4. INTENTIONAL OBJECT RELEASE

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

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

4.1. Mission Related Objects

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

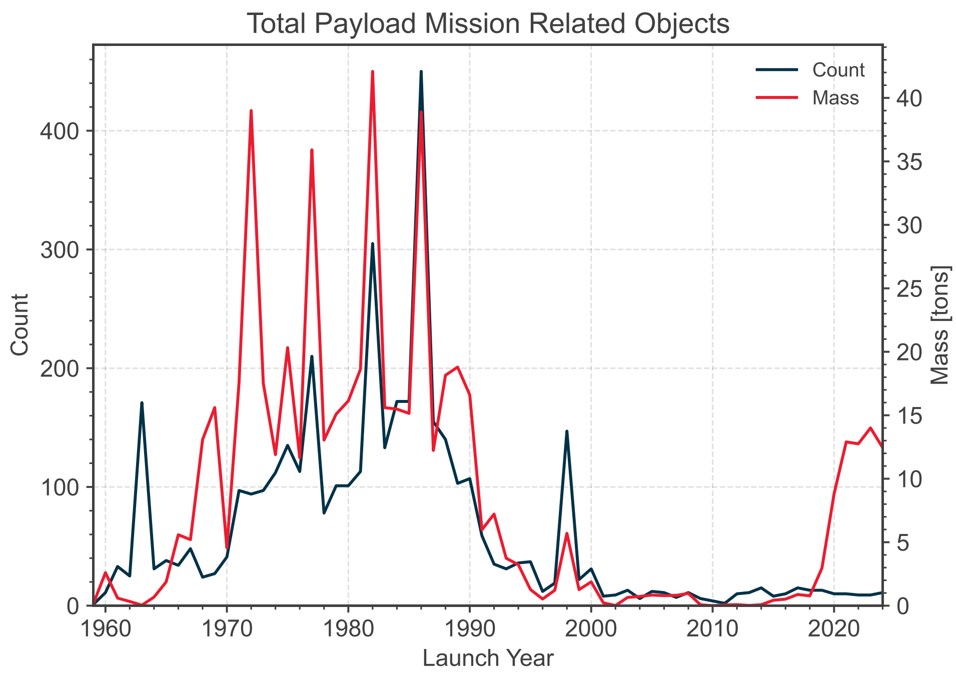


Figure 4.1: Total number and mass of catalogued mission related objects released from payloads.

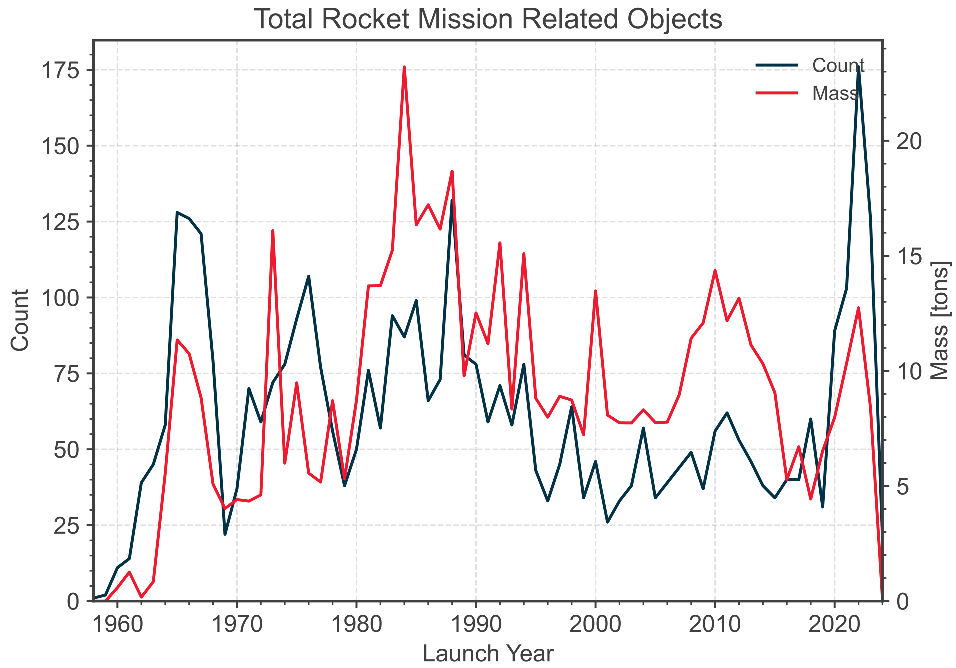


Figure 4.2: Total number and mass of catalogued mission related objects released from rocket bodies.

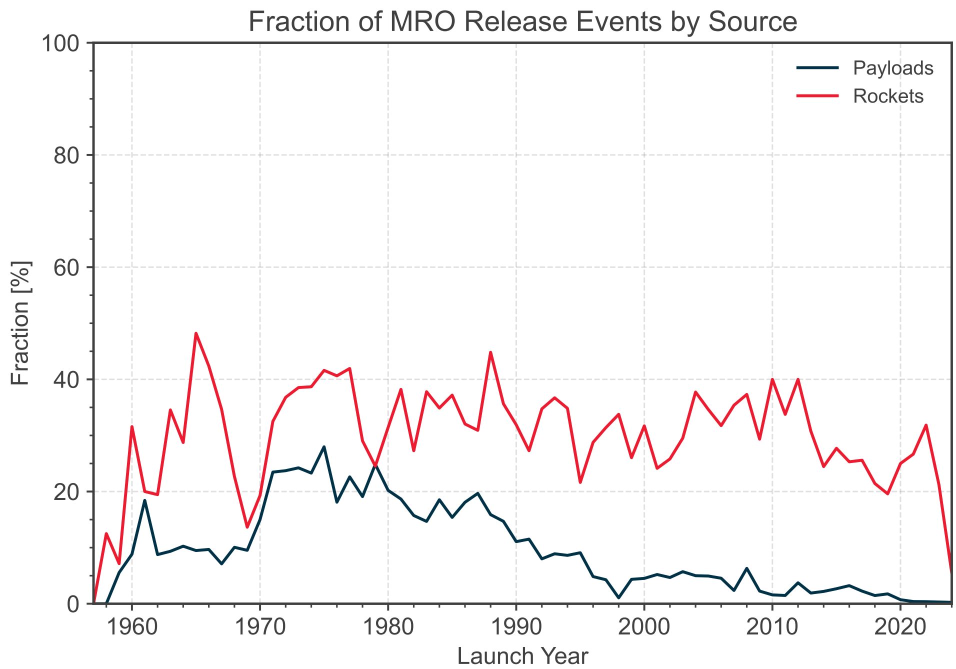


Figure 4.3: Fraction of mission related objects releases per year w.r.t. the total amount of payloads and rocket bodies injected into the space environment during that year.

