistical check based on the Kolmogorov–Smirnov test is used to assess whether enough runs are computed. If so, the resulting distribution is returned and analysed using the orbital lifetime values corresponding to different quantiles to repeat the compliance analysis. Figure 6.16 presents the trend in the share of successful disposal attempts for Payloads and Rocket bodies considering the lifetime values at the 10, 50, and 90% quantiles of the distributions.

The second analysis shows how the compliance classification has changed over the different editions of the report, considering that each edition is based on a *current* best-estimate of the residual orbital lifetime.

Figure 6.17 shows the share of successful re-/de-orbit attempts for payloads according to the different report editions. As mentioned in Section 6.1, in case of payload objects, as in the case in Figure 6.17, at least one calendar year without orbit control actions needs to pass for an object to be classified as reaching end-of-life, so the report issued in a given year covers up to the end of two years before the release year (e.g. the report issued 2017 covers until the end of 2015). Note that for this visualisation (and for the purpose of the comparison), re-orbits are still considered as successful attempts.



(a) Relative clearance of LEO_{IADC} by payloads.



(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.16: Trend of adherence to clearance of LEO_{IADC} over time, in terms of numbers excluding naturally compliant objects, considering a dispersion in the ballistic coefficient values.

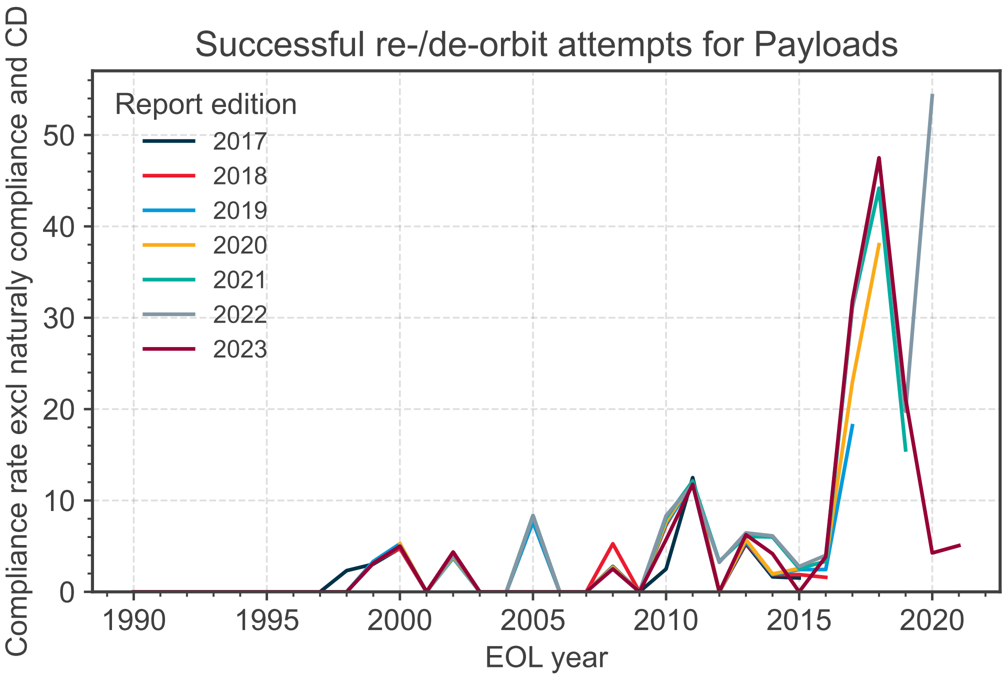


Figure 6.17: Successful re-/de-orbit attempts for payloads according to the different report editions.

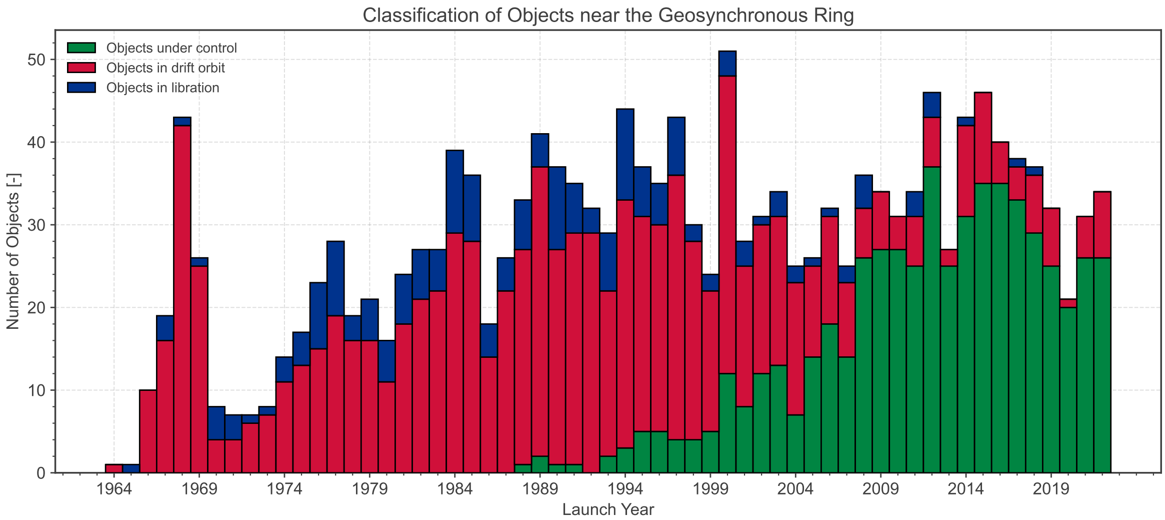
6.2. End-Of-Life Operations in Geostationary Orbit

