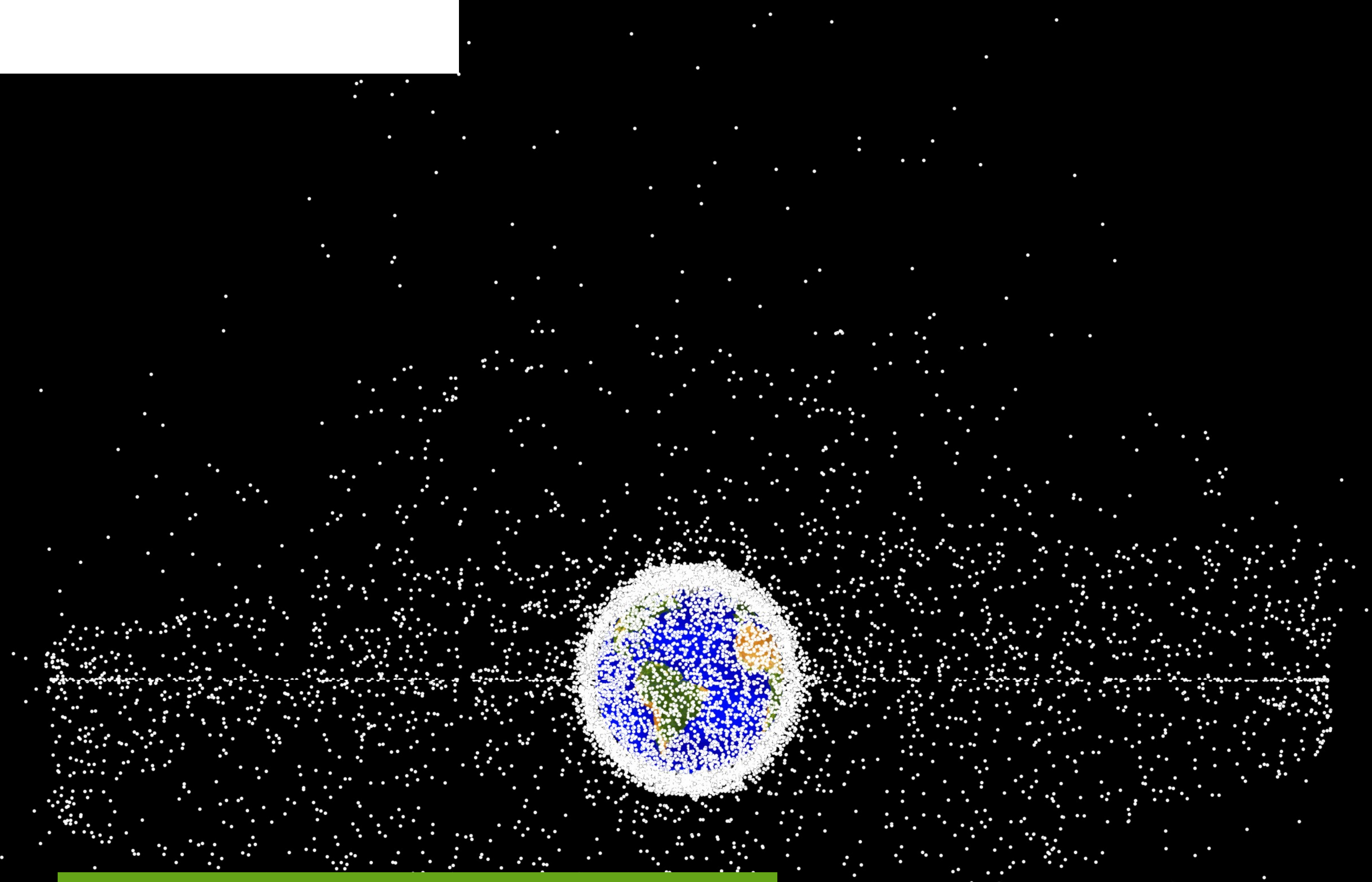

Technical Study
Space Debris

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on behalf of all HDI Global Specialty offices

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Introduction

This study by HDI Global Specialty SE presents the current state of knowledge surrounding space debris. Most insurers in the space market today provide cover for damage to satellites and other spacecraft due to collision with debris. However as this risk is expected to increase in future, space debris is a subject of growing concern for operators and insurers alike.

