2. SPACE ENVIRONMENTAL HISTORY IN NUMBERS

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

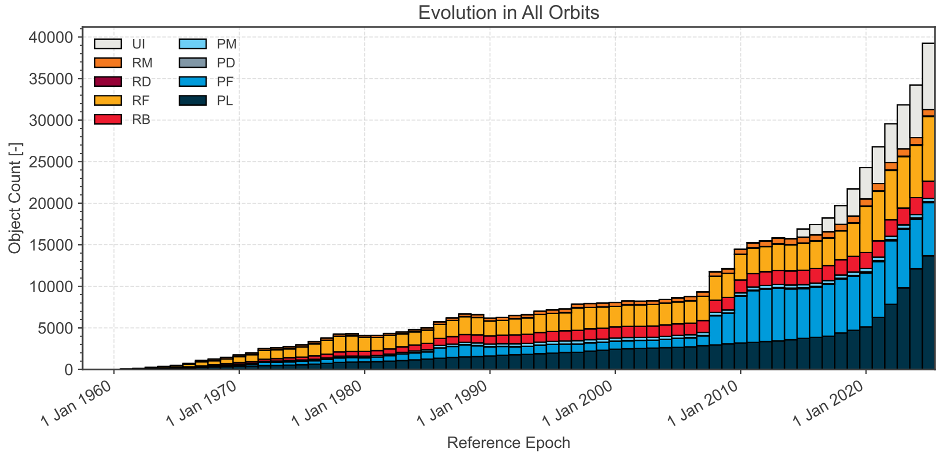
Concerning the LEO and GEO protected regions, the absolute and equivalent number of objects, mass, and area interfering with these regions are graphically represented. To obtain the equivalent object penetrating the protected regions, the physical property of the absolute object, i.e. count, mass, and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

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

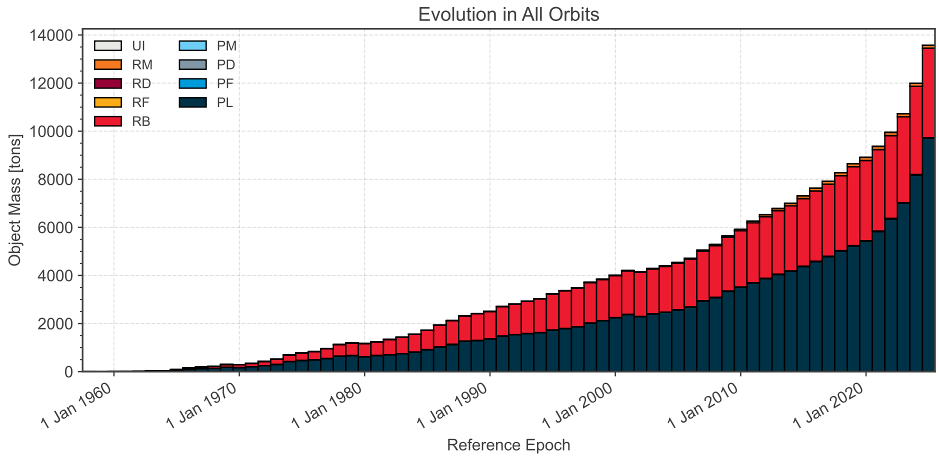
In all figures within Sections 2.1, 2.2, and 2.3, the environment parameters are presented as they are at the 1st of January of the indicated year. In all figures within Sections 2.5, 2.8, and 2.9, the environment parameters are presented as aggregated data within the indicated year. All data used to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

2.1. Overall Space Environment

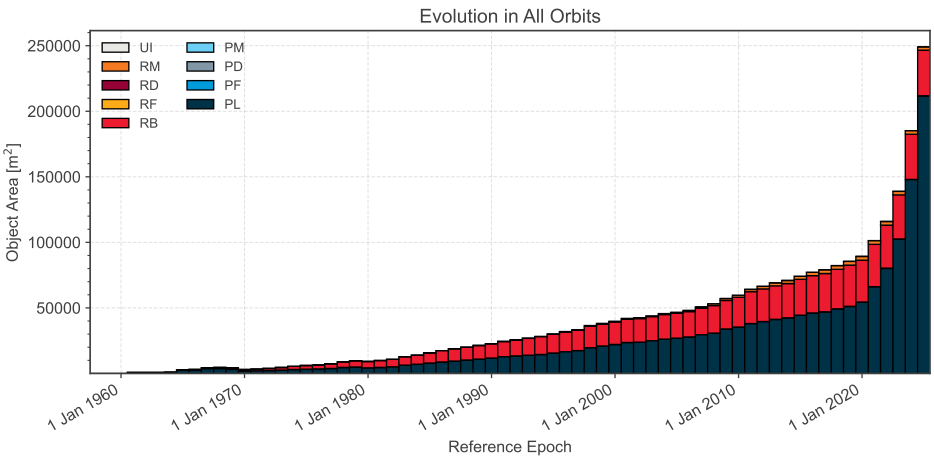
Fig. 2.1 captures the evolution of the space environment in terms of number of objects, mass, and area in geocentric orbit by object class. This data is limited to catalogued and asserted objects, and hence at any given epoch limited to the capability of the space surveillance system in use at the time. 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.

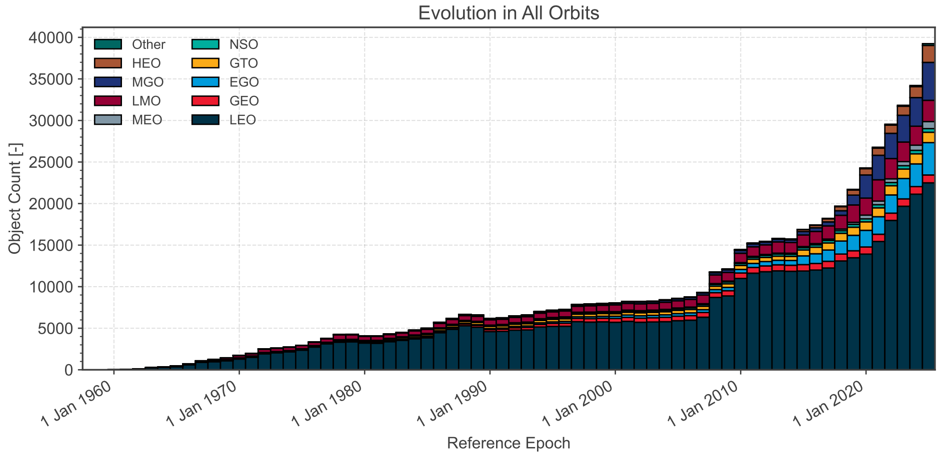


(b) Evolution of mass.

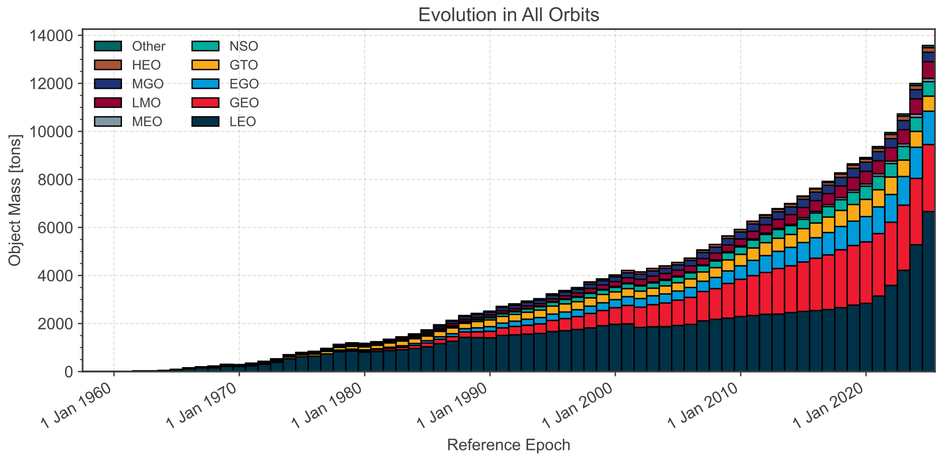


(c) Evolution of area.

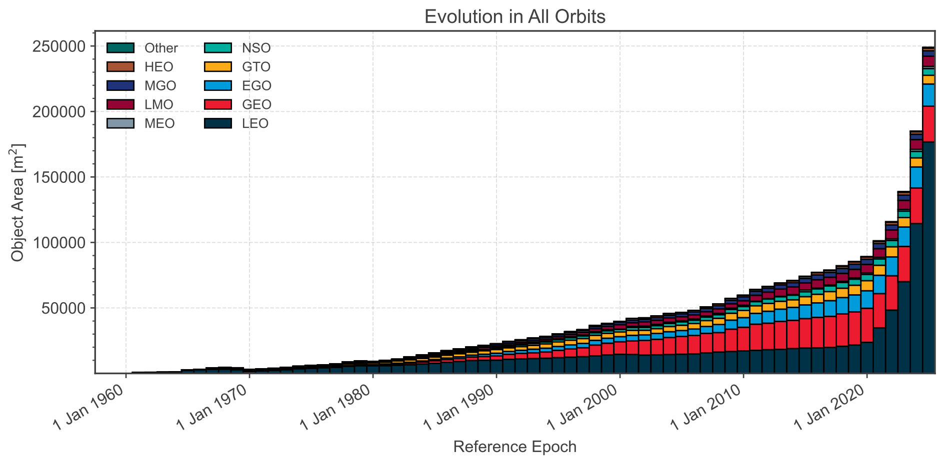
Figure 2.1: Evolution of number of objects, mass, and area in geocentric orbit by object class.



(a) Evolution of number of objects.

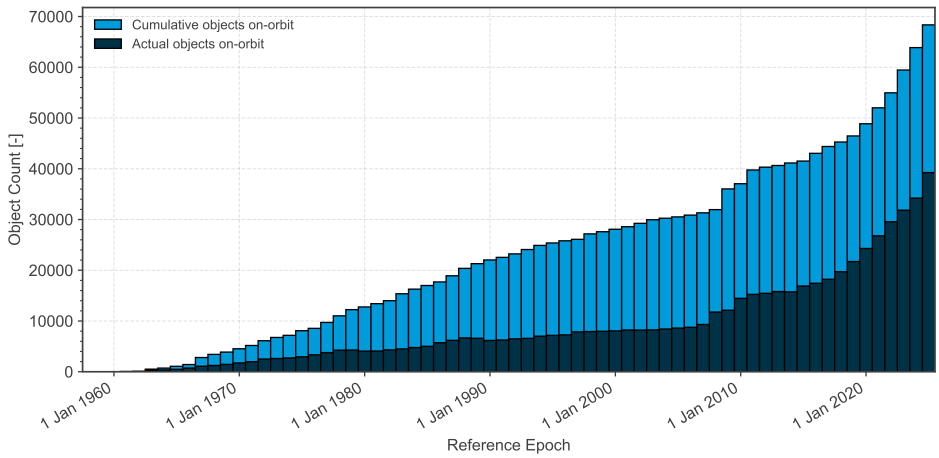


(b) Evolution of mass.

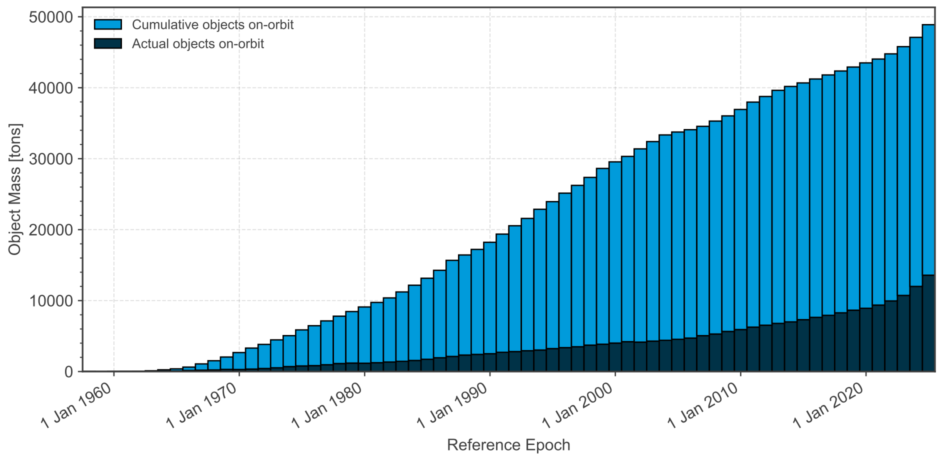


(c) Evolution of area.

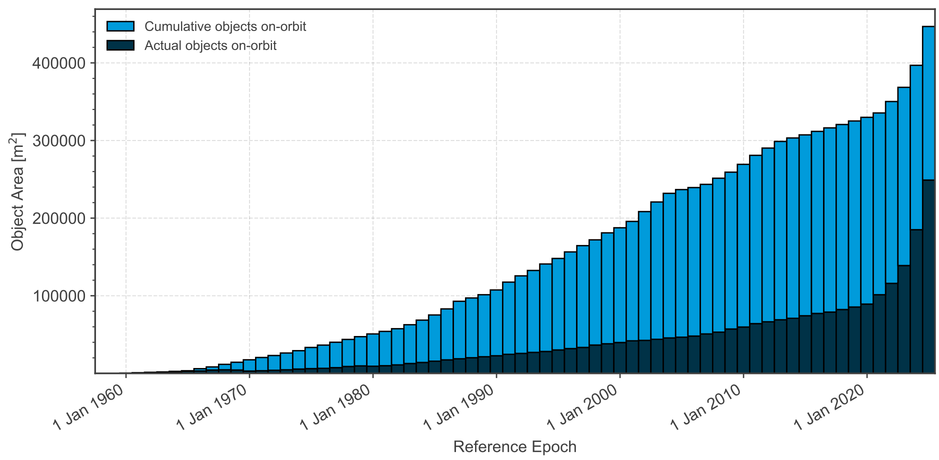
Figure 2.2: Evolution of number of objects, mass, and area in geocentric orbit by orbit class.



(a) Evolution of number of objects.



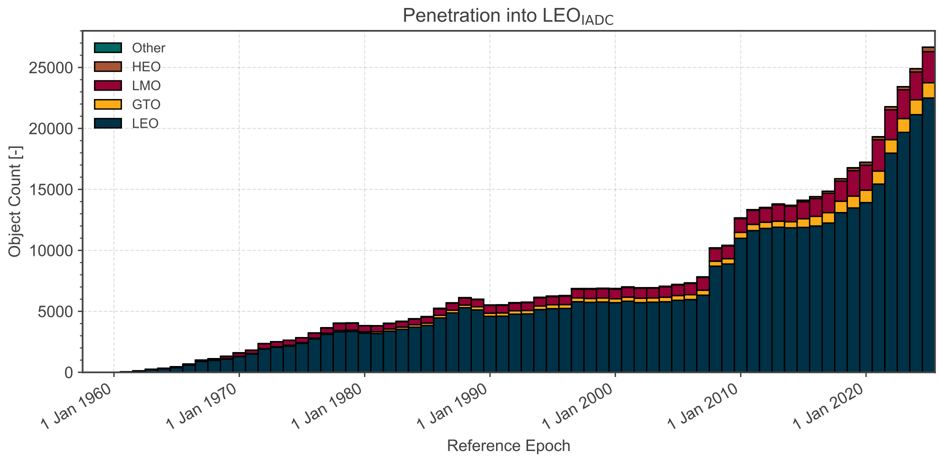
(b) Evolution of mass.



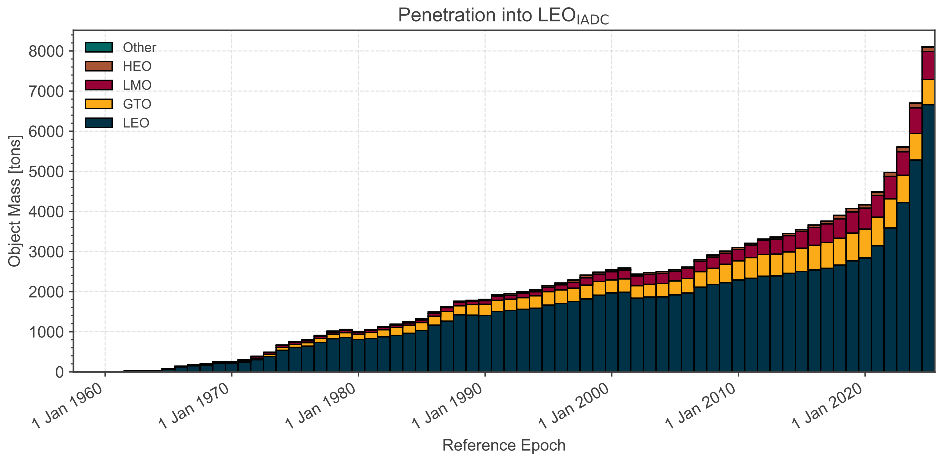
(c) Evolution of area.

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

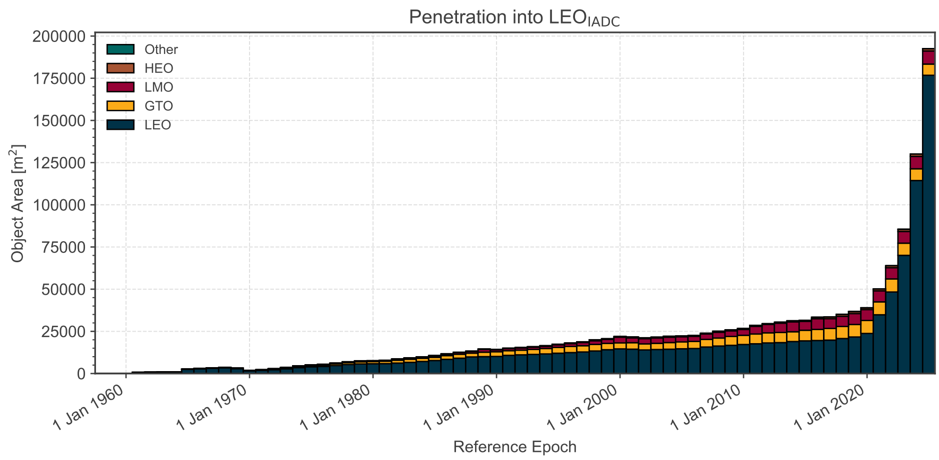
2.2. Evolution of Environment in LEO



(a) Evolution of absolute number of objects.

