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ESA's Annual Space Environment Report

Produced with the DISCOS Database

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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 [1]. 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 [2] 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* [3] and presented them to the UNCOPUOS Scientific & Technical Subcommittee. This document can serve as baseline for a non-binding policy document 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 standardization bodies such as the International Standards Organisation (ISO) with ISO/WD 24113 Space Debris Mitigation [4].

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* [5]. 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 the 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. Section 8 contains a summary of the main space environment trends identified.

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 are all artificial objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional [3].

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.

The distinction between mission related objects and fragmentations debris is clear. Objects which 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 which 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 which 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 which shall be used are defined in Table 1.2. Two regions

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	Unknown

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	$h \in [35586, 35986]$	$\delta \in [-15, 15]$

are often identified as so called protected regions by international standards, guidelines, and national legislation. These regions are specifically defined in Table 1.3 and will be referred to as such. It is important to note that all these definition are inherent to this document and can change between issues.

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 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) [6]. Orbital information on catalogued and asserted objects are correlated among the various sources to avoid duplication.

Physical properties and mission classification for the objects 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. However, for lifetime assessment data derived from space surveillance systems can be used for these objects. Further information on the individual objects which is not directly physical in nature, e.g. ownership, is deliberately not reported on in this document.

1.3 Methodology

The first aim of this report is to described 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 which 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 are 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 straight forward. The proposed metrics to observe adherence to these objectives are described in the corresponding sections and follow as close as possible [4]. In case of orbital lifetime predictions, the corresponding international standard is followed [7].

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.

1.4 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

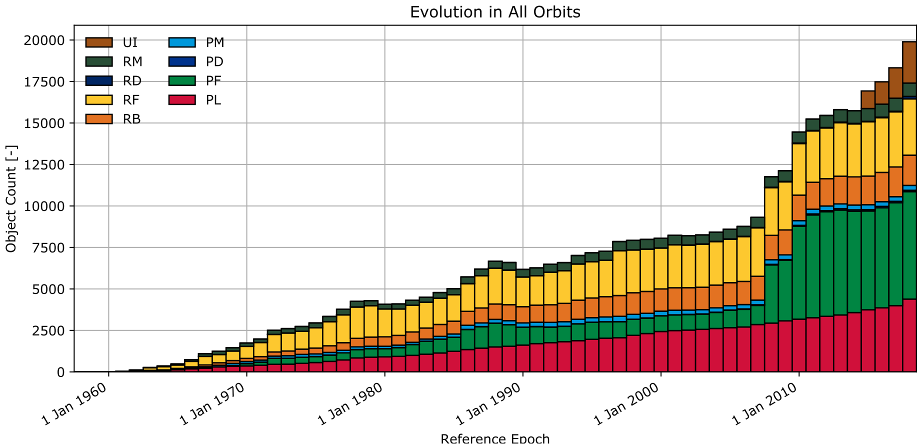
This section reports on the evolution of the space environment since the beginning of the space age. The evolution of catalogued objects in orbit is graphically represented for count, mass, and area. This data is further subdivided based on object and orbit classification. A catalogued object is only 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.

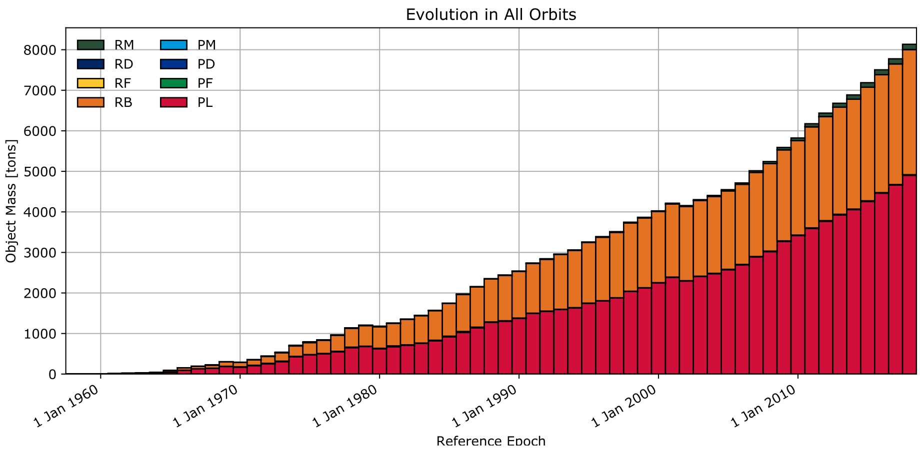
The evolution of the catalogued and asserted objects appearing in or re-entering the Earth atmosphere from the space environment is graphically represented for count, mass, and area. This data is further subdivided based on object and orbit classification. Objects which are both asserted and catalogued 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 space-flight include crew vehicles or parts thereof as well as payloads dedicated to cargo transfer, but not the rocket bodies associated to these missions. Constellations are to be understood as groups of payloads, with 10 or more members, which server the same specific mission and are consistently backed by the same entity. E.g. the Galileo navigation satellites or the PlanetLabs Flock satellites.

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 2.4, 2.6, and 2.7, the environment parameters are presented as aggregated data within the indicated year.

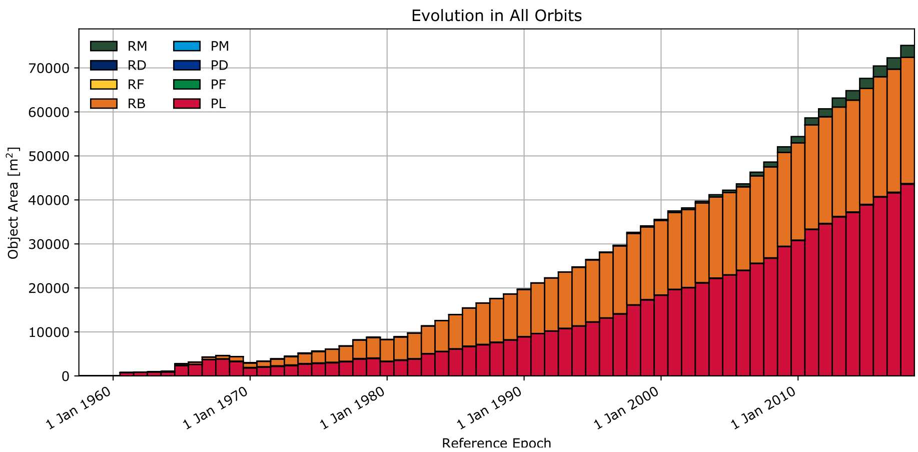
2.1 Overall Space Environment



(a) Evolution of number of objects.

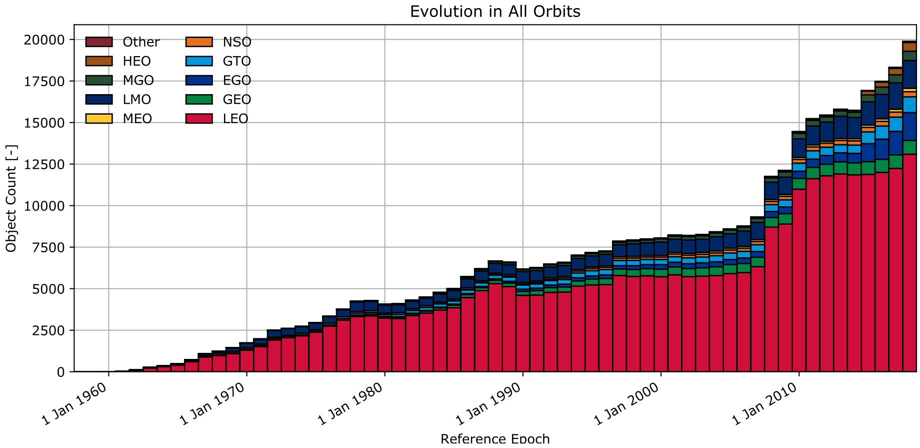


(b) Evolution of mass.

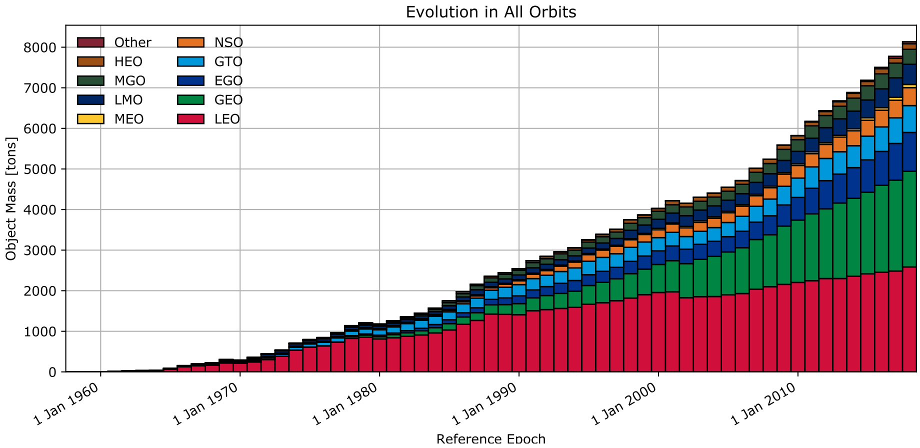


(c) Evolution of area.

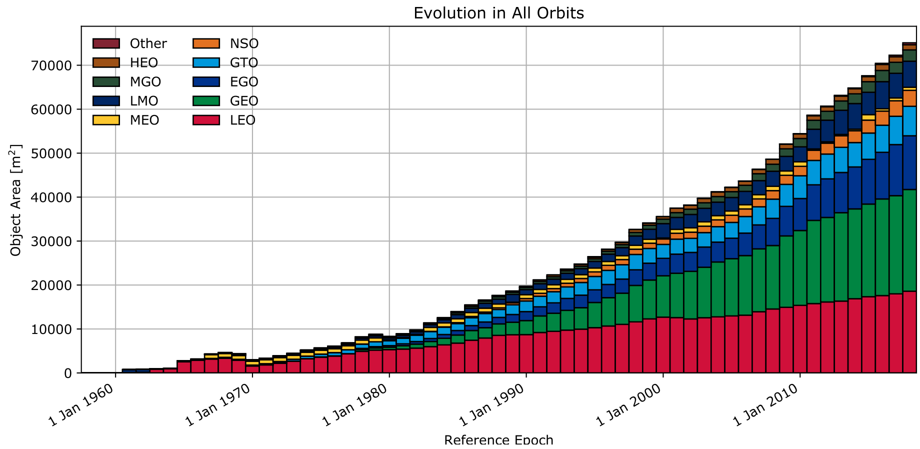
Figure 2.1: Evolution of number of objects, mass, and area in geocentric orbit by object class.



(a) Evolution of number of objects.



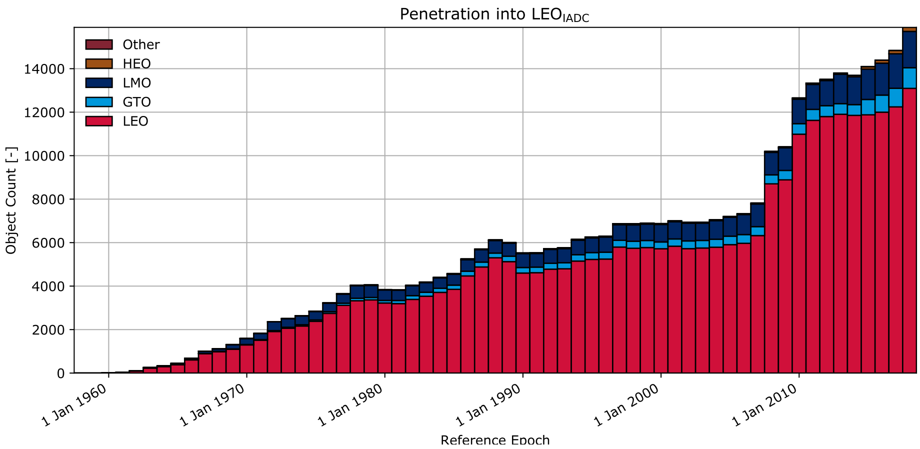
(b) Evolution of mass.



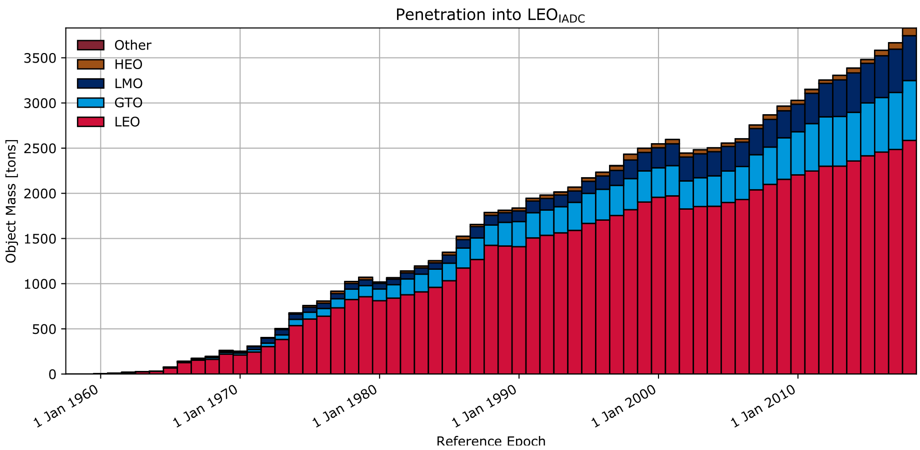
(c) Evolution of area.

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

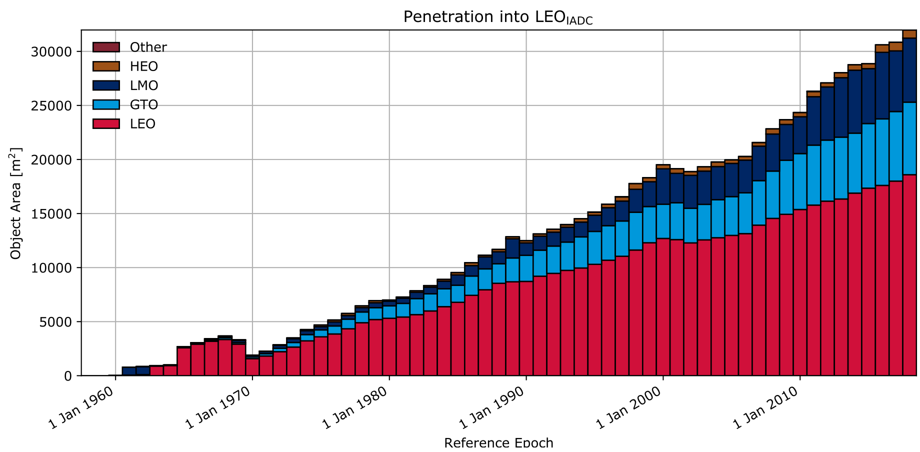
2.2 Evolution of Environment in LEO



(a) Evolution of absolute number of objects.

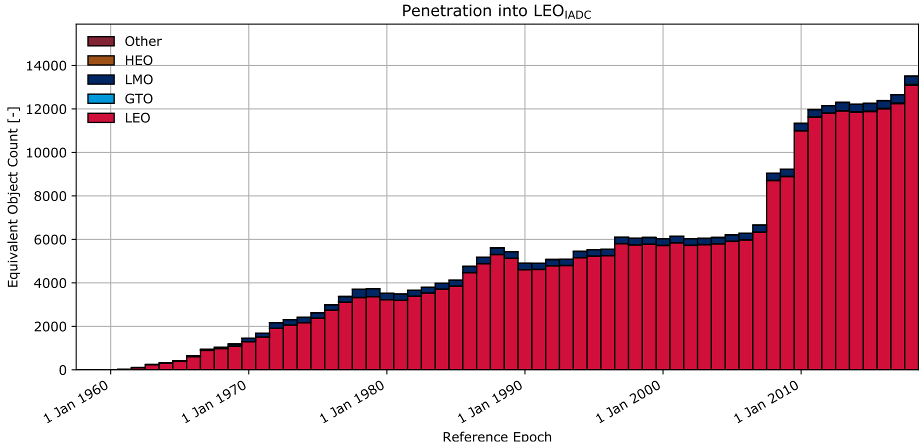


(b) Evolution of absolute mass.

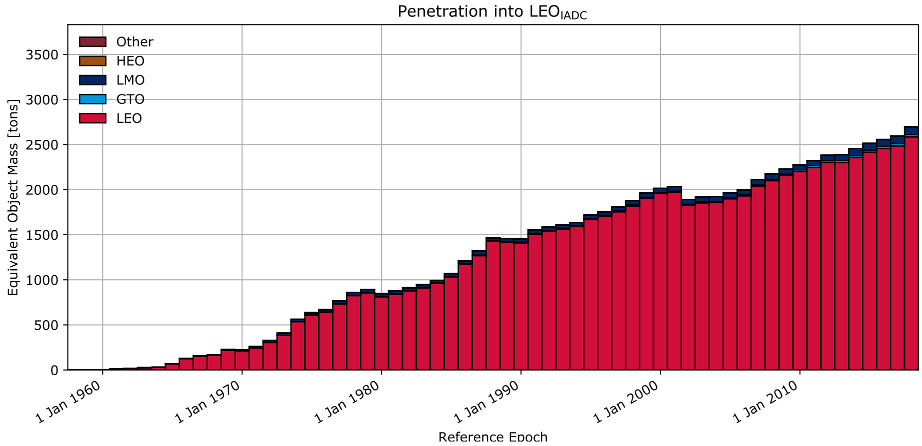


(c) Evolution of absolute area.

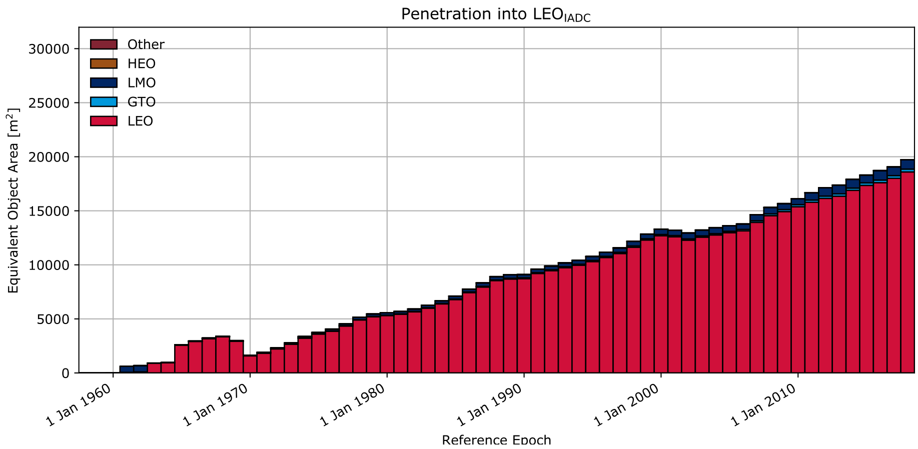
Figure 2.3: Evolution of absolute number of objects, mass and area residing in or penetrating LEO_{IADC}.



(a) Evolution of equivalent number of objects.



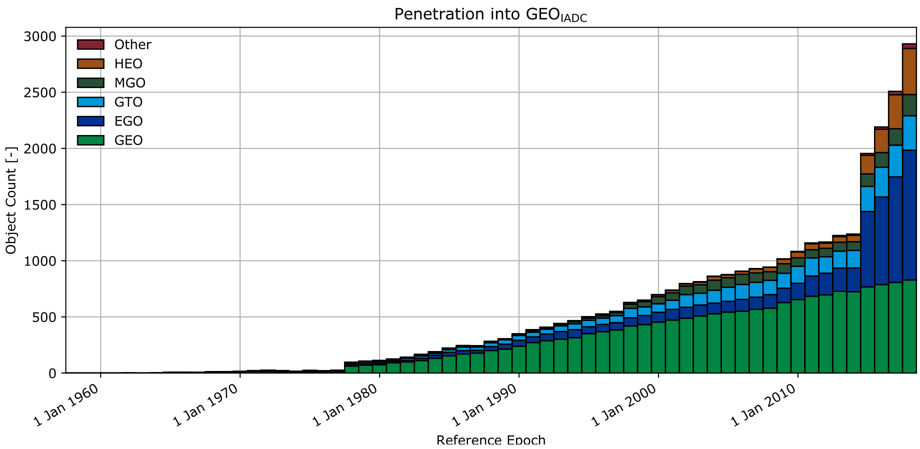
(b) Evolution of equivalent mass.



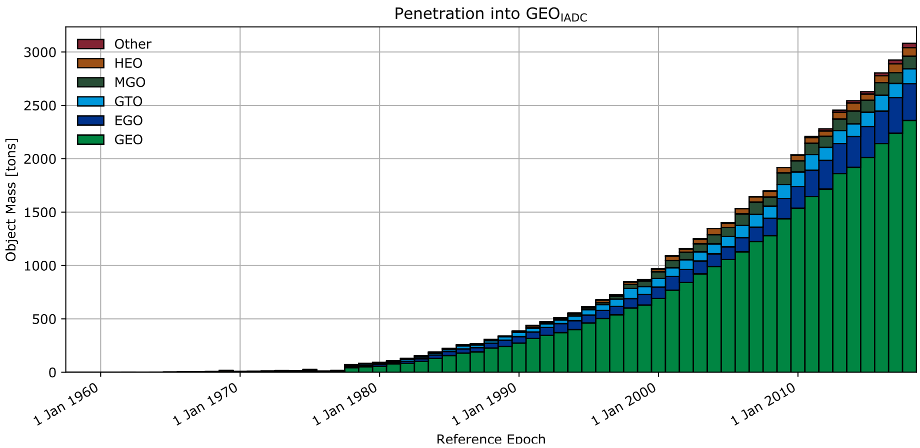
(c) Evolution of equivalent area.