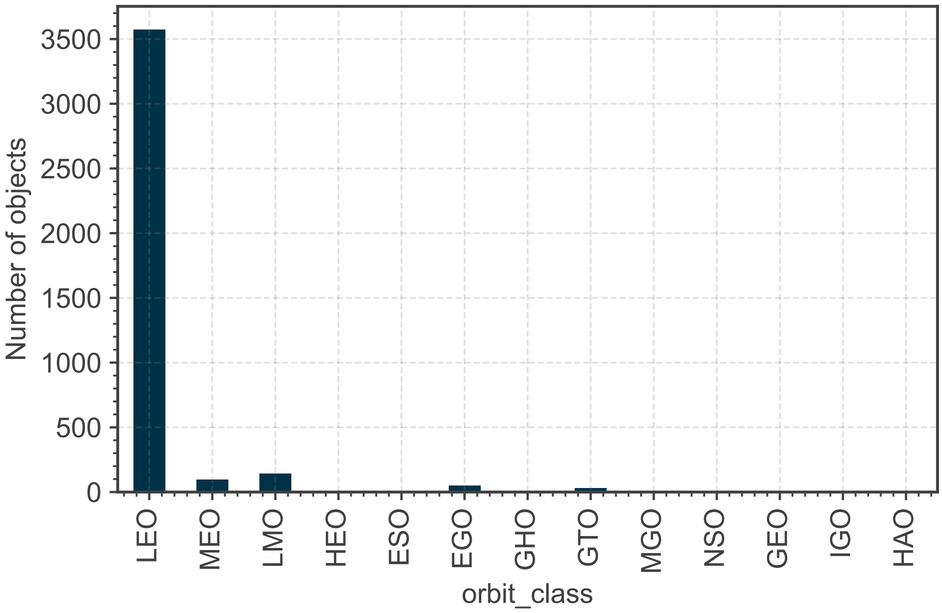


Figure 4.4: Distribution of release orbits for Payload Mission Related Objects since the start of the space age.

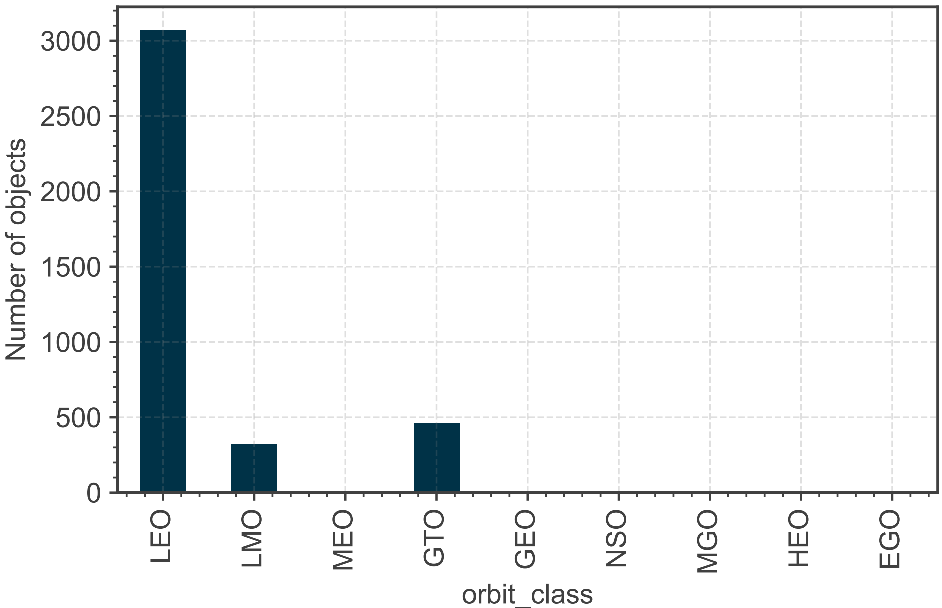


Figure 4.5: Distribution of release orbits for Rocket Body Mission Related Objects since the start of the space age.

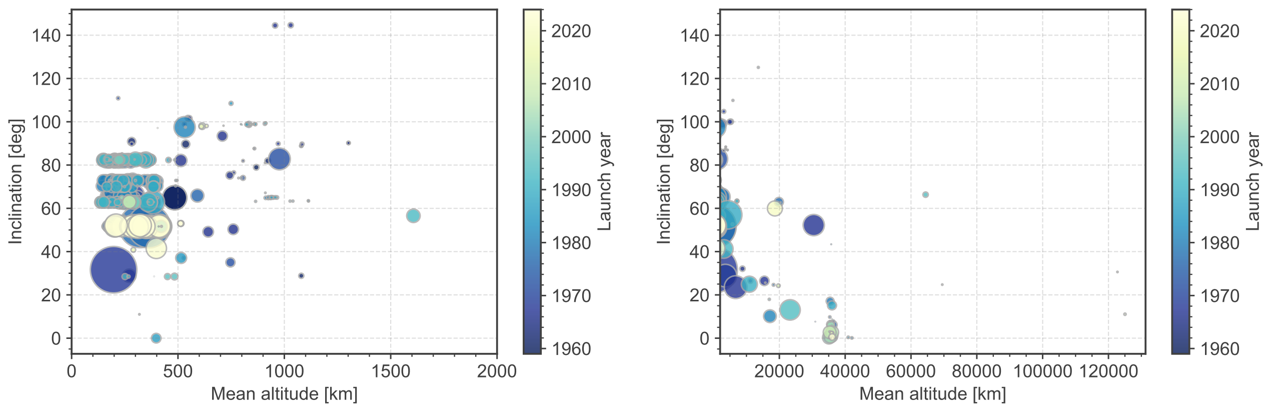


Figure 4.6: Distribution of release orbits for Payload Mission Related Objects in LEO (left) and outside LEO (right). The size of the marker is proportional to the object mass.