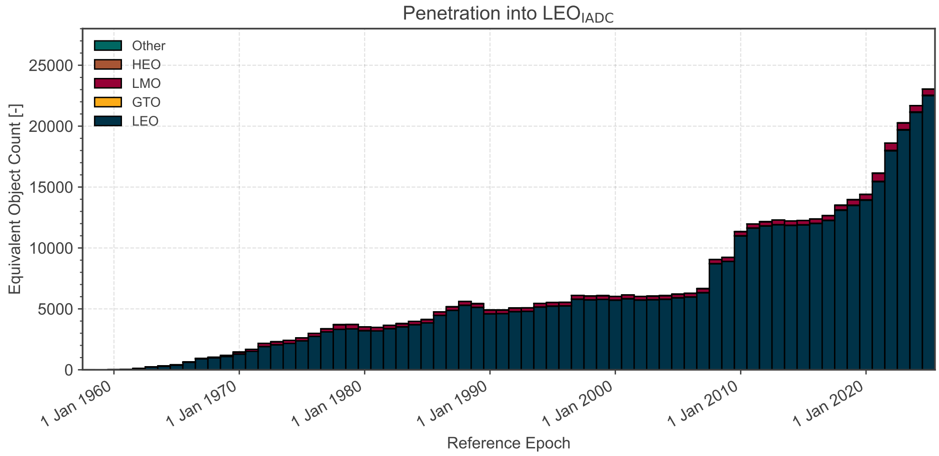


(b) Evolution of absolute mass.

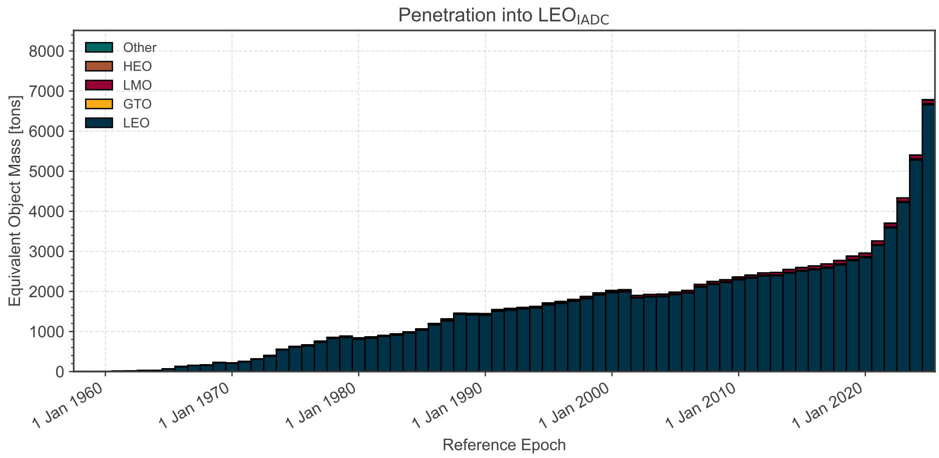


(c) Evolution of absolute area.

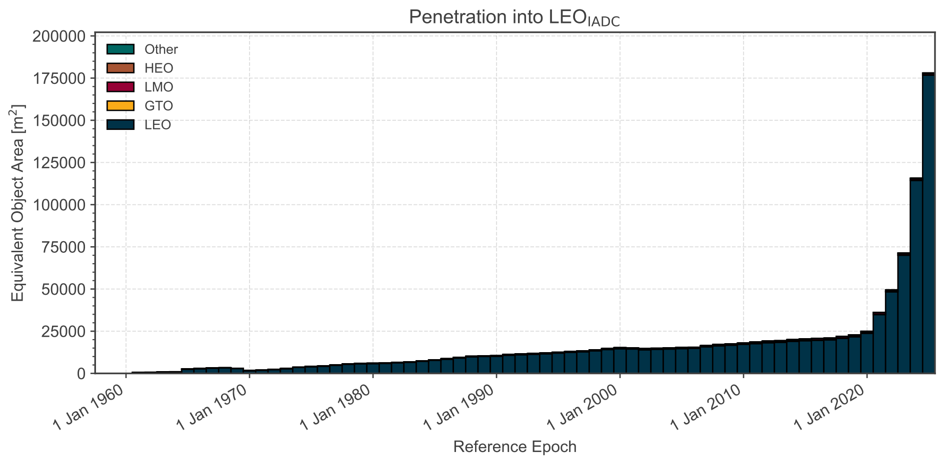
Figure 2.4: Evolution of absolute number of objects, mass and area residing in or penetrating LEO$_{IADC}$.



(a) Evolution of equivalent number of objects.



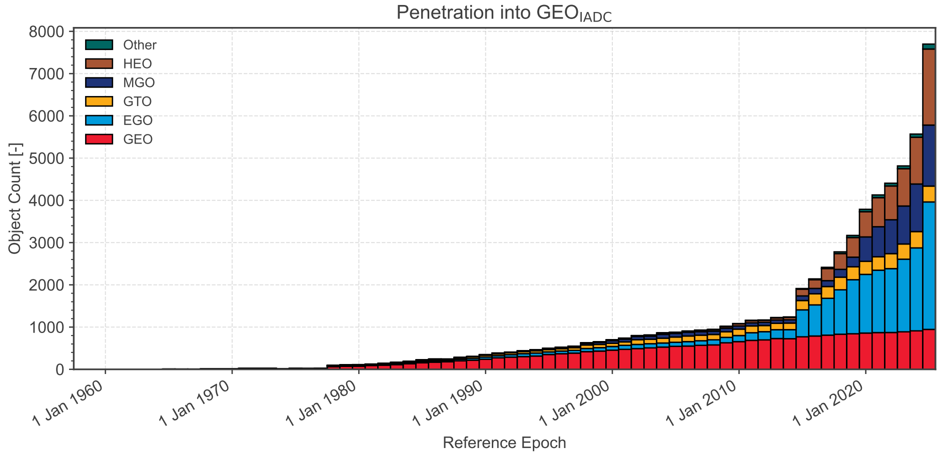
(b) Evolution of equivalent mass.



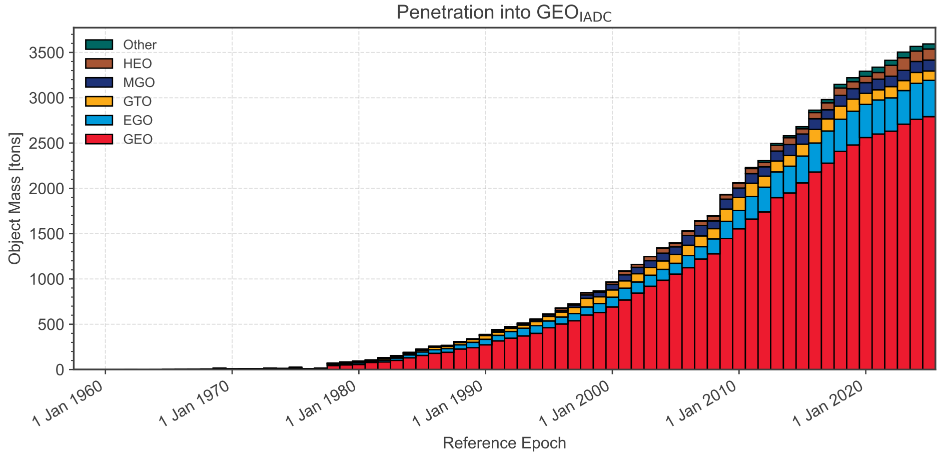
(c) Evolution of equivalent area.

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

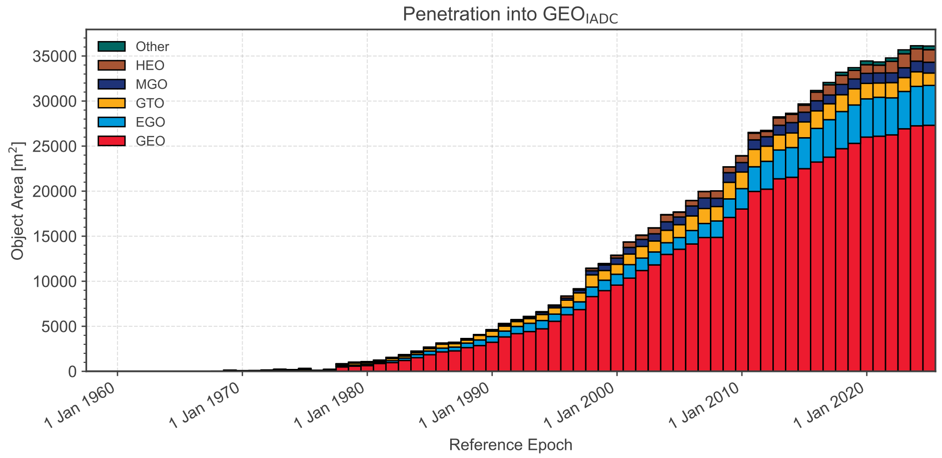
2.3. Evolution of Environment in GEO



(a) Evolution of absolute number of objects.

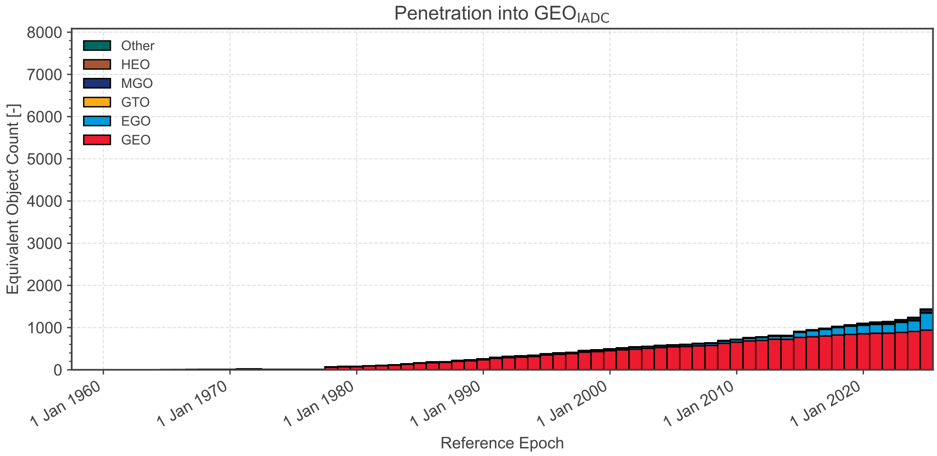


(b) Evolution of absolute mass.

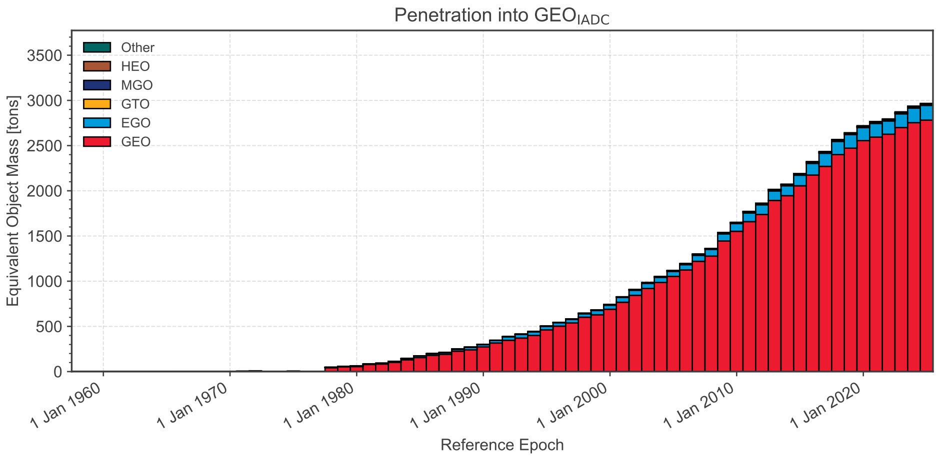


(c) Evolution of absolute area.

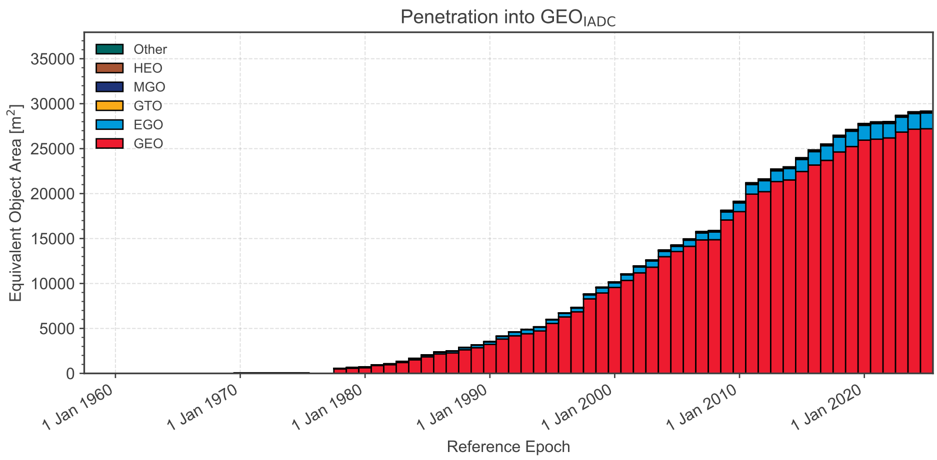
Figure 2.6: Evolution of absolute number of objects, mass and area residing in or penetrating GEO$_{IADC}$.



(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 (Meteoroid and Space Debris Terrestrial Environment Reference), at the most recent reference epoch 1st August 2024, the estimated number of space objects in orbit in the different size ranges is the following:

- 54.000 objects greater than 10 cm (including approximately 9300 active payloads),
- 1.2 million objects from 1 cm to 10 cm,
- 130 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 diameter indicated in x-axis, considering space objects crossing the LEO regime. Fig. 2.9 shows the density profiles with altitude corresponding to different minimum object 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.

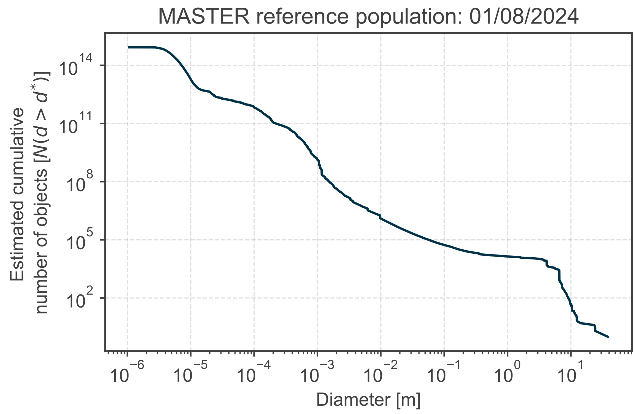


Figure 2.8: Estimated number of space objects crossing LEO as a function of the object diameter from the 01/08/2024 reference population.

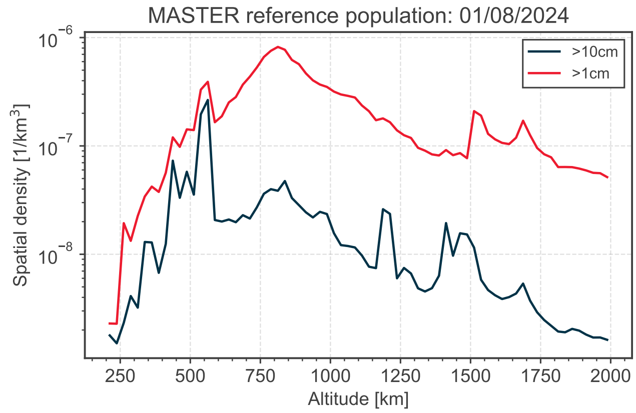


Figure 2.9: Density profiles in LEO for different space object size ranges from the 01/08/2024 reference population.

Fig. 2.10 shows the density profiles with altitude for space objects larger than 10 cm, considering only the LEO region, for the most recent reference epoch 1st August 2024, as well as for the previous MASTER population release, with reference epoch 1st November 2016. In particular, this highlights the contributions coming from constellations as well as fragmentation events.

Similarly, Fig. 2.11 shows the difference for space objects larger than 1 cm. Whereas historically, the 1 cm population mostly consisted of fragments, this paradigm has now changed for selected altitudes used by constellations, and the density of active payloads is approaching that of space debris in these heavily populated orbits.

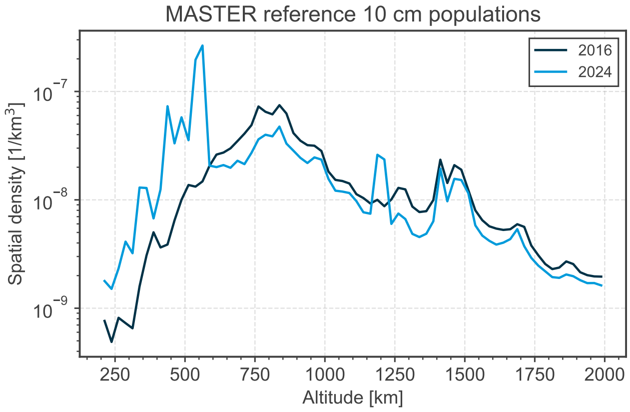


Figure 2.10: Density profiles in LEO for space objects larger than 10 cm for the 01/08/2024 and 01/11/2016 reference populations.

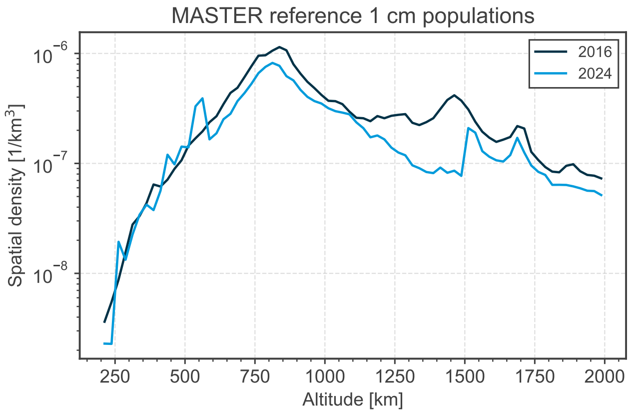


Figure 2.11: Density profiles in LEO for space objects larger than 1 cm for the 01/08/2024 and 01/11/2016 reference populations.

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 regularly used ones over recent years 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.