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

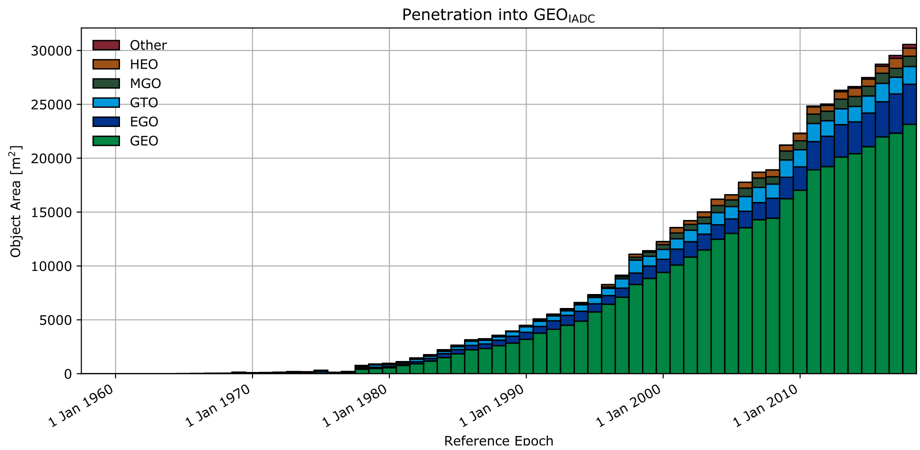
2.3 Evolution of Environment in GEO



(a) Evolution of absolute number of objects.

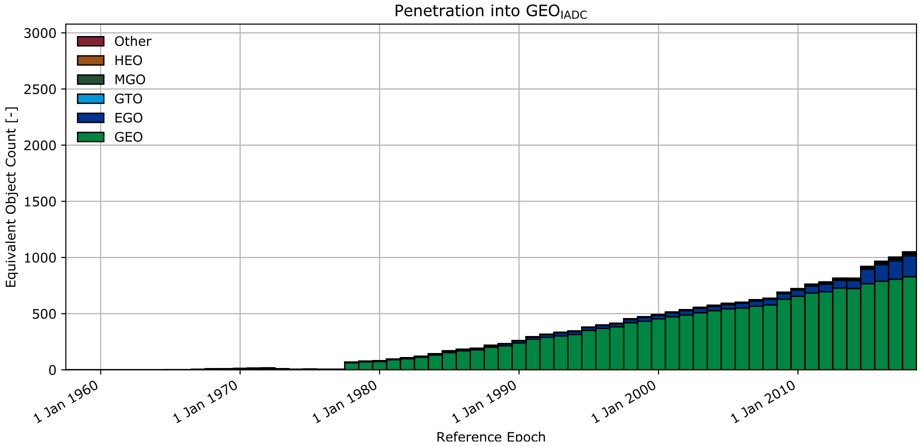


(b) Evolution of absolute mass.

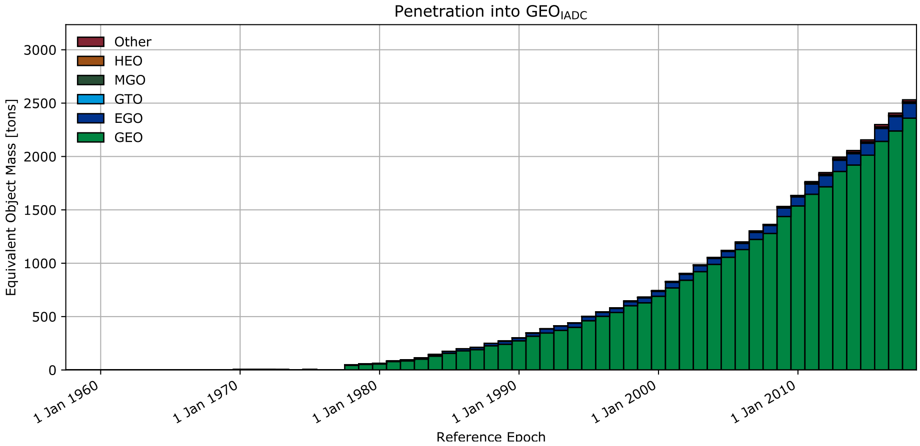


(c) Evolution of absolute area.

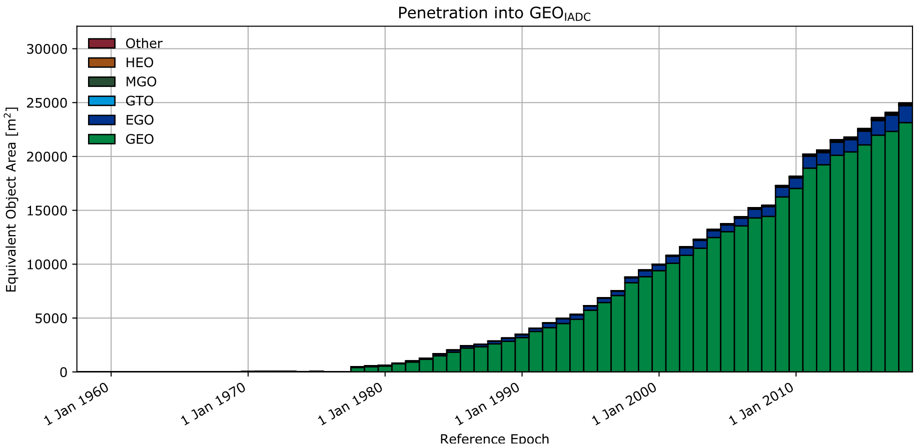
Figure 2.5: Evolution of absolute number of objects, mass and area residing in or penetrating GEO_{IADC}.



(a) Evolution of equivalent number of objects.



(b) Evolution of equivalent mass.



(c) Evolution of equivalent area.

Figure 2.6: Evolution of equivalent number of objects, mass and area residing in or penetrating GEO_{IADC}.

2.4 Usage of the Protected Regions

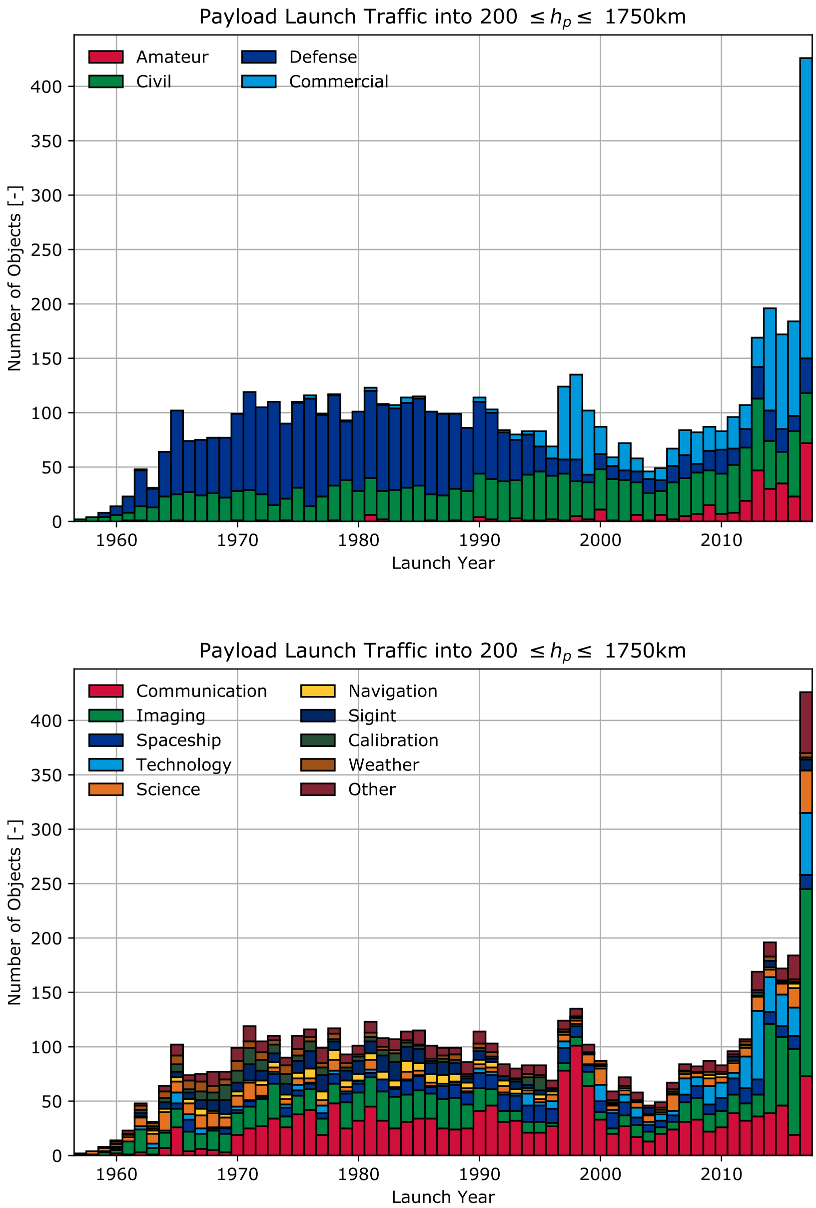


Figure 2.7: Evolution of the launch traffic near LEO_{IADC} per mission funding (top) and type (bottom).

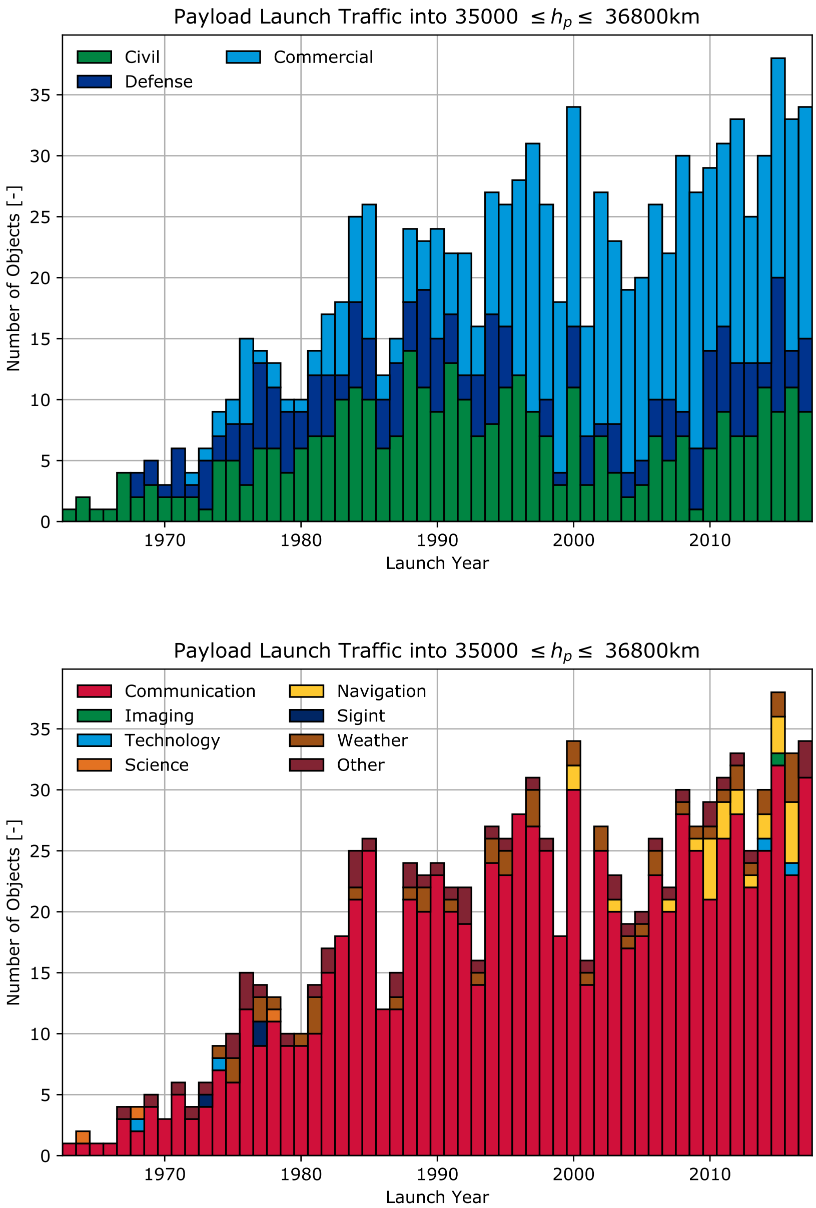
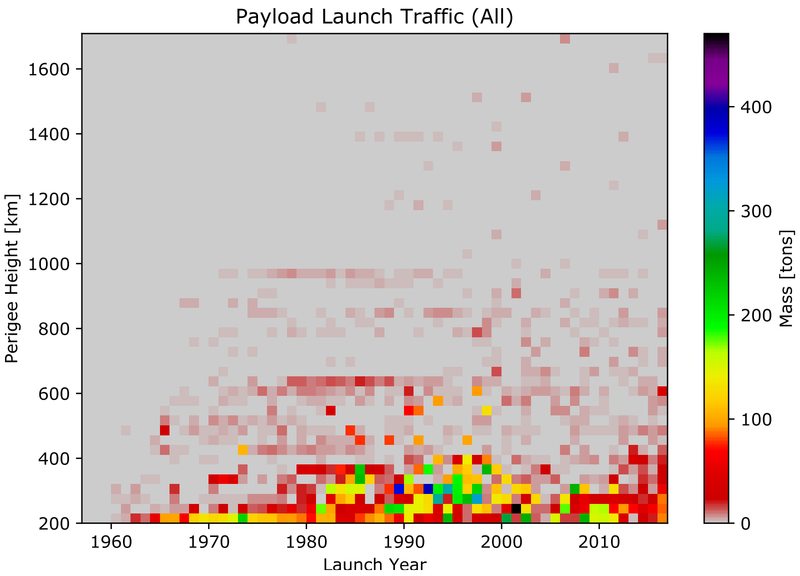
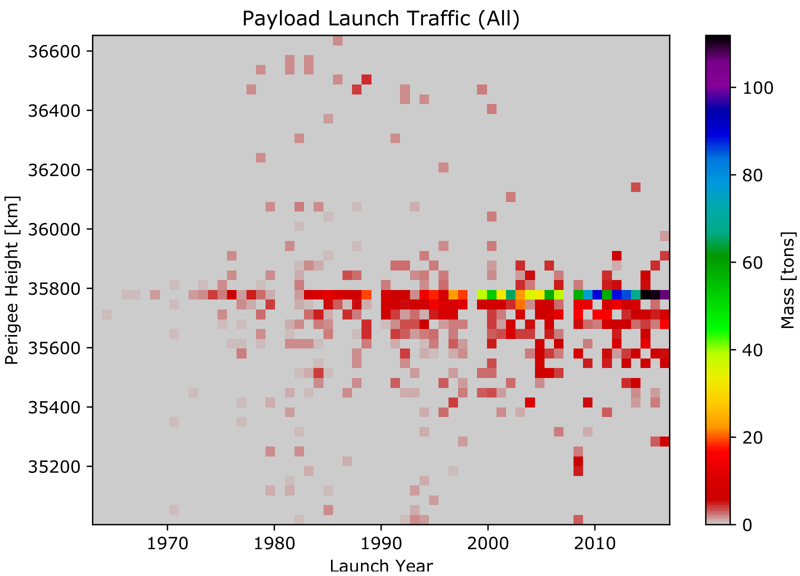


Figure 2.8: Evolution of the launch traffic near GEO_{IADC} per mission funding (top) and type (bottom).



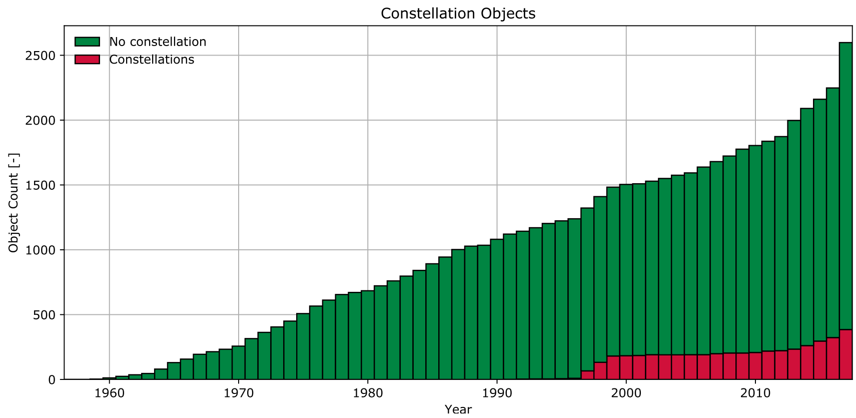
(a) LEO_{IADC}



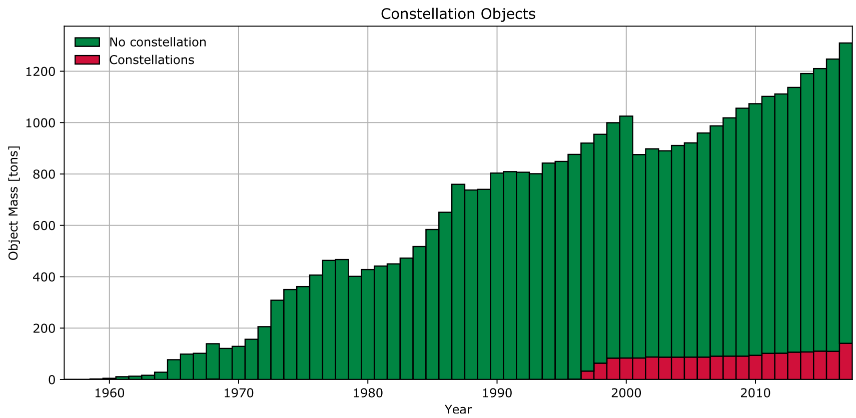
(b) GEO_{IADC}

Figure 2.9: Evolution of the launch traffic: mass injected.

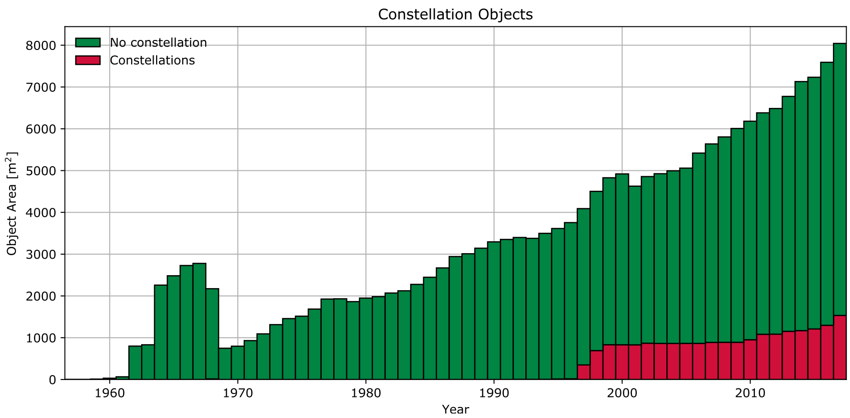
2.5 Constellations in the LEO protected region



(a) Evolution of number of objects.



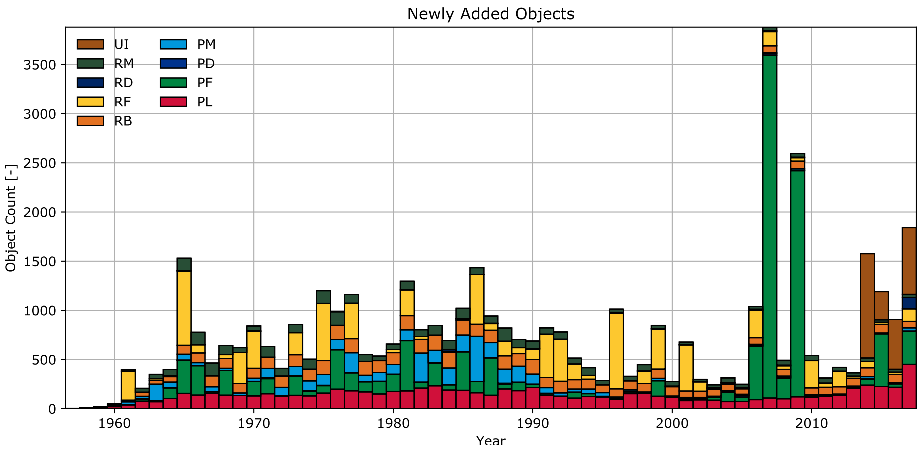
(b) Evolution of mass.



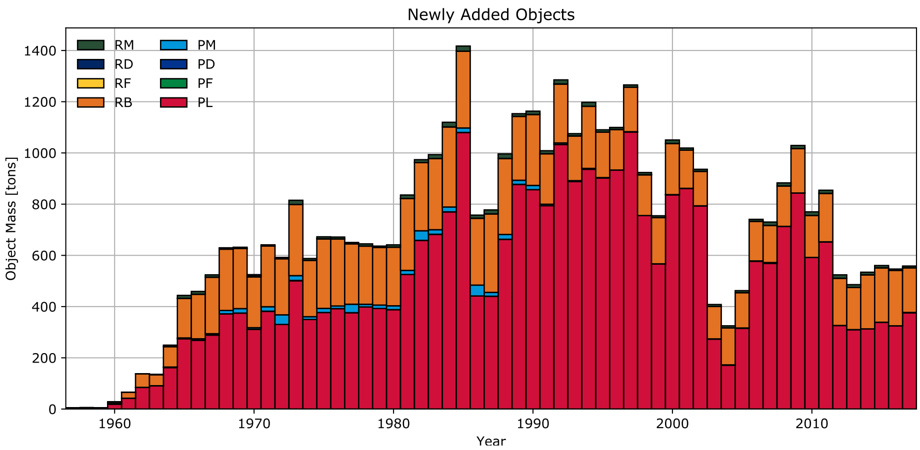
(c) Evolution of area.

Figure 2.10: Evolution of number of objects, mass, and area in LEO_{IADC} distinguishing constellations and non-constellations payloads.

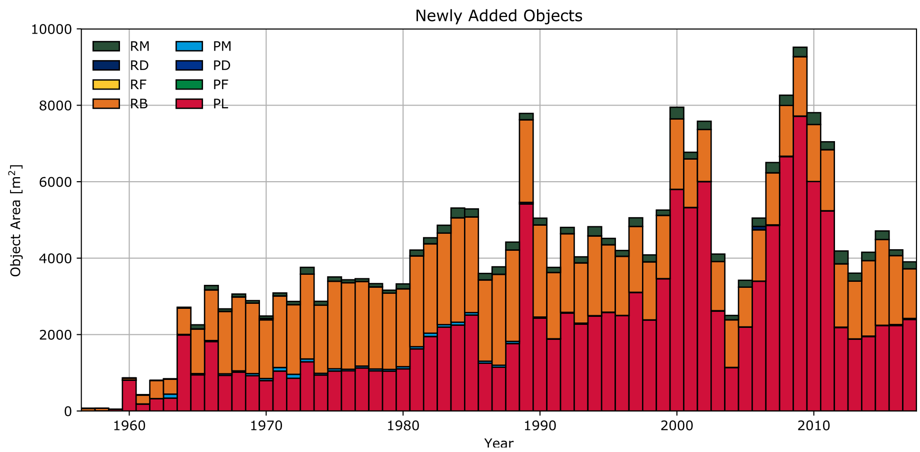
2.6 Objects Added to the Space Environment



(a) Evolution of newly added object by count.