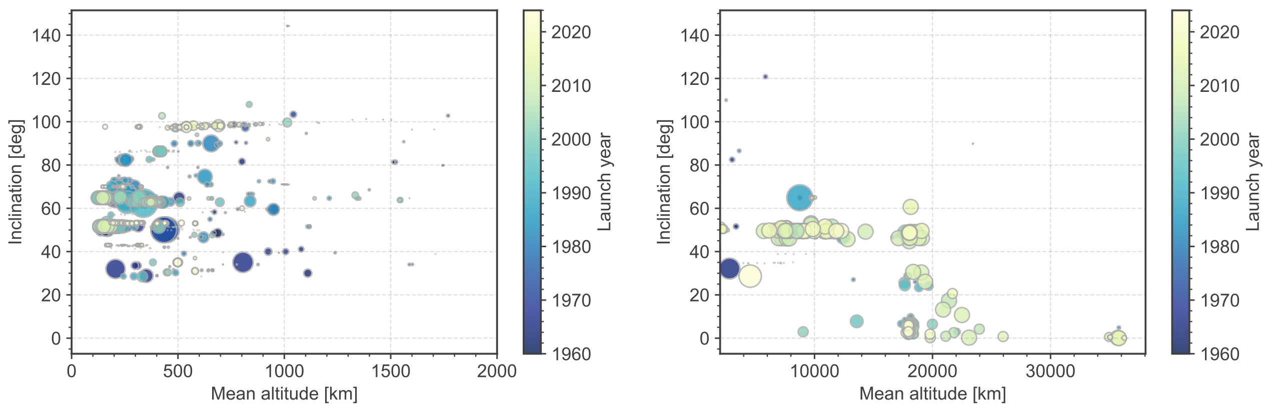


Figure 4.7: Distribution of release orbits for Rocket Body Mission Related Objects in LEO (left) and outside LEO (right). The size of the marker is proportional to the object mass.

4.2. Solid Rocket Motor Firings

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

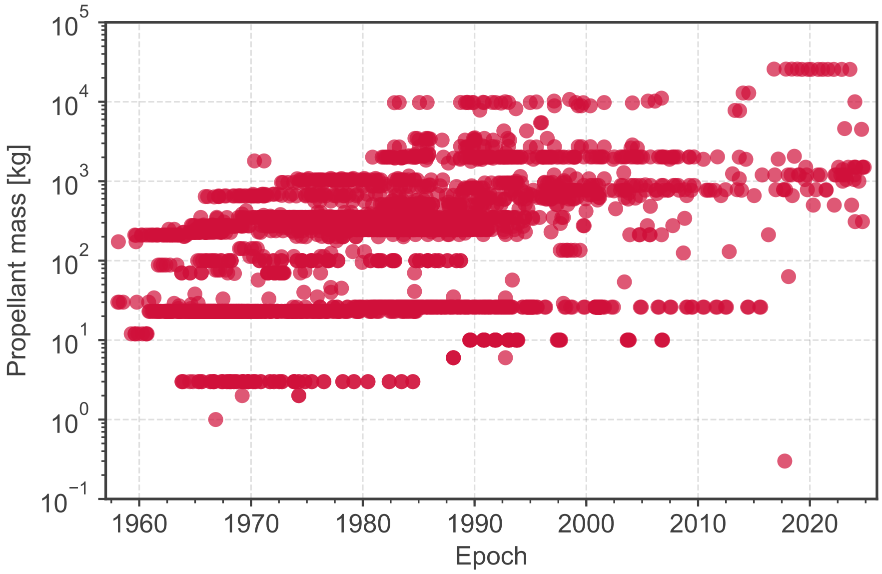


Figure 4.8: Evolution solid rocket motor firings.

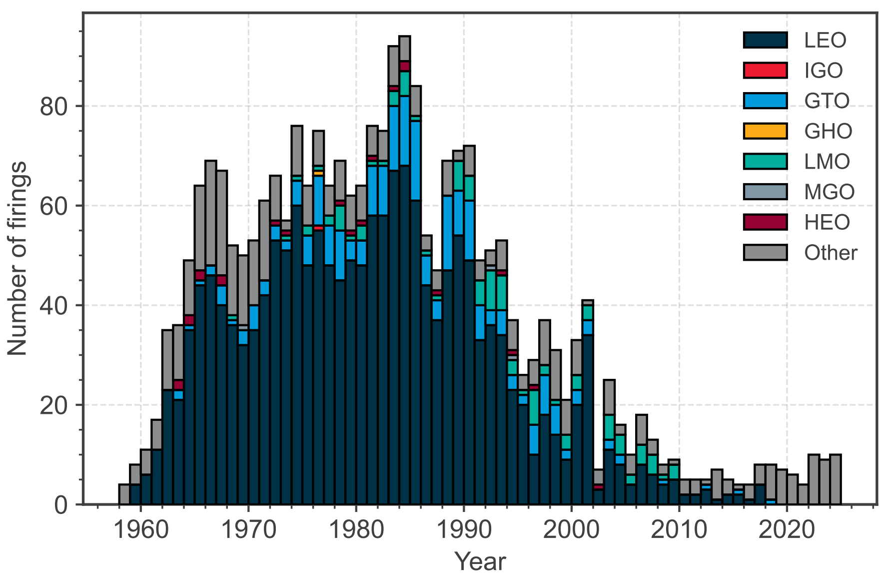


Figure 4.9: Evolution solid rocket motor firings by orbit type.

5. FRAGMENTATION HISTORY

Since the beginning of the space age until the end of 2024, there have been 656 confirmed on-orbit fragmentation events. In Fig. 5.2, the historical trend of the amount of fragmentation events per year is shown, as a function of the event date and the launch date, respectively. Fragmentation events are currently being categorised in main and sub-classes according to the assessed break-up cause. In the first list of classes, the break-up cause is fairly well known:

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

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

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

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

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

Deliberate: All intentional breakup events.

ASAT: Anti-satellite tests.

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

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

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

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

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

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

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

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

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

CZ-6A Upper Stage: The second stage of the Long March (CZ) 6A launcher (L-15 YF-115). Energic break-up events soon after launch assumed to be Propulsion related.

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

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

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

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

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

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

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

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

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

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

Meteor Class: Russian meteorological satellite family.

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

TOPAZ Leakage Class: There are two known events for TOPAZ satellites where NaK droplets have been observed in the vicinity of the parent object presumably due to leakage [22].

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

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

Assumed: Introduced for the MASTER model. Currently the only assumed events are in the GEO region, backed by information obtained during survey campaigns [23].