Unlike in LEO, no natural sink mechanism is available for the GEO protected region by which objects could leave. The solar radiation pressure on the objects will also make long term predictions subject to non-negligible uncertainties. A payload or rocket body operating in the GEO Protected Region, with either a permanent or periodic presence, shall be manoeuvred in a controlled manner during the disposal phase to an orbit that lies entirely outside the GEO Protected Region. There are different ways of ensuring that this condition is met. For example, the launch procedure for Rocket Bodies can be adapted to ensure that the release of the payloads no longer takes place directly within the geostationary orbit but below. In this case, the payload has to climb the last part into GEO_{IADC} but the launcher remains on a GTO trajectory that does not intersect the GEO protected region. For payloads within the GEO protected region, the mitigation measure has been refined, i.e. the so called IADC formulation [5], to ensure that a disposal occurs in a graveyard orbit with minimal interference. At least one of the following two conditions should be met:

- The orbit has an initial eccentricity less than 0.003 and a minimum perigee altitude ΔH (in km) above the geostationary altitude, in accordance with equation:
    1. ΔH = 235 + (1000$C_r A/m$);
    2. where C_r is the solar radiation pressure coefficient (dimensionless);
    3. A/m is the ratio of the cross-section area (in m^2) to dry mass (in kg) of the payload.
- The orbit has a perigee altitude sufficiently above the geostationary altitude that long-term perturbation forces do not cause the payload to enter the GEO Protected Region within 100 years.

In summary, clearance of the GEO protected region by payloads will be presented as *Successful Attempt*, i.e. the payload clears GEO_{IADC} in-line with the formulation above, *Insufficient Attempt* when the payloads attempt to clear the GEO_{IADC} but does not reach the criteria in the IADC formulation, and *No Attempt* otherwise. An in-depth overview of the status of objects in GEO_{IADC} and description of the summarised results shown here is available via [23].

For the rocket bodies delivering payloads in or near the GEO protected region, the long-term disposal orbits are influenced by a variety of perturbations potentially including Luni-Solar, solar radiation pressure, gravitational resonances, and atmospheric drag. This implies that long-term, i.e. over 100 years [6], clearance of both protected regions by these rocket bodies is only predictable as a stochastic estimate. To assess the adherence by rocket bodies to the disposal guidelines in a first approximation, we list the amount of rocket bodies predicted to cross one or both of the protected regions within the next 100 years after launch, as a function of the total number of rocket bodies that launch payload objects with a destination orbit in GEO. In addition, for those object crossing the LEO protected region an object is marked as *LEO-crossing* if it crosses LEO and the permanence time in the LEO region is longer than 25 years.