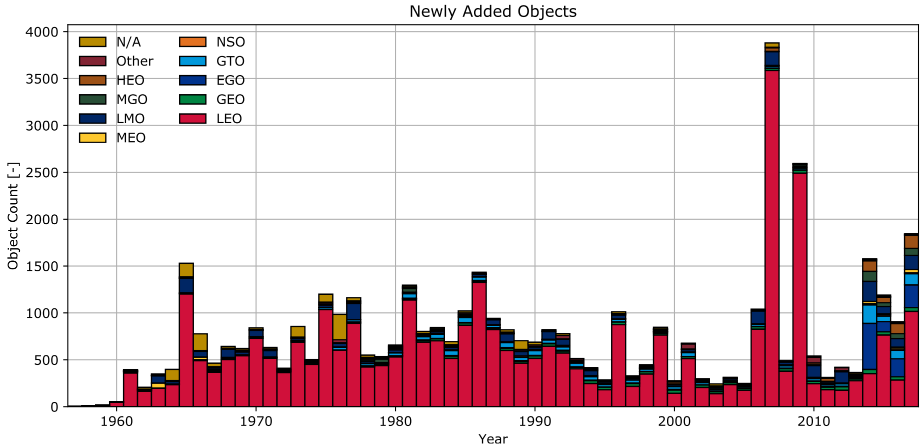


(b) Evolution of newly added mass.

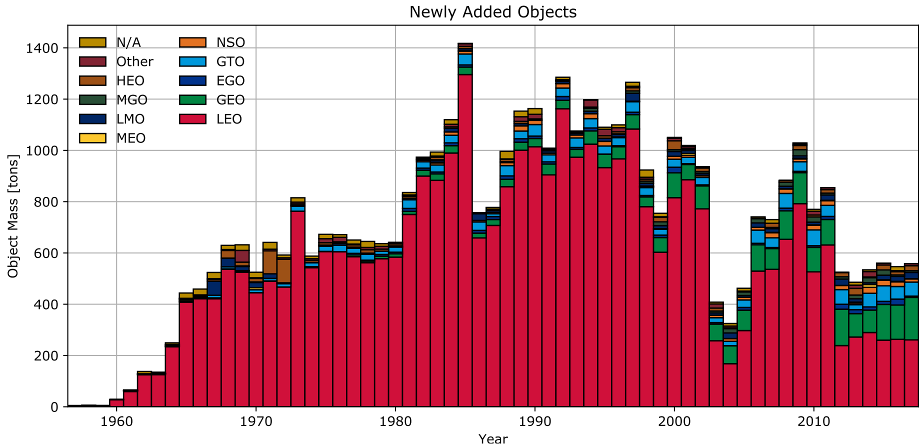


(c) Evolution of newly added area.

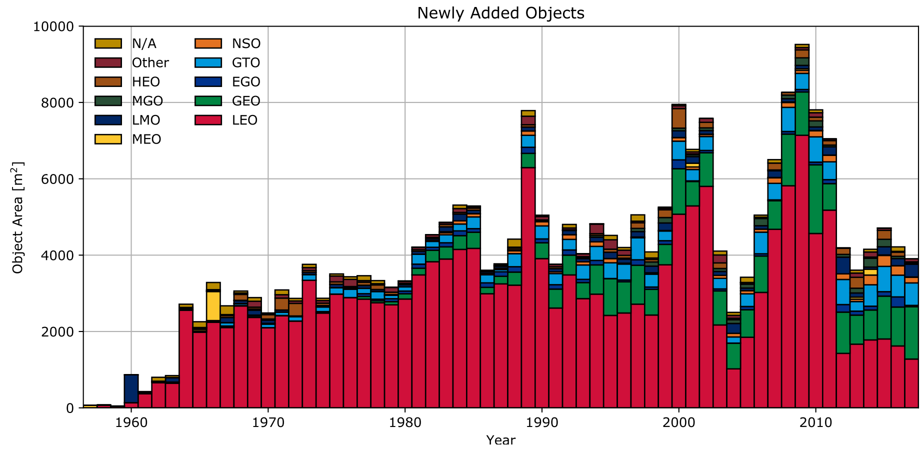
Figure 2.11: Evolution of newly added objects by object type.



(a) Evolution of newly added object by count.



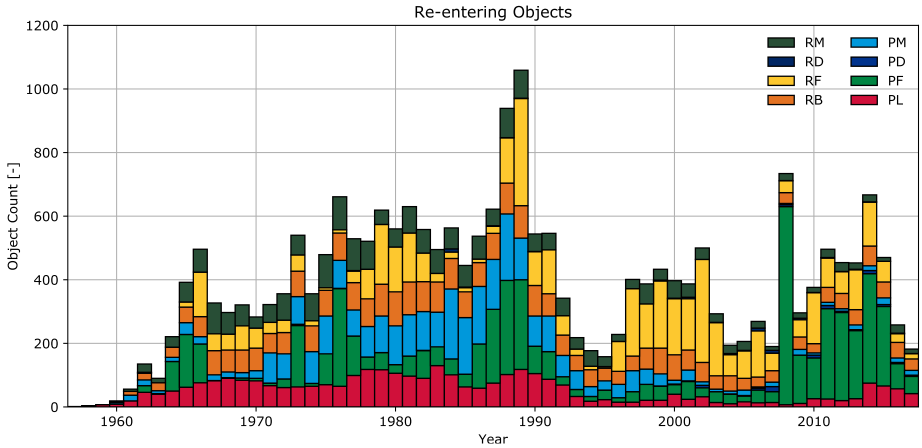
(b) Evolution of newly added mass.



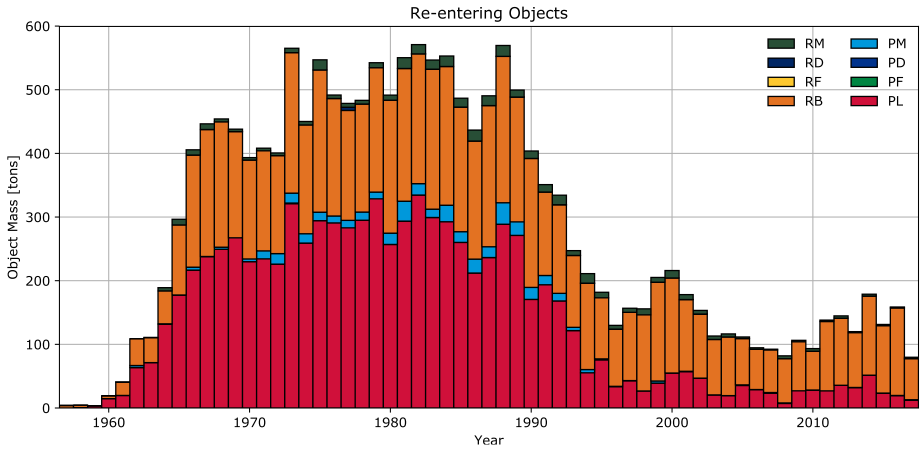
(c) Evolution of newly added area.

Figure 2.12: Evolution of newly added objects by orbit type.

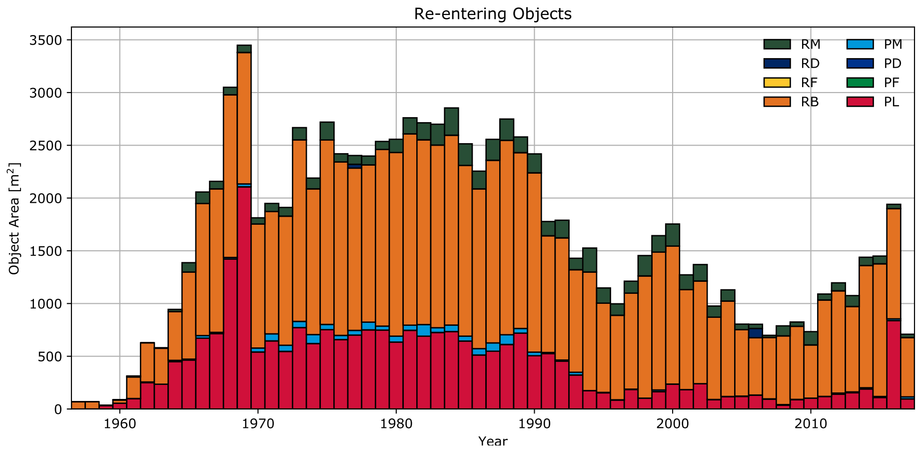
2.7 Objects Removed from the Space Environment



(a) Evolution of re-entered numbers.

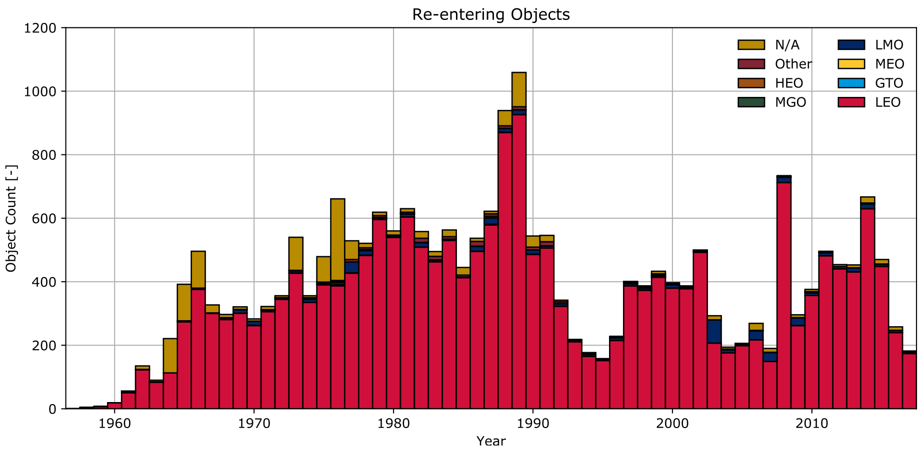


(b) Evolution of re-entered mass.

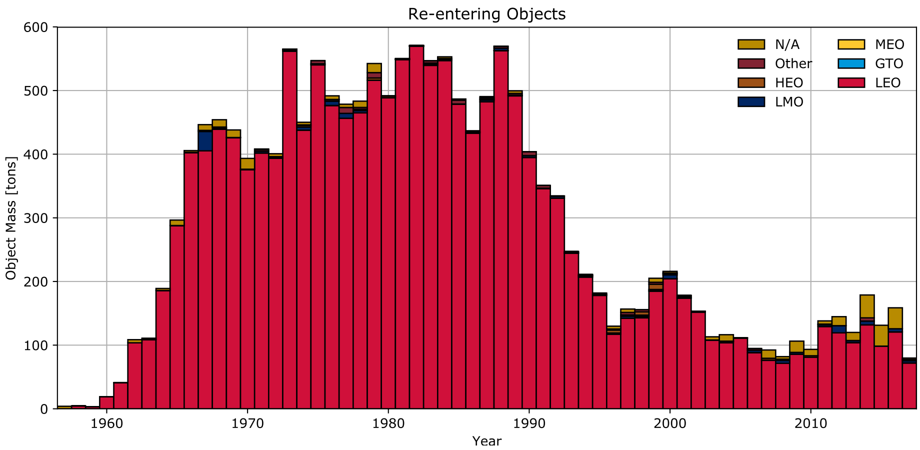


(c) Evolution of re-entered area.

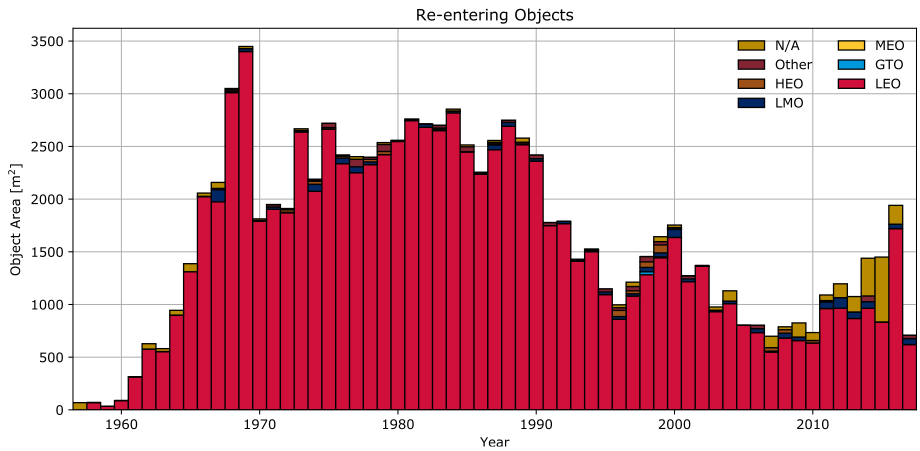
Figure 2.13: Evolution of re-entering objects by object type without human spaceflight.



(a) Evolution of re-entered numbers.

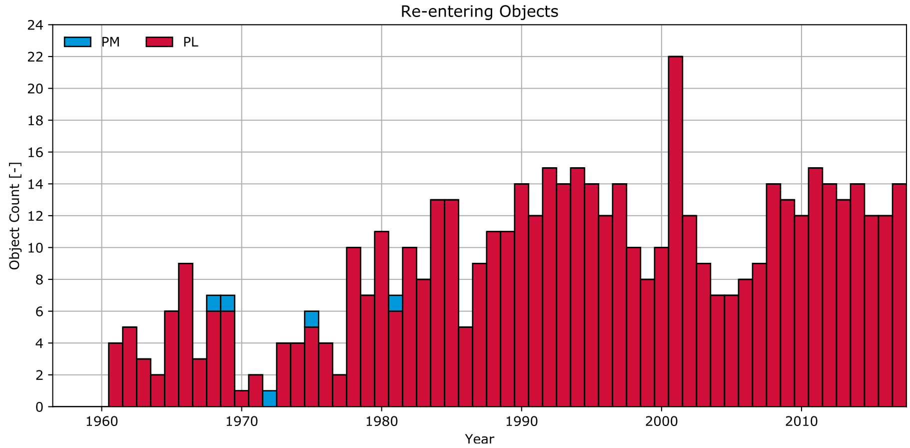


(b) Evolution of re-entered mass.

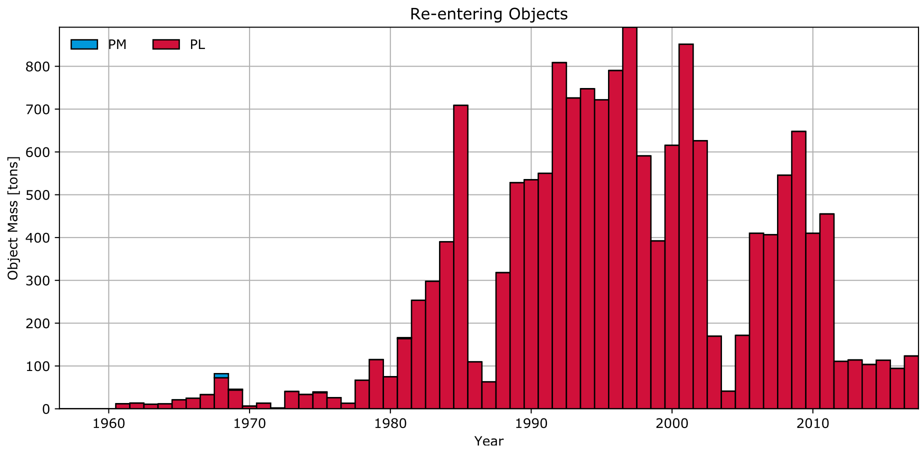


(c) Evolution of re-entered area.

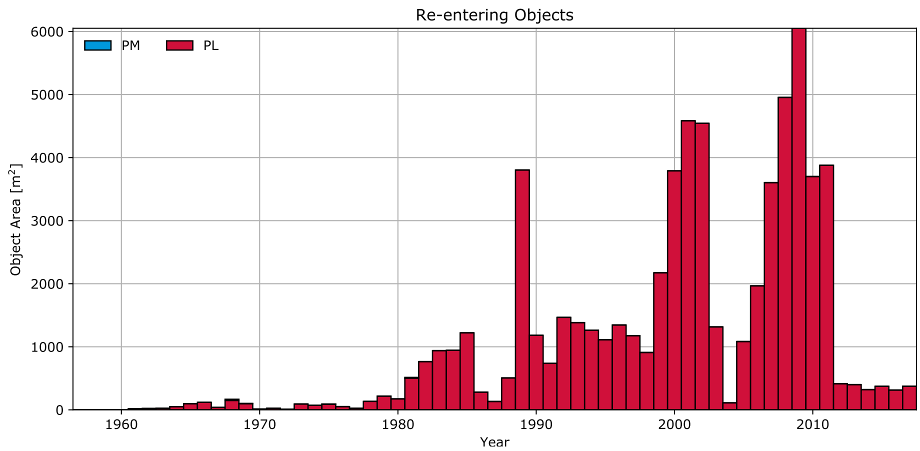
Figure 2.14: Evolution of re-entering objects by orbit type without human spaceflight.



(a) Evolution of re-entered numbers.

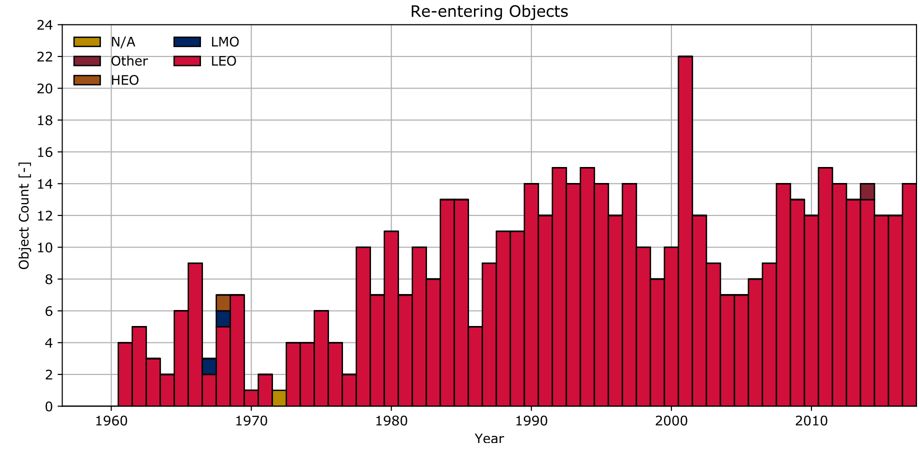


(b) Evolution of re-entered mass.

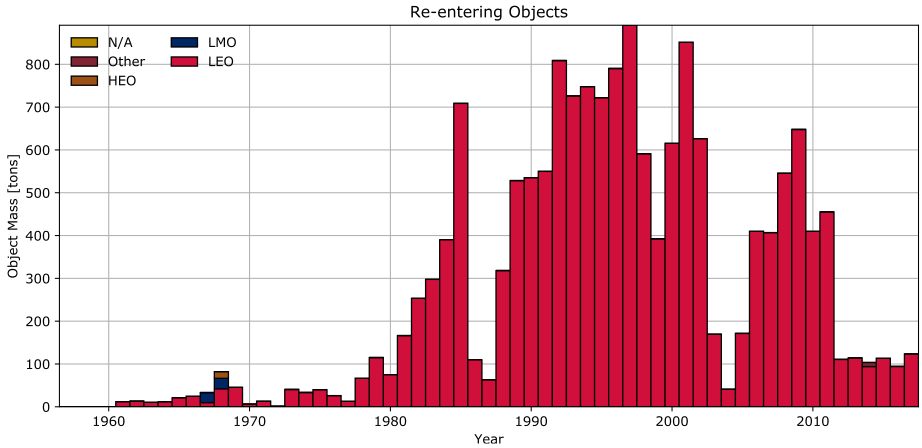


(c) Evolution of re-entered area.

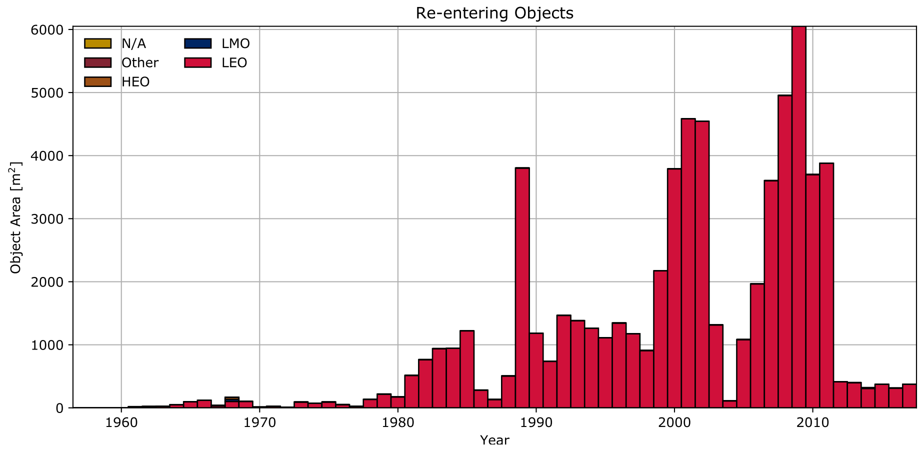
Figure 2.15: Evolution of re-entering human spaceflight objects by object type.



(a) Evolution of re-entered numbers.



(b) Evolution of re-entered mass.



(c) Evolution of re-entered area.

Figure 2.16: Evolution of re-entering human spaceflight objects by orbit type.