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

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

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

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

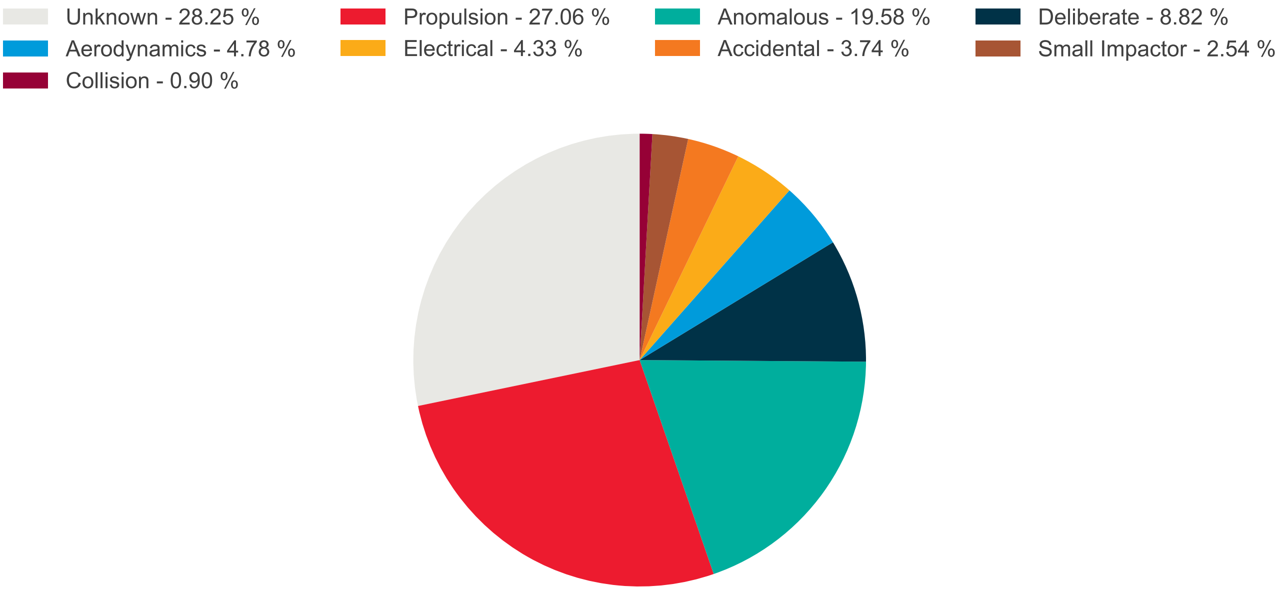
L-14B Class: The third stage of the Long March 4B (CZ-4B) launcher used a hypergolic propellant.

5.1. All fragmentation events

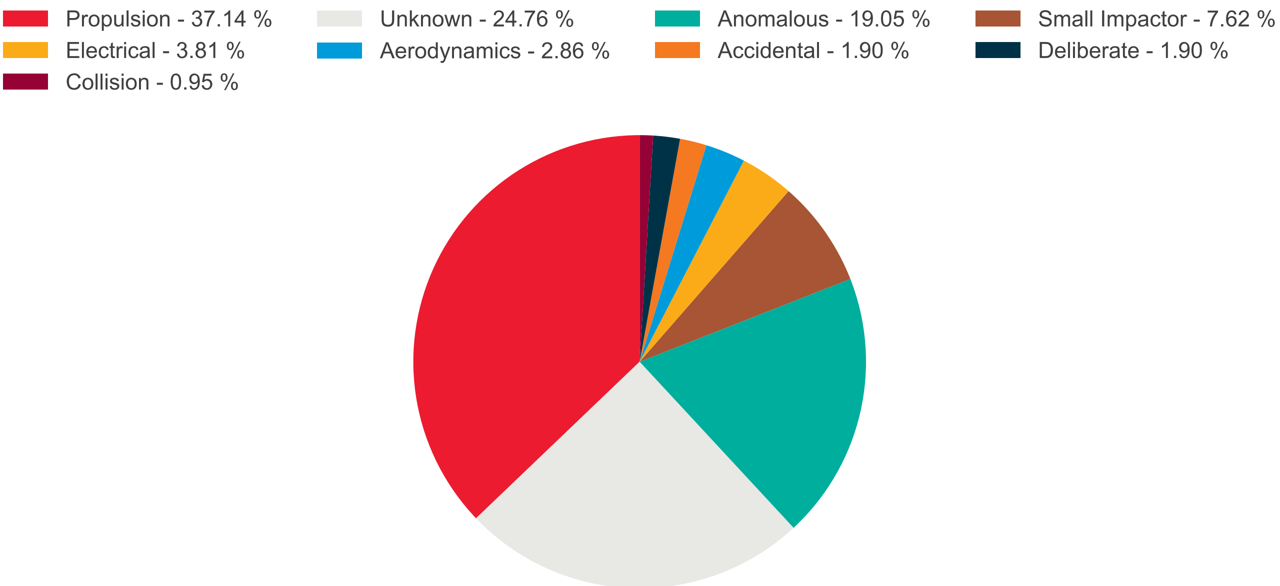
A summary of the statistics on the recorded fragmentation events is reported in Table 5.1, where *Assumed* and *Unconfirmed* were excluded from the aggregation. A breakdown of the observed fragmentation events grouped by the main classes in terms of frequency and resulting catalogued debris is given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

Table 5.1: Statistics on fragmentation events.

	All history	**Last 20 years**
Number of events	656	220
Non-deliberate events per year	9.4	10.5
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 10 years	2.4	1.7
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 25 years	1.7	1.3
Mean time (years) between launch and fragmentation	5.7	10.3
Median time (years) between launch and fragmentation	1.0	6.6

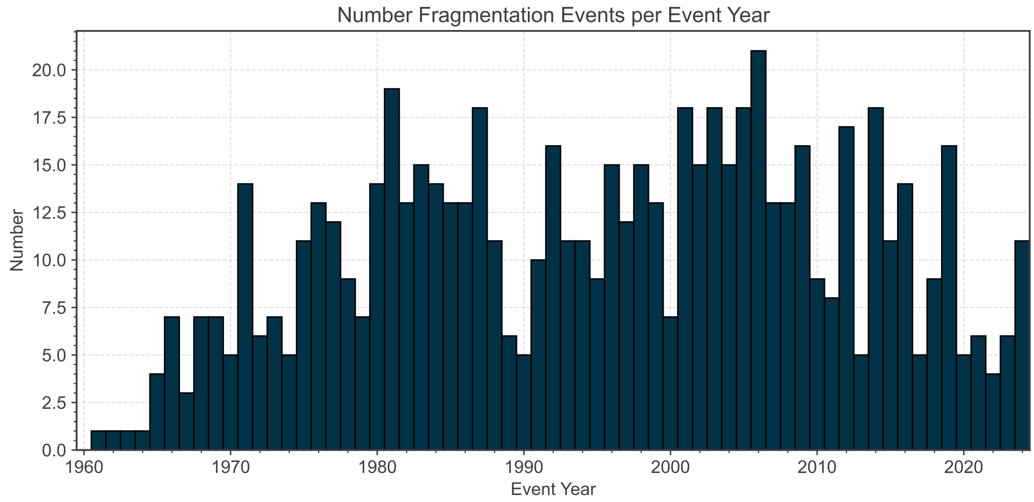


(a) Whole history.