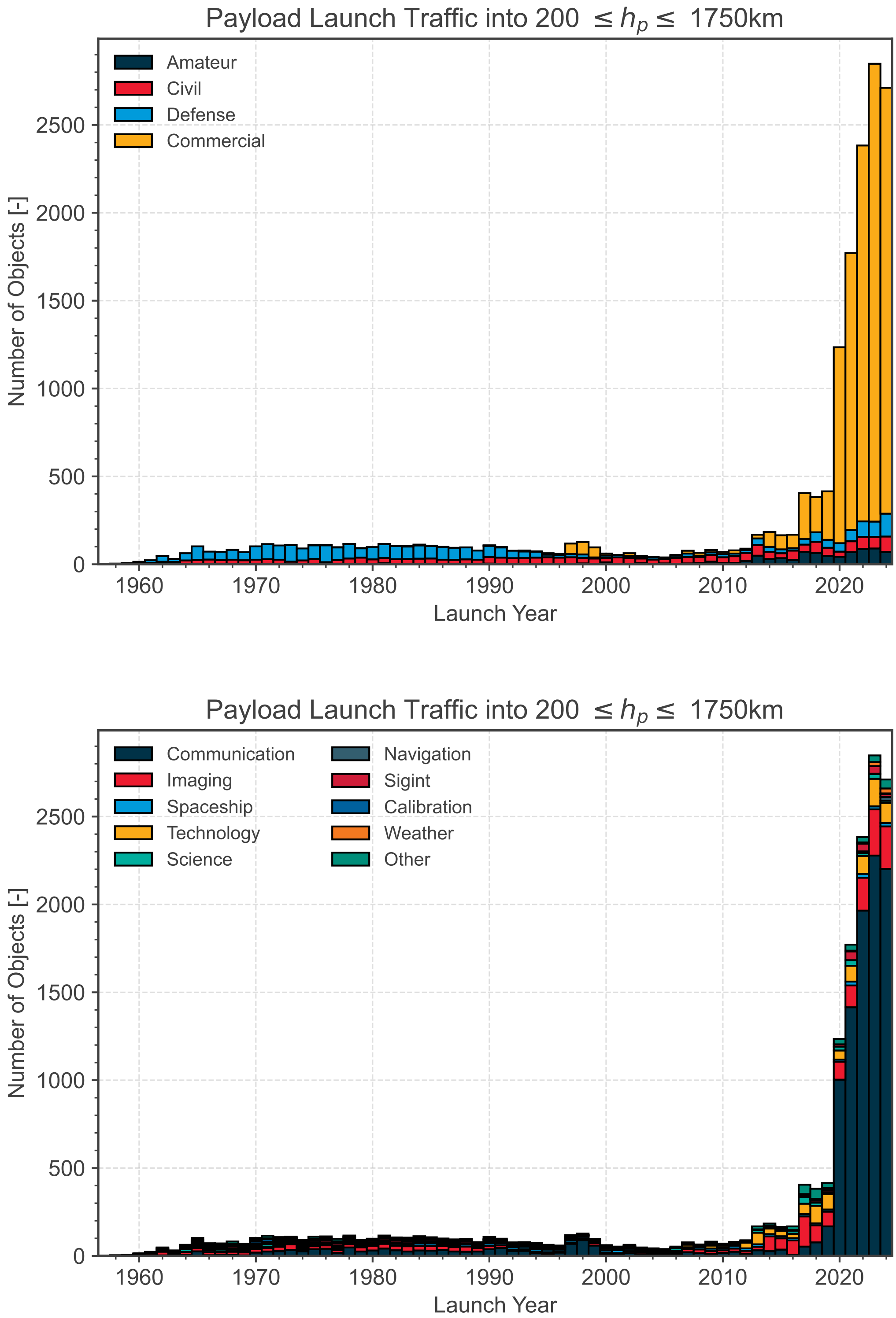
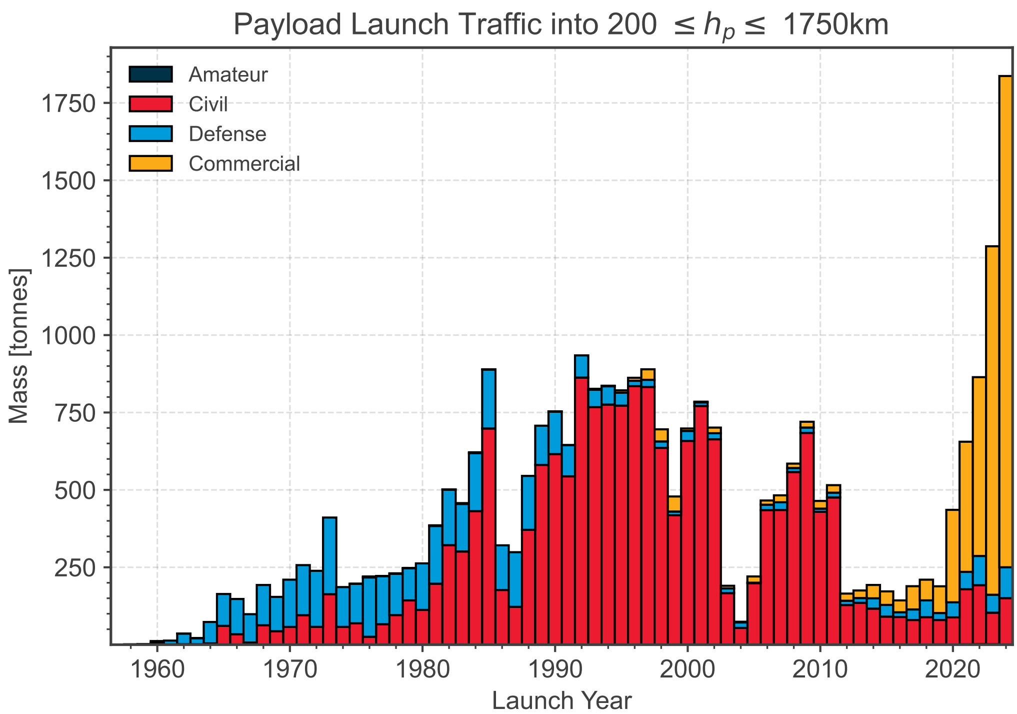


Figure 2.12: Evolution of the launch traffic near LEO_{IADC} per mission funding (top) and type (bottom).



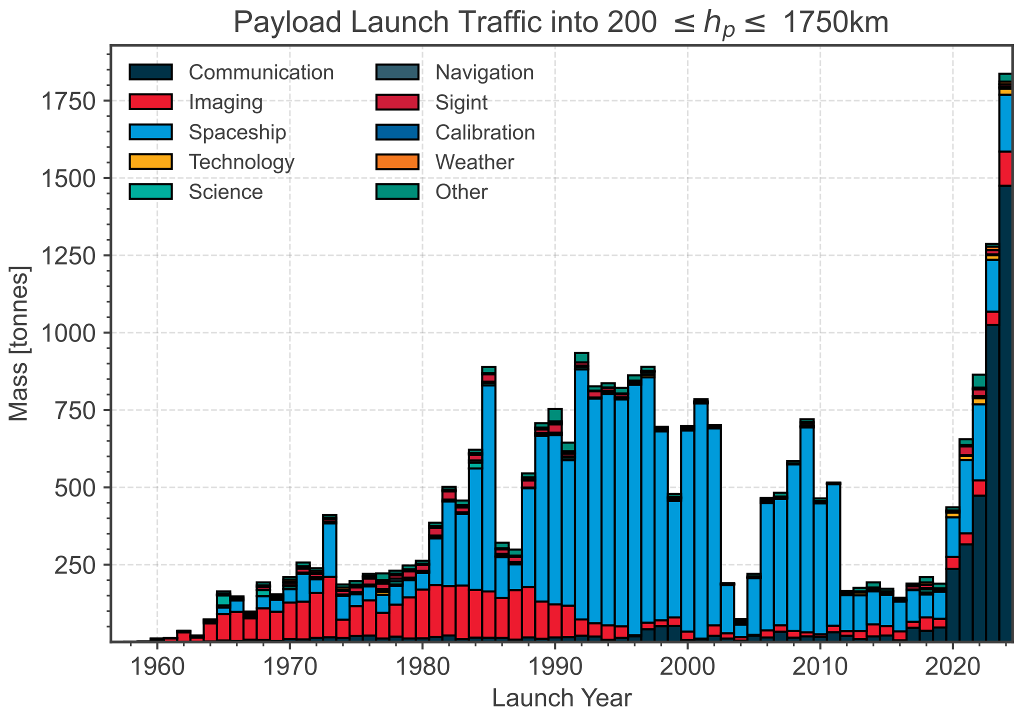
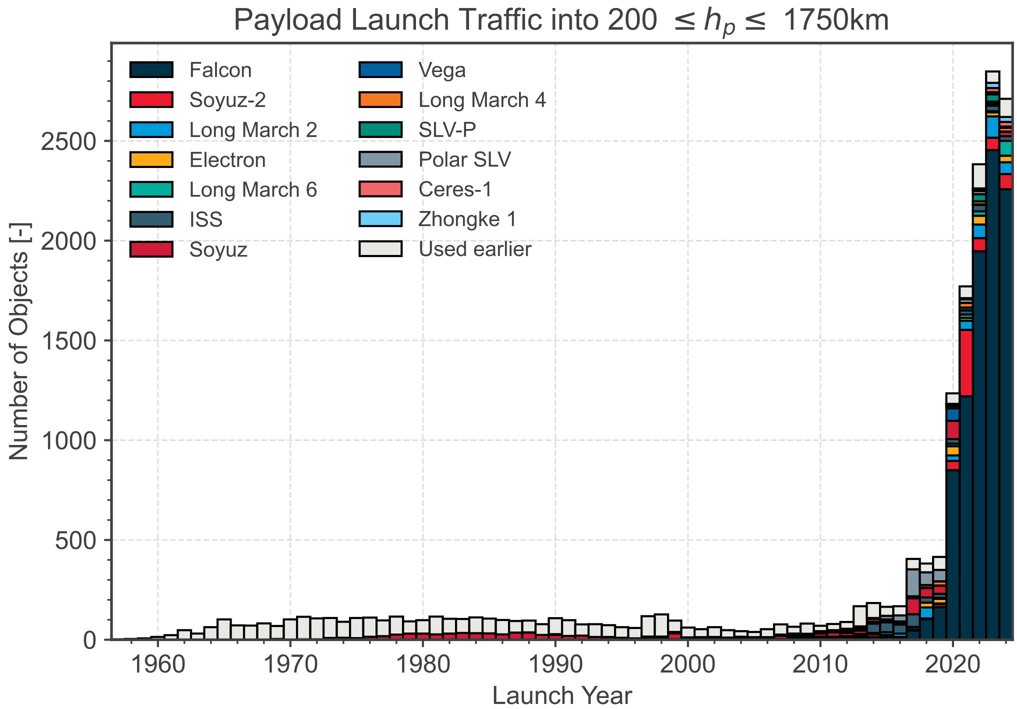


Figure 2.13: Evolution of the launch traffic near LEO_{IADC} per mission funding (top) and type (bottom) in terms of mass.



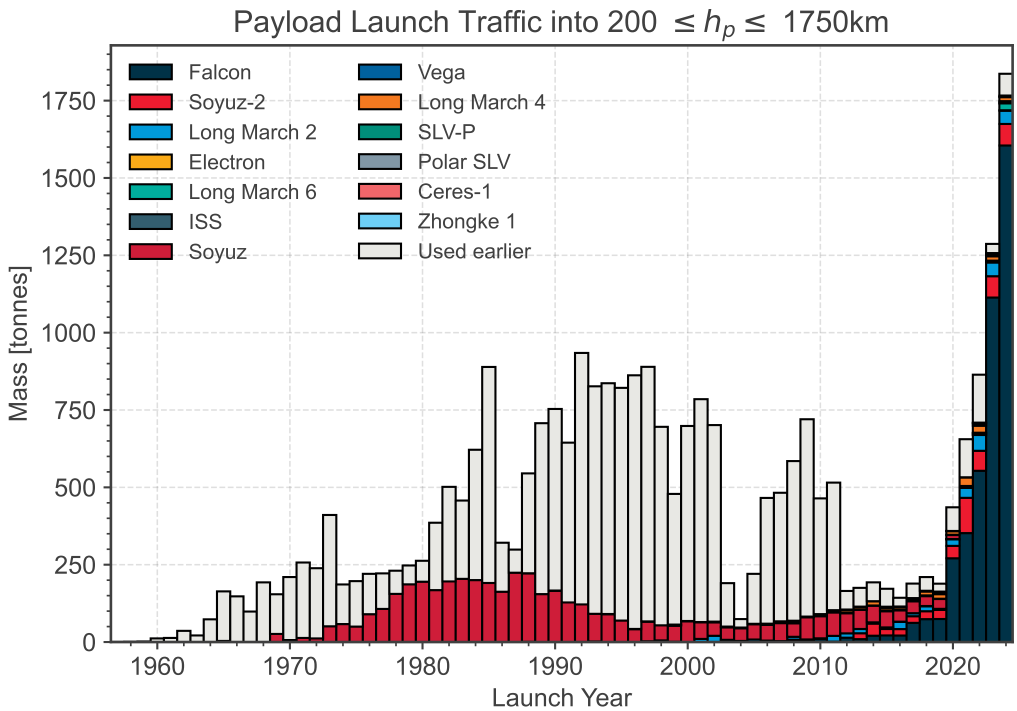
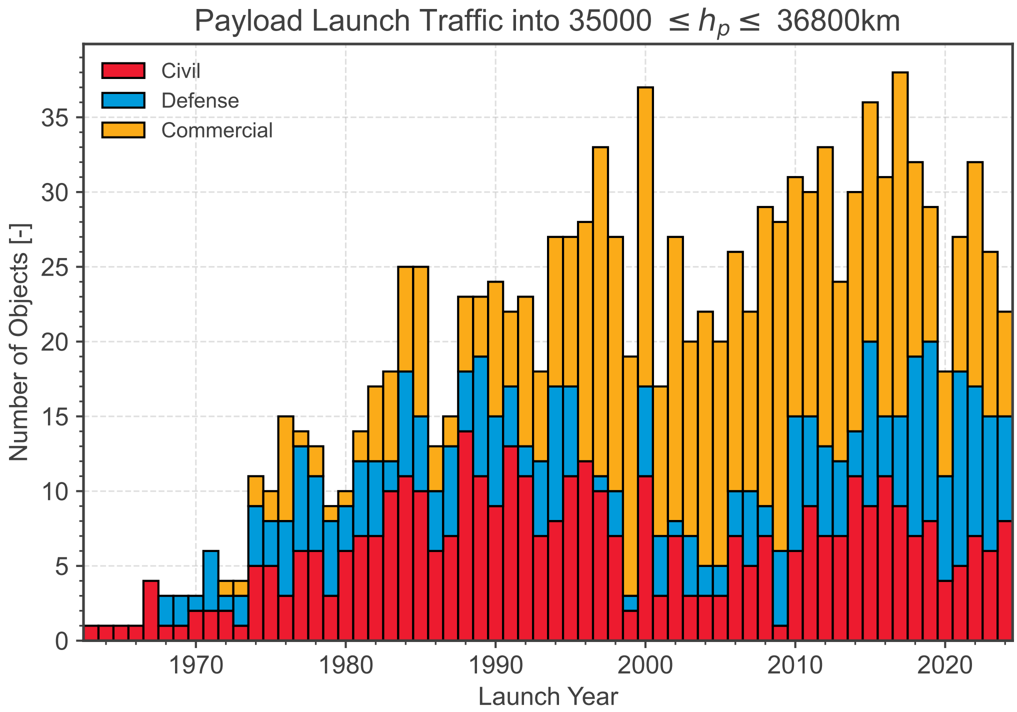


Figure 2.14: Evolution of the launch traffic near LEO_{IADC} per launcher family expressed in terms of number of objects (top) and mass (bottom).



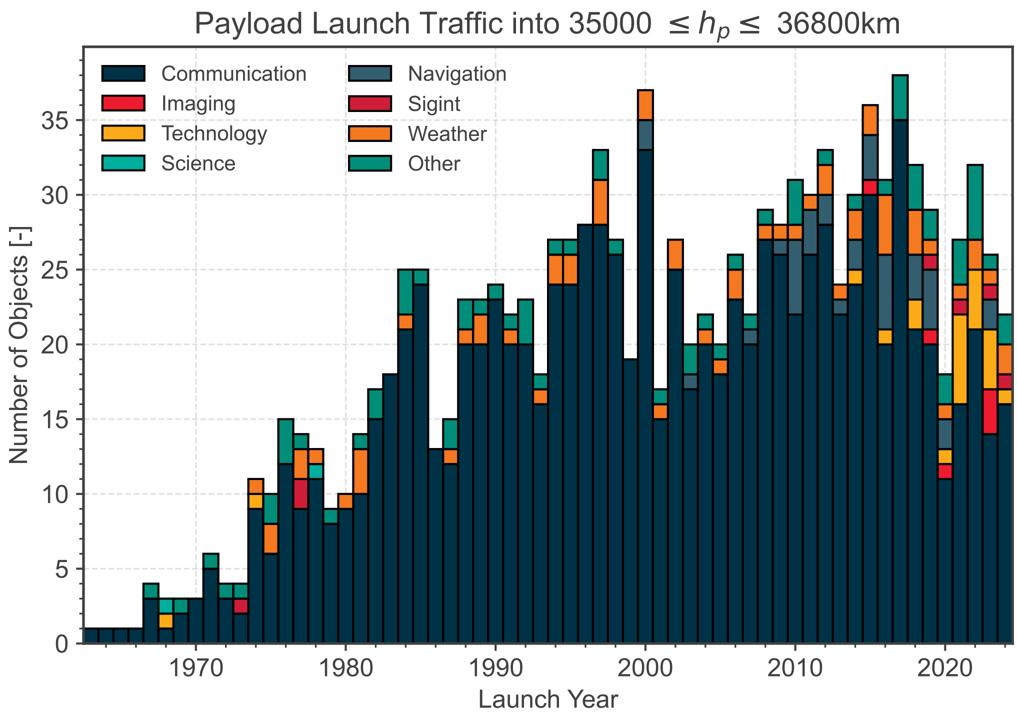
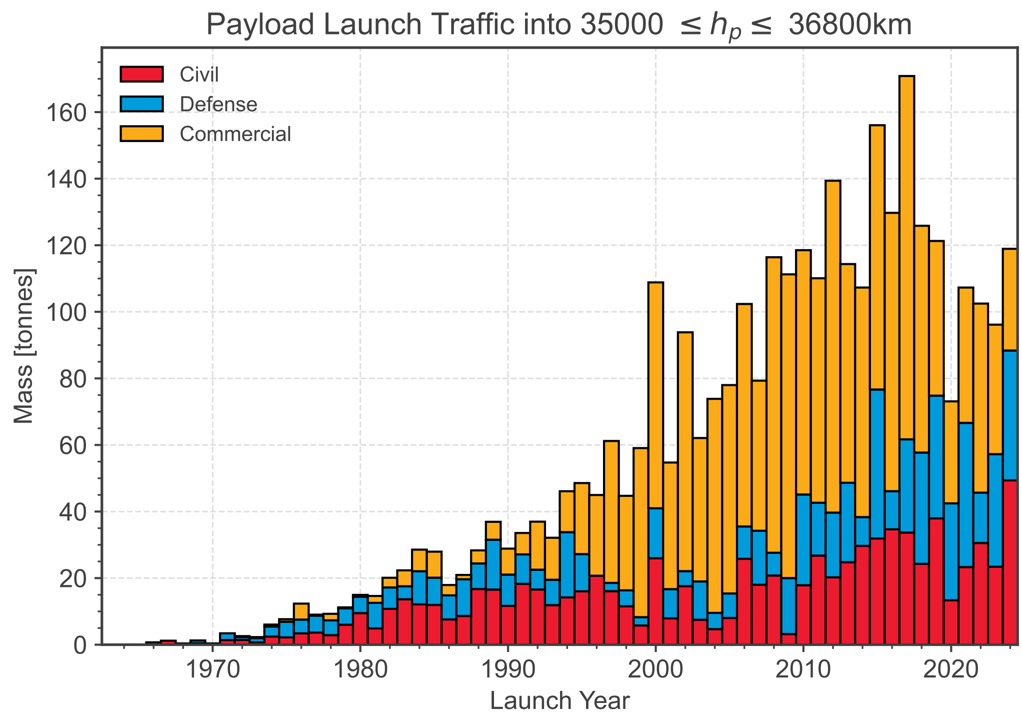


Figure 2.15: Evolution of the launch traffic near GEO_{IADC} per mission funding (top) and type (bottom).