3 Environmental Status 2017

In this section, the status of the environment as of end of 2017 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	2673	6236	72	131	833	2481	136	520	12	13094
GEO	733	3	1	2	66	0	0	0	24	829
EGO	418	1	0	44	183	35	0	0	993	1674
GTO	57	10	0	10	226	224	4	54	365	950
NSO	236	0	0	1	73	0	0	2	0	312
MEO	54	6	4	52	17	4	1	2	63	203
LMO	89	121	6	45	210	576	8	225	389	1669
MGO	67	77	0	3	165	10	2	3	236	563
HEO	28	20	0	1	48	59	0	0	368	524
Other	33	0	0	3	2	0	0	0	38	76
Total	4388	6474	83	292	1823	3389	151	806	2488	19894

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)	18	18	0	1	82	137	0	13	156	425
LEO_{IADC} (abs)	2835	6387	78	187	1303	3340	148	799	823	15900
LEO_{IADC} (eqv)	2706	6326	75	142	884	2619	138	558	65	13513
GEO_{IADC} (abs)	890	38	1	44	302	164	0	14	1478	2931
GEO_{IADC} (eqv)	785	4	1	13	105	10	0	1	132	1051
none (abs)	681	67	4	62	300	22	3	6	343	1488

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	1347.4	1.5	1.0	2.3	1228.0	0.2	0.0	4.8	0.0	2585.2
GEO	2221.9	0.0	0.0	0.7	136.6	0.0	0.0	0.0	0.0	2359.2
EGO	609.4	0.0	0.0	4.5	341.1	0.0	0.0	0.0	0.0	954.9
GTO	104.1	0.0	0.0	0.0	522.0	0.0	0.0	36.5	0.0	662.6
NSO	297.6	0.0	0.0	0.4	144.5	0.0	0.0	0.0	0.0	442.5
MEO	55.1	0.0	0.0	0.2	20.5	0.0	0.0	2.0	0.0	77.9
LMO	84.6	0.0	0.0	2.2	327.4	0.0	0.0	82.7	0.0	497.0
MGO	95.2	0.0	0.0	1.9	268.5	0.0	0.0	3.0	0.0	368.6
HEO	40.1	0.0	0.0	0.1	95.5	0.0	0.0	0.0	0.0	135.7
Other	47.8	0.0	0.0	0.1	3.2	0.0	0.0	0.0	0.0	51.1
Total	4903.2	1.5	1.0	12.4	3087.4	0.2	0.0	129.1	0.0	8134.7

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)	20.8	0.0	0.0	0.1	171.9	0.0	0.0	5.5	0.0	198.3
LEO_{IADC} (abs)	1552.7	1.5	1.0	4.6	2146.0	0.2	0.0	124.0	0.0	3830.1
LEO_{IADC} (eqv)	1383.4	1.5	1.0	3.4	1293.2	0.2	0.0	15.7	0.0	2698.4
GEO_{IADC} (abs)	2478.2	0.0	0.0	6.4	590.2	0.0	0.0	6.5	0.0	3081.2
GEO_{IADC} (eqv)	2318.7	0.0	0.0	2.0	210.2	0.0	0.0	0.4	0.0	2531.3
none (abs)	893.2	0.0	0.0	1.4	523.1	0.0	0.0	4.0	0.0	1421.7

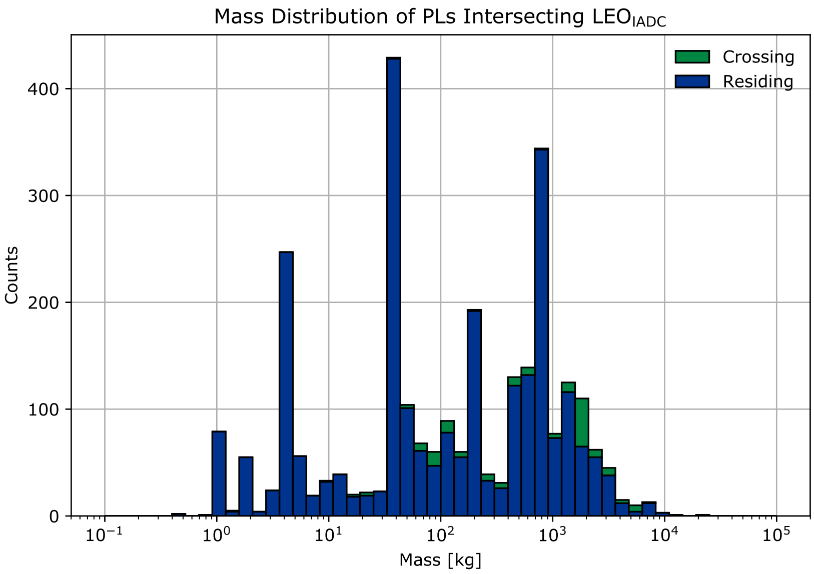
Table 3.5: Area in m^2 orbiting Earth. Objects of unknown area do not contribute to the figures presented. Other: IGO, GHO, HAO, UFO, ESO.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
LEO	8438.9	23.2	13.8	20.7	9916.3	0.0	0.0	180.5	0.0	18593.5
GEO	21674.1	0.0	0.0	3.4	1465.2	0.0	0.0	0.0	0.0	23142.6
EGO	8583.1	0.0	0.0	41.9	3588.2	0.0	0.0	0.0	0.0	12213.2
GTO	761.9	0.0	0.0	0.7	5033.3	0.0	0.0	914.8	0.0	6710.7
NSO	1954.5	0.0	0.0	0.4	1671.1	0.0	0.0	0.0	0.0	3626.0
MEO	487.9	0.0	0.0	5.5	196.5	0.0	0.0	15.2	0.0	705.2
LMO	624.8	0.0	0.0	12.0	3722.1	0.0	0.0	1566.1	0.0	5925.0
MGO	233.8	0.0	0.0	14.7	2299.0	0.0	0.0	24.7	0.0	2572.2
HEO	399.9	0.0	0.0	0.0	770.9	0.0	0.0	0.0	0.0	1170.8
Other	415.6	0.0	0.0	0.1	33.6	0.0	0.0	0.0	0.0	449.3
Total	43574.5	23.2	13.8	99.4	28696.2	0.0	0.0	2701.2	0.0	75108.3

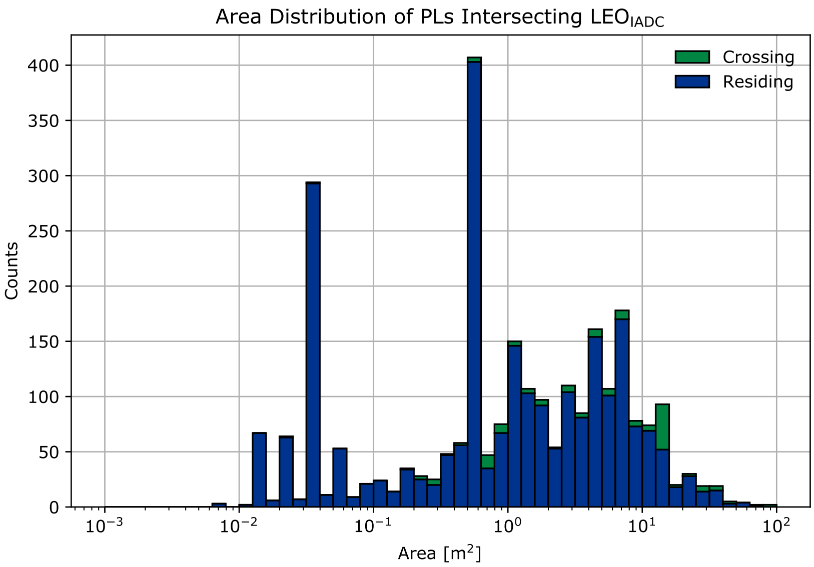
Table 3.6: Absolute and equivalent area in m^2 intersecting with the protected regions.

	PL	PF	PD	PM	RB	RF	RD	RM	UI	Total
both (abs)	156.7	0.0	0.0	0.0	1803.4	0.0	0.0	281.8	0.0	2241.9
LEO_{IADC} (abs)	10011.3	23.2	13.8	33.4	19238.3	0.0	0.0	2661.4	0.0	31981.4
LEO_{IADC} (eqv)	8608.0	23.2	13.8	24.2	10648.0	0.0	0.0	411.6	0.0	19728.9
GEO_{IADC} (abs)	24208.3	0.0	0.0	51.7	6009.6	0.0	0.0	290.0	0.0	30559.7
GEO_{IADC} (eqv)	22703.6	0.0	0.0	17.6	2239.0	0.0	0.0	19.5	0.0	24979.6
none (abs)	9511.6	0.0	0.0	14.3	5251.7	0.0	0.0	31.6	0.0	14809.2

3.1 Status of Environment in LEO

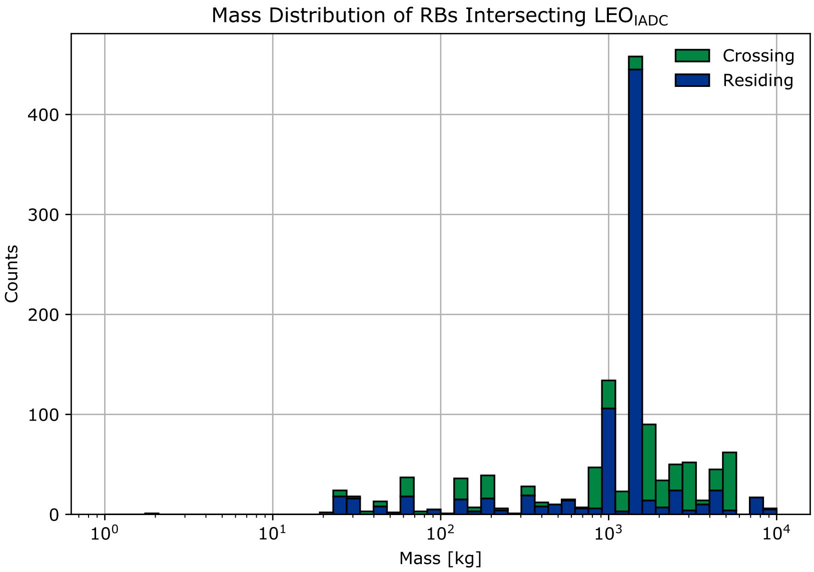


(a) Mass histogram of payloads in LEO.

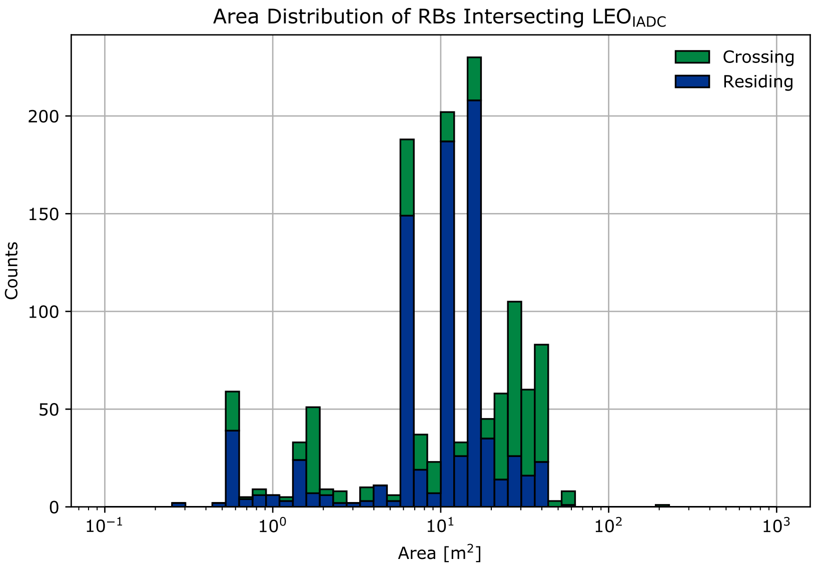


(b) Area histogram of payloads in LEO.

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

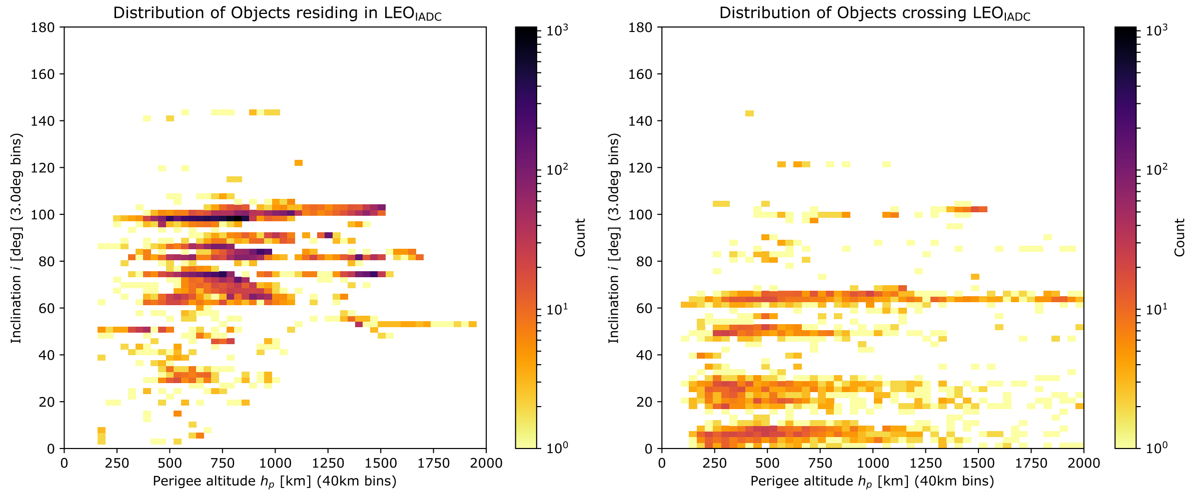


(a) Mass histogram of rocket bodies in LEO.



(b) Area histogram of rocket bodies in LEO.

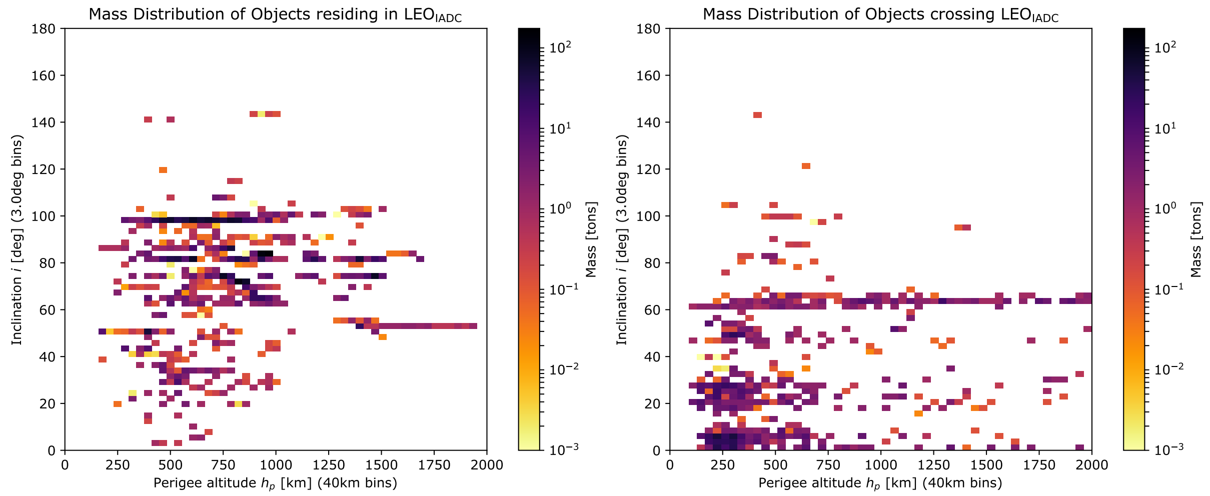
Figure 3.2: Distribution of mass and area of rocket bodies in LEO.



(a) Distribution of objects residing in LEO.

(b) Distribution of objects crossing LEO.

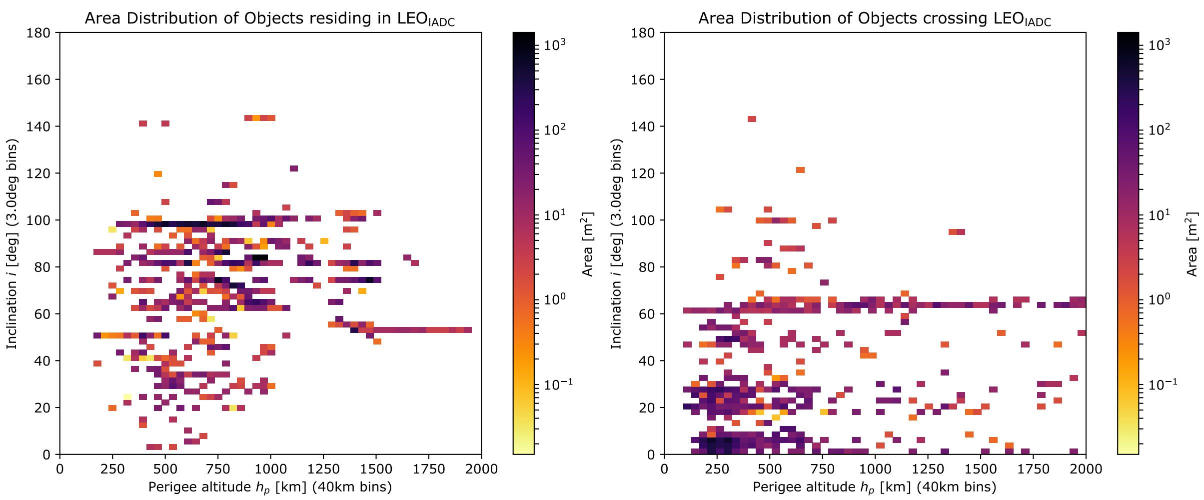
Figure 3.3: Distribution of number of objects in LEO as a function of inclination and perigee altitude.



(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.

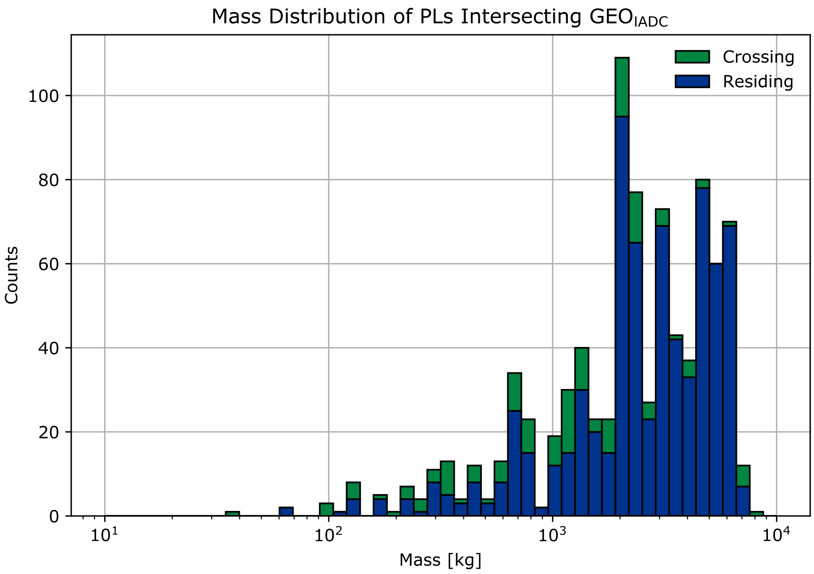


(a) Area distribution of objects residing in LEO.

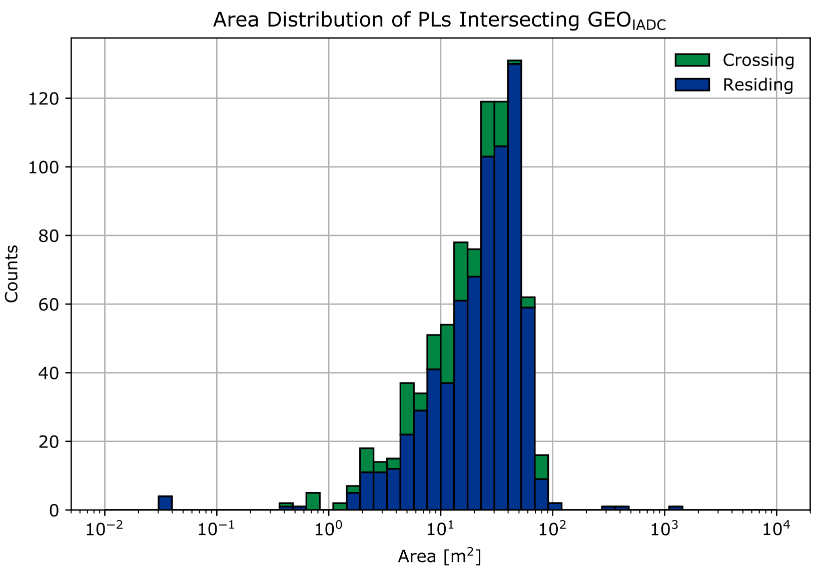
(b) Area distribution of objects crossing LEO.

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

3.2 Status of Environment in GEO

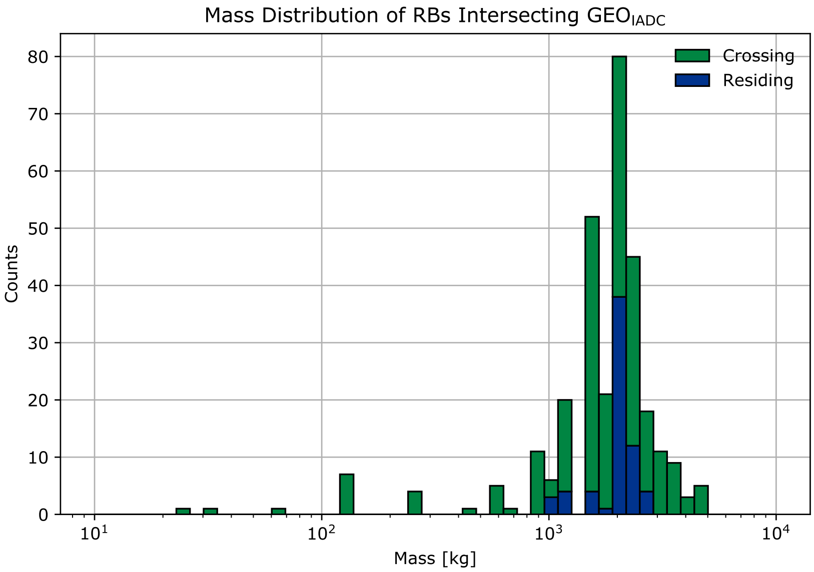


(a) Mass histogram of payloads in GEO.