The space in which most satellites orbit the Earth is shared not only by a growing number of active satellites, but also millions of individual pieces of space debris. This debris ranges in size from defunct satellites and rocket bodies weighing several tonnes each, to waste product particles and components on the millimetre scale.

Each of these objects is orbiting Earth at high velocity, and poses a hazard to active spacecraft and the future use of Earth orbits. Collisions between active spacecraft and debris are known to have occurred, and this issue is set to become a greater risk over the coming decades as the number of objects increases.

The study is arranged over five sections as follows:

- **Section I** discusses how debris is classified and distributed according to size, altitude, and other metrics.
- **Section II** describes some of the models used by space organisations to simulate the space debris population, and their projections of its future growth.
- **Section III** presents several examples of major debris-creating events, and other events involving the collision of debris with active satellites.
- **Section IV** describes the various responses to space debris, including mitigation and remediation activities such as Post Mission Disposal and Active Debris Removal.
- **Section V** reviews the present insurance standpoint including first-party insurance and Third-Party Liability.

A summary of the key points raised in each section is given before the conclusion.

Image credit: University of Colorado Boulder

Introduction continued

Why is space debris an issue?

Access to space is becoming an ever more crucial aspect of modern civilisation; from the need to provide global communication and navigation services, entertainment, and Earth observation. As more satellites are launched to support these and numerous other activities, the chances of a collision with the existing space debris population increases. Given that any collision in space is detrimental or even catastrophic to the satellite(s) involved, the risk is not only damage to the satellite itself as shown in Figure 1, but also loss of the data and services that it provides.

Risk to current space activity

There are currently well over one million objects of debris 1 cm or greater in diameter in Earth orbit. It is pertinent to note from the offset that popular culture has exaggerated the risks of collisions in space through films, articles, and graphics. Some in the space community have referred to the collision hazard as a crisis, while others have dramatised the issue producing graphics that show the Earth as a ‘fuzzy marble’ obscured by a dense cloud of dots representing space debris [3]. These representations should be interpreted with an understanding that the dots have been scaled-up to make them more visible, as shown in Figure 2. In reality, objects are more widely separated than they appear in these representations, which reflect the *relative* rather than the *absolute* density of objects.

While the risk to any one satellite today remains low relative to other risks such as the launch, hardware failure, and manufacturing defects; space debris is a risk taken seriously by the majority of spacecraft manufacturers, operators, and insurers. This risk is clearly demonstrated by

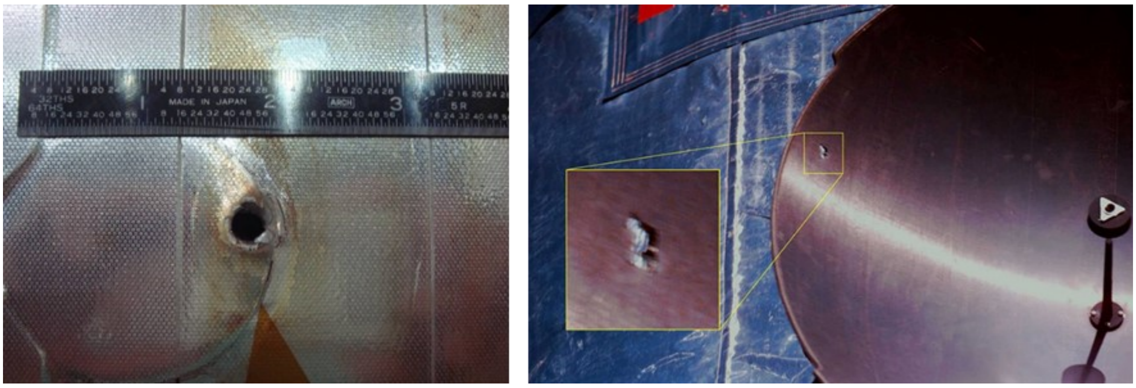

Figure 1 – Images showing damage caused by collisions with space debris: impact on radiator of Space Shuttle Endeavour during STS-118 (left) [1], an impact that penetrated the antenna dish of the Hubble Space Telescope (right) [2].