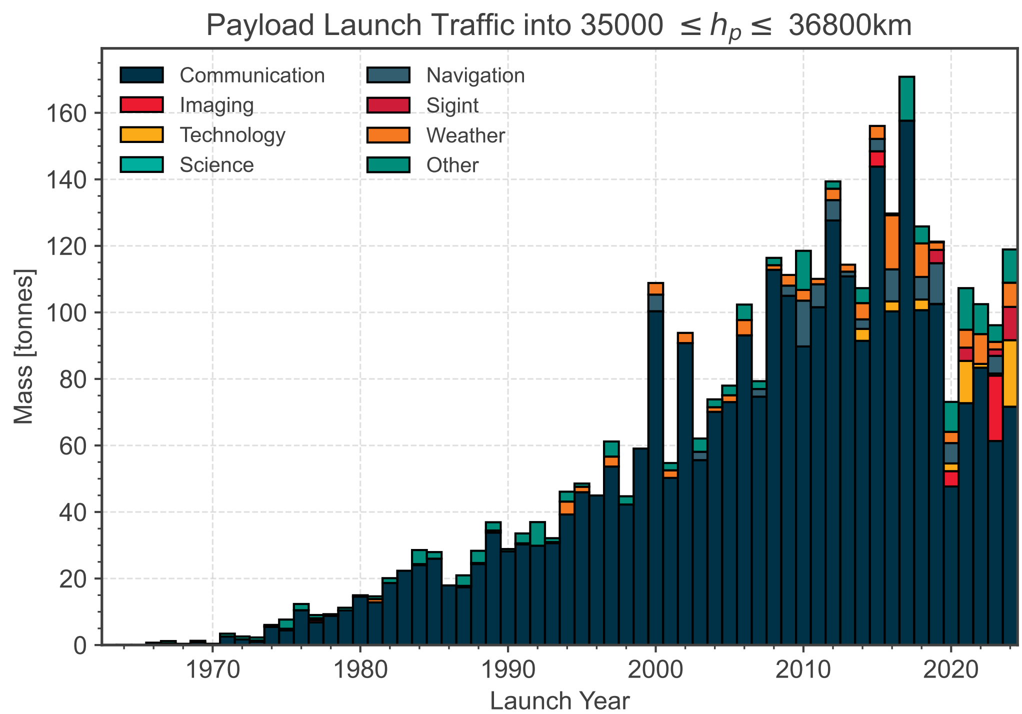
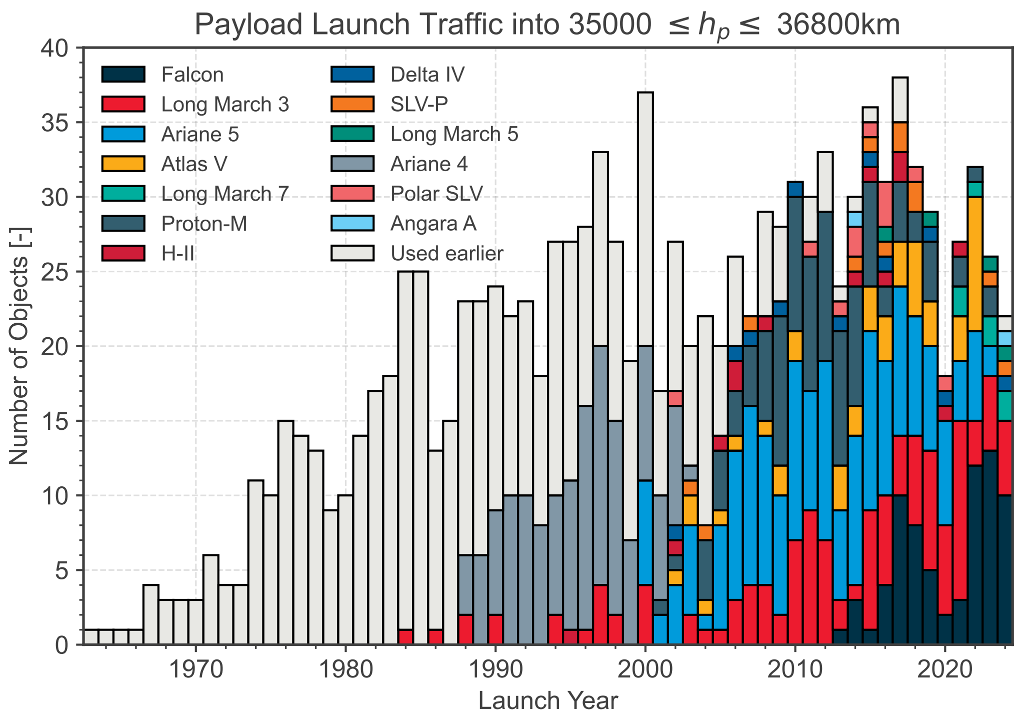


Figure 2.16: Evolution of the launch traffic near GEO_{IADC} per mission funding (top) and type (bottom) in terms of mass.



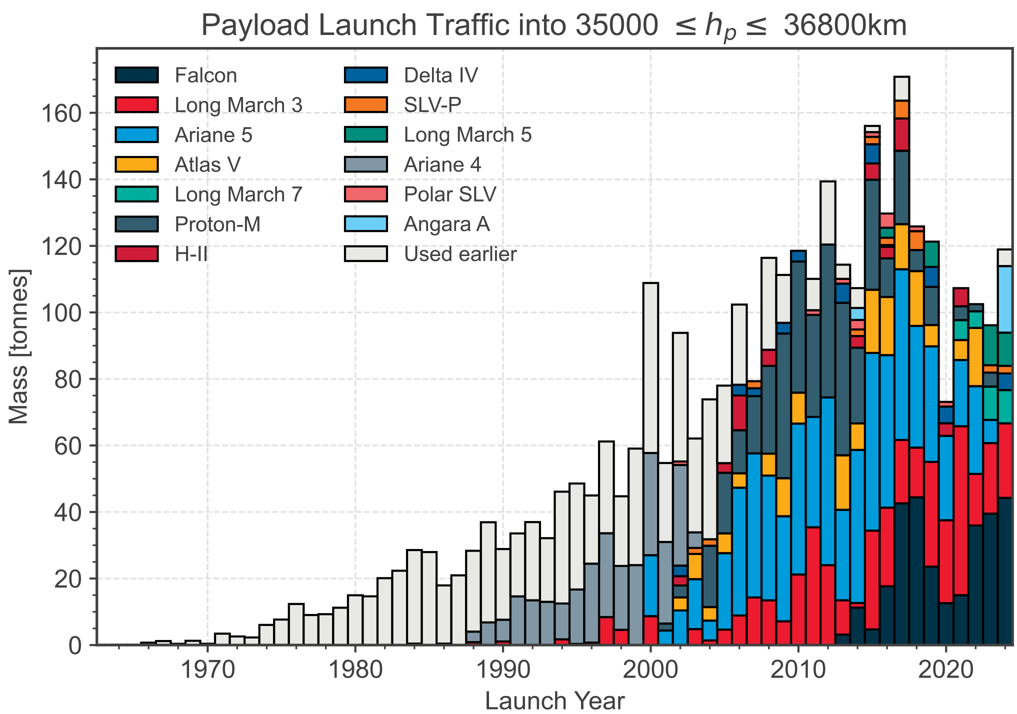
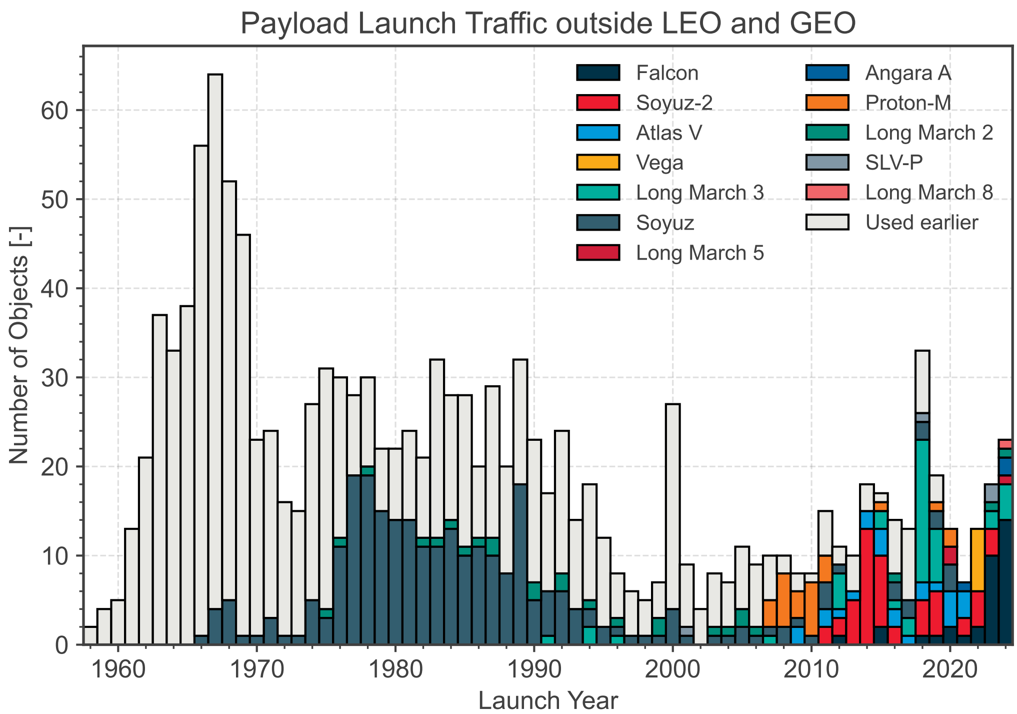


Figure 2.17: Evolution of the launch traffic near GEO_{IADC} per launcher family expressed in terms of number of objects (top) and mass (bottom).



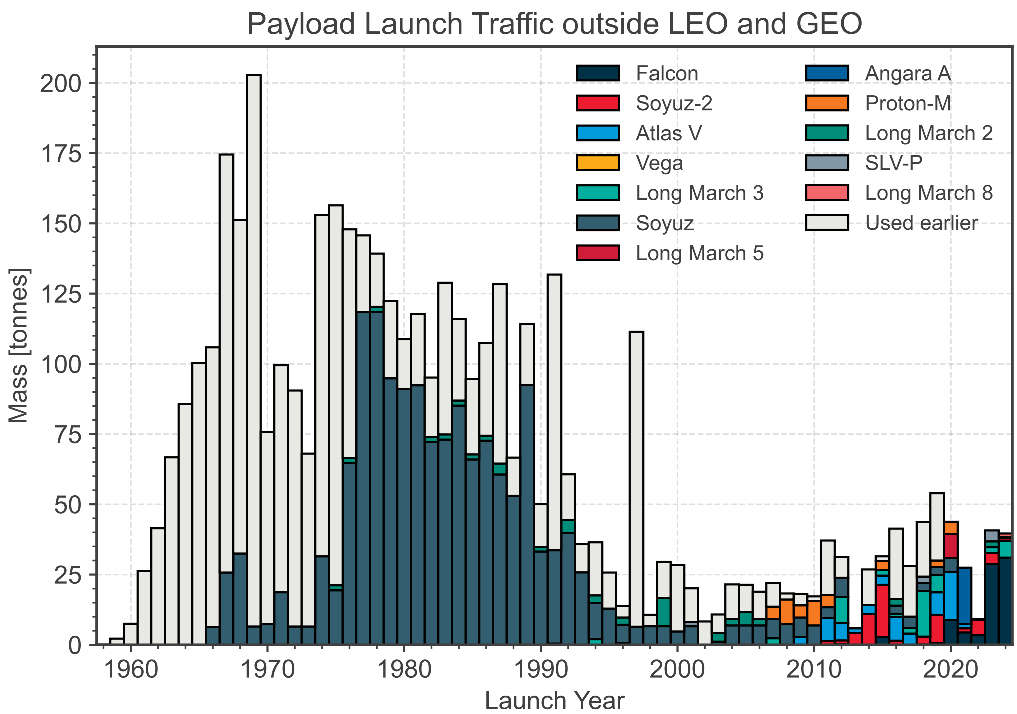
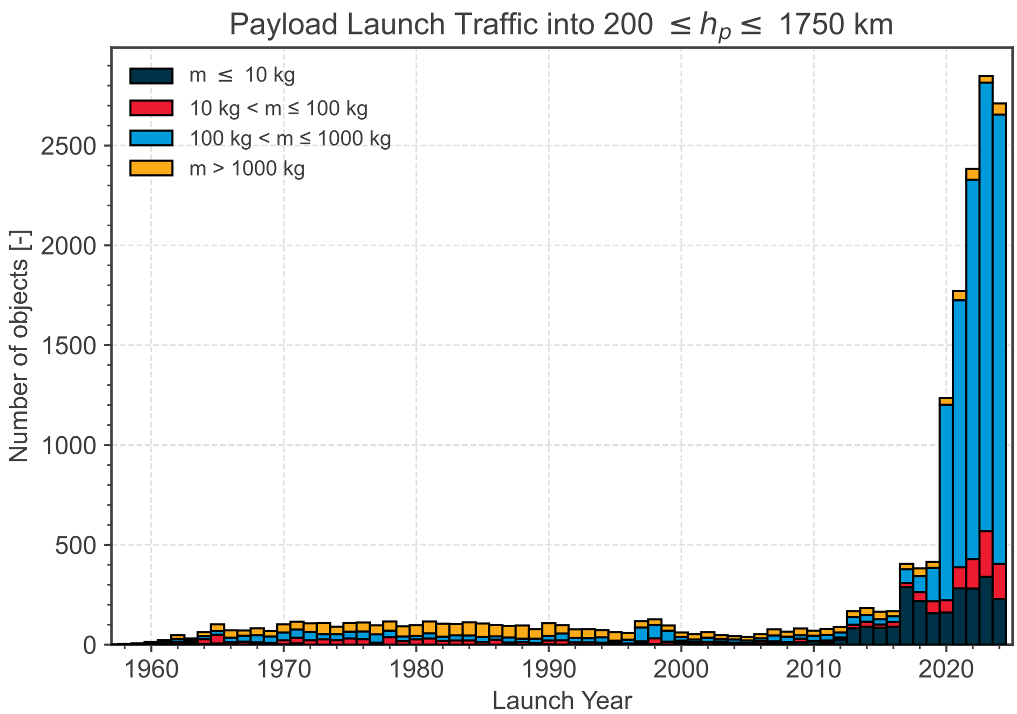


Figure 2.18: Evolution of the launch traffic outside LEO_{IADC} and GEO_{IADC} per launcher family expressed in terms of number of objects (top) and mass (bottom).