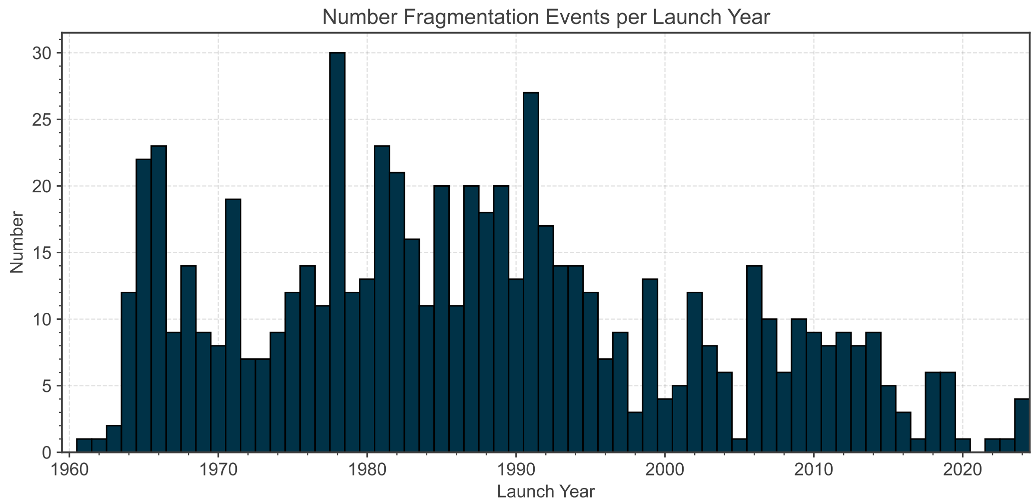


(b) Last 10 years.

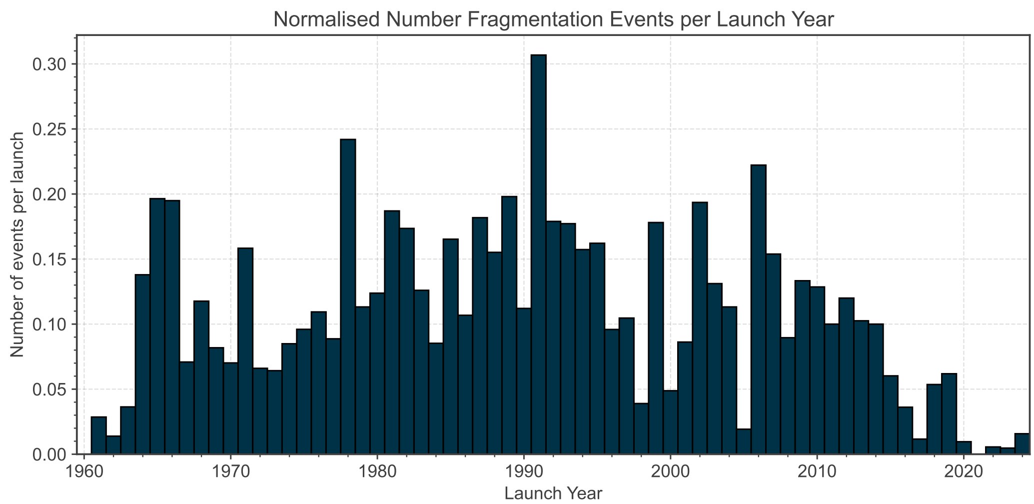
Figure 5.1: Event causes and their relative share for all past fragmentation events.



(a) Number of fragmentation events per event year.

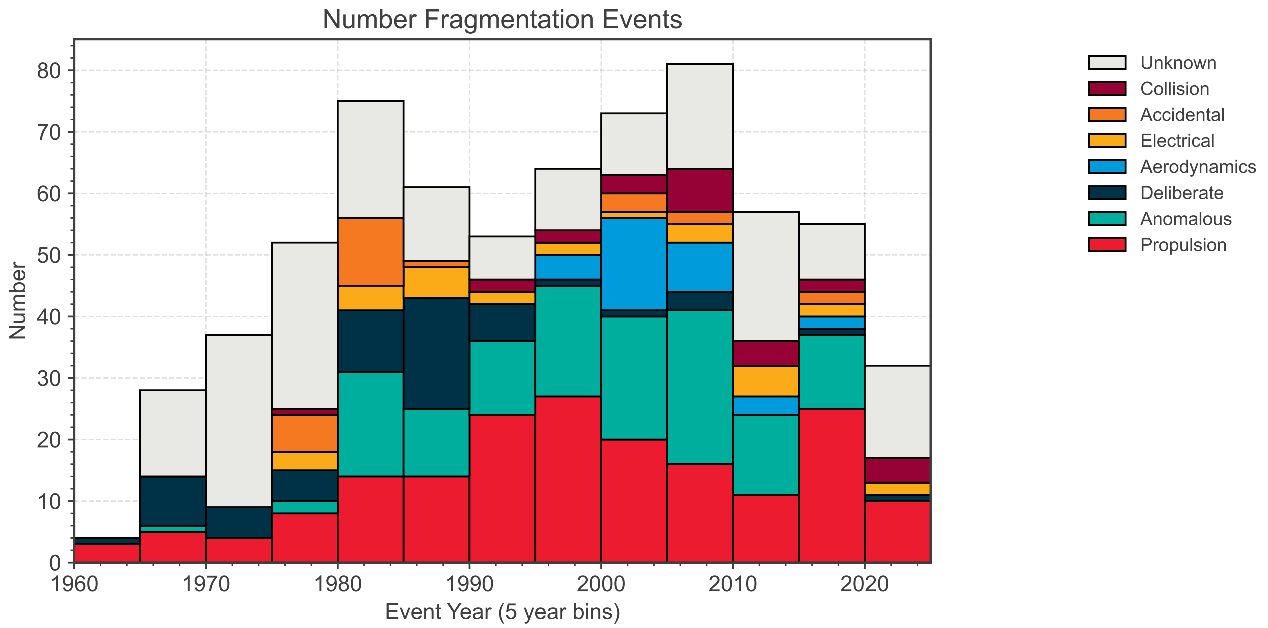


(b) Number of fragmentation events per launch year.