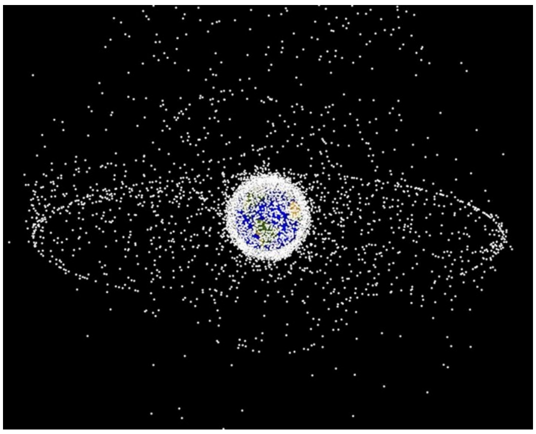

Figure 2 – Objects in Earth orbit that were being tracked as of 2019. Approximately 95% of these objects are space debris i.e. not functional satellites. Although the dots do not reflect the absolute density of objects, they provide a visualisation of where the greatest orbital debris populations exist [2].

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a number of notable incidents that have occurred within the last 20 years. Notably there have been several events that have dramatically increased the space debris population (including one most recently in 2021), and several cases of active satellites being hit by space debris. The International Space Station (ISS) has seen a significant increase in debris avoidance manoeuvres, with seventeen manoeuvres taking place between 2009 and 2017, compared to eight manoeuvres in the 1999-2008 timeframe [4].

Risk to future space activity

It is the risk space debris poses to future space activity that is of greatest concern. There is a clear upward trend in the number of space debris objects in orbit (see Figure 3), and therefore an increase in the density of the debris 'cloud' surrounding the Earth. Various models show this trend continuing at different rates depending on the approach towards prevention, mitigation, and remediation taken by spacefaring nations. In addition, there are many *massive derelicts* (large inactive objects) in orbit that could cause a rapid spike in the space debris population if they were to be involved in a collision.

Notably the space debris population would continue increasing even if no more satellites were put into orbit, since collisions between the existing debris will continue to occur [6]. However the space industry has put more satellites into orbit within the last five years than at any other time in history. The main driver behind this is the deployment since 2019 of 'mega' constellations such as *Starlink* and *OneWeb*. These constellations could double or even triple the number of operational satellites in orbit within the next five years [4]. The implication is that as the space surrounding the planet becomes more crowded, collisions become more likely. In addition, every collision will generate many more items of debris, increasing the possibility of future collisions still further.

Taken to its ultimate end state, the *Kessler syndrome* proposed by Donald Kessler in 1978 describes a runaway effect in which collisions