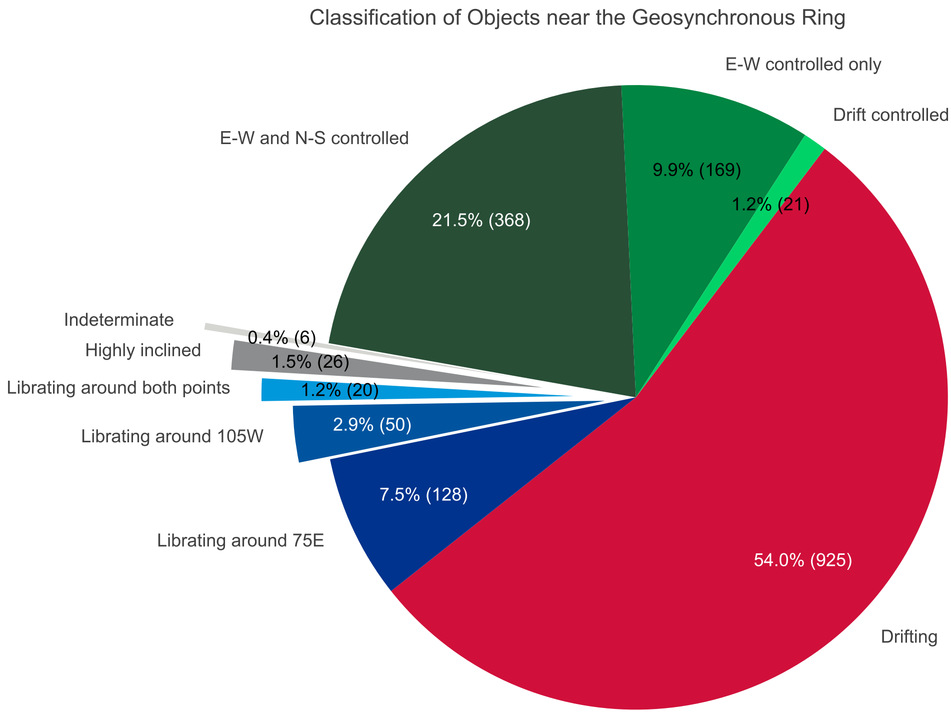
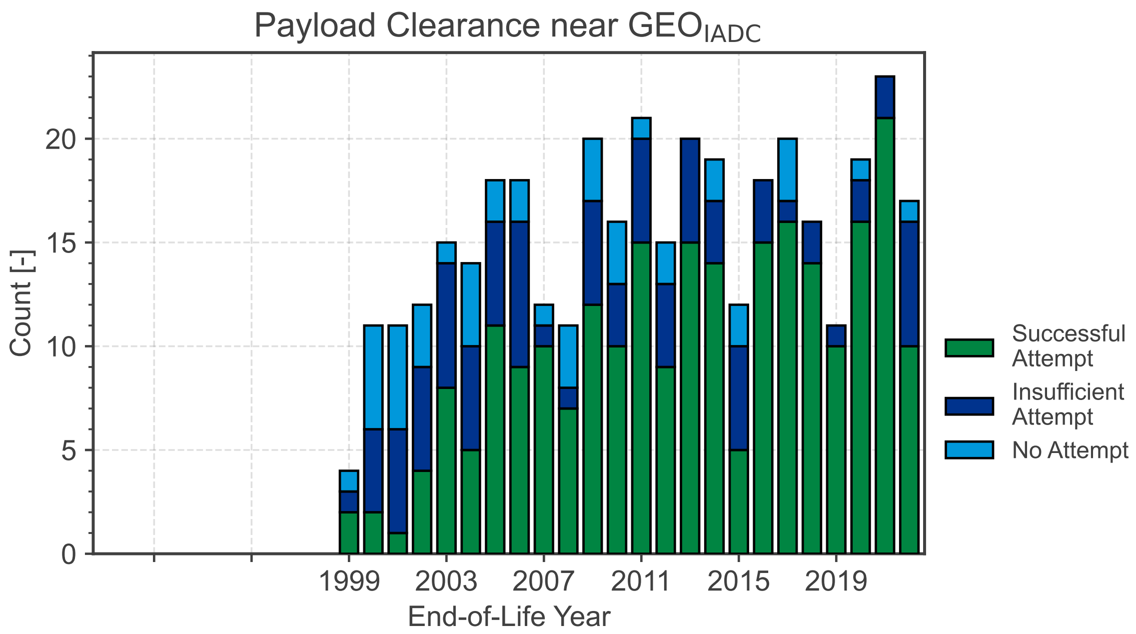
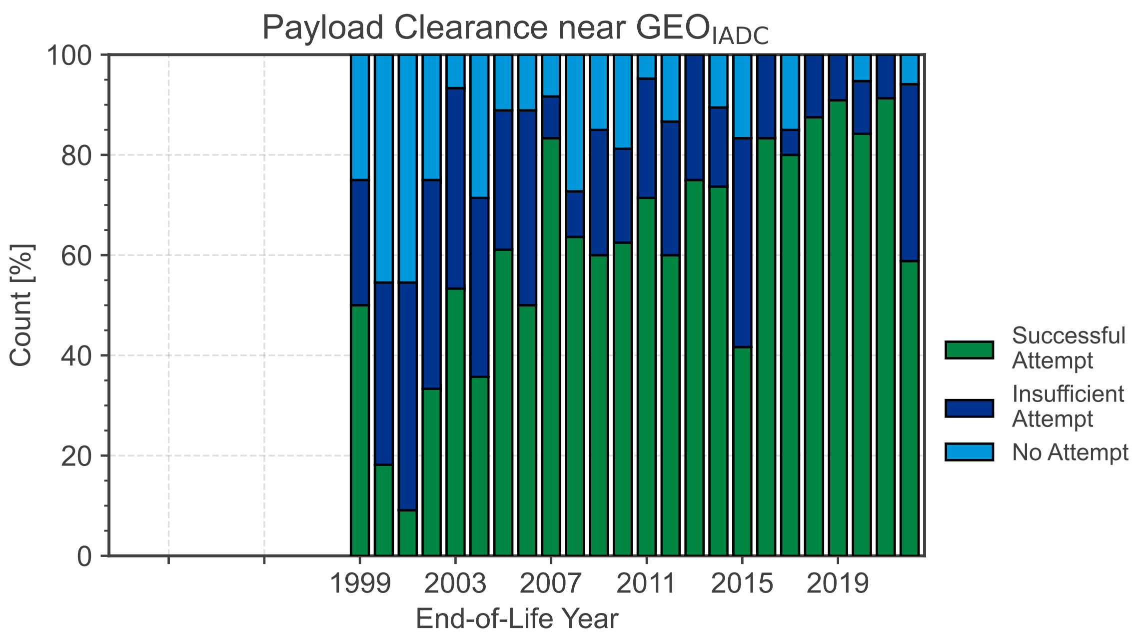


Figure 6.18: Orbital evolution status of payloads near the Geostationary orbit during 2022.

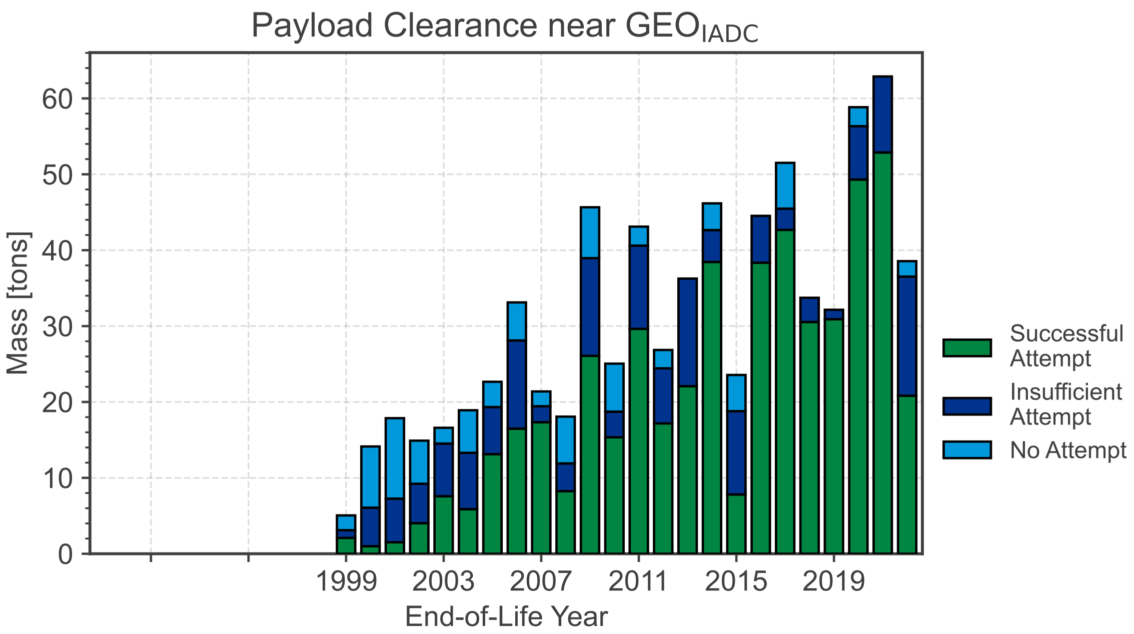


(a) Absolute clearance near GEO$_{IADC}$.