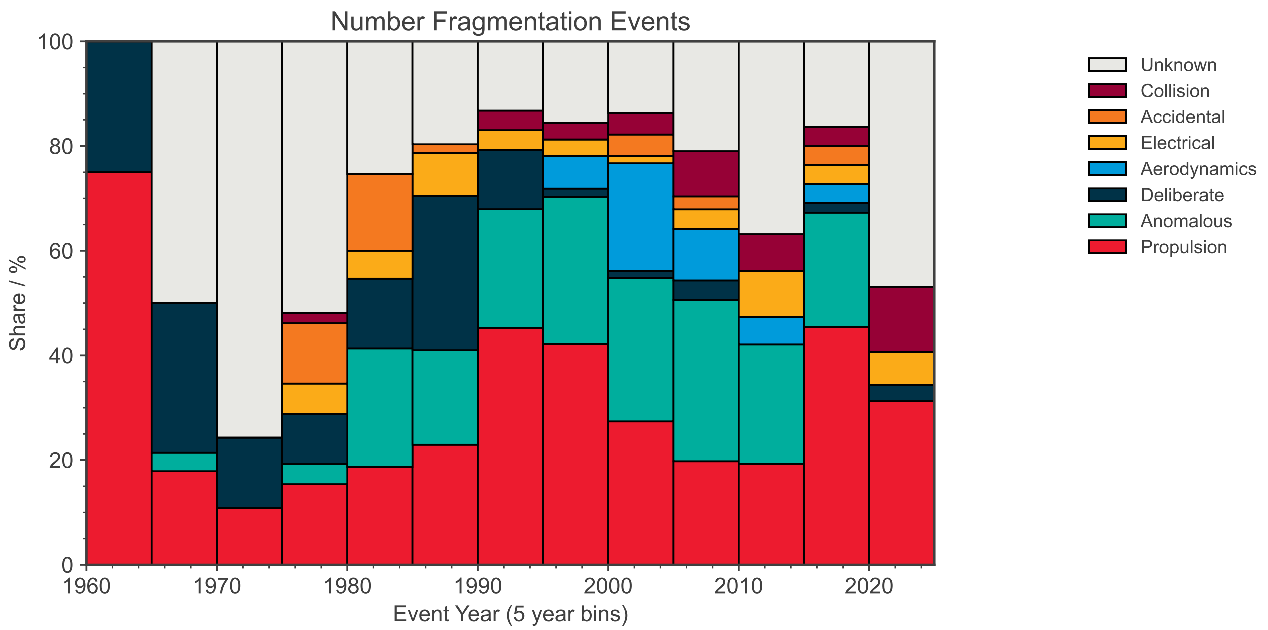


(c) Number of fragmentation events per launch year normalised by the number of launches in that year.

Figure 5.2: Historical trend of fragmentation events.

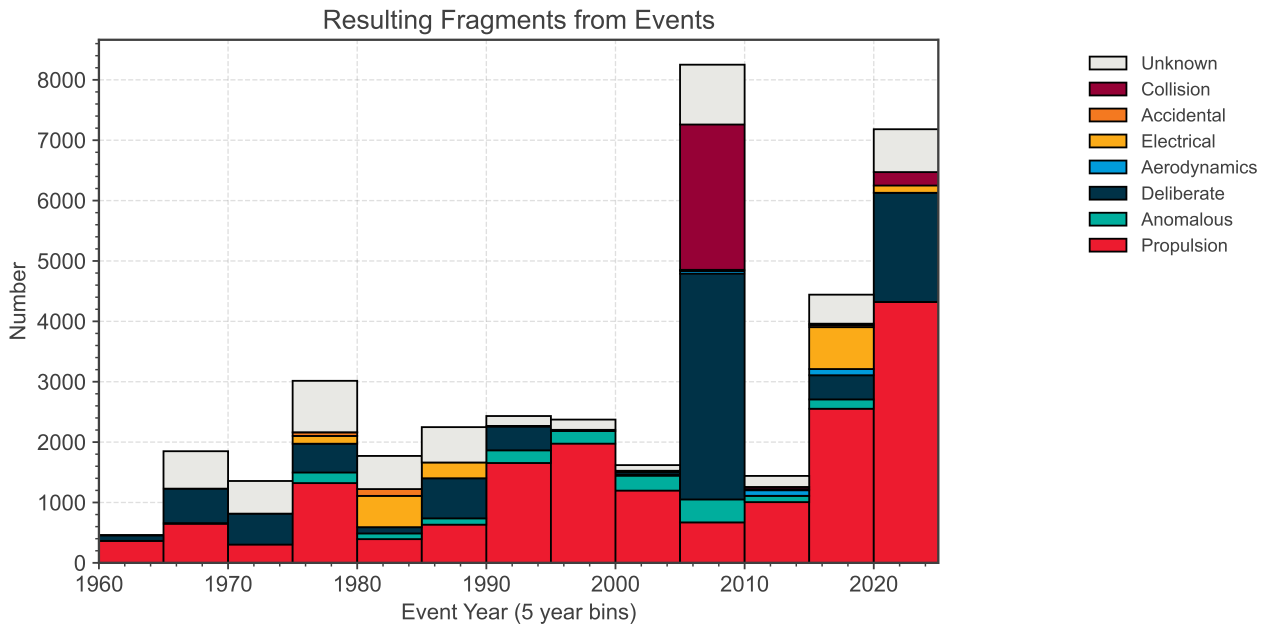


(a) Absolute number of fragmentation events per event cause.

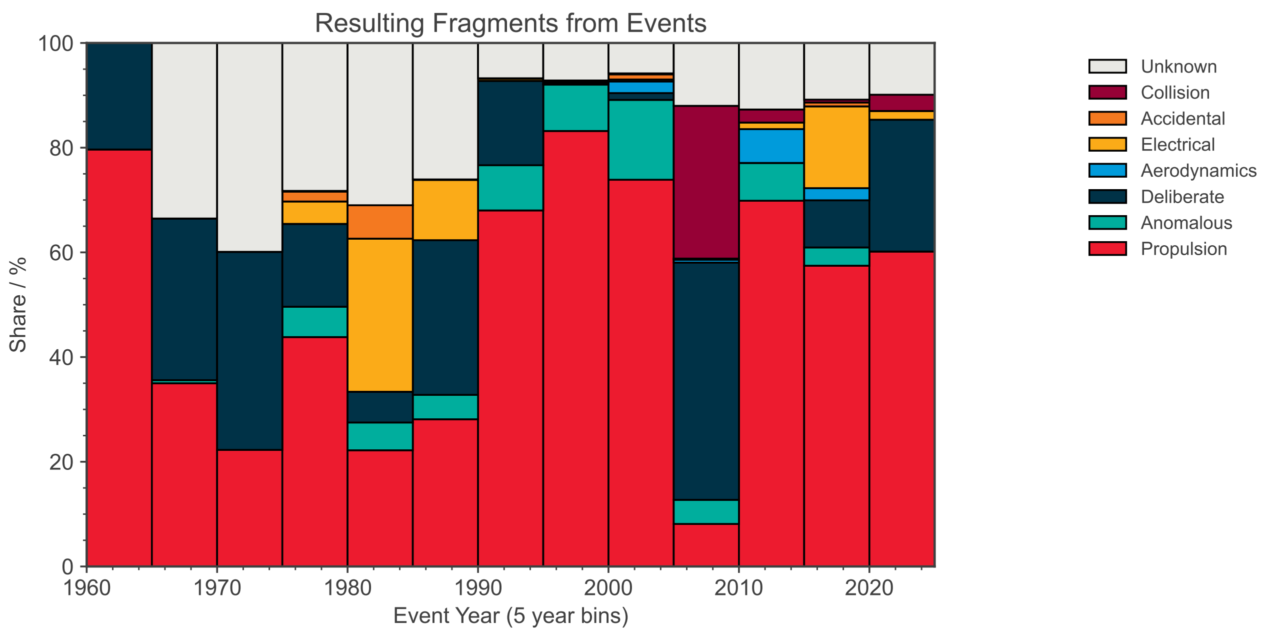


(b) Relative number of fragmentation events per event cause.