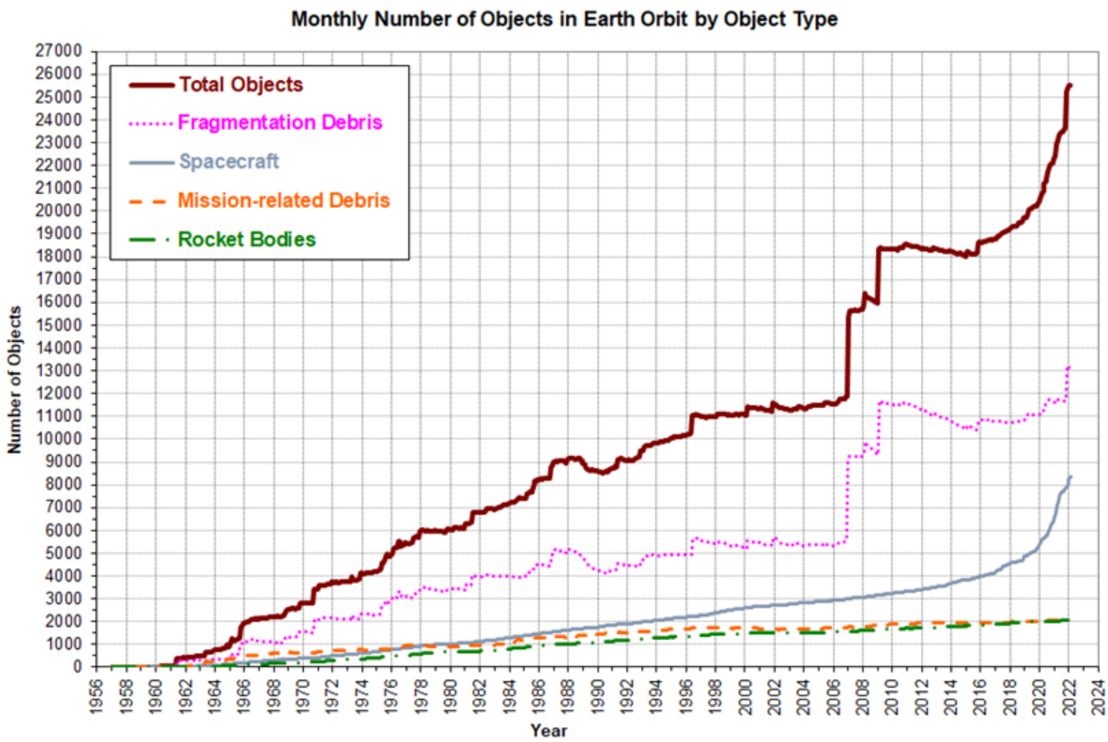


Figure 3 – Chart showing the trend in growth of the number of objects >10 cm in LEO, as catalogued by the U.S. Space Surveillance Network. Credit: NASA ODPO [5], 2022.

Introduction continued

between space debris cascade and render sections of space unusable [7]. While the tipping point at which this process comes into play has not yet been reached, many fear that we are headed in this direction. Access to space for the benefit of future generations depends on a stable orbital environment where debris does not prohibit the use of satellites and other space systems.

Sources of debris

Space debris is produced in a wide range of processes both deliberate and accidental. The sources of this debris are almost always either the launch vehicles (rockets) used to put spacecraft in space, or the spacecraft themselves once in orbit.

Sources of deliberate debris include:

- Objects released during separation of the spacecraft from the launch vehicle or during in-orbit commissioning.
  - Spring release mechanisms between spacecraft and launcher.
  - Debris from explosive bolts and pyrotechnic devices.
  - Large structural elements (dispensers) left in-orbit in the event of a multiple launch.
  - Hold-down mechanisms released during deployment of antennae, solar panels, and other appendages.
  - Protective covers from optical, attitude, and other sensor systems.
- Upper stage rocket bodies following spacecraft separation.
- All debris generated by the destruction of satellites in orbit via tests of Anti-Satellite weapons (ASAT).
- Spacecraft that have reached the end of their lives and subsequently left to deorbit naturally over a number of years.
- Small particles of Aluminium oxide (a waste product) from solid rocket motors.

Sources of accidental debris include:

- Damage to or destruction of satellites or rocket bodies in-orbit (referred to as fragmentation events).
  - Due to an unintended collision with either another spacecraft or existing debris.
  - Due to an unintended explosion (e.g. of the propellant tanks or batteries) or structural failure.
- Intact spacecraft that have suffered a failure in-orbit and consequently become inactive.
- Objects such as tools lost by astronauts during space walks (see Figure 4).

Collectively these sources of debris all contribute to the cloud of debris that now encircles the Earth. The next section of this study will discuss how this debris is classified and distributed by size, altitude, and other metrics.

Figure 4 – An example of space debris, in this case a foot restraint (top right) that was lost from the Challenger Shuttle in February 1984 [8].