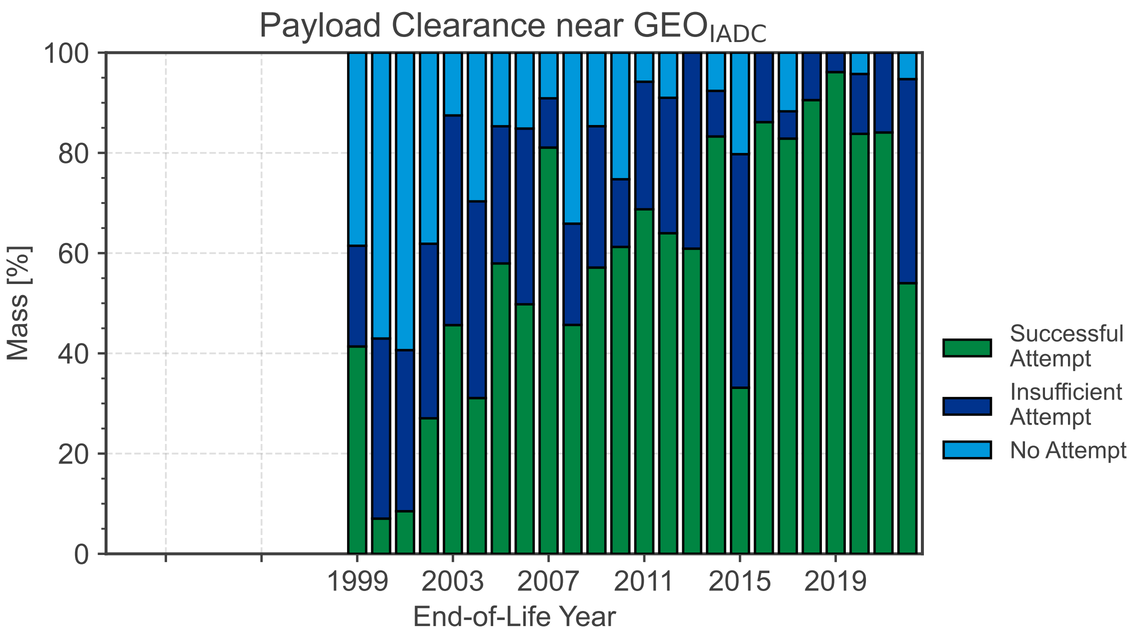


(b) Relative clearance near GEO$_{IADC}$.

Figure 6.19: Trend of adherence to the disposal guideline in GEO$_{IADC}$.

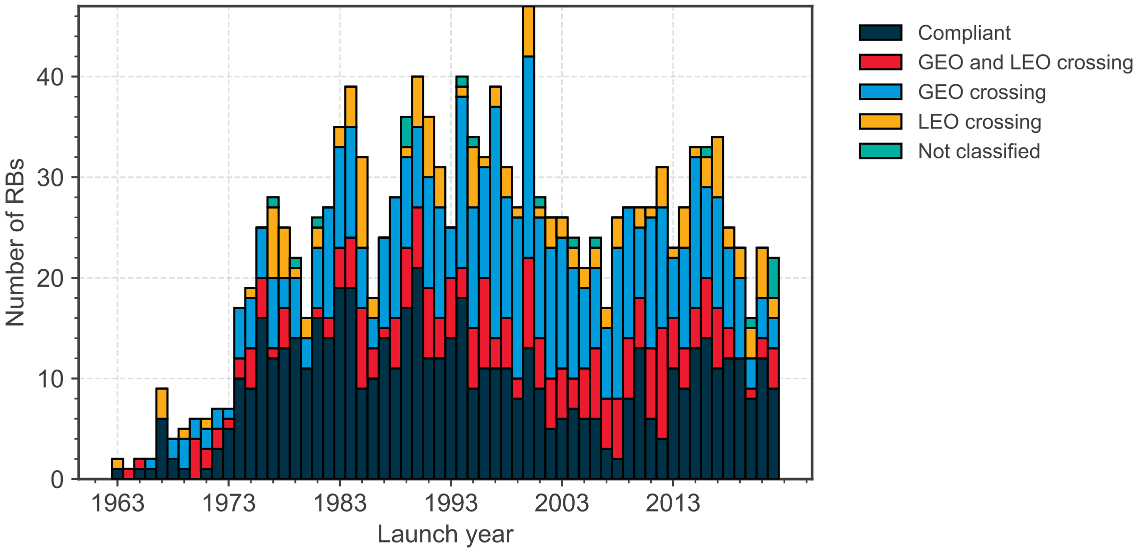


(a) Absolute mass clearance near GEO$_{IADC}$.