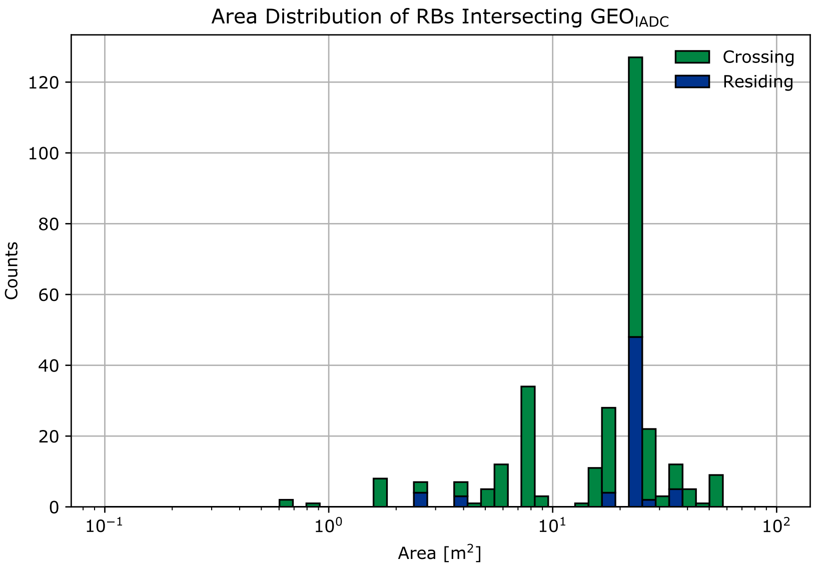


(b) Area histogram of payloads in GEO.

Figure 3.6: 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 3.7: Distribution of mass and area of rocket bodies in GEO.

3.3 Fragmentations in 2017

In Table 3.7 all established fragmentation events of the year 2017 are shown. For a description of the event categories, please consult Section 5.

Table 3.7: Fragmentation events in 2017.

Event epoch	Mass [kg]	Cat. objects	Orbit	Event cause
2017-06-17	4000.0	1	EGO	Unknown
2017-07-01	4000.0	13	EGO	Unknown
2017-08-25	2763.0	0	GEO	Propulsion
2017-09-03	56.0	9	LMO	Propulsion
Total	10819.0	23		

3.4 Changes to the Environment in 2017

In this section, the change to the environment during 2017 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	403	336	1	26	31	81	115	23	1	1017
GEO	35	0	0	0	0	0	0	0	5	40
EGO	1	0	0	2	2	0	0	0	237	242
GTO	1	0	0	0	15	16	0	6	81	119
NSO	7	0	0	0	3	0	0	0	0	10
MEO	0	0	0	2	1	0	0	0	33	36
LMO	1	0	2	0	6	17	0	4	120	150
MGO	1	0	0	1	3	0	0	0	70	75
HEO	0	0	0	0	5	13	0	0	118	136
Other	2	0	0	0	0	0	0	0	13	15
N/A	0	0	0	1	0	0	0	0	0	1
Total	451	336	3	31	66	127	115	33	678	1840

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)	0	0	0	0	10	20	0	0	35	65
LEO_{IADC} (abs)	405	336	3	26	57	127	115	33	220	1322
LEO_{IADC} (eqv)	403	336	2	26	32	87	115	24	17	1042
GEO_{IADC} (abs)	38	0	0	3	12	20	0	0	381	454
GEO_{IADC} (eqv)	35	0	0	0	1	1	0	0	28	65
none (abs)	8	0	0	2	7	0	0	0	112	129

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	188.4	0.0	0.0	1.2	71.3	0.0	0.0	0.1	0.0	261.0
GEO	165.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	165.7
EGO	1.6	0.0	0.0	0.0	3.4	0.0	0.0	0.0	0.0	5.1
GTO	2.5	0.0	0.0	0.0	49.0	0.0	0.0	3.2	0.0	54.7
NSO	6.3	0.0	0.0	0.0	5.7	0.0	0.0	0.0	0.0	12.1
MEO	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	1.1
LMO	3.4	0.0	0.0	0.0	17.7	0.0	0.0	3.4	0.0	24.5
MGO	0.0	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.0	7.0
HEO	0.0	0.0	0.0	0.0	19.3	0.0	0.0	0.0	0.0	19.3
Other	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0
Total	376.0	0.0	0.0	1.2	174.5	0.0	0.0	6.7	0.0	558.4

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)	0.0	0.0	0.0	0.0	39.1	0.0	0.0	0.0	0.0	39.1
LEO_{IADC} (abs)	194.3	0.0	0.0	1.2	157.3	0.0	0.0	6.7	0.0	359.5
LEO_{IADC} (eqv)	189.5	0.0	0.0	1.2	75.6	0.0	0.0	0.8	0.0	267.0
GEO_{IADC} (abs)	175.3	0.0	0.0	0.0	42.5	0.0	0.0	0.0	0.0	217.9
GEO_{IADC} (eqv)	166.4	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	168.3
none (abs)	6.3	0.0	0.0	0.0	13.8	0.0	0.0	0.0	0.0	20.1

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	843.2	0.0	0.0	24.8	405.3	0.0	0.0	5.0	0.0	1278.3
GEO	1371.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1371.3
EGO	11.4	0.0	0.0	0.0	23.2	0.0	0.0	0.0	0.0	34.5
GTO	14.3	0.0	0.0	0.0	428.9	0.0	0.0	145.2	0.0	588.3
NSO	71.4	0.0	0.0	0.0	78.7	0.0	0.0	0.0	0.0	150.1
MEO	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	6.0
LMO	7.0	0.0	0.0	0.0	295.2	0.0	0.0	30.7	0.0	332.8
MGO	0.0	0.0	0.0	0.2	29.0	0.0	0.0	0.0	0.0	29.2
HEO	0.0	0.0	0.0	0.0	33.8	0.0	0.0	0.0	0.0	33.8
Other	79.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	79.2
Total	2397.7	0.0	0.0	25.0	1300.0	0.0	0.0	180.8	0.0	3903.5

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)	0.0	0.0	0.0	0.0	284.2	0.0	0.0	0.0	0.0	284.2
LEO_{IADC} (abs)	864.5	0.0	0.0	24.8	1163.1	0.0	0.0	180.8	0.0	2233.2
LEO_{IADC} (eqv)	845.6	0.0	0.0	24.8	451.4	0.0	0.0	16.8	0.0	1338.5
GEO_{IADC} (abs)	1461.8	0.0	0.0	0.2	307.4	0.0	0.0	0.0	0.0	1769.4
GEO_{IADC} (eqv)	1377.3	0.0	0.0	0.0	17.2	0.0	0.0	0.0	0.0	1394.5
none (abs)	71.4	0.0	0.0	0.0	113.7	0.0	0.0	0.0	0.0	185.1

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	42	53	2	14	33	15	1	14	0	174
LMO	0	0	2	0	1	0	0	0	0	3
Other	0	0	0	0	1	0	0	0	0	1
N/A	0	1	0	1	1	1	0	0	0	4
Total	42	53	4	14	35	15	1	14	0	178

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	12.2	0.0	0.0	0.8	56.8	0.0	0.0	2.2	0.0	72.0
LMO	0.0	0.0	0.0	0.0	3.5	0.0	0.0	0.0	0.0	3.5
Other	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	2.0
N/A	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	2.2
Total	12.2	0.0	0.0	0.8	62.3	0.0	0.0	2.2	0.0	77.5

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	96.1	0.0	0.0	19.2	473.1	0.0	0.0	31.4	0.0	619.8
LMO	0.0	0.0	0.0	0.0	56.9	0.0	0.0	0.0	0.0	56.9
Other	0.0	0.0	0.0	0.0	32.3	0.0	0.0	0.0	0.0	32.3
Total	96.1	0.0	0.0	19.2	562.3	0.0	0.0	31.4	0.0	709.0

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 which are designed to be released after they are no longer required, e.g. covers protecting instruments during launch, or combustion related products which 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 expulsed 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 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.

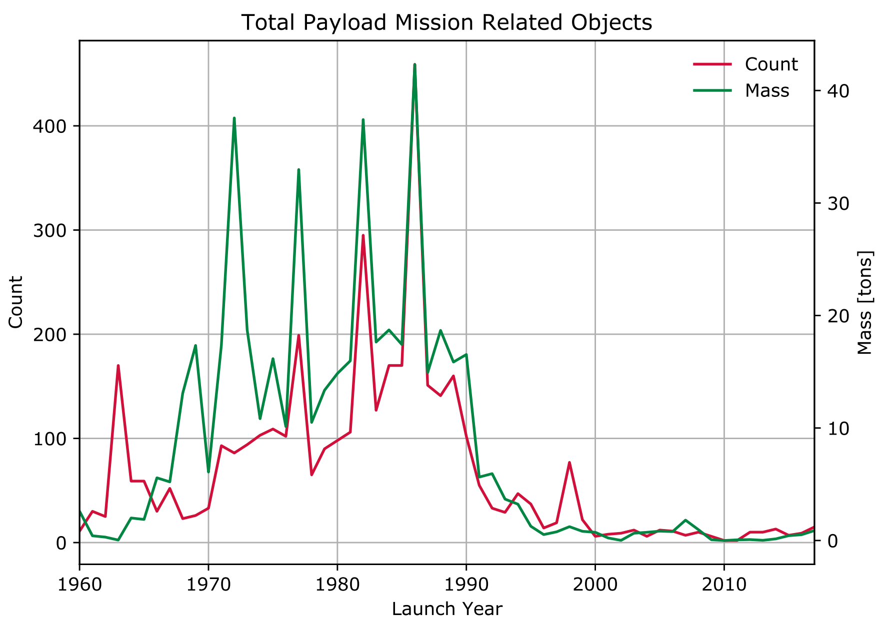


Figure 4.1: Total number and mass of catalogued mission related objects released from payloads.

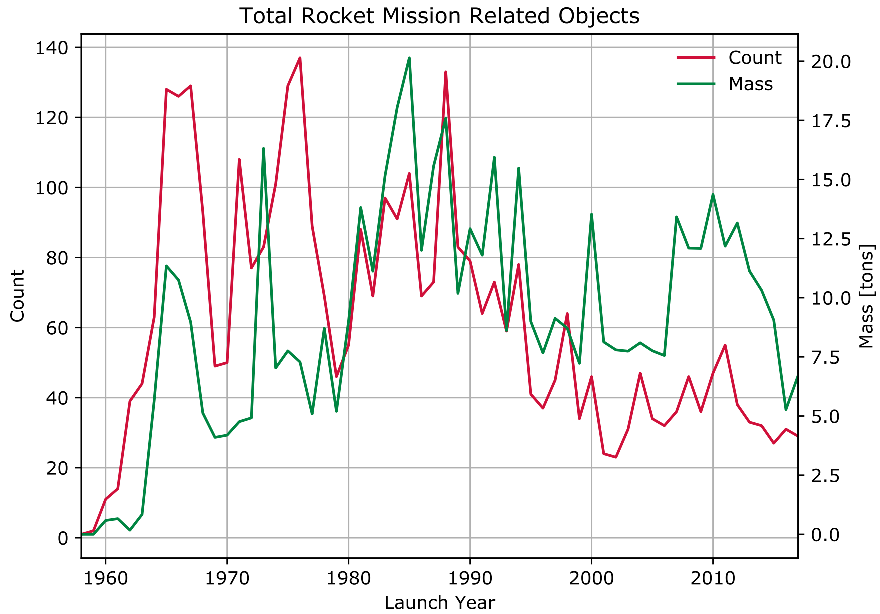


Figure 4.2: Total number and mass of catalogued mission related objects released from rocket bodies.

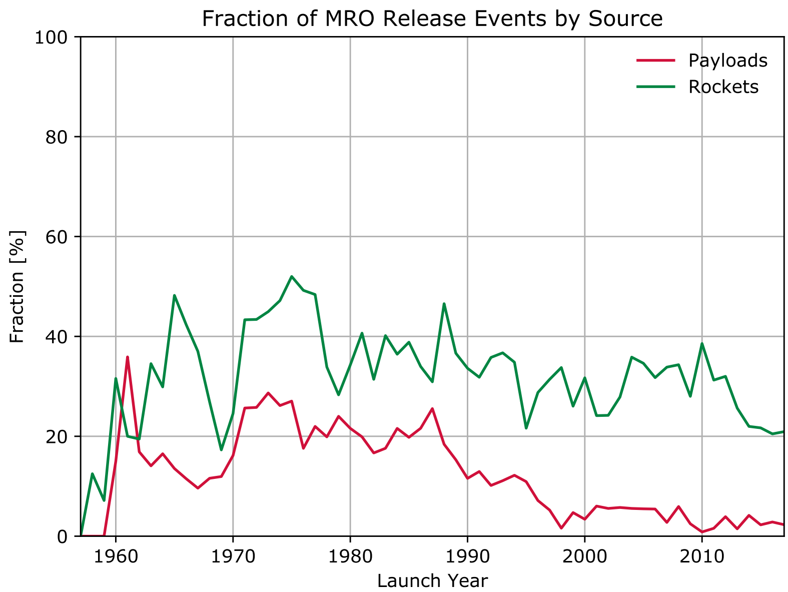


Figure 4.3: Fraction of mission related objects releases per year w.r.t. the total amount of payloads and rocket bodies injected into the space environment during that year.

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.

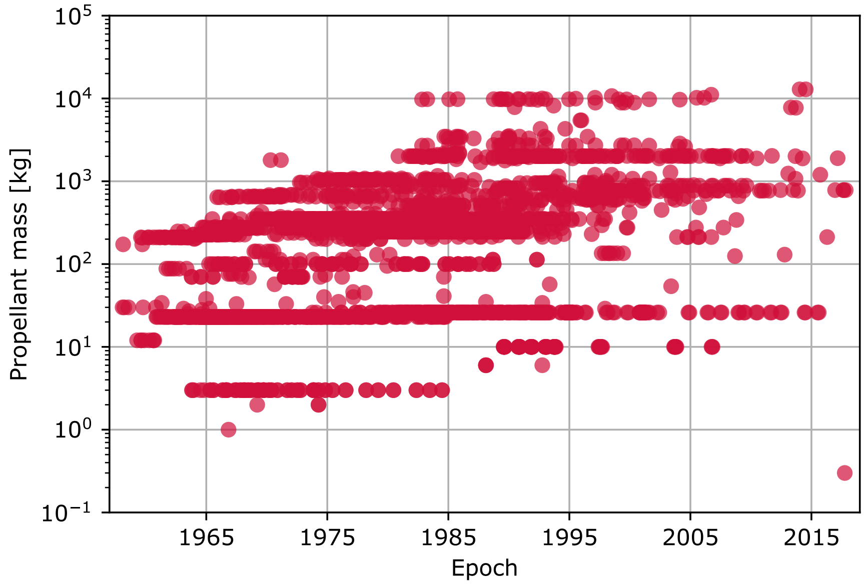


Figure 4.4: Evolution solid rocket motor firings.

5 Fragmentation History

Since the beginning of the space age until the end of 2017 , there have been 489 confirmed on-orbit fragmentation events. In Figure 5.1, 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 which 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 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, 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.

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

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

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.

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.

Delta upper stage There were several events for Delta second stages due to residual propellants until depletion burns were introduced in 1981.

SL-12 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.

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

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.

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.

Transit class satellites of the U.S. Navy's first satellite navigation system operational between 1964 and 1996.

Scout class refers to the Altair upper stage of the Scout rocket family.

Meteor class Russian meteorological satellite family.

Vostok class refers to the upper stage of the Vostok rocket (Blok E)

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

Assumed Introduced for the MASTER model [8]. Currently the only assumed events are in the GEO region, backed by information obtained during survey campaigns.

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

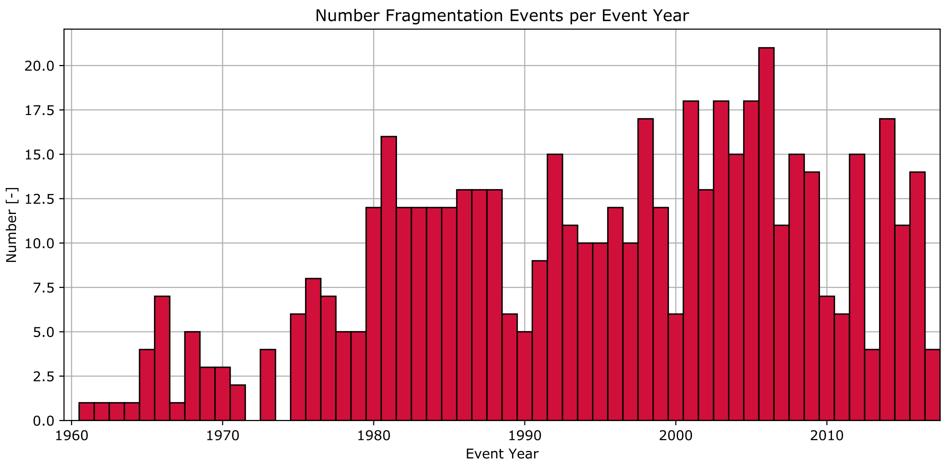
Delta 4 class events with several catalogued objects for the Delta Cryogenic Second Stages (DCSS).

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

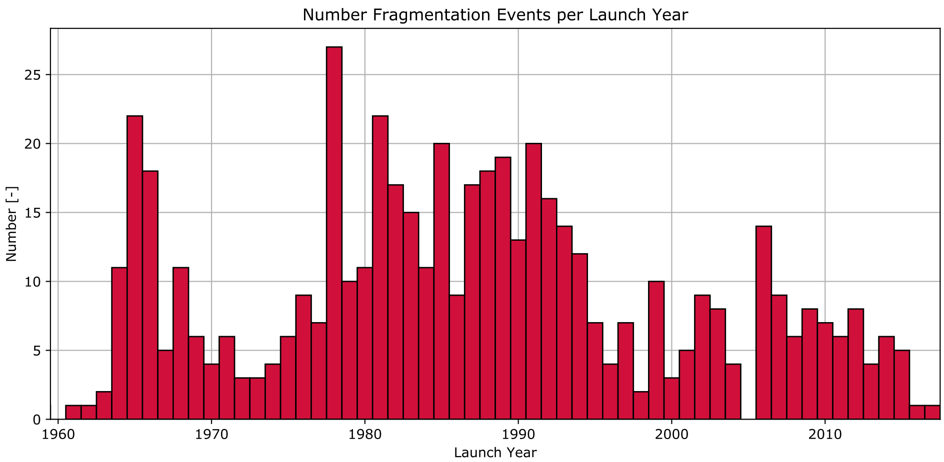
H-IIA class The second stage of the H-IIA launcher used a cryogenic propellant.

A breakdown of the observed fragmentation events grouped by the main classes, but excluding *Assumed* and *Unconfirmed*, in terms of frequency and resulting tracked fragments is given in Figure 5.2 and Figure 5.3, respectively. It shows that fragmentation events are not a relic of the past but even modern satellites continue to suffer from these events. On average, there are **8.1** non-deliberate fragmentation events per year in Earth orbits (taking the past two decades into account). Not all events, however, are critical from the point of view of the orbital lifetime of the generated fragments. Many events result in only a few fragments and fragments from events in low altitudes may decay within a short time period. As an example, counting only those events where 90% of the generated fragments have a lifetime of greater than 25 years, the annual rate of events would drop from **7.3** to **2.4**. Alternatively, one would obtain **2.9** events, if the minimum lifetime is reduced to greater than 10 years in this example.

By looking at the historical data it takes **7.8** and **2.1** years, respectively mean and median, after launch for a fragmentation event to occur, if it occurs at all. Taking only the past 20 years into account, the numbers change to **11.6** and **9.3** years, for mean and median, respectively.

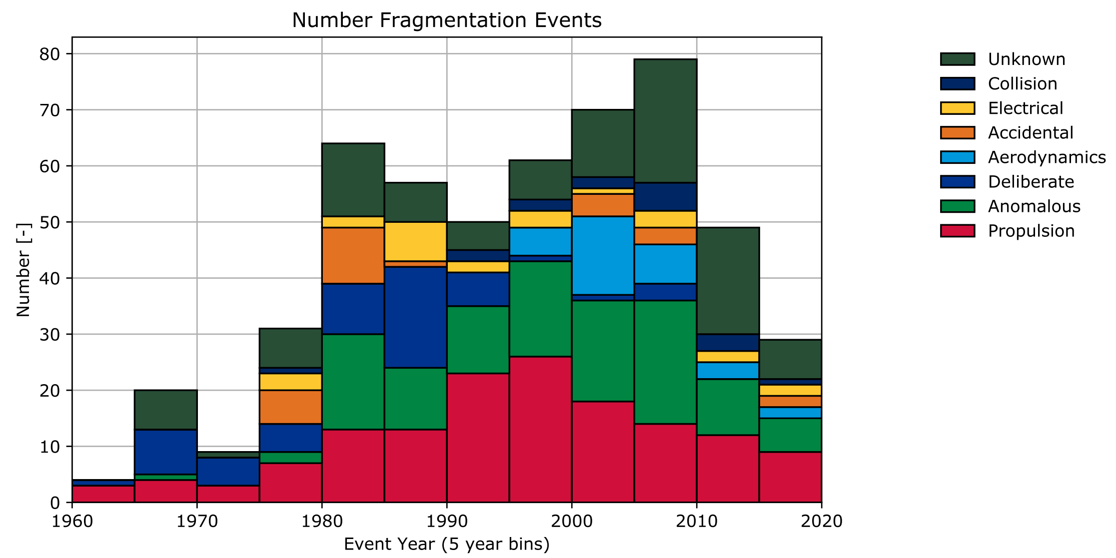


(a) Number of fragmentation events per event year.