I. Space Debris Classification and Distribution

Space debris is classified primarily by size and altitude. Debris ranges in size from defunct satellites and rocket bodies weighing several tonnes each, to waste products and components on the millimetre scale. This debris is distributed across a range of altitudes; from the LEO (Low Earth Orbit) region below 2,000 km, to the GEO (Geostationary Earth Orbit) region around 36,000 km in altitude. The classification of the current debris population by these and other metrics is discussed in this section.

I.1 Size

Physical size is the primary metric used to classify the space debris population. The European Space Agency (ESA) refers to a three-category classification, as given in Table 1. As can be seen, the number of small objects in-orbit far surpasses the number of large objects.

The size of an individual object is important given the implications this has for trackability, and the level of damage that can be caused if that object were to be involved in a collision. The larger an object the more damage it is likely to cause in a collision with another object, and the greater the number of new debris objects that are likely to be created. Notably it is the large number of smaller objects in orbit that drives the *current* collision hazard, while the rarer large objects are likely to drive the *future* collision hazard.

The reason that even tiny pieces of debris can be so destructive is the high velocity that they have in orbit, typically several kilometres per second (km/s). The relative velocity between many objects that come close to each other in LEO is often on the order of 10 km/s – ten times faster than a rifle bullet. At such speeds, an impact of a small piece of debris (1mm to 1cm) with a satellite releases energy ranging from the equivalent of being hit by a baseball (enough to cause localised surface damage) up to being hit by an anvil falling from a height of two stories (enough to cause severe or even catastrophic damage) [10]. The impact of a large object (> 10 cm) at these speeds would likely result in complete destruction of the satellite (a ‘fragmentation event’).

The high number of small objects in orbit drives the current collision hazard, while the rarer large objects are likely to drive the future collision hazard.

I.1.1 Trackable debris (large and medium sized objects)

Of the total space debris population, only those objects within the large and medium size categories are currently trackable, as shown in Table 1. These objects represent only a small proportion (< 1%) of the total space debris population; however because of the ability to track this debris, it is feasible to act upon potential collisions, for example through spacecraft avoidance manoeuvres.

Objects in the large category are tracked continuously at a high level of precision by space surveillance systems such as the U.S. Space Surveillance Network (SSN). The SSN tracks and maintains a public catalogue of more than 22,000 such objects [11]. An object is considered

Category	Diameter	Number in orbit	Trackability
Large	> 10 cm	36,500	Tracked and catalogued
Medium	1 cm to 10 cm	1,000,000	Trackable but with lower reliability
Small	1 mm to 1 cm	130,000,000	Not currently tracked

Table 1 – ESA categorisation of space debris by size, approximate numbers in orbit as of August 2022, and trackability [9].

catalogued when it is tracked reliably enough such that a precise orbit can be determined and updated over time.

Objects in the medium category are trackable with current technology but the reliability of this tracking varies, with some only being tracked intermittently (i.e. via periodic radar surveys) and at lower levels of precision. Notably, the deployment by the U.S. Space Force of a new space surveillance radar known as *Space Fence* in March 2020 has enabled the tracking of medium sized objects. Data from this will be fed into the SSN, leading to a significant increase in the size of the catalogued objects database [12]. Separately, the private company *LeoLabs* has recently completed the Kiwi Space Radar and Costa Rica Space Radar that together aim to catalogue objects down to 2 cm in size [13].

It is also relevant to note that the altitude of debris impacts its trackability. For example tracking systems may be able to detect objects of 10 cm diameter in LEO, however only objects of about 1 meter diameter in GEO. The higher altitude at GEO makes object resolution more difficult, and as such different technologies may be better suited to tracking this debris (e.g. optical detection over ground-based radar) [8].