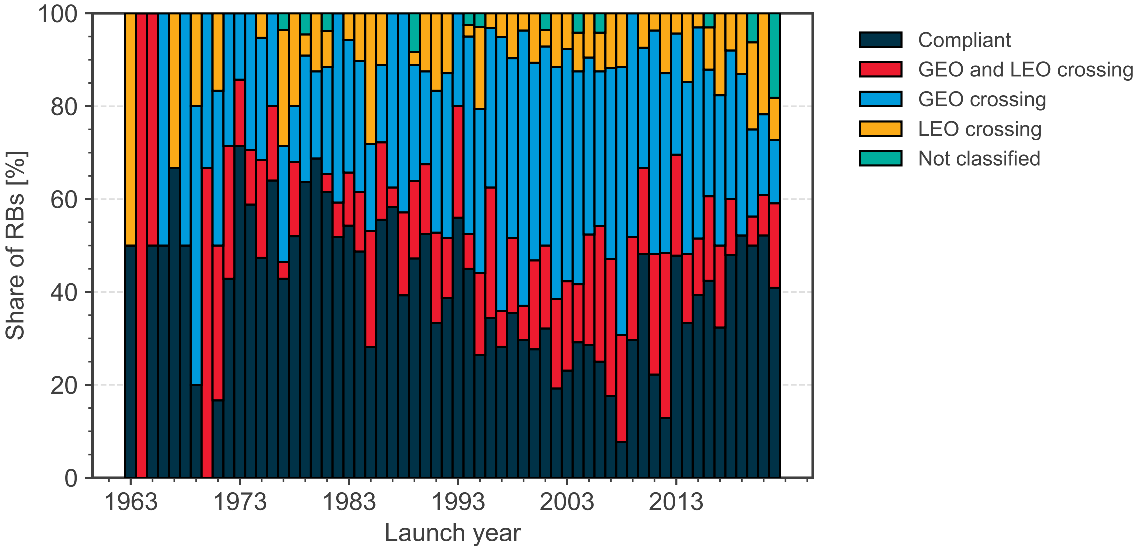


(b) Relative mass clearance near GEO$_{IADC}$.

Figure 6.20: Mass trend of adherence to the disposal guideline in GEO$_{IADC}$.



(a) Absolute clearance near GEO_{IADC}.

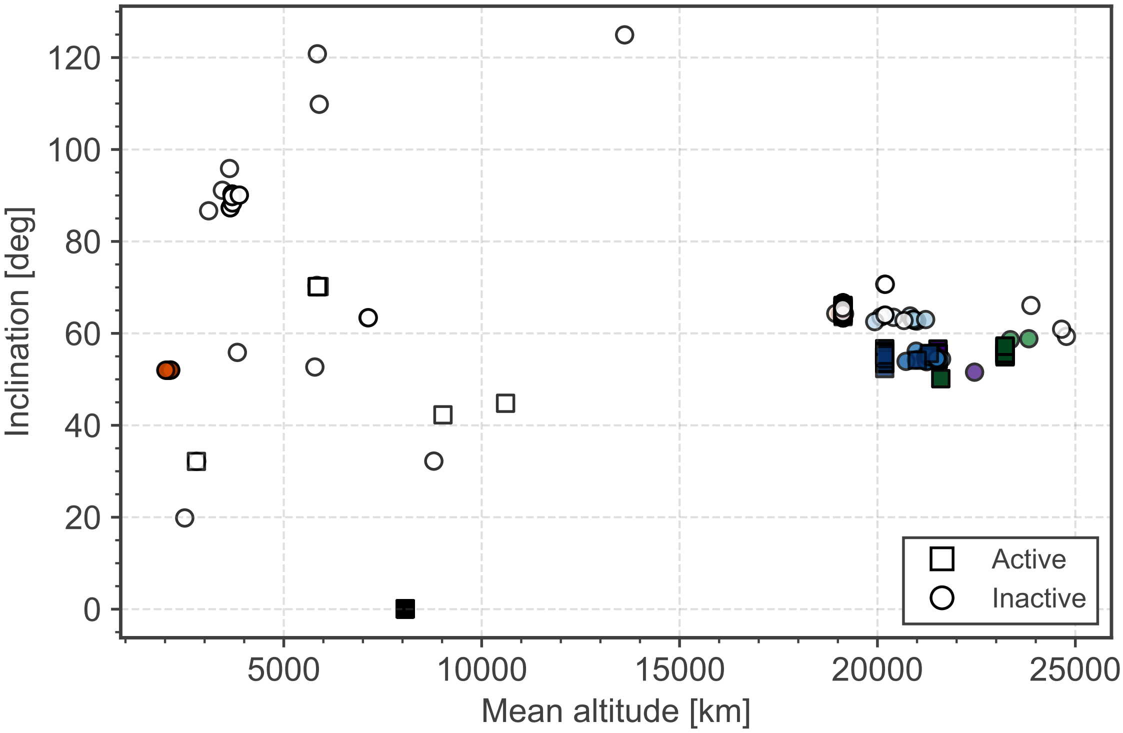


(b) Relative clearance near GEO_{IADC}.

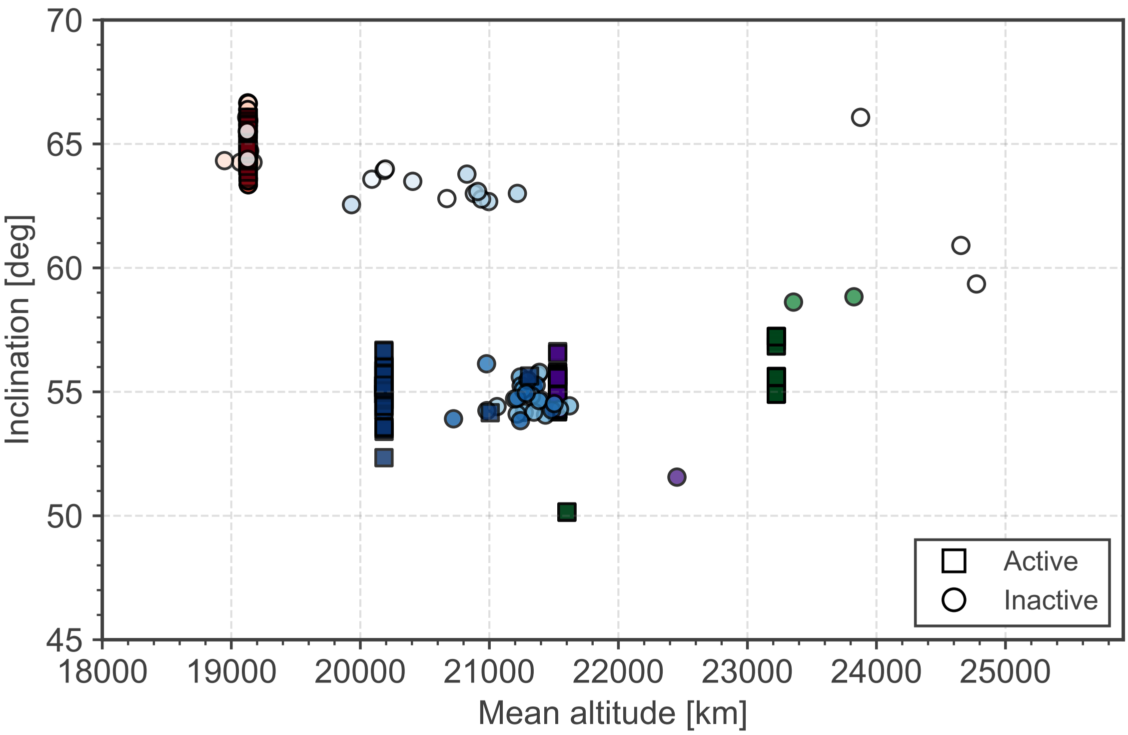
Figure 6.21: Trend of adherence to the disposal guideline for rocket bodies used to insert satellites in GEO_{IADC}.