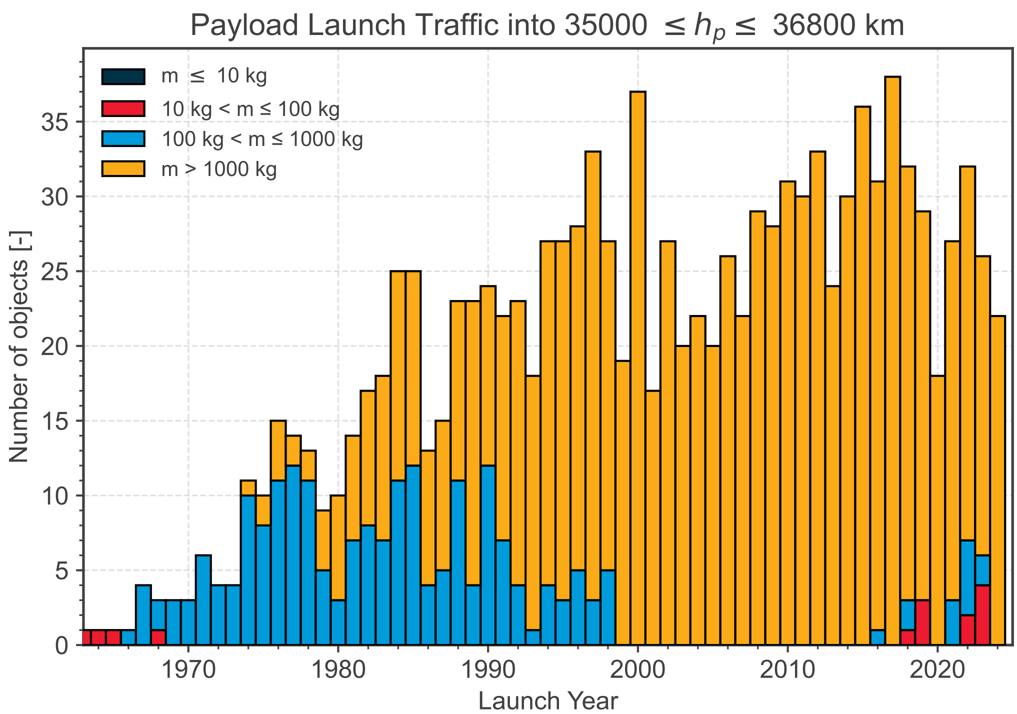
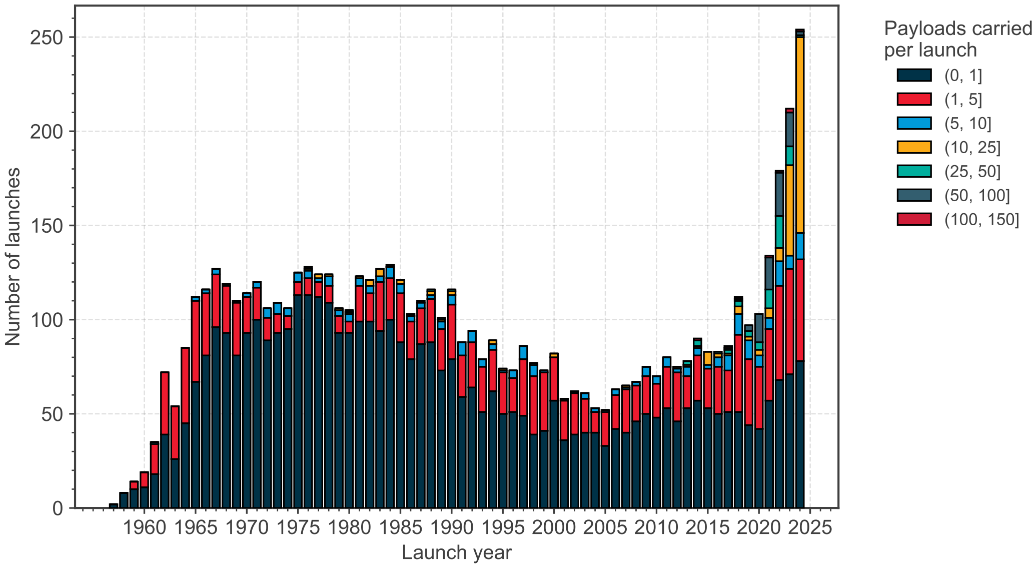
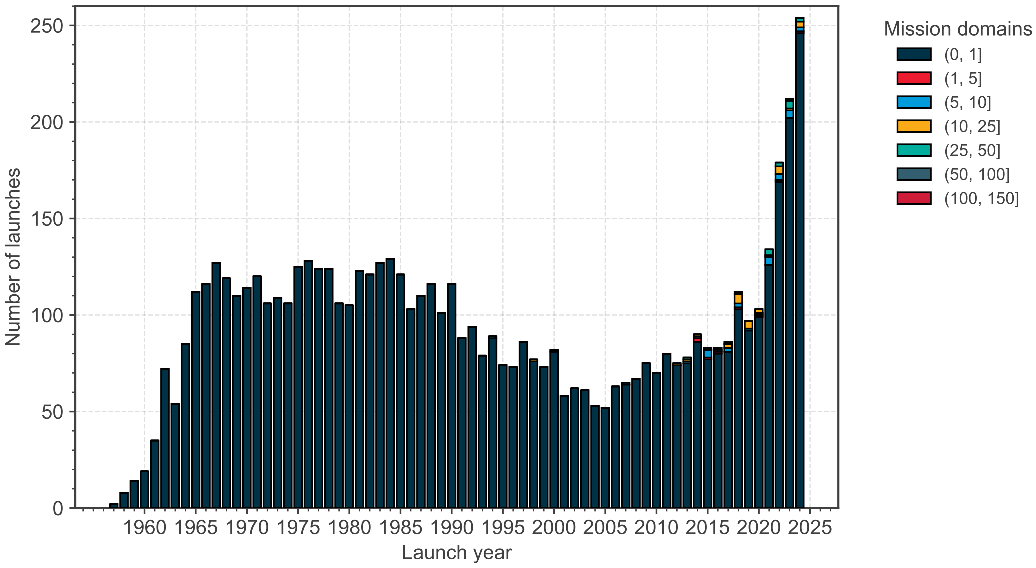


Figure 2.19: Evolution of the launch traffic per mass category in terms of number of objects in LEO_{IADC} (top) and GEO_{IADC} (bottom).



(a) Payloads



(b) Mission domains

Figure 2.20: Evolution of the launch traffic.

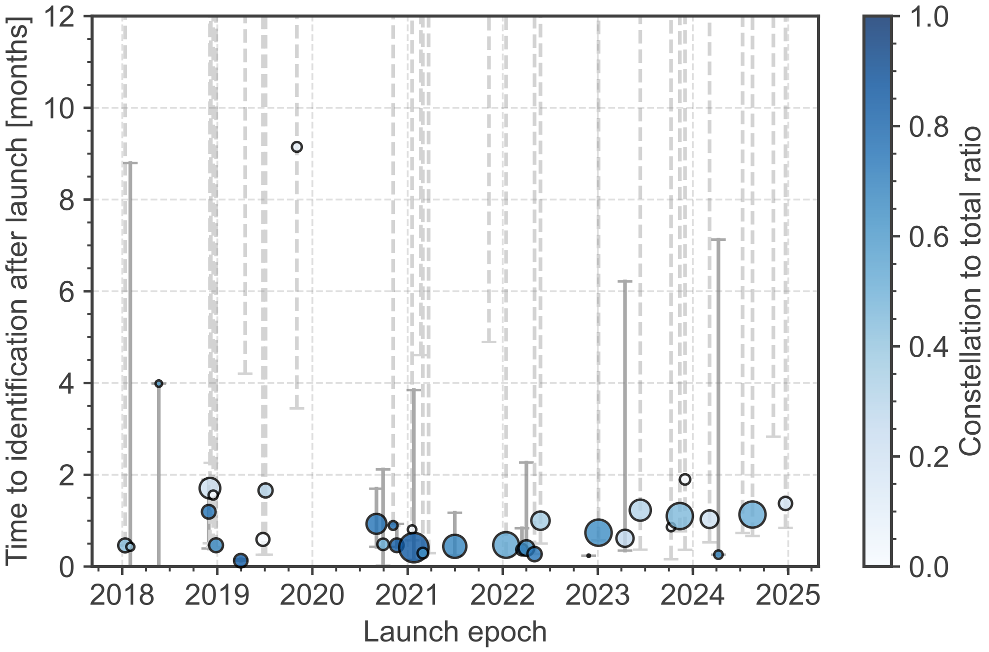
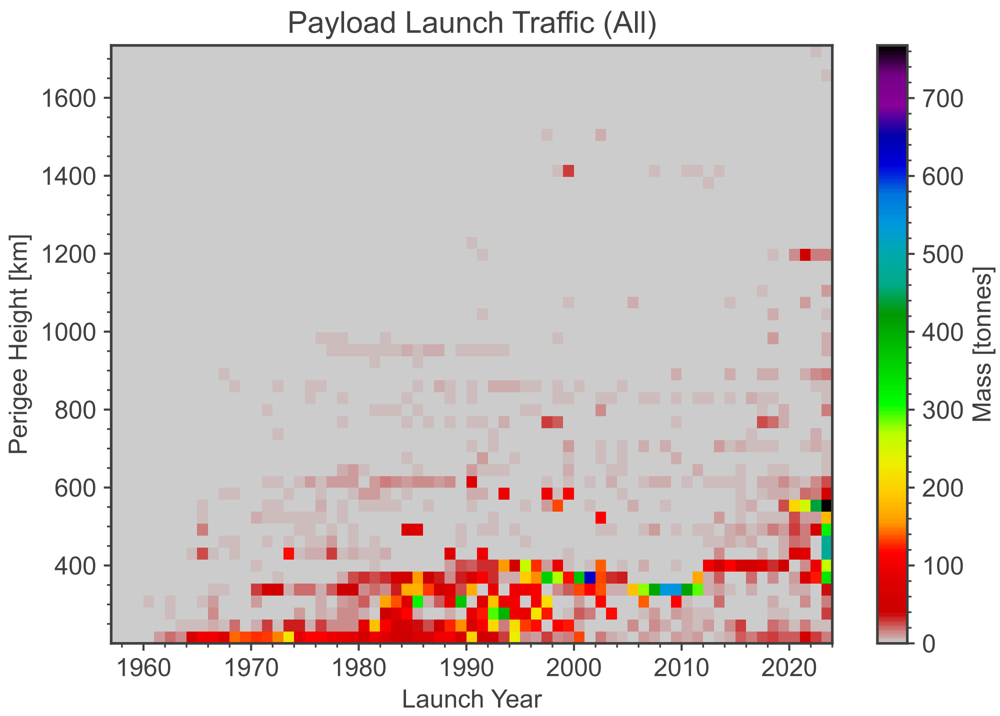
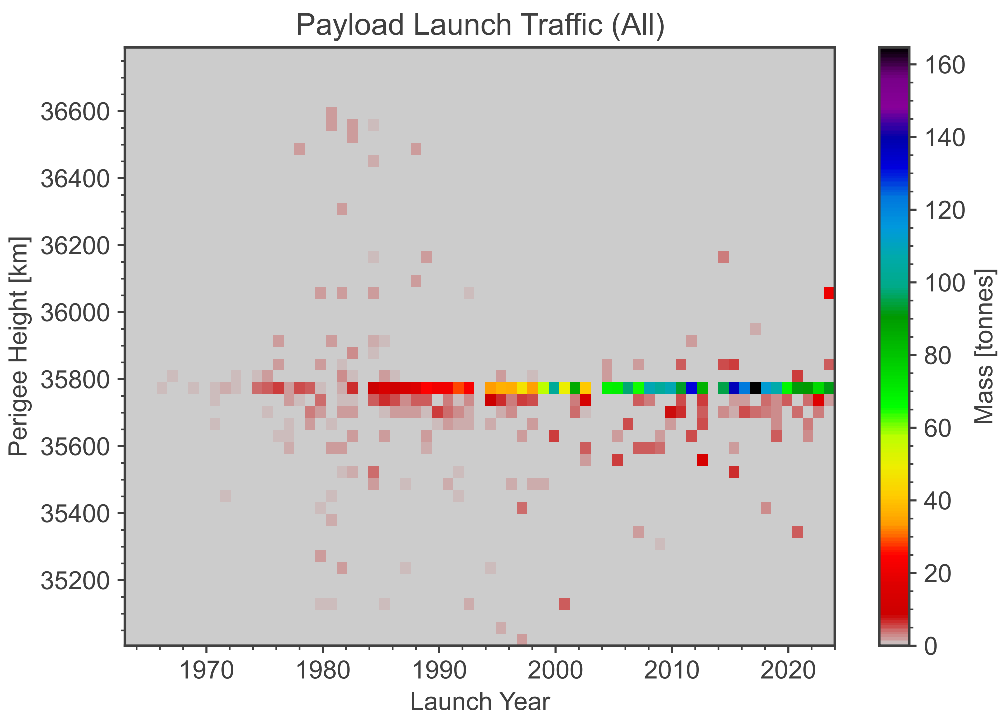


Figure 2.21: Identification rate for rideshare launches.

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. Fig. 2.21 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.

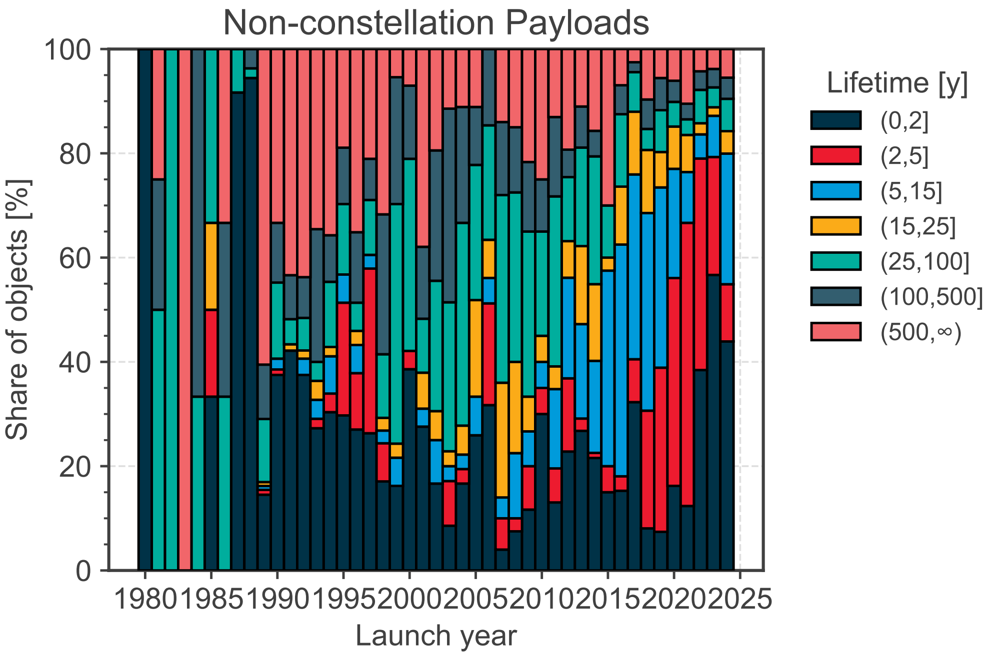


(a) LEO_{IADC}

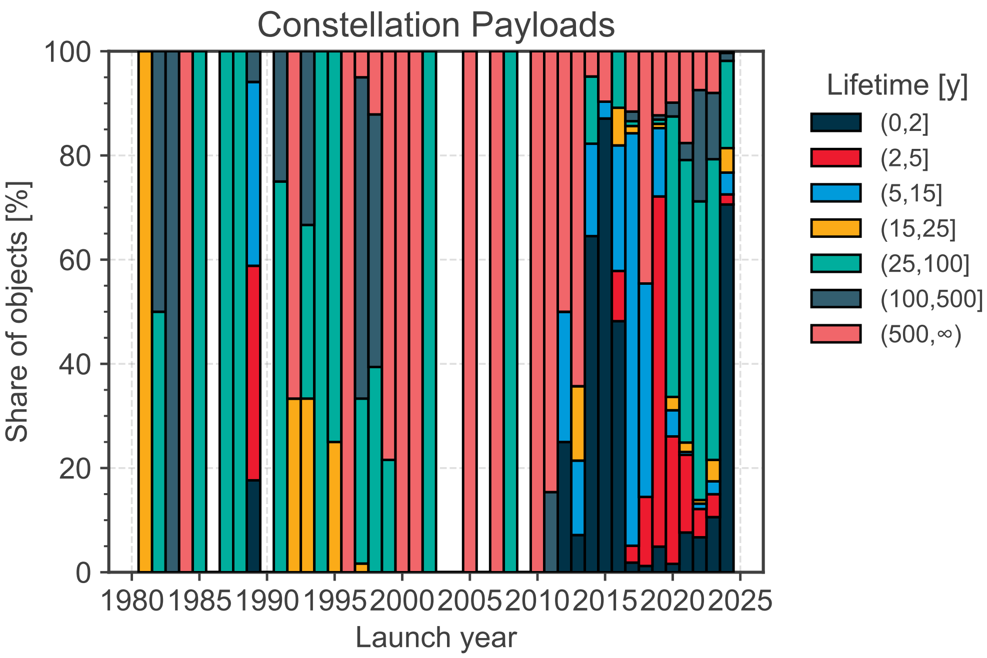


(b) GEO_{IADC}

Figure 2.22: Evolution of the launch traffic: mass injected.

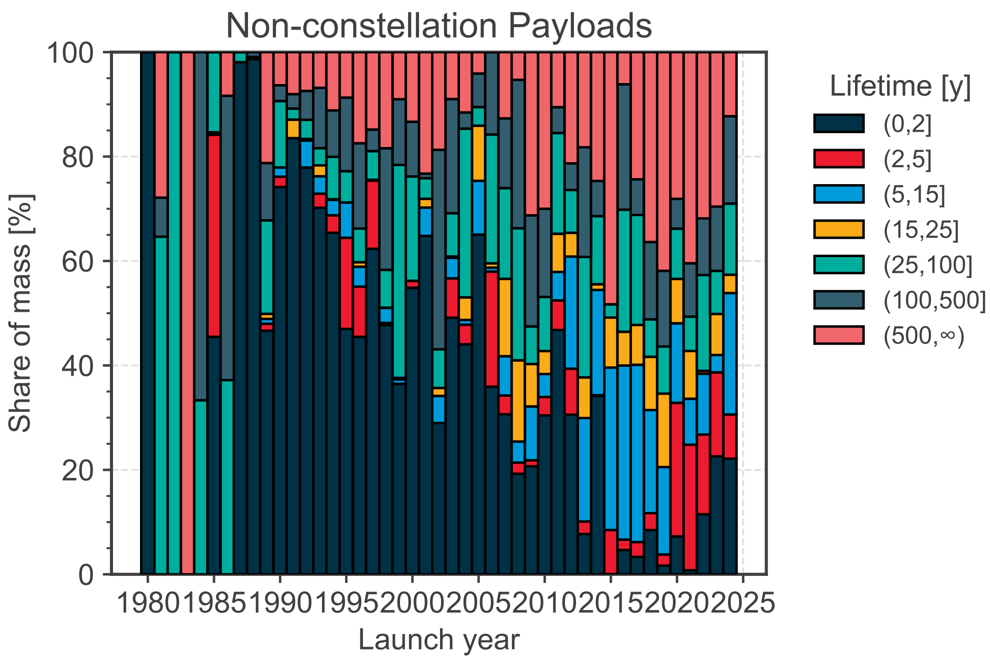


(a) Payload objects not belonging to constellations

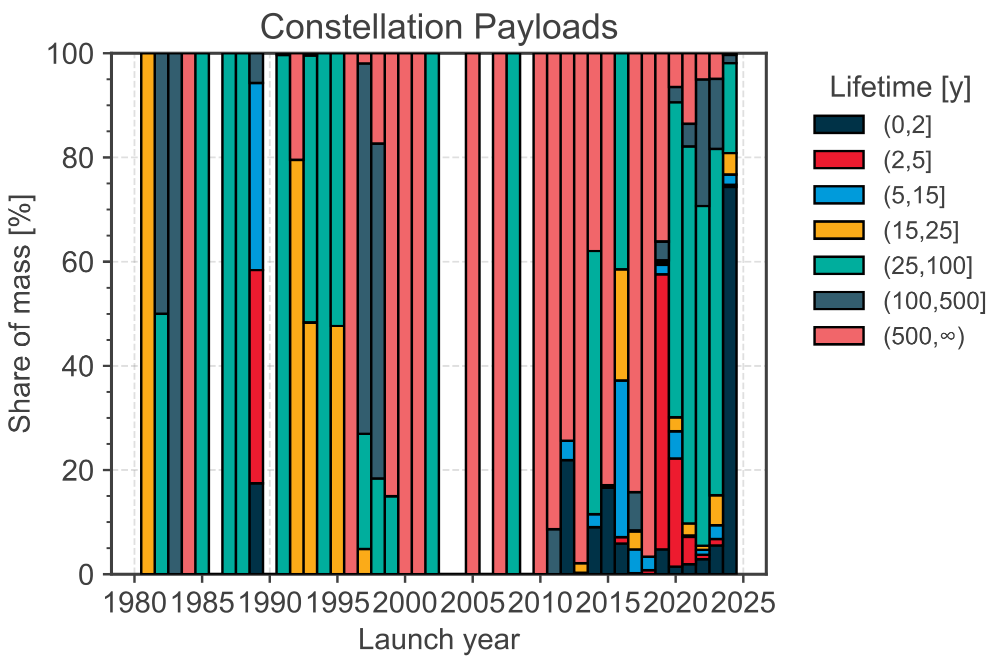


(b) Payload ojects belonging to constellations

Figure 2.23: Estimated lifetime for the Payload destination orbits by launch year: share of objects.