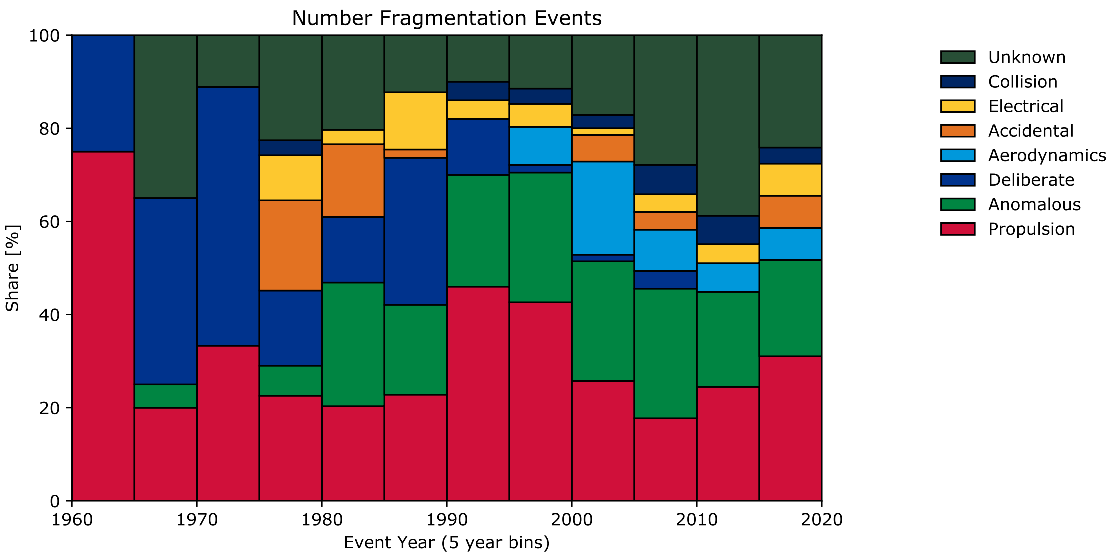


(b) Number of fragmentation events per launch year.

Figure 5.1: Historical trend of fragmentation events.

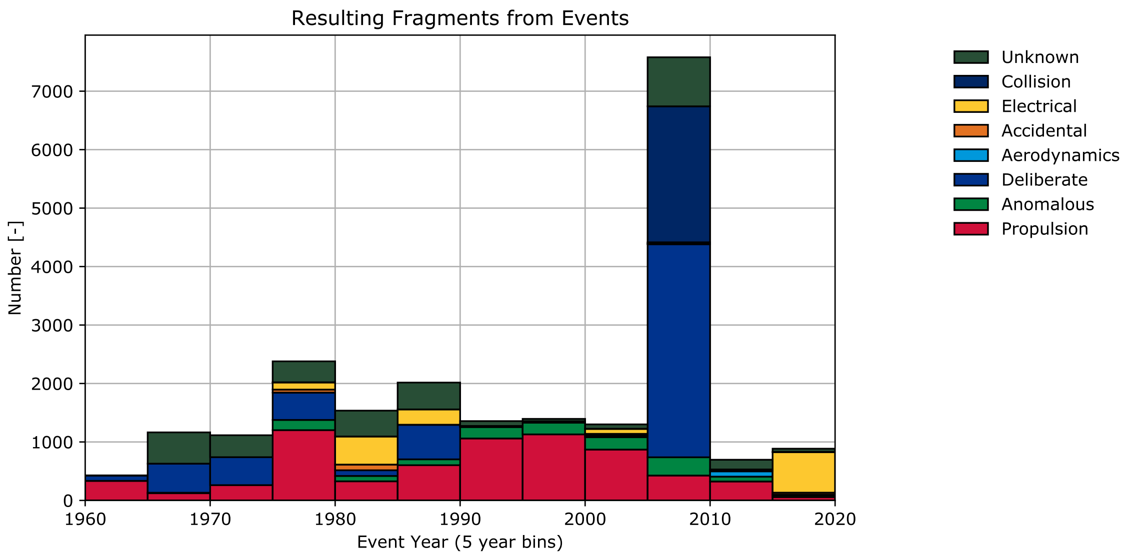


(a) Absolute number of fragmentation events per event cause.

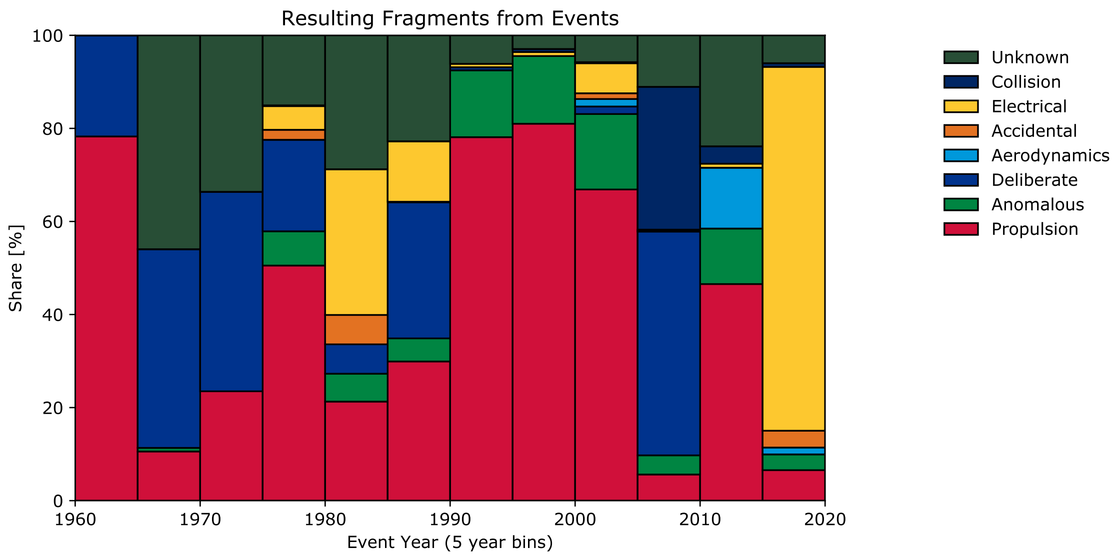


(b) Relative number of fragmentation events per event cause.

Figure 5.2: 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 5.3: Historical trend of numbers of fragments produced by fragmentation events.

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 2016, for rocket body clearance of LEO_{IADC} goes up to 2017, and for payload clearance of GEO_{IADC} goes up to 2017.

In this section, the trends of adherence to the end-of-life disposal guidelines are illustrated.

Figure 6.1 Share and Achievements of space objects clearing LEO_{IADC}.

Figure 6.2 Sharing in behaviour classes when clearing LEO_{IADC} for payloads.

Figure 6.3 Sharing in behaviour classes when clearing LEO_{IADC} for rocket bodies.

Figure 6.4 Shares of success level clearing LEO_{IADC} w.r.t. the (non-)compliance rate.

Figure 6.5 Summary clearance in LEO_{IADC}.

Figure 6.6 Summary mass clearance in LEO_{IADC}.

Figure 6.7 Summary clearance in LEO_{IADC} excluding naturally compliant objects.

Figure 6.8 Summary clearance in LEO_{IADC} considering payloads and rocket bodies together.

Figure 6.9 Breakdown per mass category of payloads reaching end of life in LEO_{IADC}.

Figure 6.10 Breakdown per decade of observed behavioural classes for payloads with a mass below 10.0 kg.

Figure 6.11 Breakdown per decade of observed behavioural classes for payloads with a mass between 10.0 and 100.0 kg.

Figure 6.12 Breakdown per decade of observed behavioural classes for payloads with a mass between 100.0 and 1000.0 kg.

Figure 6.13 Breakdown per decade of observed behavioural classes for payloads with a mass above 1000.0 kg.

Figure 6.14 Orbital evolution status of payloads near the Geostationary orbit.

Figure 6.15 Summary clearance in GEO_{IADC}.

Figure 6.16 Summary mass clearance in GEO_{IADC}.

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, there occurs a natural cleansing of space debris from these regions. 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. The mitigation measure itself does not indicate how it has to be achieved, but various standards provide an order of preference for various methodologies. 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 [9]. For the purpose of this report, objects leaving the LEO protected region by re-orbiting above it will be considered as having met the mitigation measures even though it is against the spirit of those measures to leave space debris in orbit.

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. Human spaceflight (HS) related missions are analysed separately, as they skew results in terms of mass and count affected. These mission include crew vehicles as well as cargo payloads, but not the rocket bodies which 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 is met by the mission orbit, a disposal action has been attempted but it was unsuccessful or insufficient;
- *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*, i.e. injected into an orbit which fulfils the 25 year lifetime measure, *Successful Attempt* when compliant after an attempt to reduce its orbital lifetime or re-orbit above LEO_{IADC}, *Insufficient Attempt* when not compliant but having attempted to reduce its orbital lifetime or re-orbit above LEO_{IADC}, or *No Attempt* when not compliant with no attempt at all.

6.2 Evolution of compliance shares

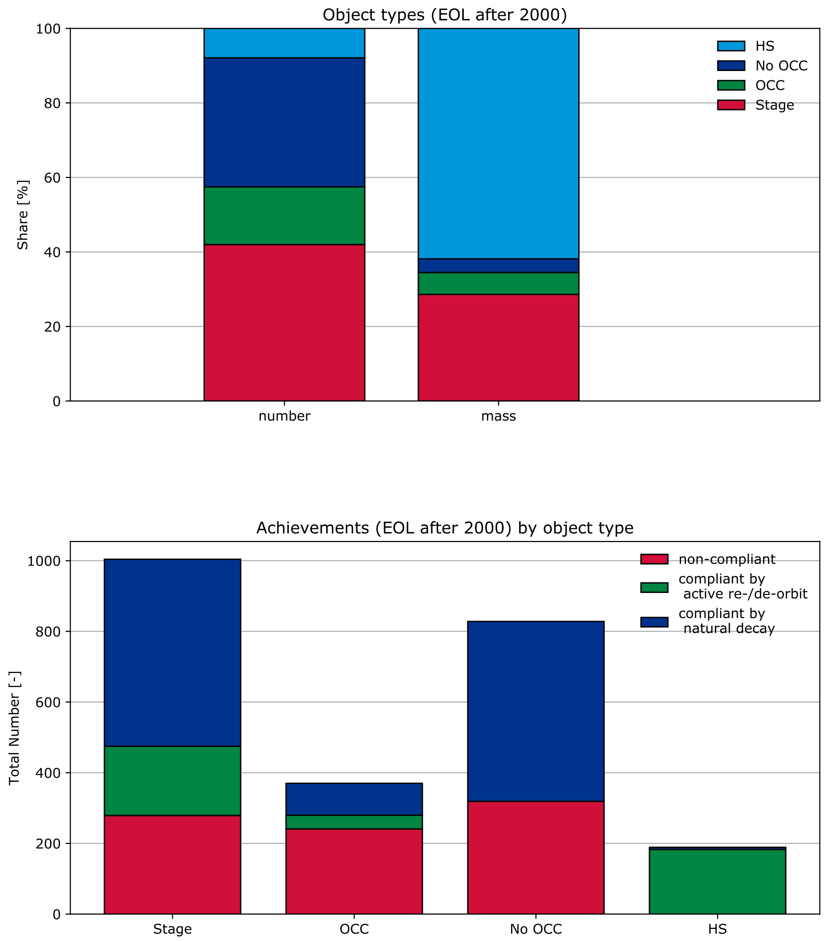
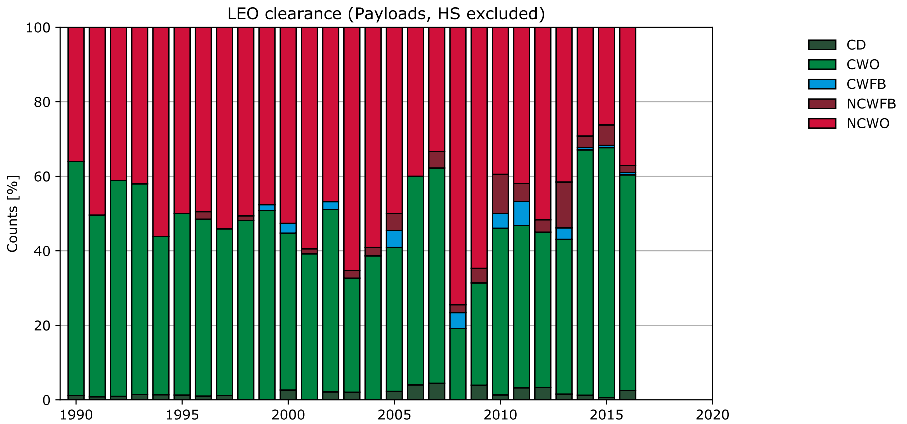


Figure 6.1: Share of payload and rocket bodies in terms of mass and number (top) and compliance in terms of clearing the LEO protected region (bottom).



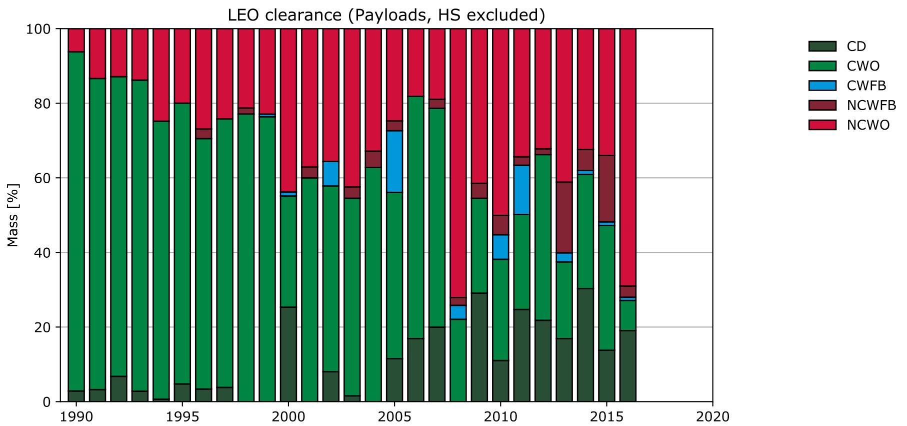
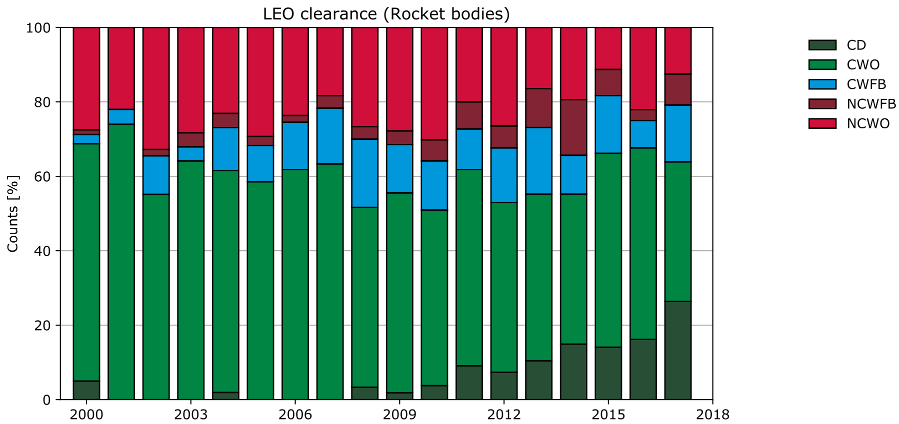


Figure 6.2: Relative share in terms of number (top) and mass (bottom) of disposal behaviour classes for payloads in LEO, excluding objects associated with human spaceflight.



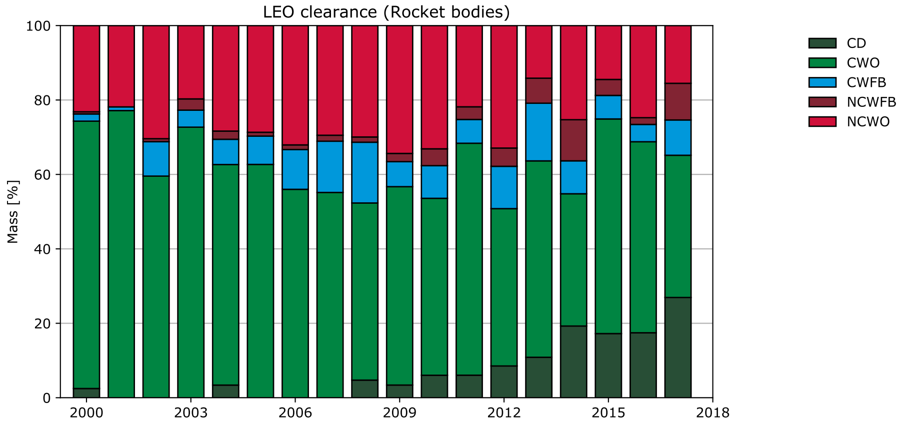


Figure 6.3: Relative share in terms of number (top) and mass (bottom) of disposal behaviour classes for Rocket Bodies in LEO.

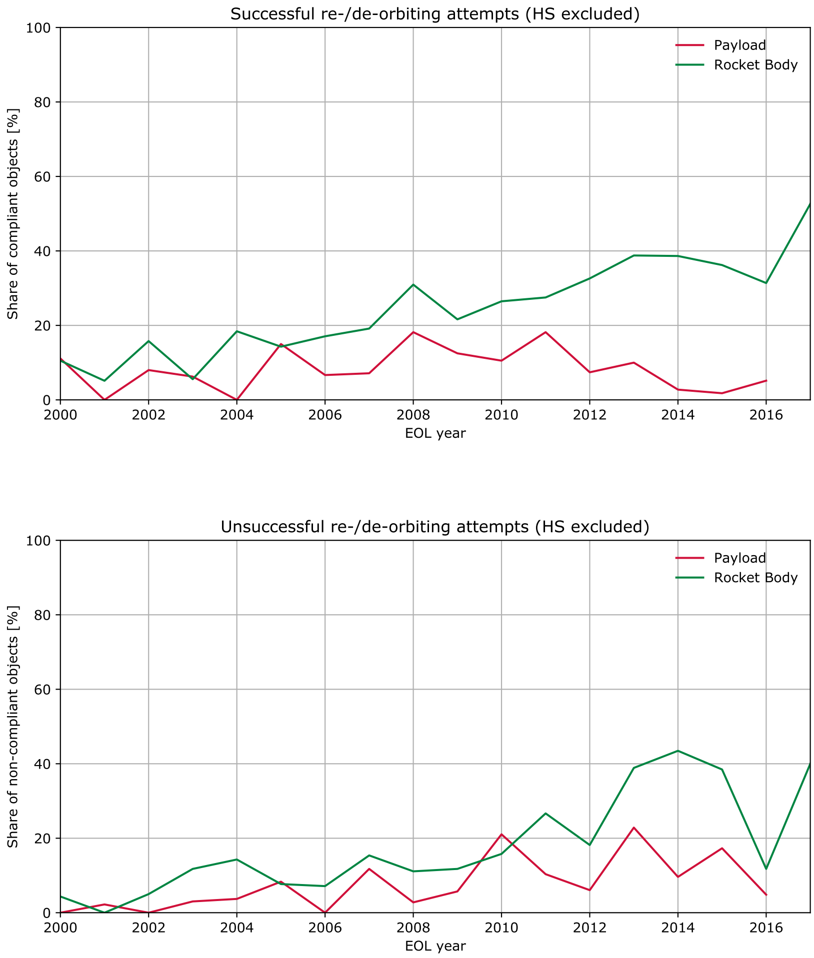
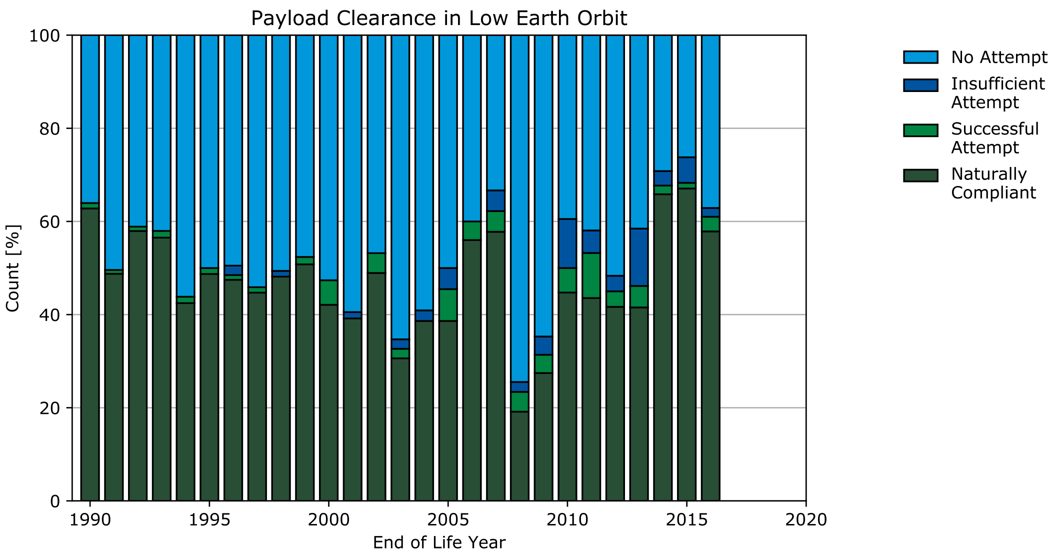
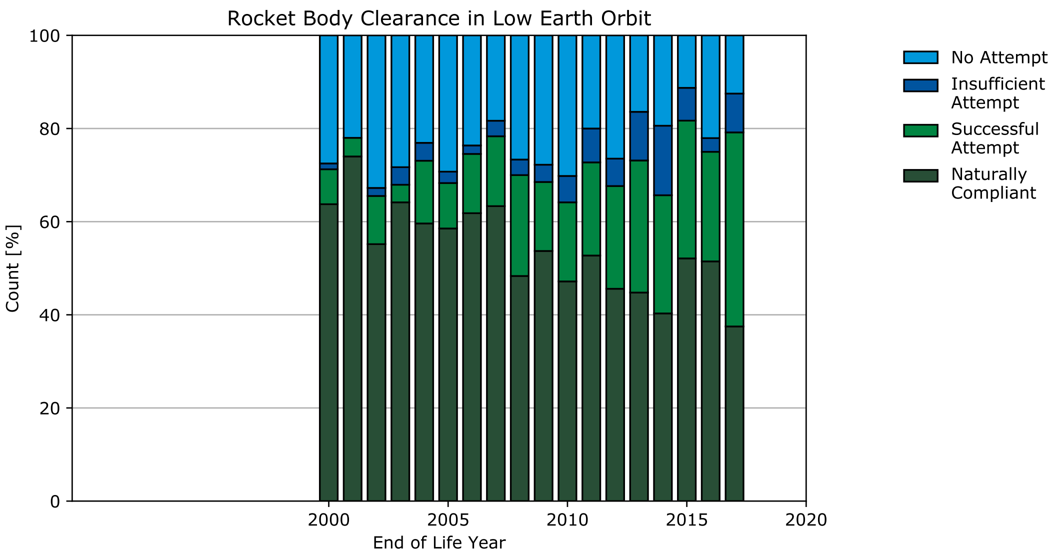


Figure 6.4: Relative shares of success w.r.t. compliance (top) and non-compliance (bottom), excluding objects associated with human spaceflight.