6.3. End-Of-Life Operations in MEO

Compared to the LEO_{IADC} and GEO_{IADC} regions, MEO contains relatively fewer objects in a larger volume of space. Notwithstanding the resulting lower space debris density, the region is of importance for global navigation and communication constellations, and crossed by space objects with large eccentricity and semi-major axis orbits. Space debris mitigation guidelines call for the avoidance of space debris dense regions by means of targeted disposals, even outside the protected regions [2]. With this perspective in mind, it is instructive to show the orbital disposal behaviour of Payload objects in this region.



(a) MEO region



(b) GNSS constellations

Figure 6.22: Distribution of payloads in MEO in mean altitude and inclination, distinguishing by activity status (symbols) and constellation (colour).

7. ENVIRONMENT METRICS

7.1. Environmental Index in 2022

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 [24] 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 [25] 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 [26]. 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 (97%), with the largest contribution coming from spent rocket bodies.

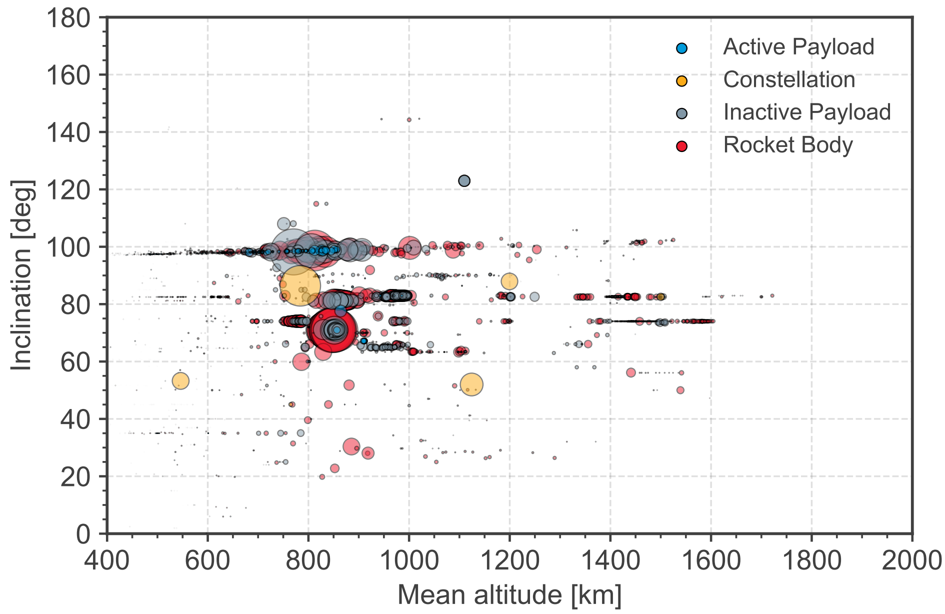


Figure 7.1: Index value for objects in LEO. The size of the marker is proportional to the debris index of the object or constellation.

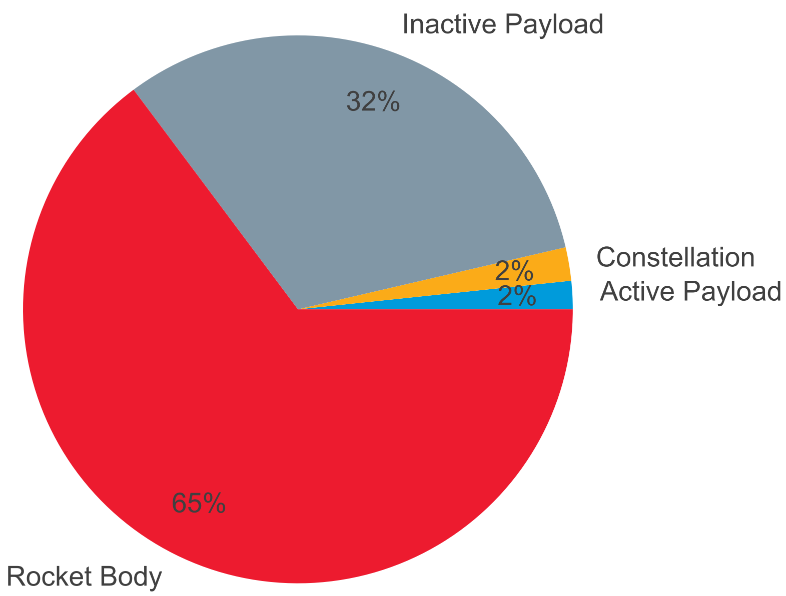


Figure 7.2: Distribution of the total index among object categories.