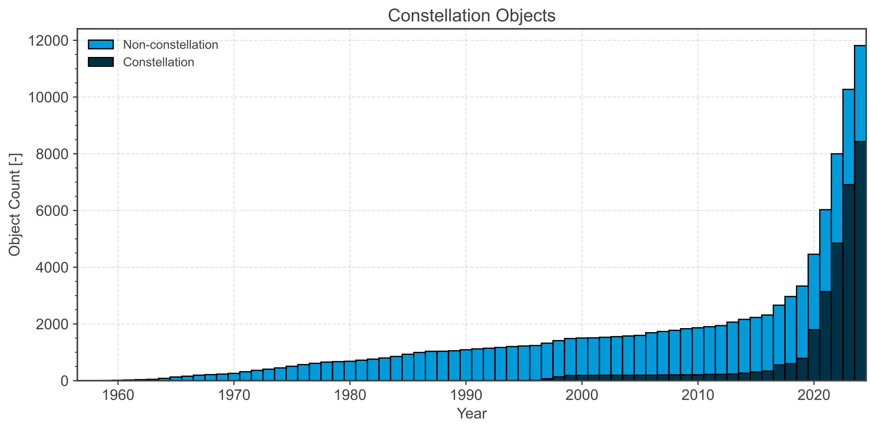
(a) Payload objects not belonging to constellations



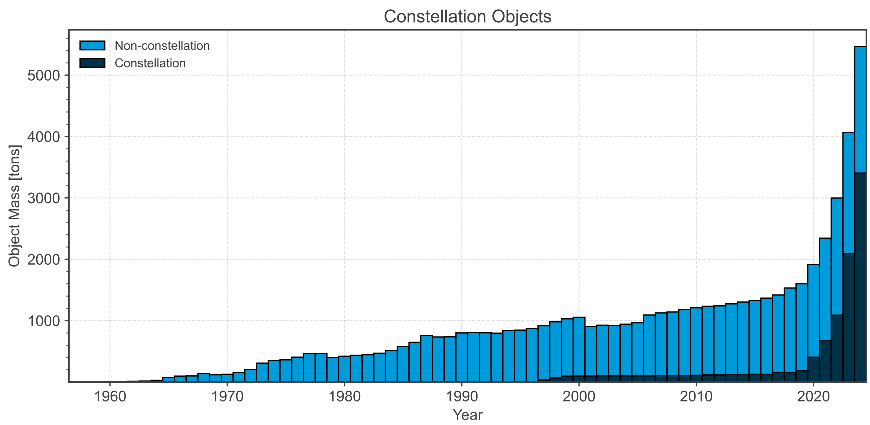
(b) Payload objects belonging to constellations

Figure 2.24: Estimated lifetime for the Payload destination orbits by launch year: share of mass.

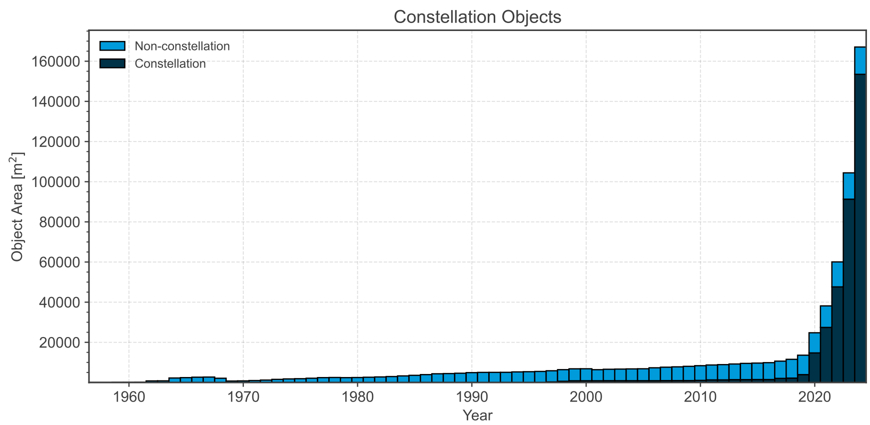
2.6. Constellations in the LEO protected region



(a) Evolution of number of objects.



(b) Evolution of mass.



(c) Evolution of area.

Figure 2.25: Evolution of number of objects, mass, and area in LEO_{IADC} distinguishing constellations and non-constellation payloads.

2.7. Active payloads in the LEO protected region

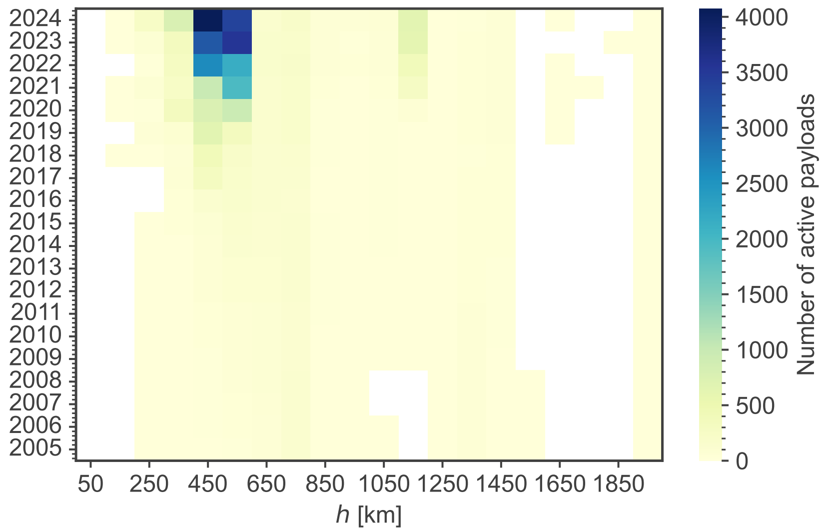


Figure 2.26: Distribution of active payloads in LEO by year and mean altitude.

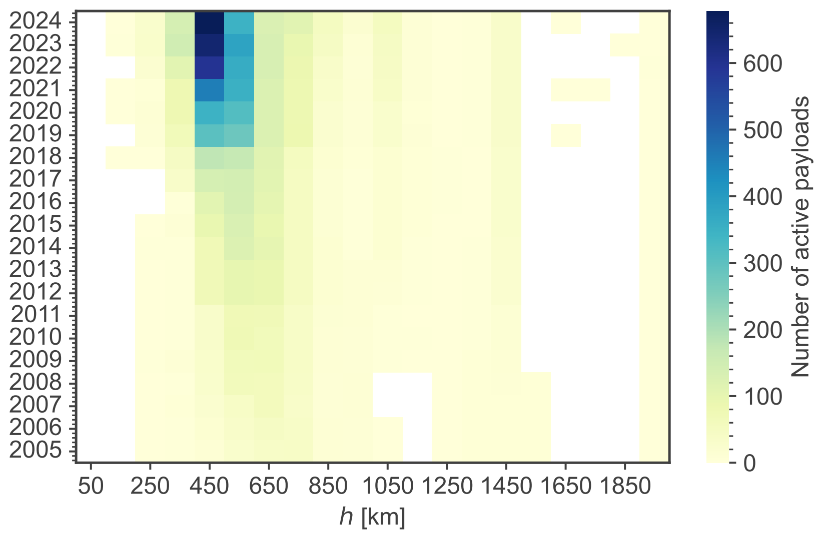


Figure 2.27: Distribution of active payloads not belonging to constellations in LEO by year and mean altitude.

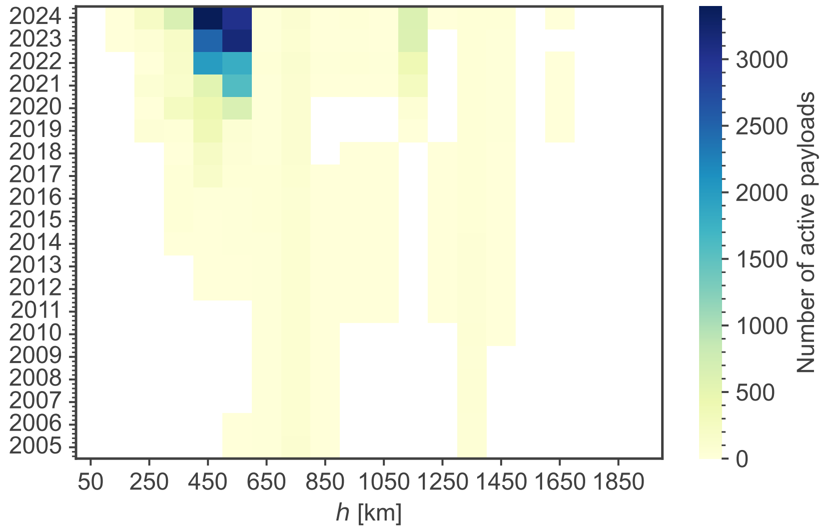


Figure 2.28: Distribution of active payloads belonging to constellations in LEO by year and mean altitude.

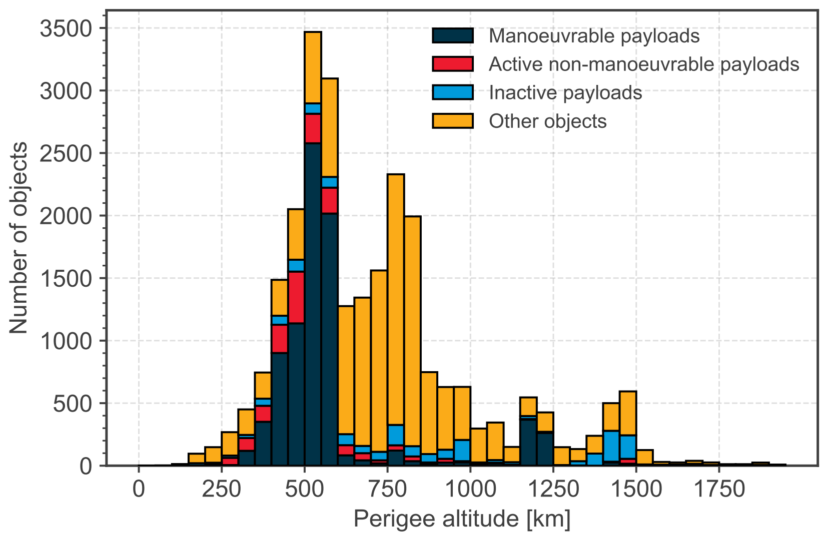


Figure 2.29: Number of manoeuvrable and active objects as a function of the perigee altitude.

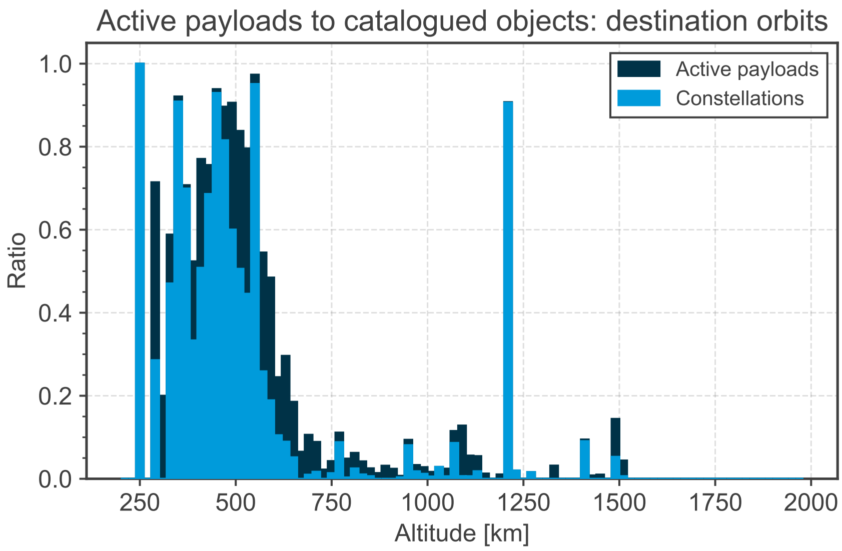


Figure 2.30: Ratio of active and constellation objects over the total number of catalogued objects.

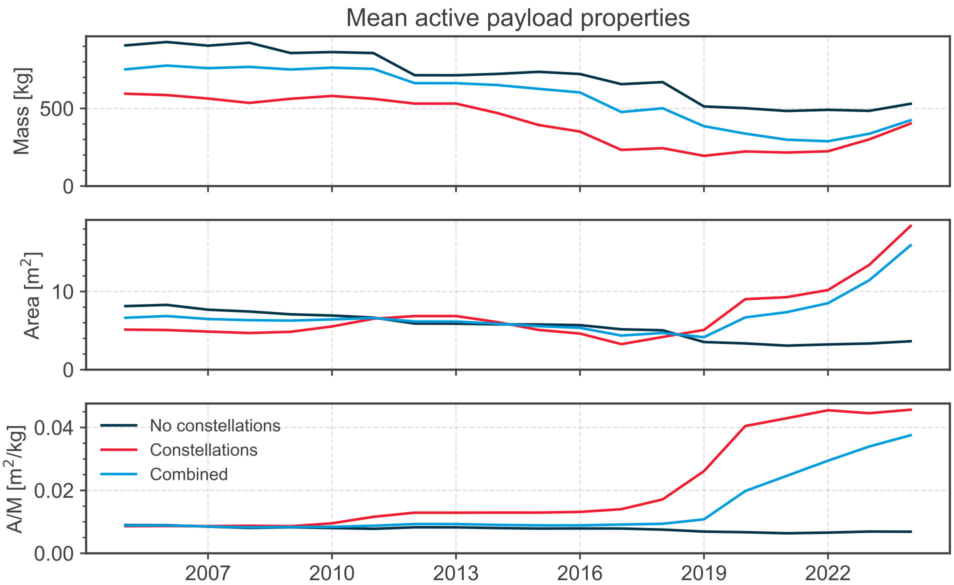
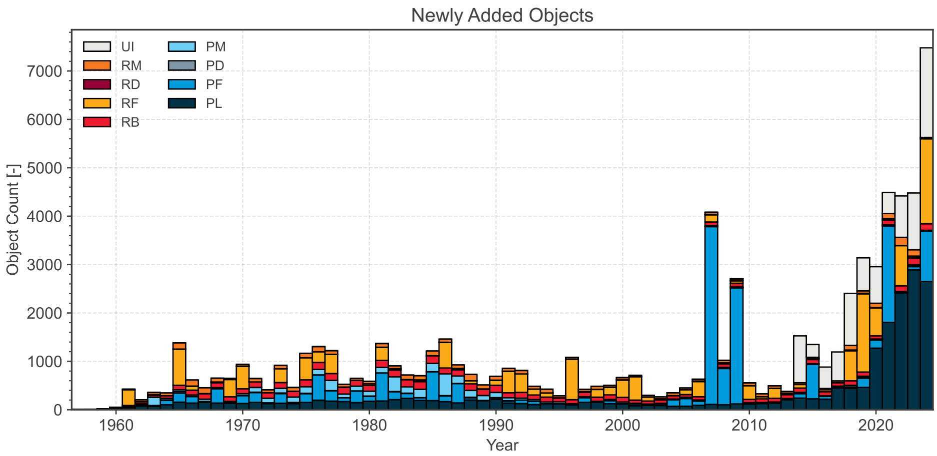
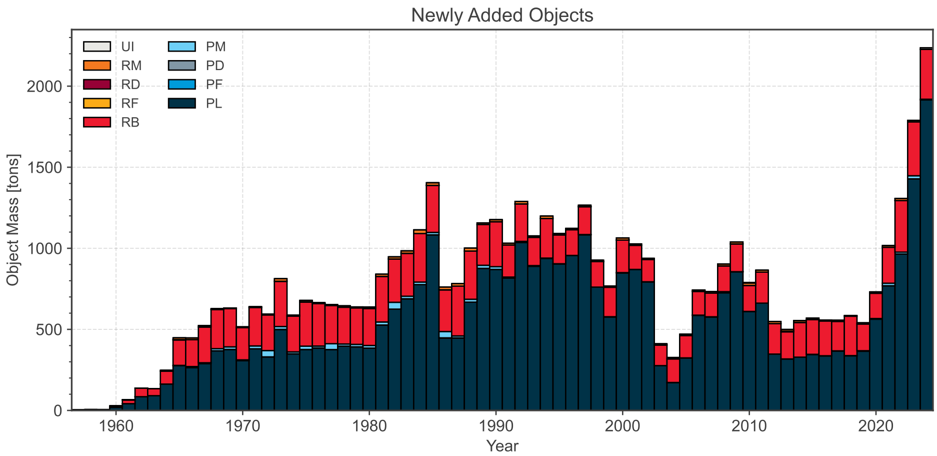


Figure 2.31: Payload parameters for active payloads in LEO over time.