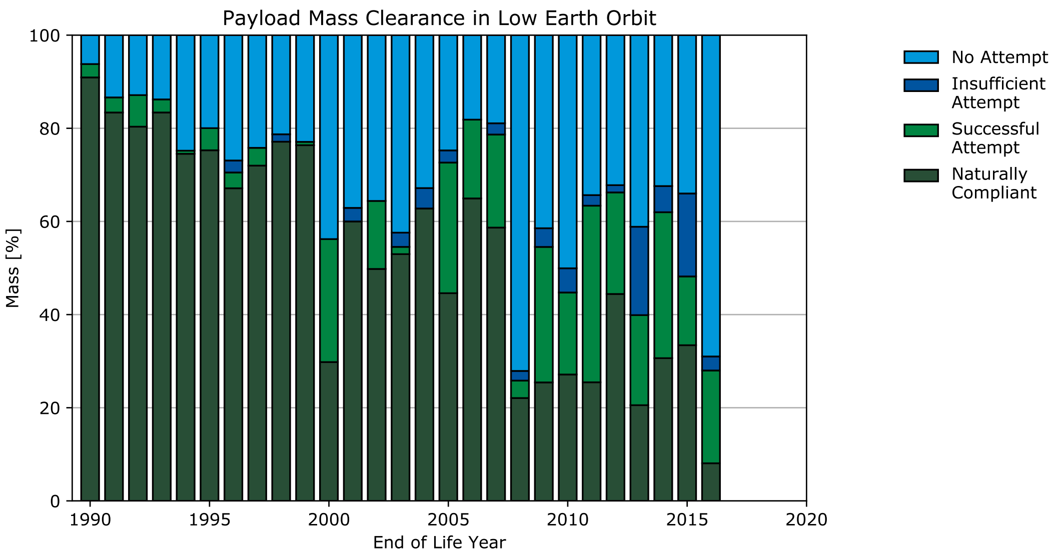


(a) Relative clearance of LEO_{IADC} by payloads.

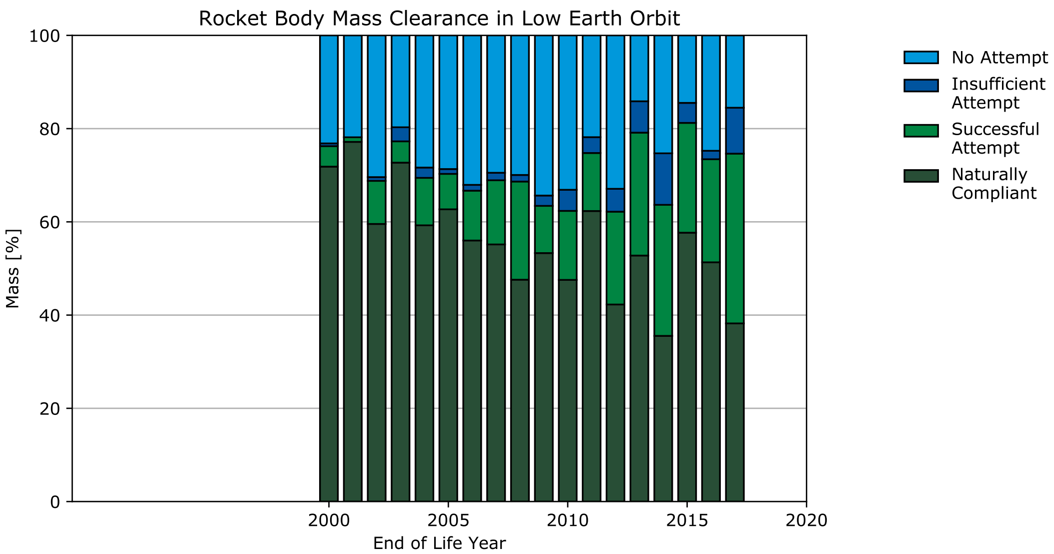


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.5: Trend of adherence to clearance of LEO_{IADC} in terms of numbers.

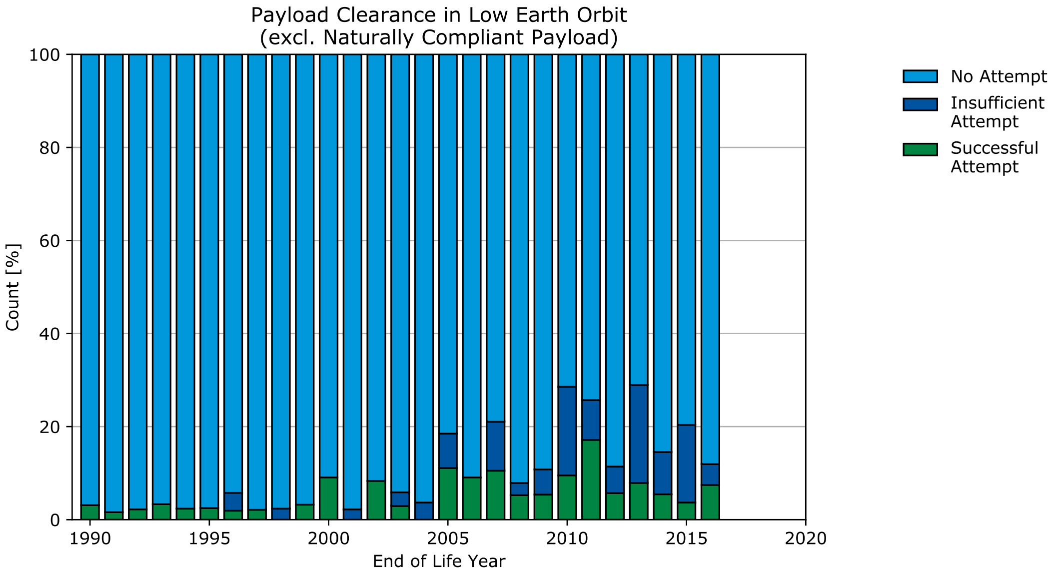


(a) Relative clearance of LEO_{IADC} by payloads.

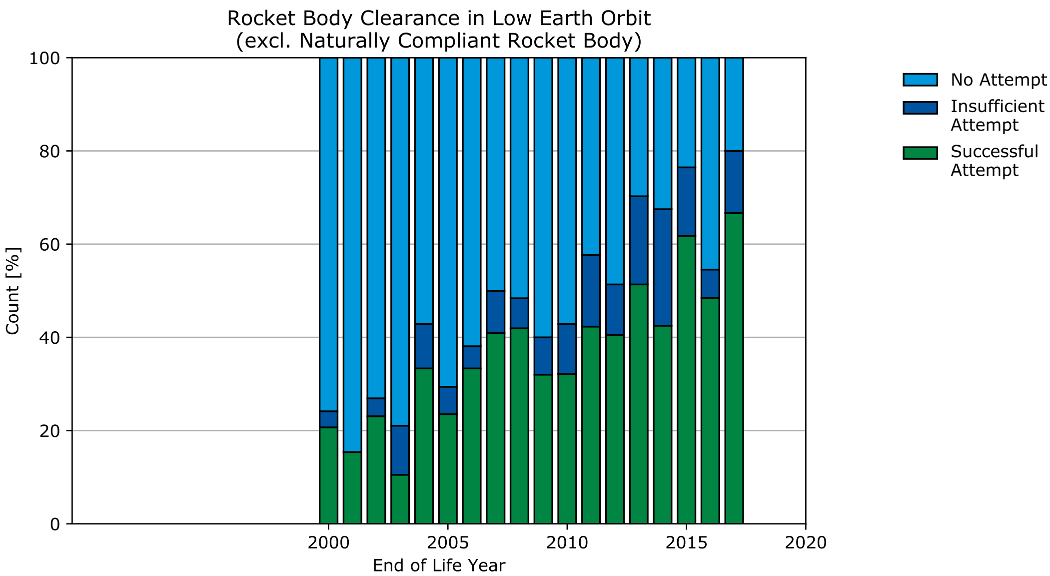


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.6: Trend of adherence to clearance of LEO_{IADC} in terms of mass.

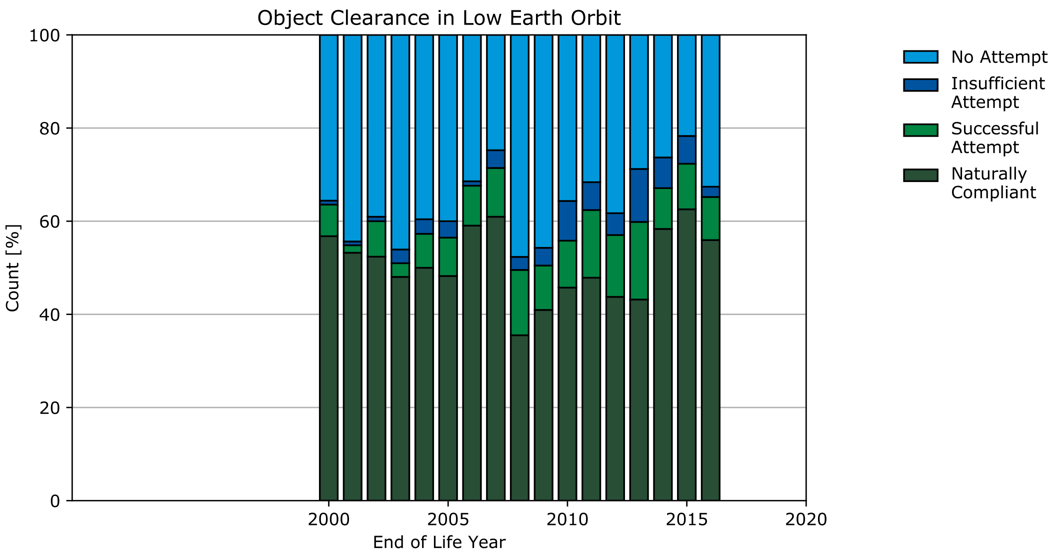


(a) Relative clearance of LEO_{IADC} by payloads.

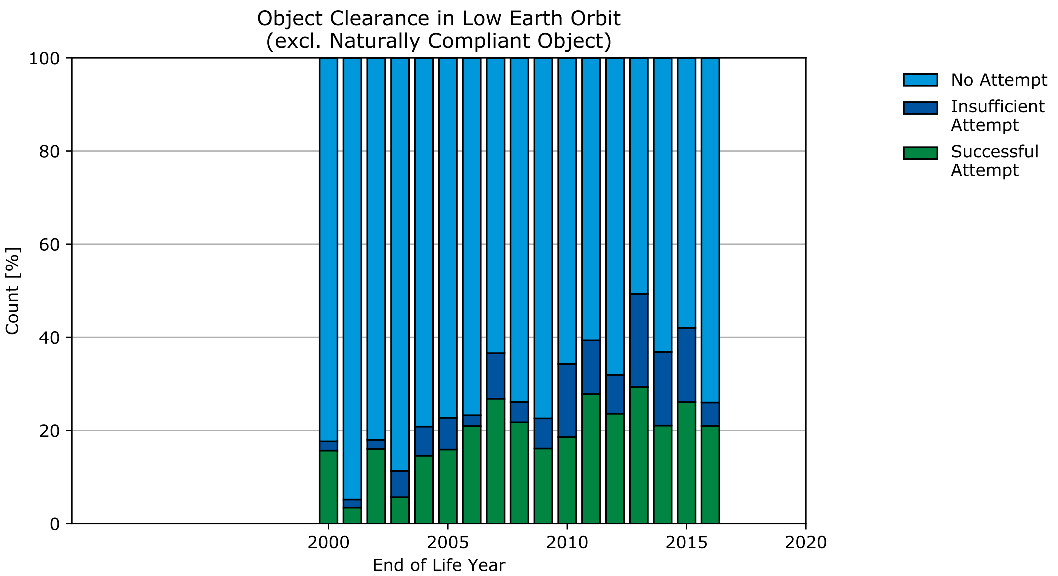


(b) Relative clearance of LEO_{IADC} by rocket bodies.

Figure 6.7: Trend of adherence to clearance of LEO_{IADC} in terms of numbers excluding naturally compliant objects.



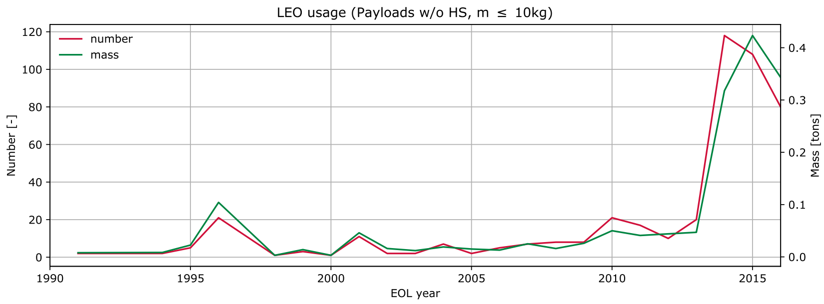
(a) Relative clearance of LEO_{IADC}.



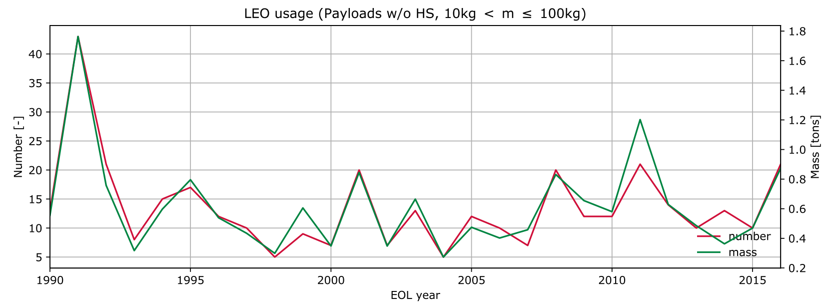
(b) Relative clearance of LEO_{IADC} excluding naturally compliant objects.

Figure 6.8: Trend of adherence to clearance of LEO_{IADC} in terms of numbers considering payloads and rocket bodies together.

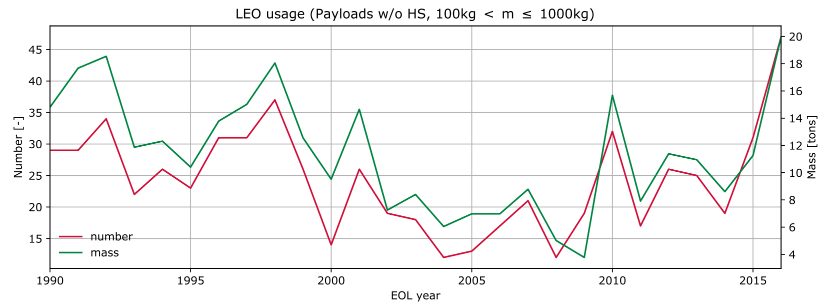
6.3 Evolution of behavioural classes per mass breakdown



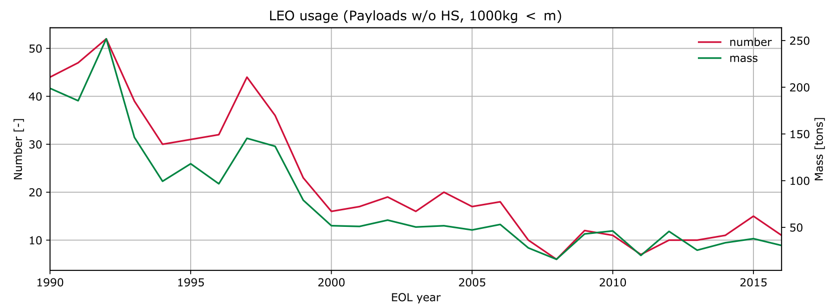
(a) Less than 10.0 kg.



(b) Between 10.0 and 100.0 kg

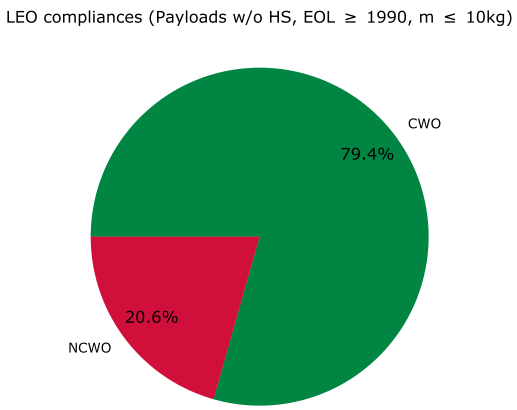


(c) Between 100.0 and 1000.0 kg

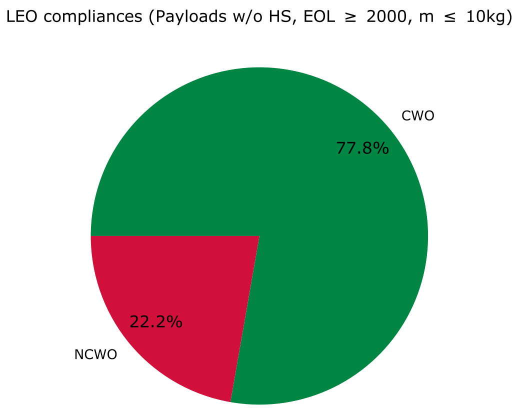


(d) Above 1000.0 kg

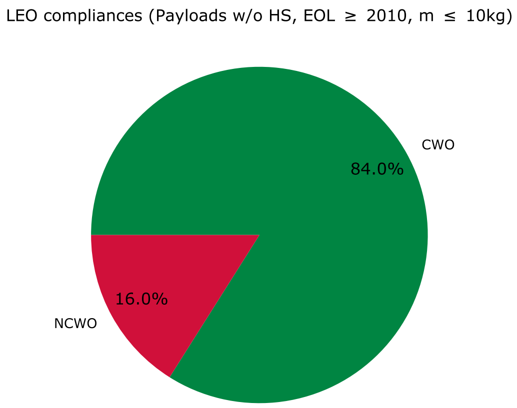
Figure 6.9: Breakdown per mass category of payloads reaching end of life in LEO_{IADC}.



(a) 1990

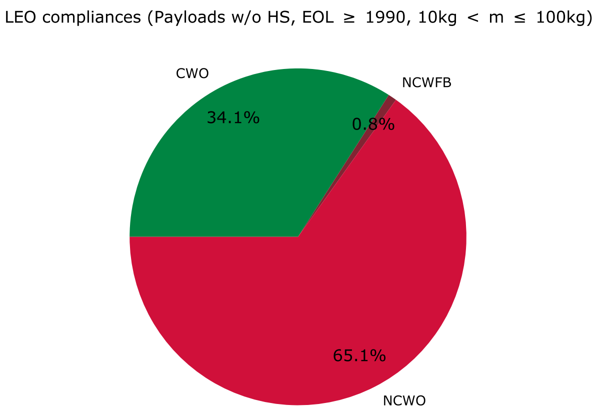


(b) 2000

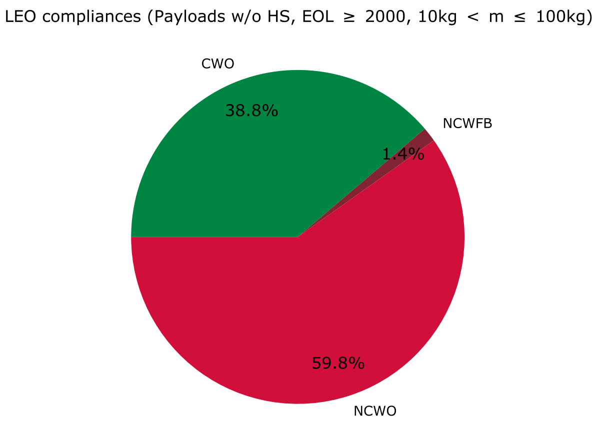


(c) 2010

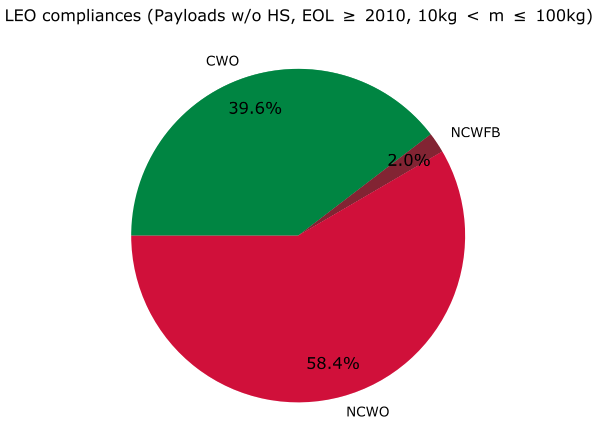
Figure 6.10: Breakdown per decade of observed behavioural classes for payloads with a mass below 10.0 kg.



(a) 1990

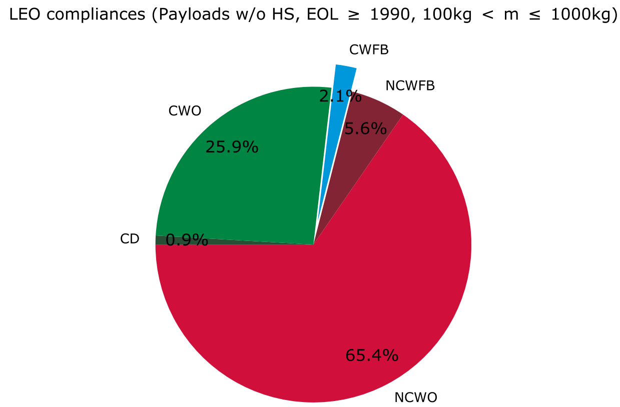


(b) 2000

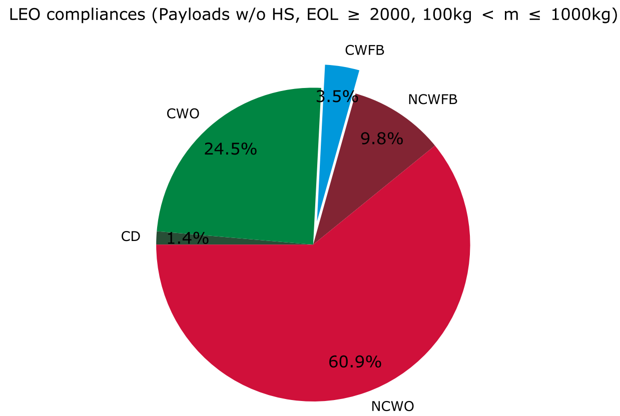


(c) 2010

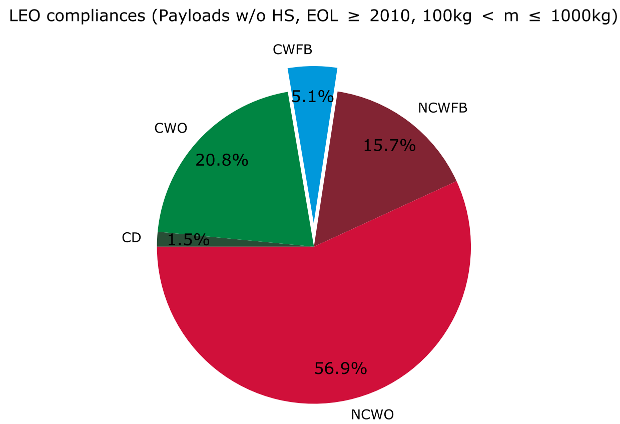
Figure 6.11: Breakdown per decade of observed behavioural classes for payloads with a mass between 10.0 and 100.0 kg.