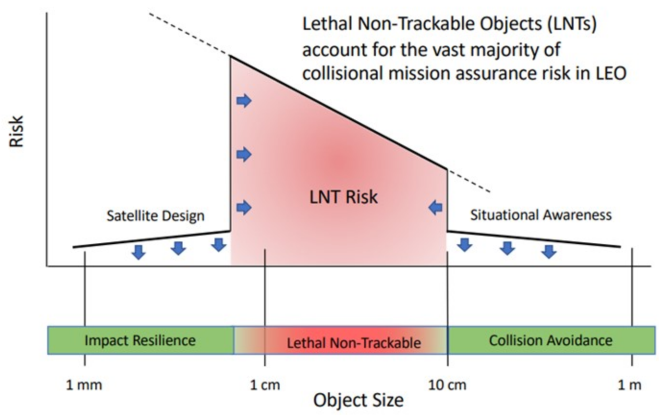


Figure 5 – Impact of LNT on the risk profile for a typical LEO satellite [14], 2019 (improved tracking capabilities have since pushed the right-hand side of the red LNT region towards the left).

I.1.2 Non-trackable debris (small objects)

The vast majority (> 99%) of the space debris population is in the small size category and is not currently tracked (see Table 1). Because of the inability of current resources to systematically track this debris, it is not possible to accurately predict potential collisions and therefore provide any 'just-in-time' collision avoidance.

> The vast majority (> 99%) of the space debris population is in the small size category and is not currently tracked.

Of particular concern are objects referred to as Lethal Non-Trackable (LNT) debris. This debris is too small to be tracked, yet large enough to be lethal in the event of a collision with a satellite (i.e. debris between 5 mm and 1 cm in diameter). These LNT objects dominate the current collision risk profile of operational spacecraft (see Figure 5) as they are far more numerous than other types of debris and cannot be avoided [11]. LNT objects make up more than 95% of the mission-terminating collisional risk for a typical LEO satellite [14]. Sources of LNTs include explosions of satellites and abandoned upper stage rocket bodies that have occurred over decades of activity, as well as major collision events (see section III.1).

Non-trackable debris is already suspected of being responsible for a number of spacecraft anomalies and failures including WorldView-2 (2016, LEO), Sentinel-1A (2016, LEO), AMC-9 (2017, GEO), and Express 80 (2020, GEO) among others (see section III.2 for more details).

I.1.3 Massive derelicts

Exceptionally large objects of space debris are referred to as *massive derelicts*. These objects, consisting of abandoned rocket bodies and non-operational payloads or satellites, are much greater than 10 cm in size and normally on the order of at least several metres in diameter and several tonnes in mass.

Massive derelicts are significant given that it is the high mass of these large objects that is likely to drive the future collision hazard. This is because explosions or collisions of these objects with other space debris has the potential to cause rapid spikes in the space debris population due to the large mass involved (refer to Figure 3 and section III.1). In such events, large amounts of trackable and LNT debris is expected to be produced.

Explosions or collisions of massive derelicts with other space debris has the potential to cause rapid spikes in the space debris population due to the large mass involved.

As of 2019, over a third of the nearly 15,000 rocket bodies and payloads ever deployed in space remain orbiting the Earth as massive derelict objects. This consists of over 3,000 non-operational payloads and nearly 2,200 abandoned rocket bodies, totalling ~ 6,000 tonnes of derelict mass [15]. The accumulation of these objects over time is shown in Figure 6.

The distribution of massive derelicts however is not uniform, with over a third (nearly 2,000 objects) residing in a portion of LEO between 600 and 2,000 km in altitude (referred to as 'LEO high'). On top of this, a quarter of these objects in LEO high are concentrated within three 'clusters' (see section I.3.1) centred at 775, 850, and 975 km. Close approaches of less than 1,000 m occur on average 1,000 times a year between objects within these three clusters [16].

I.2 Altitude

The distribution of space debris is commonly described using its altitude. The altitude of debris is important given that these objects share the regions of space in which most space activity takes place. These regions are generally referred to as either LEO, GEO, or MEO. Each of these regions is distinct in the space debris risks that it presents.