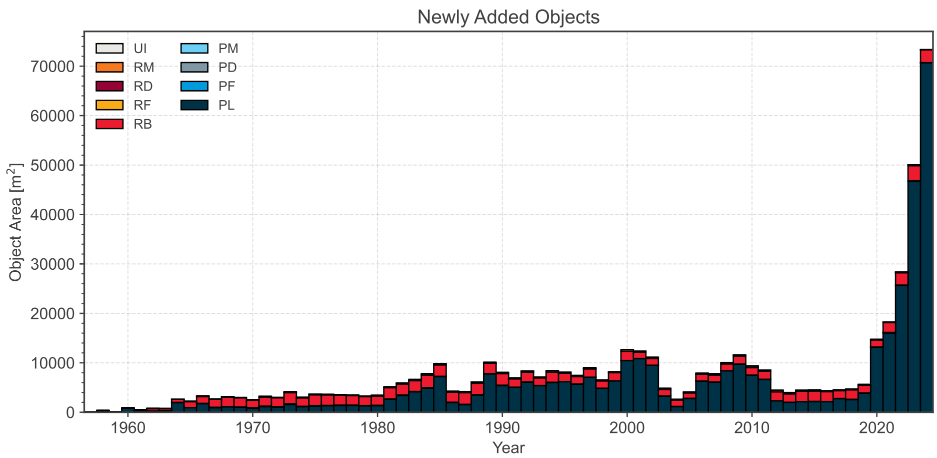
2.8. New Catalogued Objects in the Space Environment



(a) Evolution of newly added object by count.

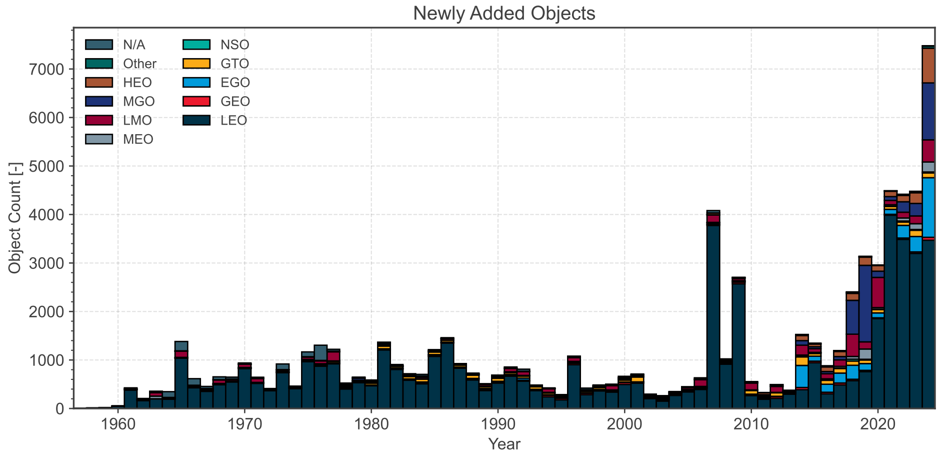


(b) Evolution of newly added mass.

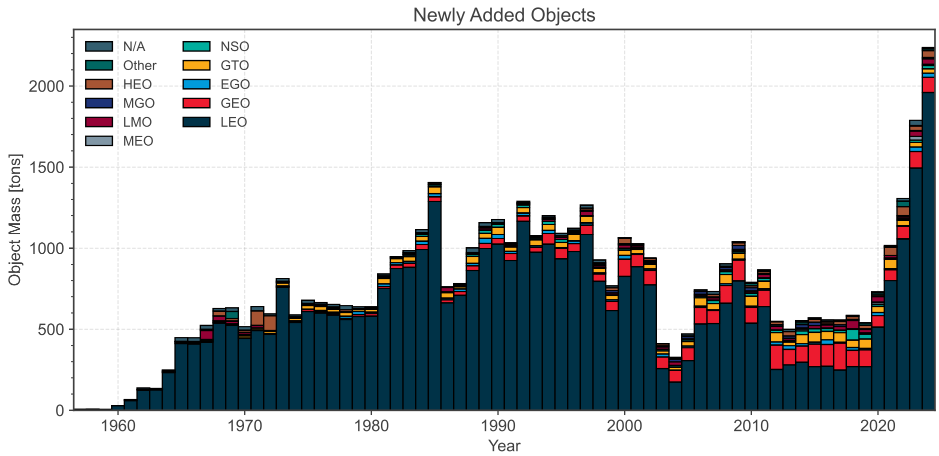


(c) Evolution of newly added area.

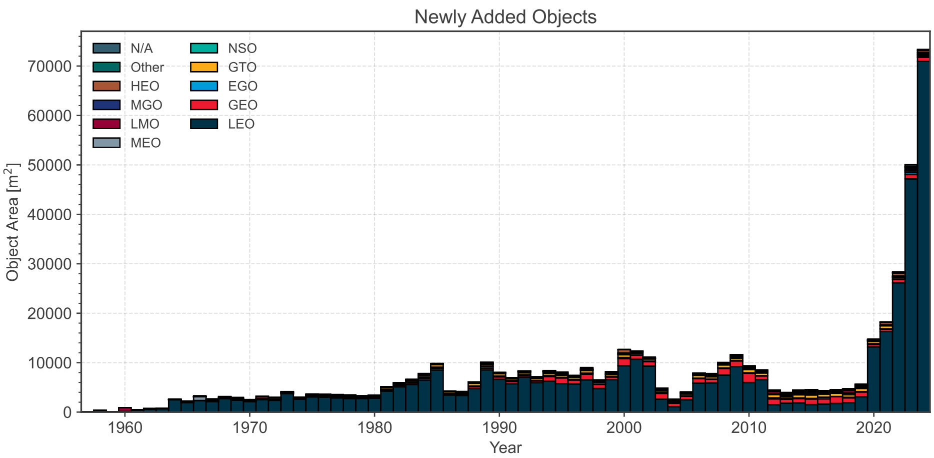
Figure 2.32: Evolution of newly added objects in each year by object type.



(a) Evolution of newly added object by count.



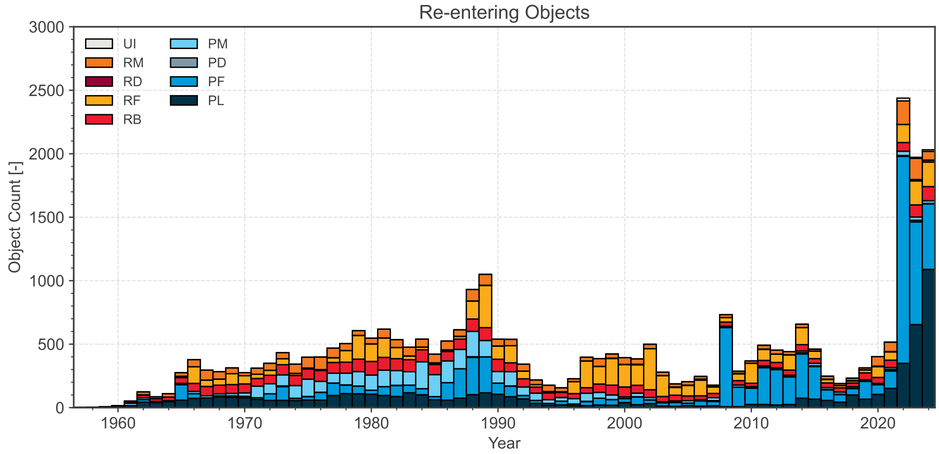
(b) Evolution of newly added mass.



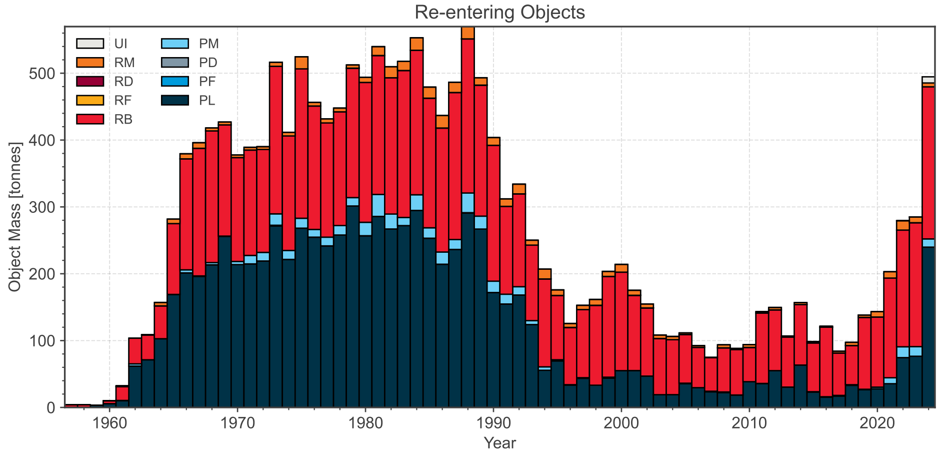
(c) Evolution of newly added area.

Figure 2.33: Evolution of newly added objects in each year by orbit type.

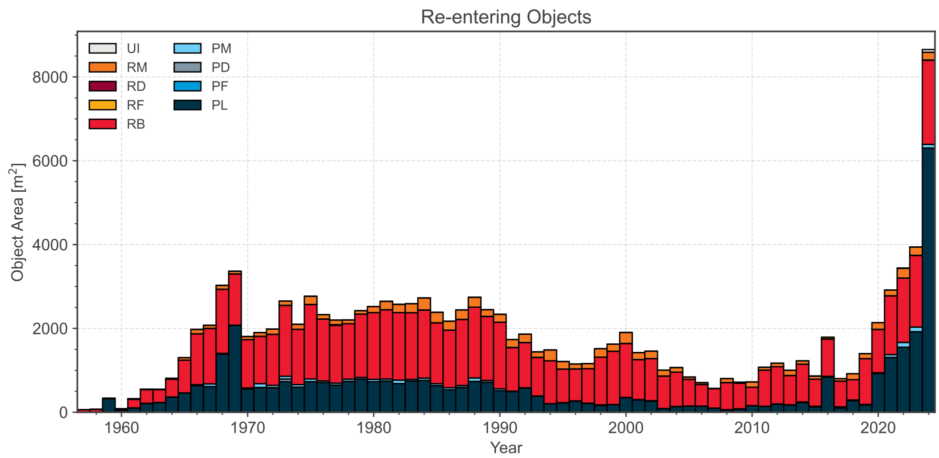
2.9. Objects Removed from the Space Environment



(a) Evolution of re-entered numbers.

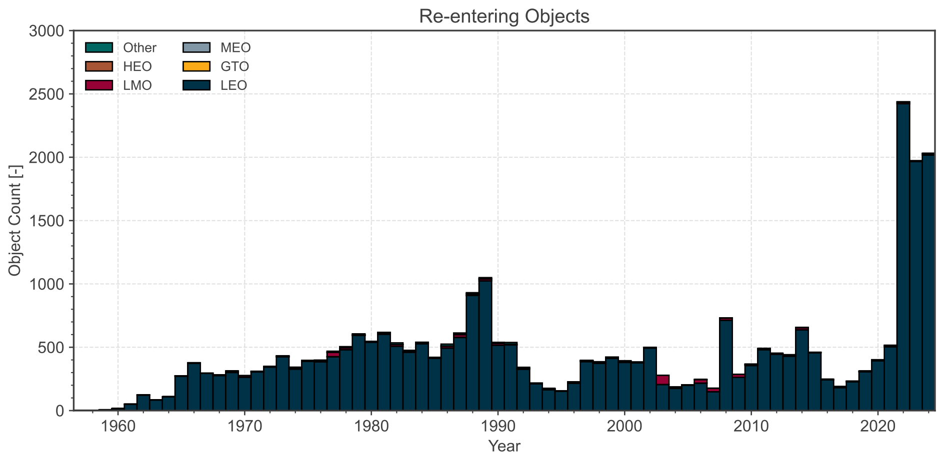


(b) Evolution of re-entered mass.

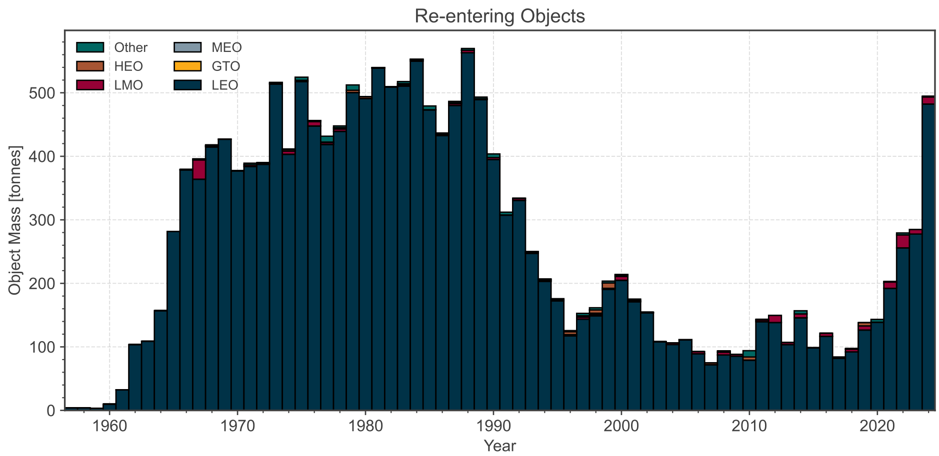


(c) Evolution of re-entered area.

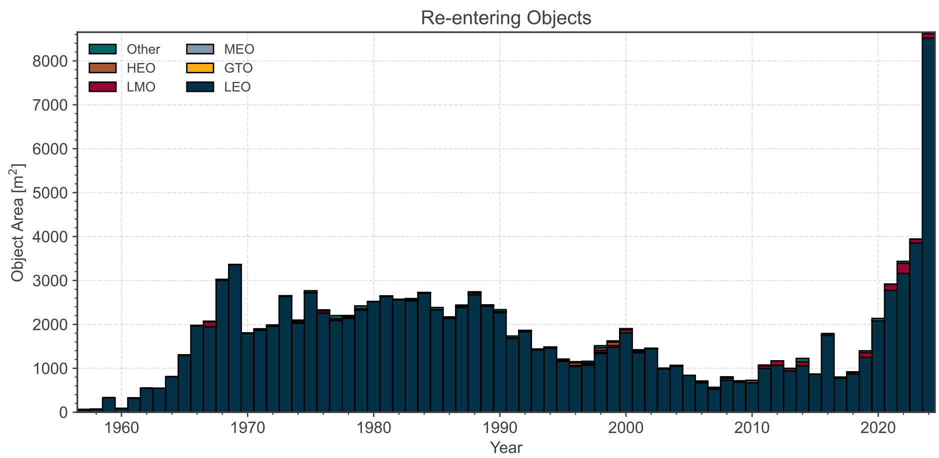
Figure 2.34: Evolution of re-entering objects in each year by object type without human spaceflight.



(a) Evolution of re-entered numbers.

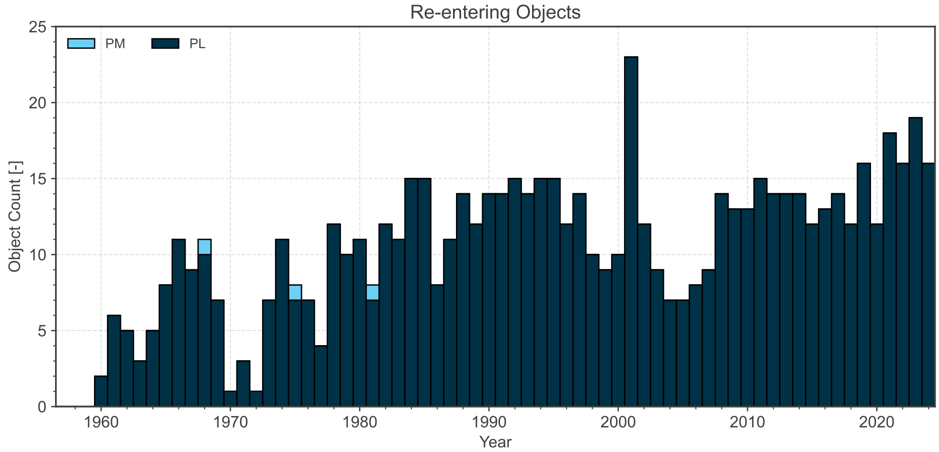


(b) Evolution of re-entered mass.

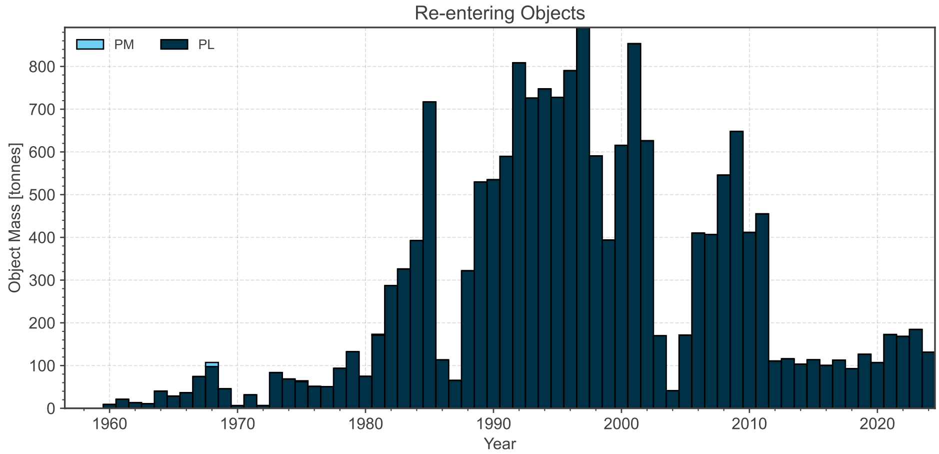


(c) Evolution of re-entered area.