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



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



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

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

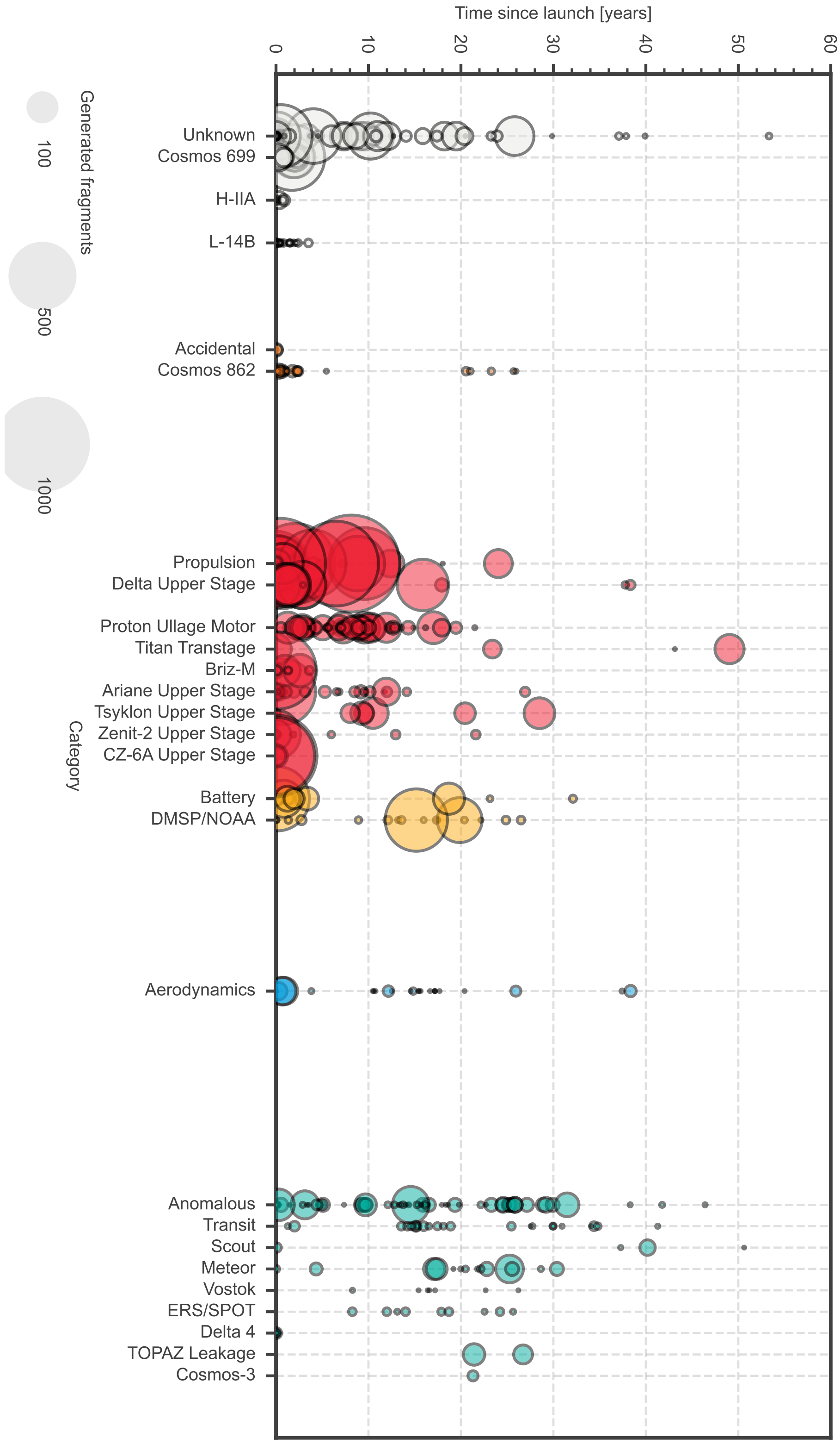


Figure 5.5: Elapsed time between fragmentation and launch by category. The bubble size indicates the number of generated fragments.

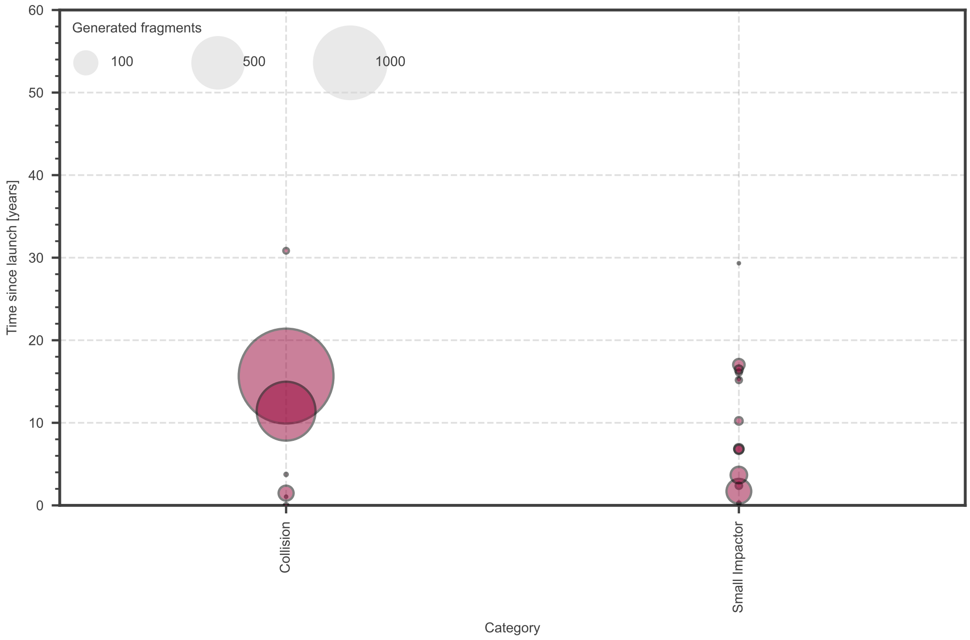


Figure 5.6: Elapsed time between fragmentation and launch for collision events. The bubble size indicates the number of generated fragments.