I.2.1 LEO

The LEO (Low Earth Orbit) region extends from the upper atmosphere to an altitude 2,000 km above the Earth's surface. At these low altitudes, satellites travel much faster than in GEO, taking about 90 minutes to complete an orbit. Historically the LEO region has been used for Earth observation satellites, human exploration (e.g. the International Space Station which orbits at 400 km), and technology demonstration or scientific missions (e.g. the Hubble Space Telescope). However since the early 2000's a growing number of small satellite missions, many developed by new commercial manufacturers, have utilised LEO due to its relative ease of access. Since 2019 the number of satellites in LEO has grown rapidly due to the deployment of several 'mega' constellations

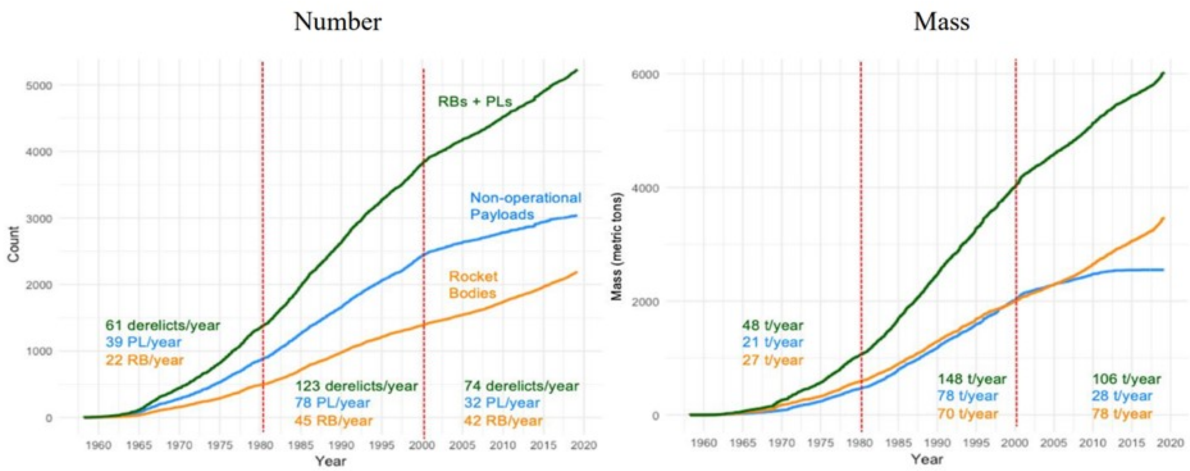


Figure 6 – Accumulation of massive derelicts in Earth orbit, showing a constant increase in both number and mass [15], 2019.

such as Starlink and OneWeb.

As of 2021 there were about 2,600 operational satellites in LEO [11], however by July 2022 SpaceX alone had approximately 3,000 Starlink satellites in orbit with plans to launch many thousands more (a single Falcon 9 launch can deliver up to 60 satellites). LEO is already the most crowded region of space and is forecast to become more so over the coming decades, largely as a result of constellations.

LEO is generally assumed to have the highest collision probability of all orbital regions, with one study from 2017 (Frey and Lemmens [17]) putting the cumulative probability of collisions in LEO at 1.5×10^{-1} per year (equivalent to one collision every 7 years). Notably this study ignored collisions with objects smaller than 10 cm, however the general consensus among those in the space industry is that LEO carries a probability of collision two to three orders of magnitude greater than in any other region [11] [18]. The main reasons for this are:

- Higher density of both active satellites and debris,
- Higher orbital speeds,
- The presence of clusters of massive derelicts.

The distribution of tracked objects across LEO altitudes as catalogued by the US SSN is shown in Figure 7.

The annual collision probability for these catalogued objects as a function of altitude is shown in Figure 8. Notably, above 650 km the collision probability among space debris is greater than that involving operational spacecraft [11].