(a) 1990

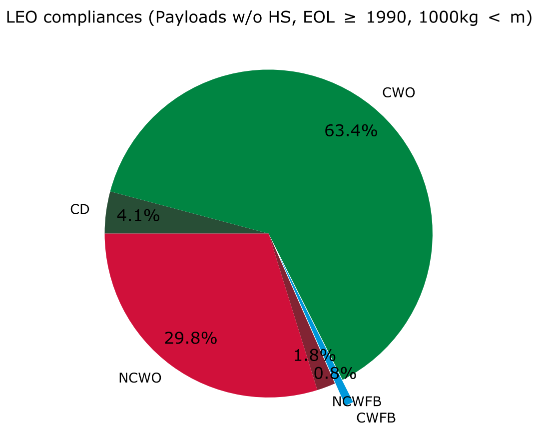


(b) 2000

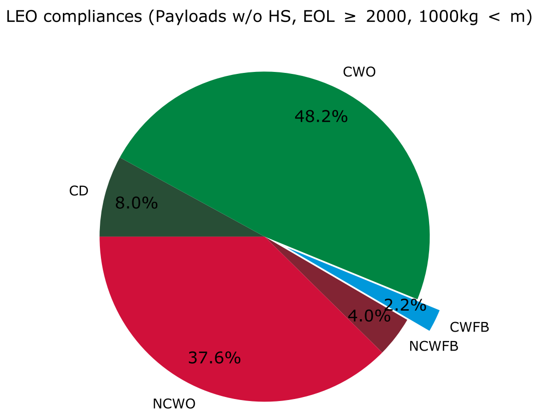


(c) 2010

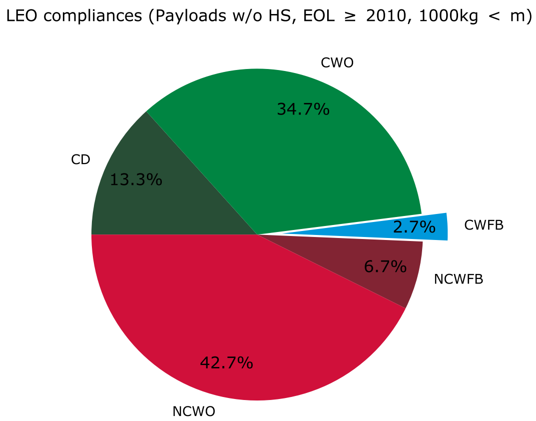
Figure 6.12: Breakdown per decade of observed behavioural classes for payloads with a mass between 100.0 and 1000.0 kg.



(a) 1990



(b) 2000



(c) 2010

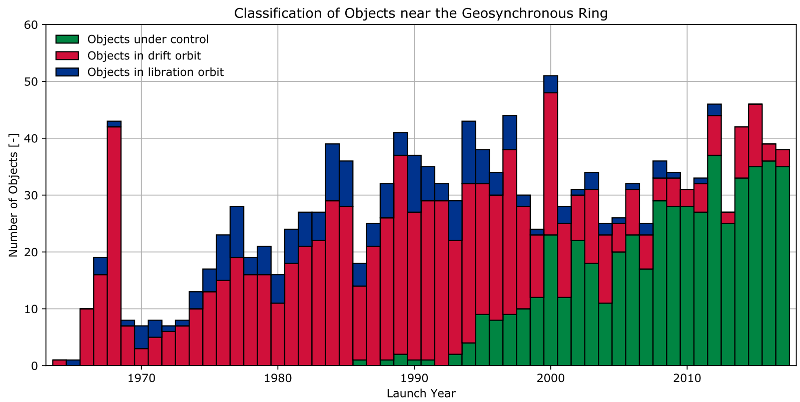
Figure 6.13: Breakdown per decade of observed behavioural classes for payloads with a mass above 1000.0 kg.

6.4 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 been 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 which 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 [3], 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. $\Delta H = 235 + (1000 C_r A/m)$;
  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 attempts 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 [10].



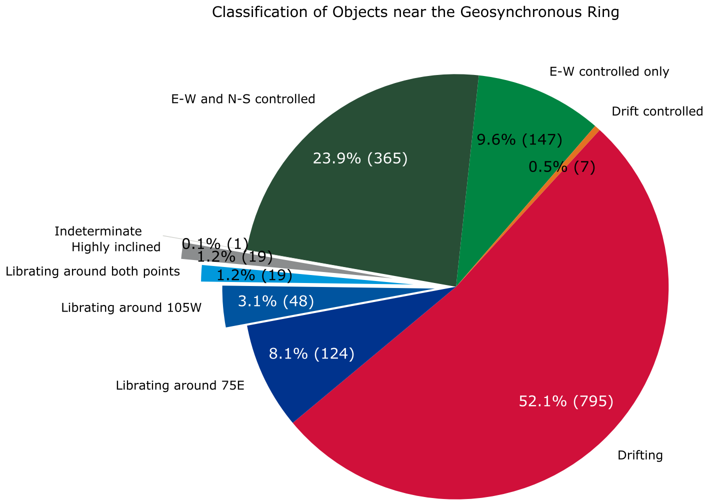
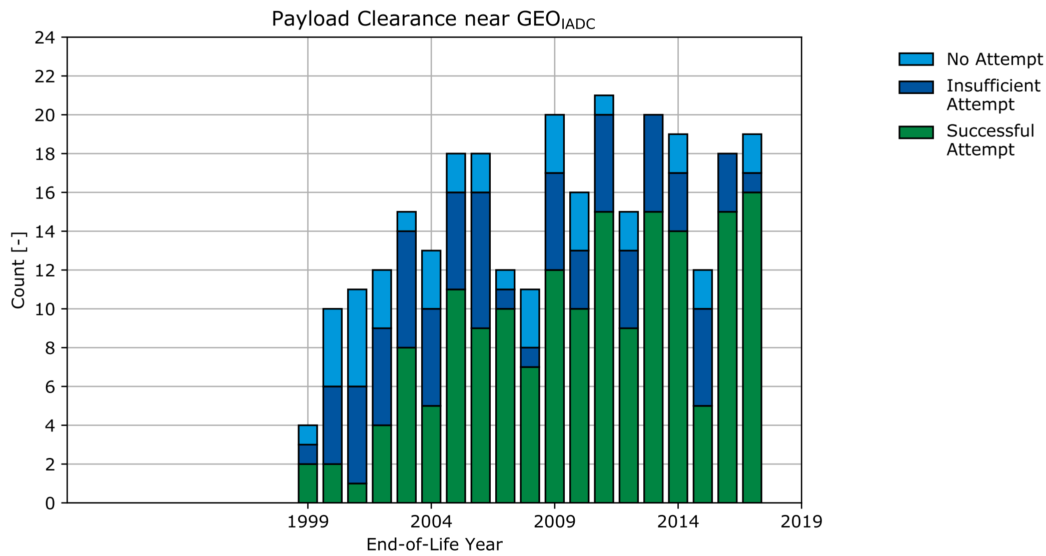
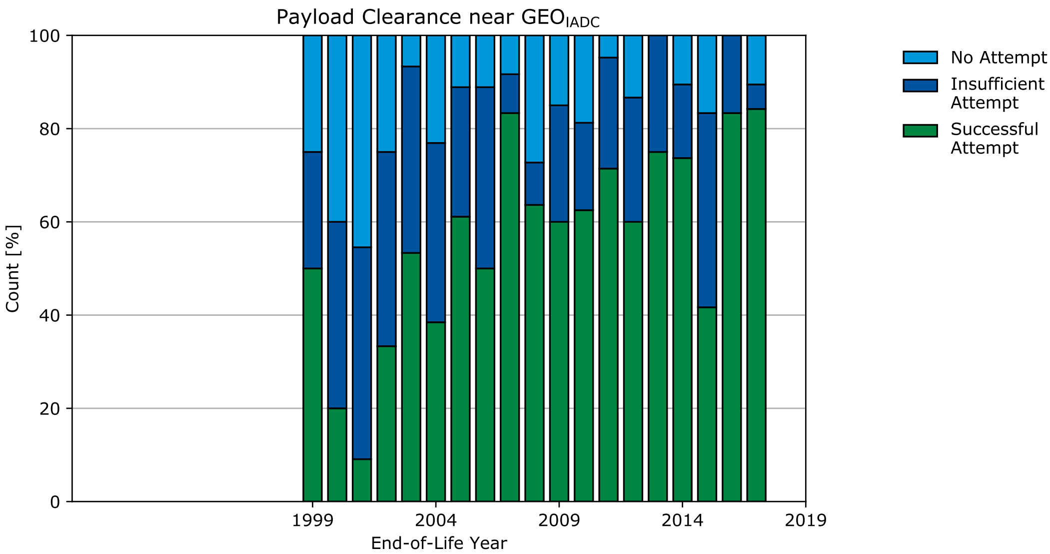


Figure 6.14: Orbital evolution status of payloads near the Geostationary orbit during 2017.

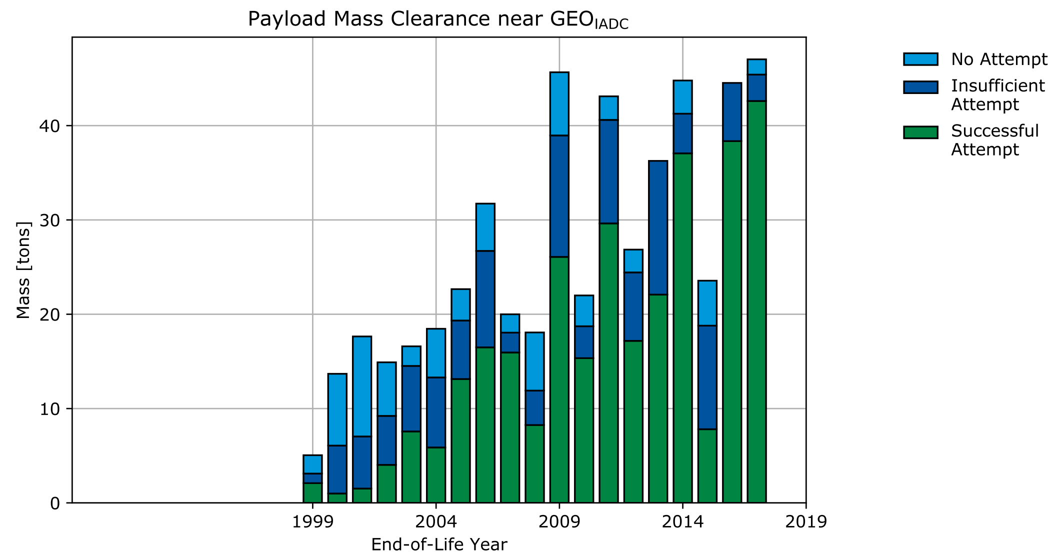


(a) Absolute clearance near GEO_{IADC}.

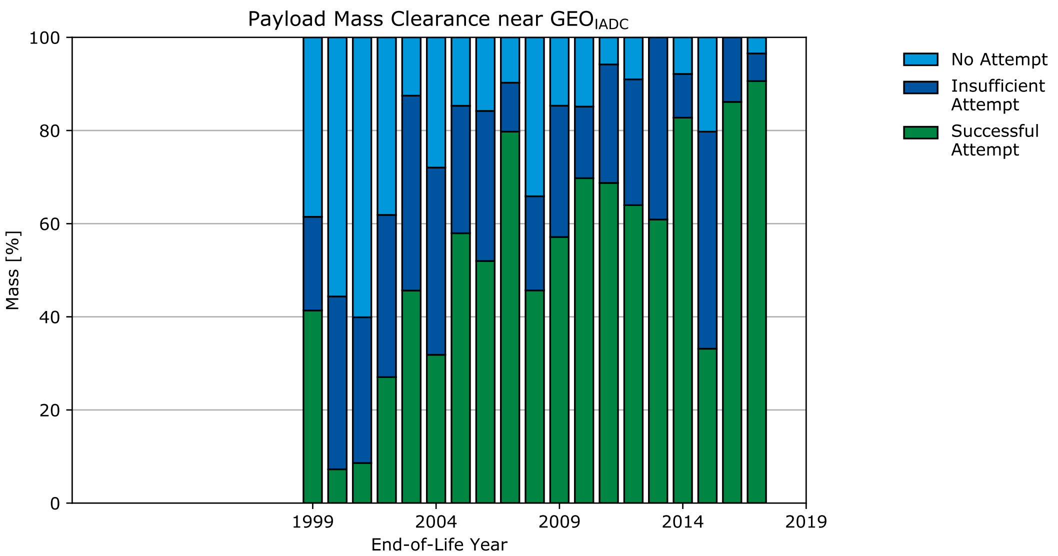


(b) Relative clearance near GEO_{IADC}.

Figure 6.15: 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 6.16: Mass trend of adherence to the disposal guideline in GEO_{IADC}.

7 Environmental Index in 2017

The effect of adherance to space debris mitigation guidelines and regulation on a global level has a direct influence on the avoidance of the Kessler syndrome. In order to quantify the relation between them, and hence quantify what sustainable space activities could look like, 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. This choice is motivated by the observation that the long term evolution of the space debris environment is highly affected by the fragmentation of large intact objects.

The term *probability* represents the probability of a catastrophic collision, which is dependent on the flux of debris able to trigger a collision, the cross-sectional area of the object, and a reference time. The flux values are obtained from MASTER considering the last available orbit of the studied object in DISCOS. The physical properties and the activity status of the objects are retrieved from as well DISCOS. More details on the approach can be found in [11].

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 [12] and modelling the evolution of its density over time under the effect of atmospheric drag. A small set of target synthetic spacecraft is defined to represent the population of operational satellite. 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.

This metric can be used to compare one mission against another, and, by summing up the value for all the objects, to get an insight on the status of the environment as a whole and on the distribution of the risk. Moreover, this kind of metrics can be used to assess how the current use of space compares to the *capacity* of the environment.

The figures in the following look at the cumulative value of the index over the whole LEO region. Fig. 7.1 shows the risk distributed among rocket bodies (RB), inactive payloads (NPL) and active payloads (APL). The vast majority, 93.6%, of the risk is associated to non-active objects. Fig. 7.2 shows the contribution to the current environment risk level as a function of the object launch year. The same analysis can be performed considering two opposite scenarios:

- no PMD: in this scenario, no spacecraft performs a Post-Mission Disposal (PMD) manoeuvre. For spacecraft that have actually performed such a manoeuvre, the last available state before the disposal is considered and propagated to obtain the estimated orbital regime at the epoch of analysis
- all PMD: in this scenario, all active spacecraft launched after 1990 perform a successful PMD manoeuvre a the end of their missions.

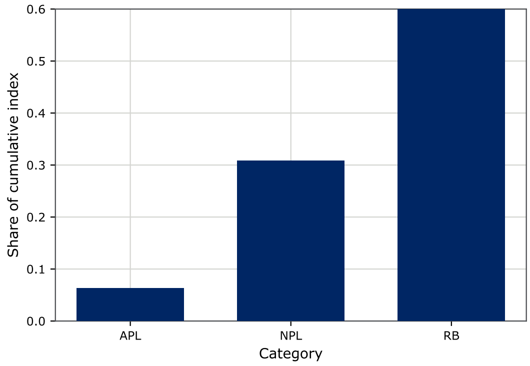


Figure 7.1: Distribution of the fragmentation risk among rocket bodies (RB), inactive payloads (NPL) and active payloads (APL).

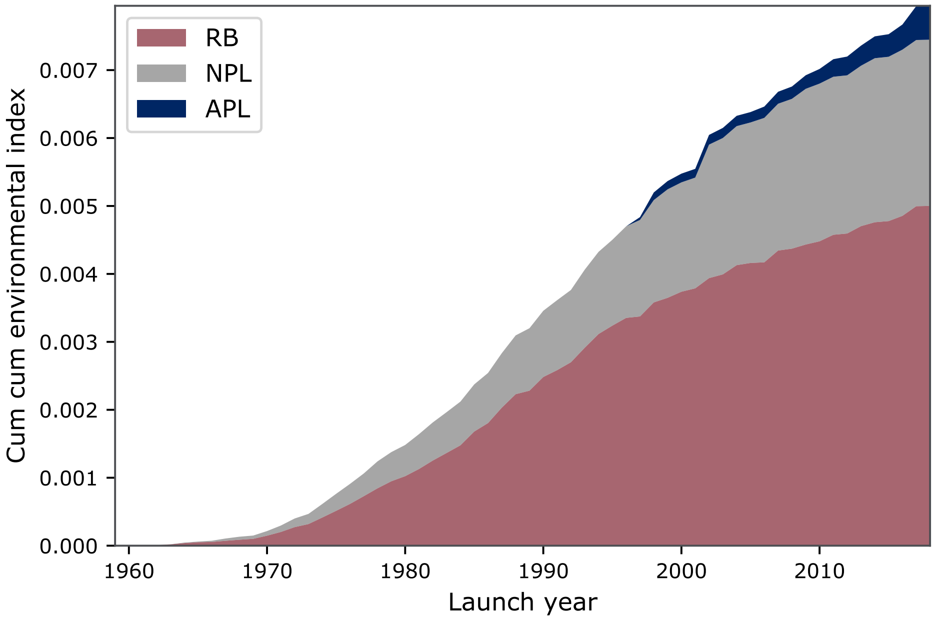


Figure 7.2: Contribution to the current environment risk level as a function of the launch year. The colours indicate the object category: rocket bodies (RB), inactive payloads (NPL) and active payloads (APL).

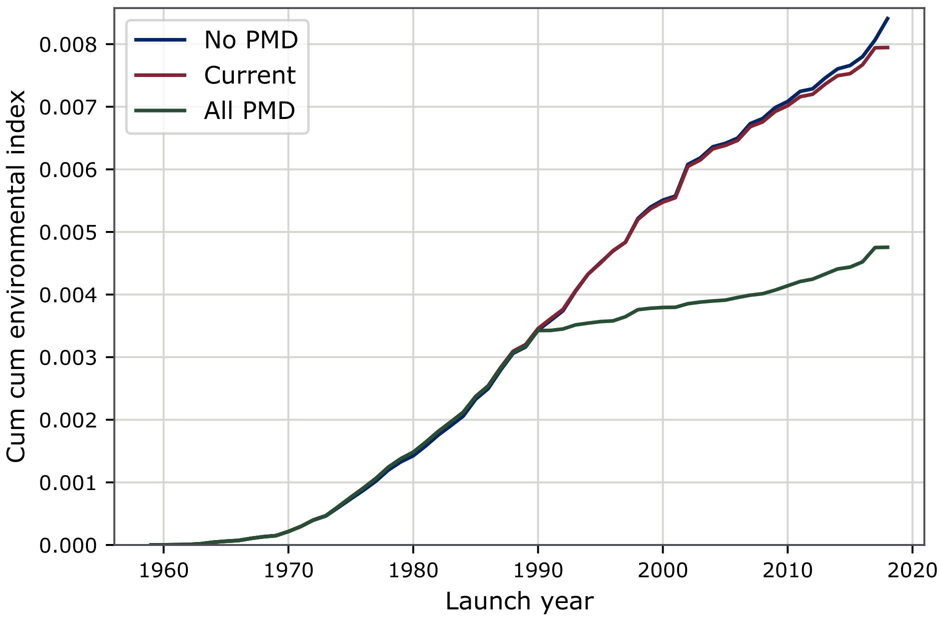


Figure 7.3: Contributions to the current environment risk level as a function of the launch year in three different scenarios of implementation of PMD measures.

8 Summary

The status of the Space Environment was 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. Some summarising statements can be made derived from the presented data:

- The amount of objects, their combined mass, and there 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.
- On average, 7.3 non-deliberate fragmentations occur in the space environment every year, a number which is stable however the impact of each event is variable. This number drops significantly to 2.4 when the lifetime of the generated fragments is considered a factor of importance.
- The amount of mission related objects released into the space environment is steadily declining, but still significant for Rocket Bodies.
- Launch traffic into the LEO protected regions is on the rise, fuelled by the proliferation of small payloads, i.e. below 10.0 kg in mass, during the last few years in terms of number, but not contributing significantly to the mass.
- Around 84% of small payloads, i.e. below 10.0 kg in mass, launched recently and injected into the LEO protected region operate in orbits which naturally adhere to the space debris mitigation measures.
- Between 30 and 60% of all payload mass recently reaching end-of-life in the LEO protected region does so in orbits which adhere to the space debris mitigation measures.
- Around 70% of all rocket body mass recently reaching end-of-life does so in orbits which adhere to the space debris mitigation measures on protecting LEO_{IADC}. A significant amount of this is due to controlled re-entries after launch, a practice which is increasing and was above 20% in 2017.
- Between 15 and 20% of payloads recently reaching end-of-life in the LEO protected region in a non-compliant orbit attempt to comply with the space debris mitigation measures. Around of 5% do so successfully.
- Between 50 and 70% of rocket bodies recently reaching end-of-life in the LEO protected region in a non-compliant orbit attempt to comply with the space debris mitigation measures. Around of 50% do so successfully.
- Around 90% of all payloads recently reaching end-of-life in the GEO protected region attempt to comply with the space debris mitigation measures. Around 80 % do so successfully.

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