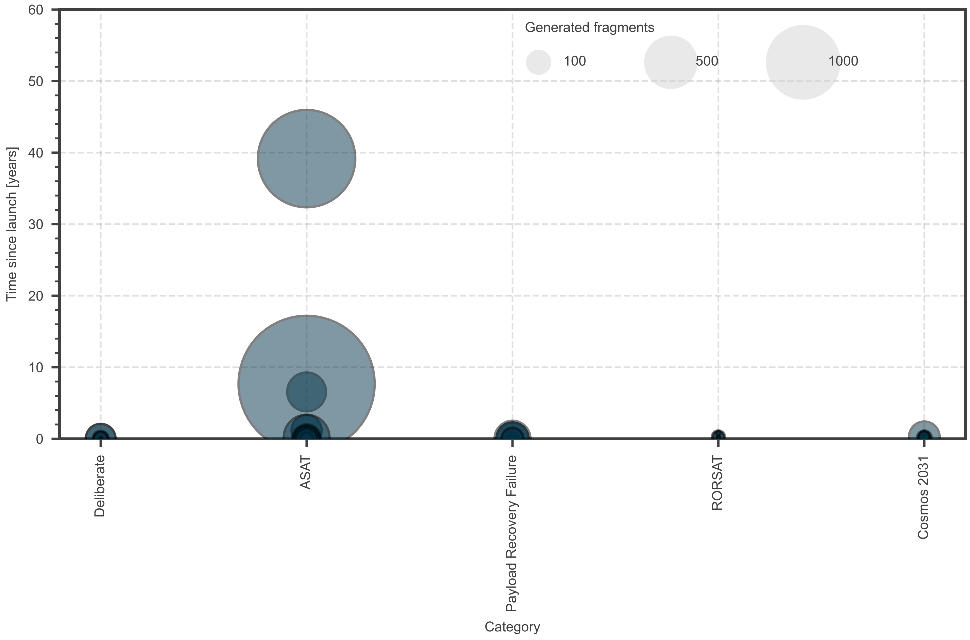


Figure 5.7: Elapsed time between fragmentation and launch for deliberate events. The bubble size indicates the number of generated fragments.

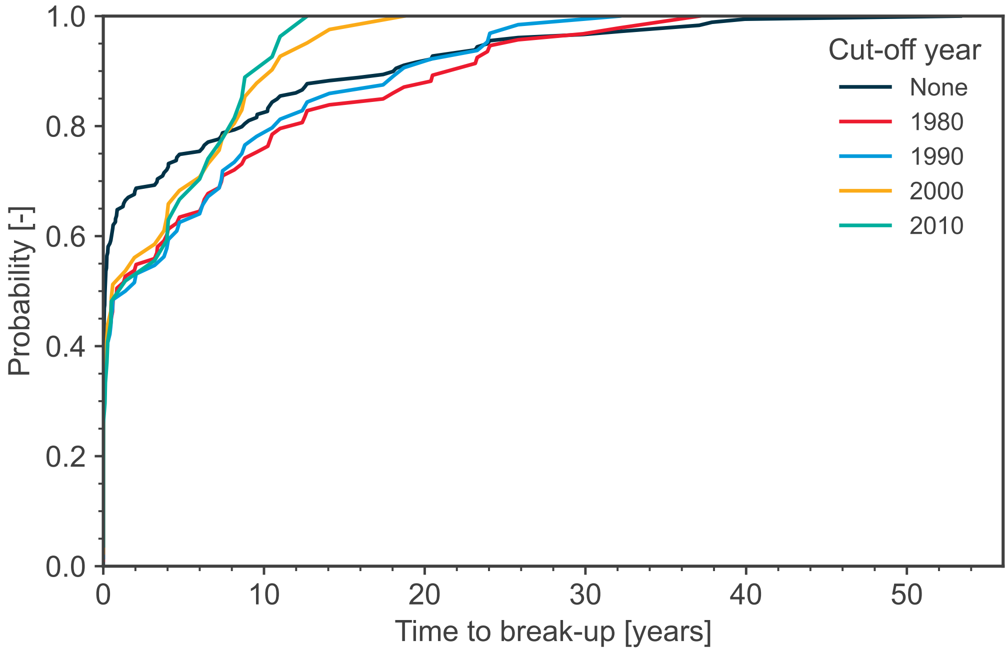


Figure 5.8: Cumulative distribution function (CDF) for the elapsed time between fragmentation and launch for non-system related fragmentation events, with different cut-off values on the launch year.

5.2. Non-system related fragmentation events

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

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

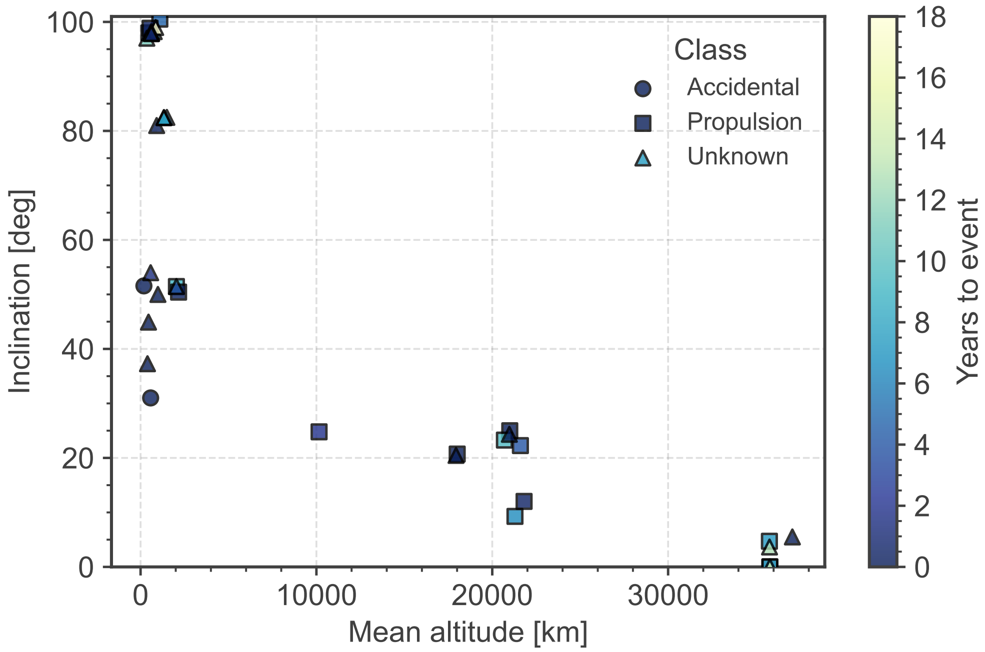


Figure 5.9: Distribution of non-system related fragmentation events in mean altitude, inclination, and time to fragmentation.

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

	All history	Last 18 years
Number of events	177	52
Non-deliberate events per year	2.7	2.7
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 10 years	0.7	0.4
Yearly rate of events where 50% of the generated fragments have a lifetime of greater than 25 years	0.5	0.3
Mean time (years) between launch and fragmentation	5.6	10.3
Median time (years) between launch and fragmentation	1.3	5.2