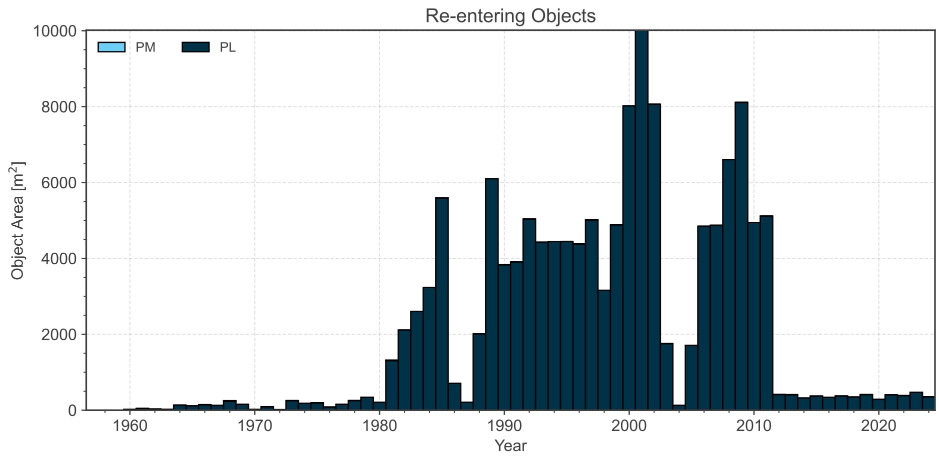
Figure 2.35: Evolution of re-entering objects in each year by orbit type without human spaceflight.



(a) Evolution of re-entered numbers.

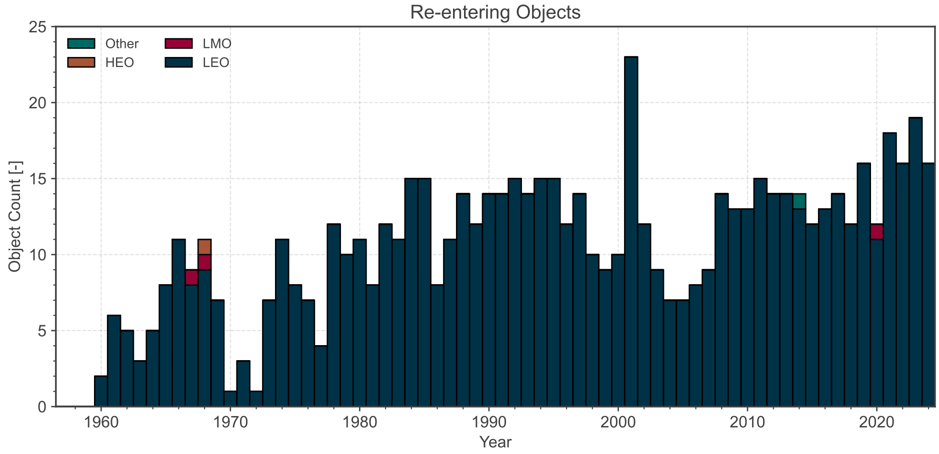


(b) Evolution of re-entered mass.

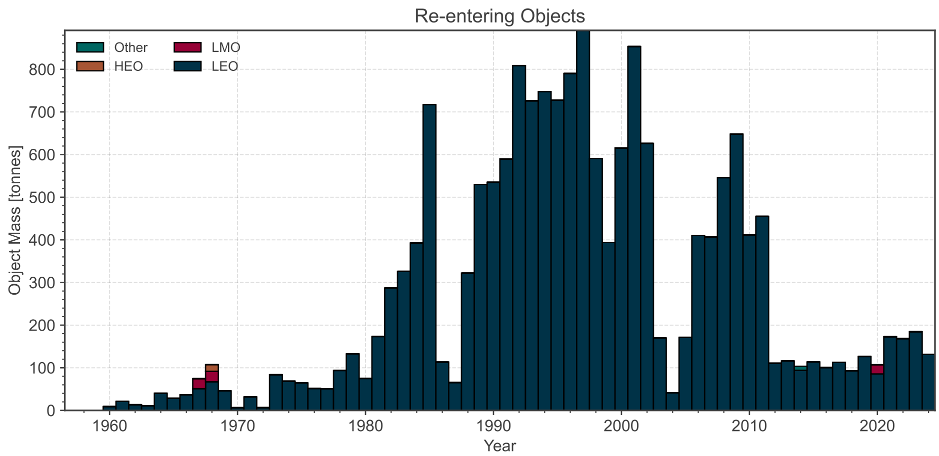


(c) Evolution of re-entered area.

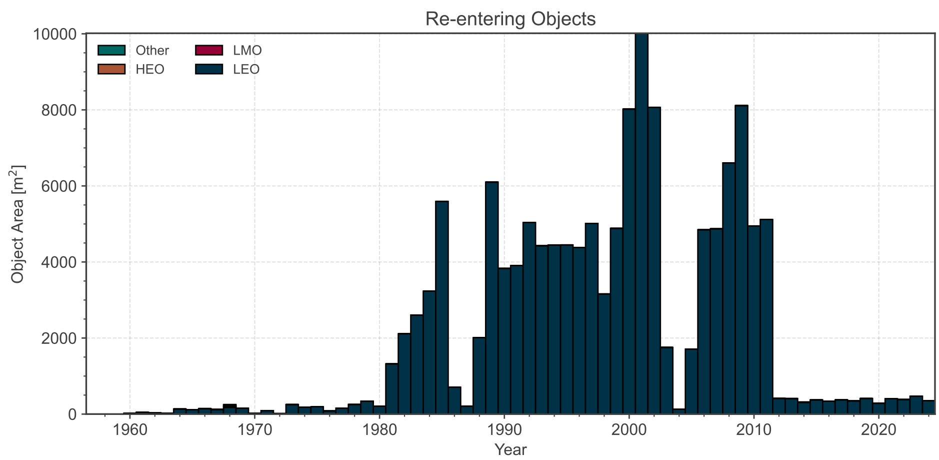
Figure 2.36: Evolution of re-entering human spaceflight objects in each year by object type.



(a) Evolution of re-entered numbers.

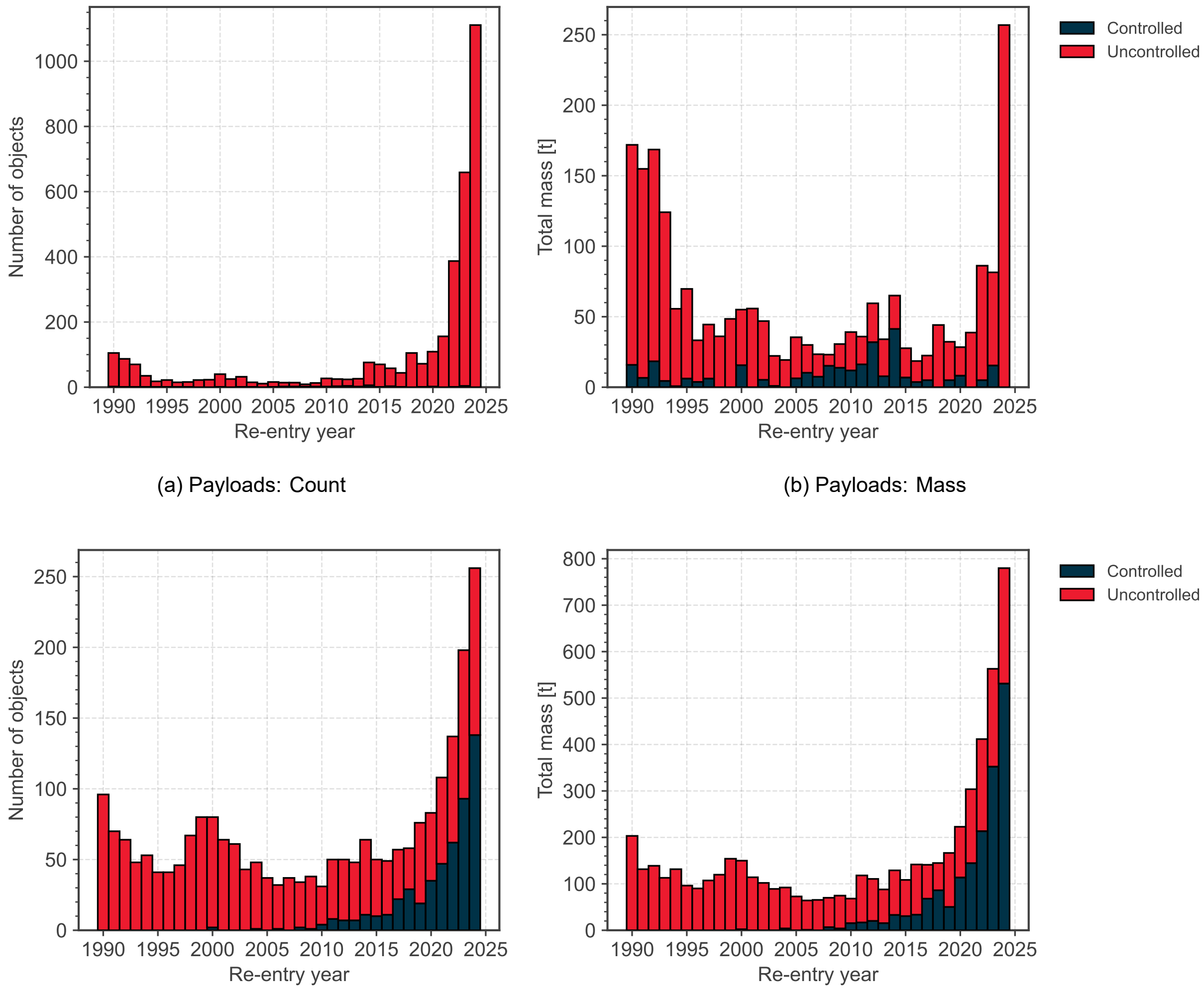


(b) Evolution of re-entered mass.



(c) Evolution of re-entered area.

Figure 2.37: 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 2.38: 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 1980s 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 82 objects related to NPSs known to have entered Earth orbit, out of which 7 are asserted but not catalogued. A total of 7 out of those 82 have re-entered, and the orbital distribution on the remainder is presented in Figure 2.39.

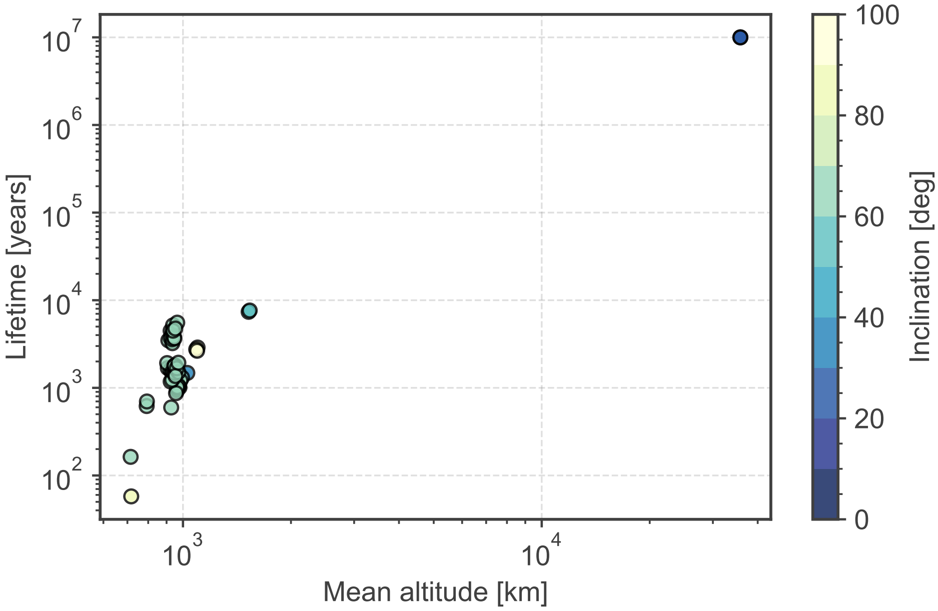


Figure 2.39: Distribution of space objects with nuclear power sources with mean altitude, orbital lifetime, and inclination.

2.11. Registration of Objects Launched in Outer Space

The United Nations Register of Objects Launched into Outer Space [15] and its implementation was established as consequence of the Convention on Registration of Objects Launched into Outer Space [16]. 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.

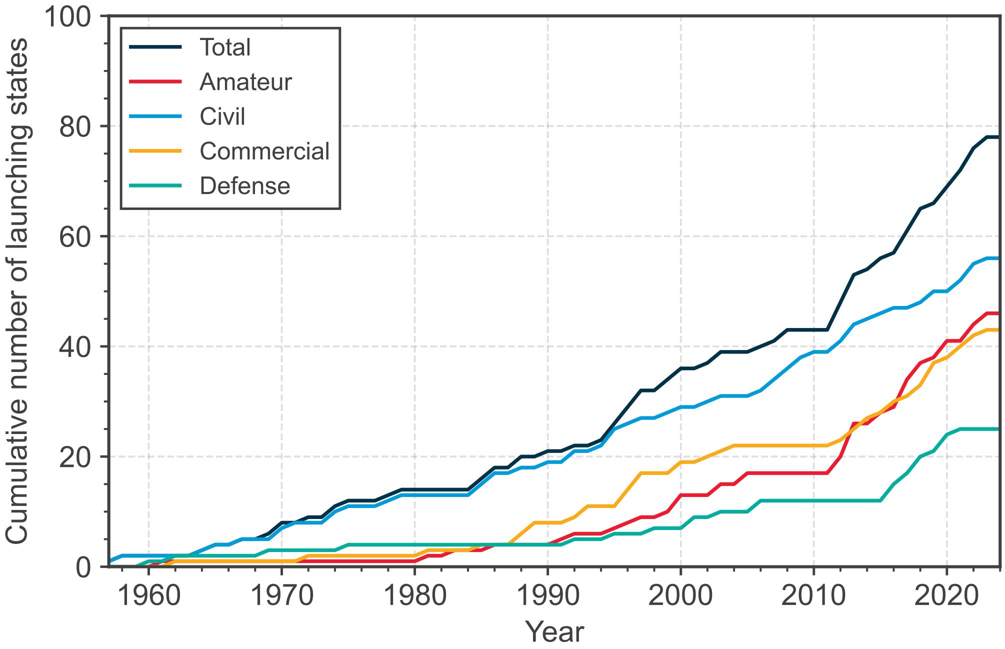


Figure 2.40: Launching states with at least one registered space object over time by category.

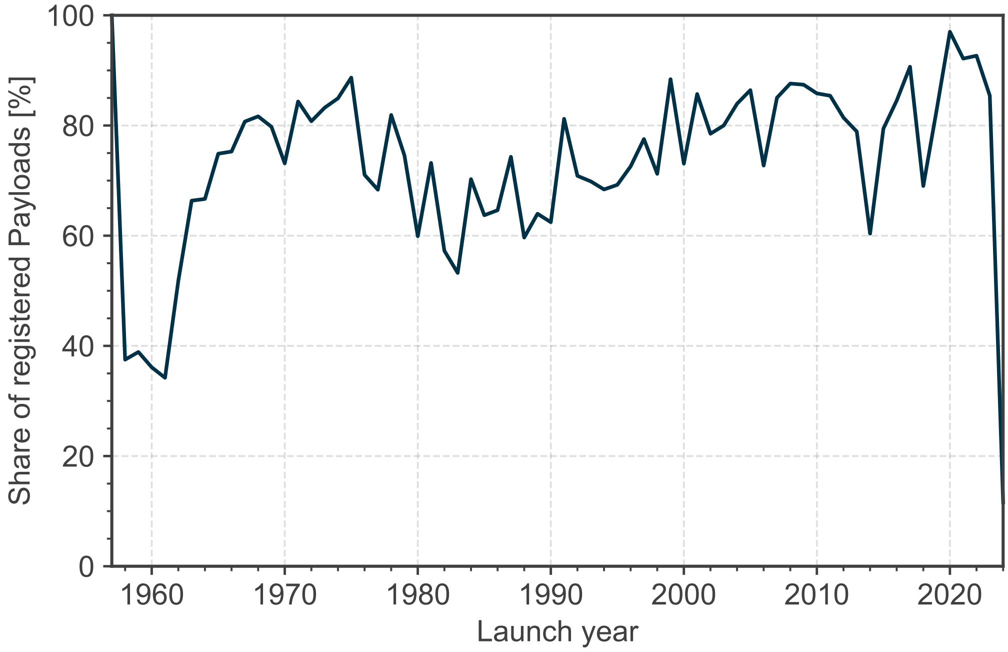


Figure 2.41: Share of registered payloads over the total of launched payloads by launch year.

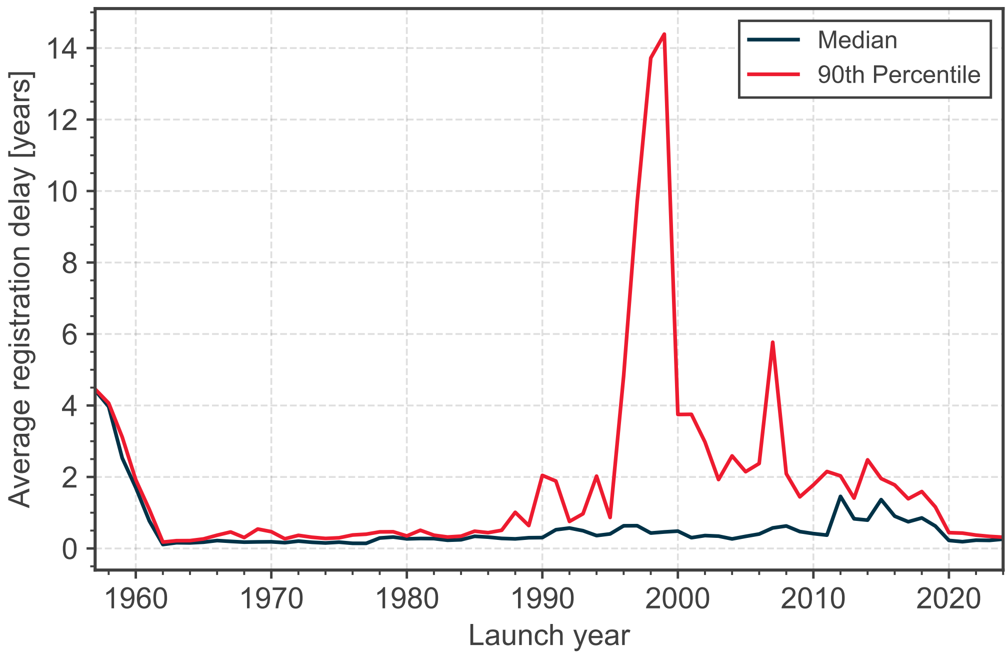


Figure 2.42: Delay between launch and registration by launch year.