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* 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 2022.

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 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 2023). For each object, physical characteristics such as mass, cross-sectional area, and orbital parameters are retrieved 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 yearly explosion rate is taken from the last decade statistics on non-system related fragmentations in Table 5.2. In addition, for the *No future launches* scenario, no explosion event is simulated after the first 18 years as Fig. 5.8 shows how 95% of the non-system related fragmentation events occur within 18 years since the launch.

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 2022, discounting the contribution from constellations. For each of the constellations currently in orbit, a model of deployment and replenishment was defined using the publicly available data. A capability to successfully perform collision avoidance manoeuvres is assumed for as long as a Payload object is 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 constellation, 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 for objects with End-Of-Life equal or later than 2015. In particular, the post-mission disposal success rate is set equal to 55% for rocket bodies, 40% for payloads, and 90% for constellations. The value for payloads is higher than the observed rates to reflect the slow but upwards trend, and is combined with the shifting traffic towards destination orbits with lifetimes below 25 years. The value for constellations is above the historically observed rates but statistically valid rates could not yet be derived from the current active population. As such, it is set to the bare minimum identified in [2] 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. collision leading to the complete destruction of target and impactor, are shown in Fig. 7.3 and Fig. 7.4: the dark line represents the mean value over all the Monte Carlo runs and the light coloured lines indicate the outcome of the single 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 [27].

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 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 [28], the implementation of all space debris mitigation are necessary to avoid and adverse future.

Establishing the space debris growth rates based on the status of yearly 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, but 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.

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 the *no-further launches* ones.

Similarly, in Fig. 7.7 same scenarios are evaluated by the risk index introduced in Section 7.1. 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. 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 as increasing in all cases.

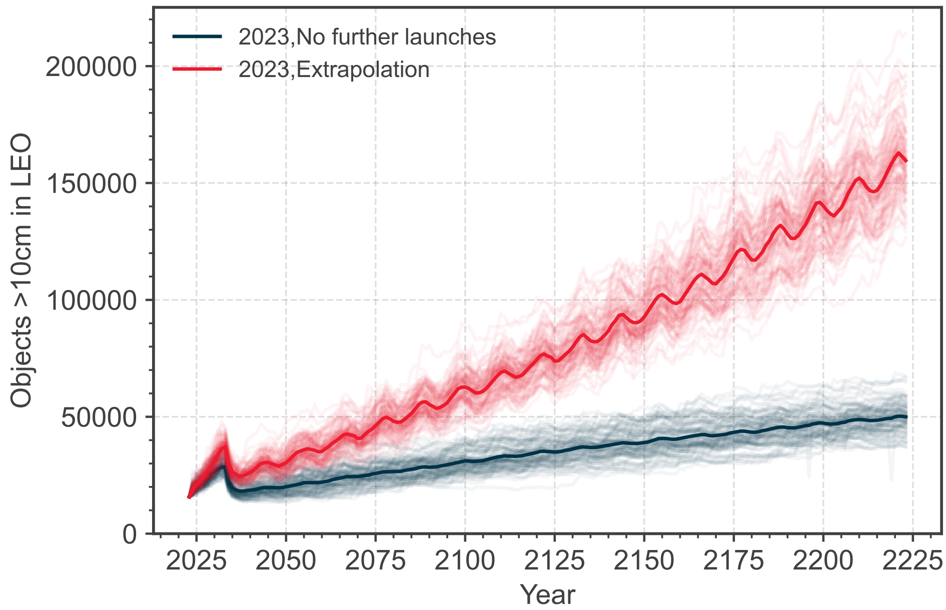


Figure 7.3: Number of objects in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

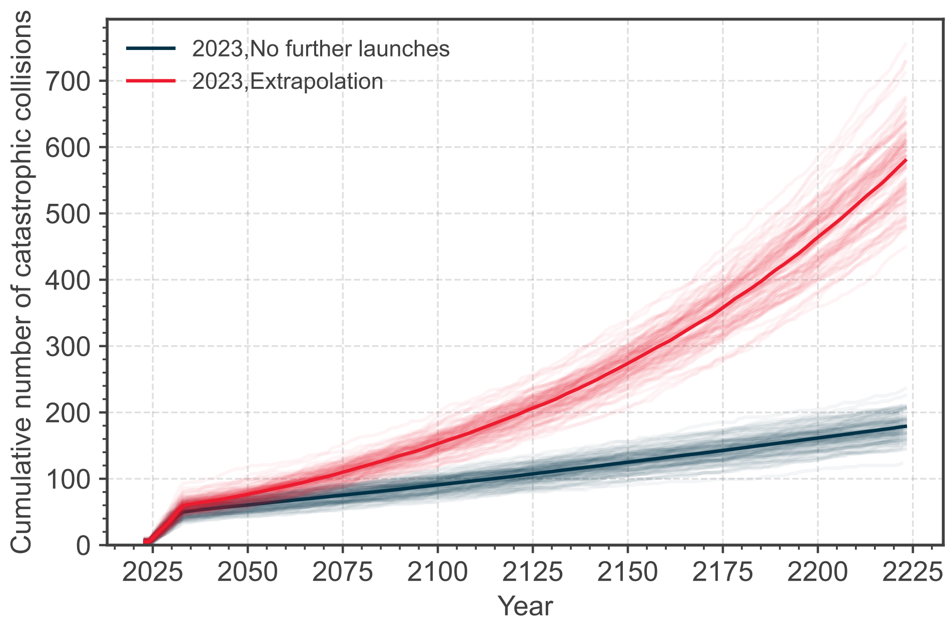


Figure 7.4: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

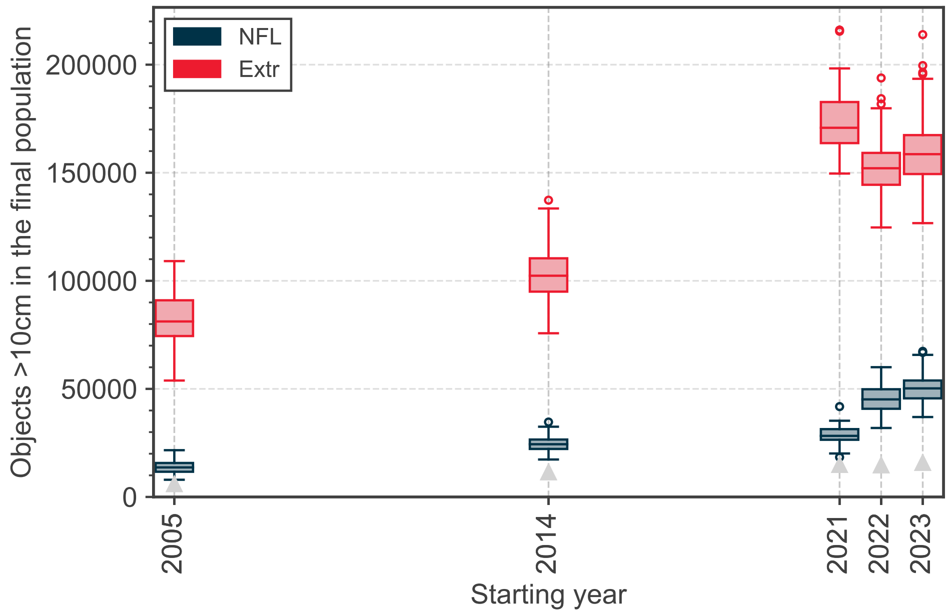


Figure 7.5: Number of objects in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

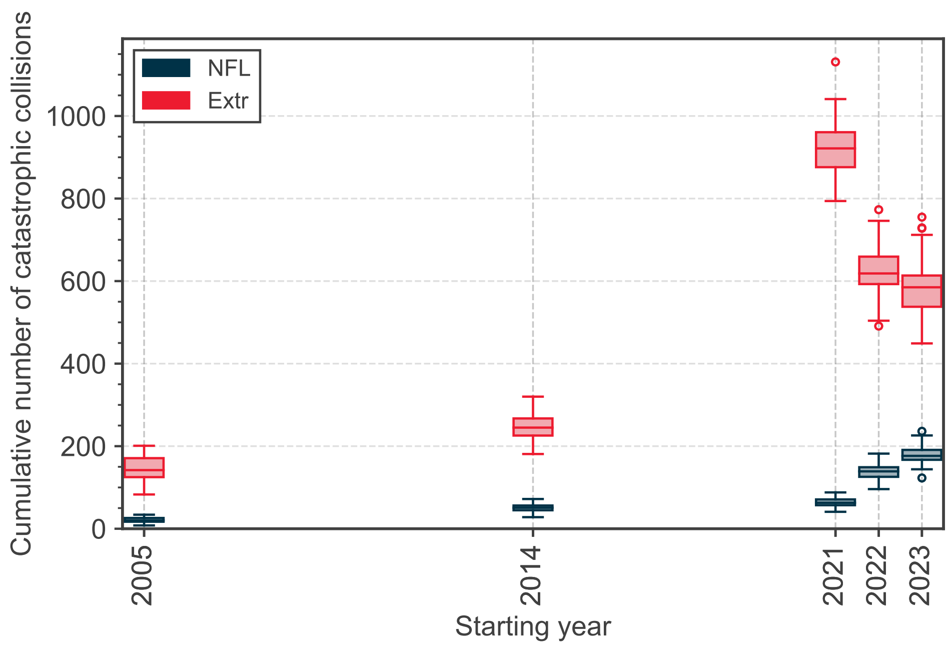


Figure 7.6: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

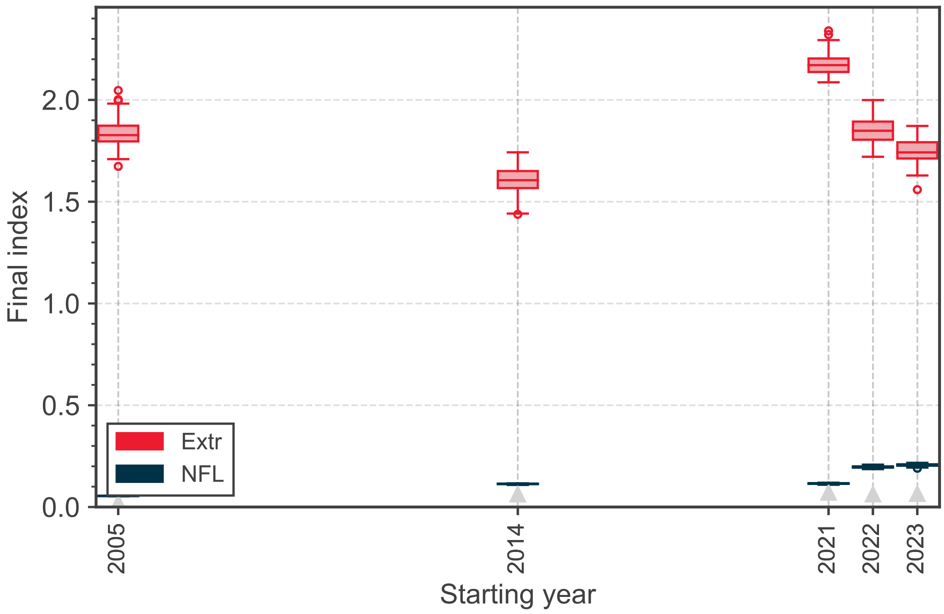


Figure 7.7: Index value in different scenarios.

References

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