Some spacecraft in LEO (particularly those with on-board propulsion) can remove themselves from orbit at the end of life (EOL) by performing a deorbit manoeuvre to lower their altitude and re-enter the atmosphere, burning up in the process. However others either cannot or do not perform such a manoeuvre. These are left for their orbits to naturally lose altitude due to drag caused by the upper atmosphere, which may take between months or decades depending on the orbit. Spacecraft in the uppermost LEO altitudes may never lose altitude by this action and without external influence these may stay in-orbit, posing a collision risk for very long periods of time.

Significantly, collisions between large objects in LEO may produce thousands more smaller fragments than collisions of similar objects in GEO. The reason for this is the higher relative velocity between objects in LEO compared to

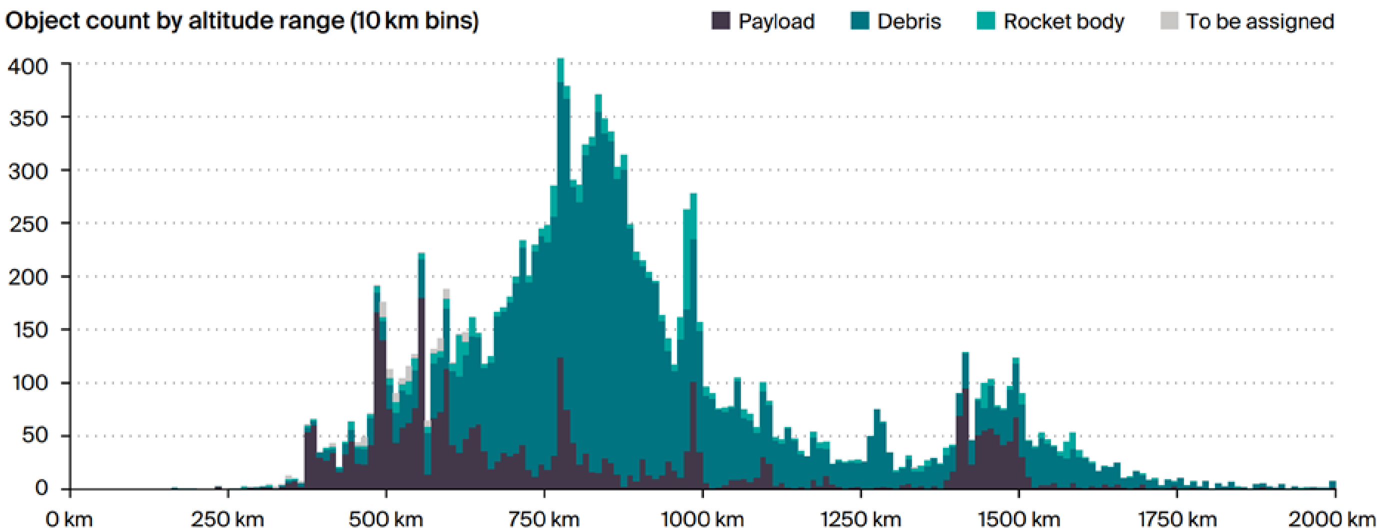


Figure 7 – Catalogue of LEO space objects tracked by the US SSN as of May 2020. Note that the 'Payload' category comprises both operational and non-operational objects [11].

GEO, and greater inclinations in LEO (28°–115° vs 0°–15°). These factors make typical collisions in LEO about 400 times more destructive than those in GEO [8]. The inclination of an orbit is its tilt, measured as an angle relative to the equatorial plane.

The presence of massive derelicts presents the greatest risk for debris generation in LEO since these objects could generate tens of thousands of LNT debris in the event of a collision. Several concentrations of these objects exist in clusters within the LEO region, presenting a further enhanced risk at specific altitudes (see section I.3.1).

I.2.2 GEO

The GEO (Geostationary Earth Orbit) region is a unique orbit at an altitude of 35,786 km and 0° inclination (i.e. an orbit in the same plane as the equator), as shown in Figure 9. GEO is unique because a satellite in this orbit remains above the same point on the Earth's surface. Because of this feature the orbit is particularly well-suited to broadcasting and other telecommunication systems. GEO is thus the most popular orbit for large, high-capacity

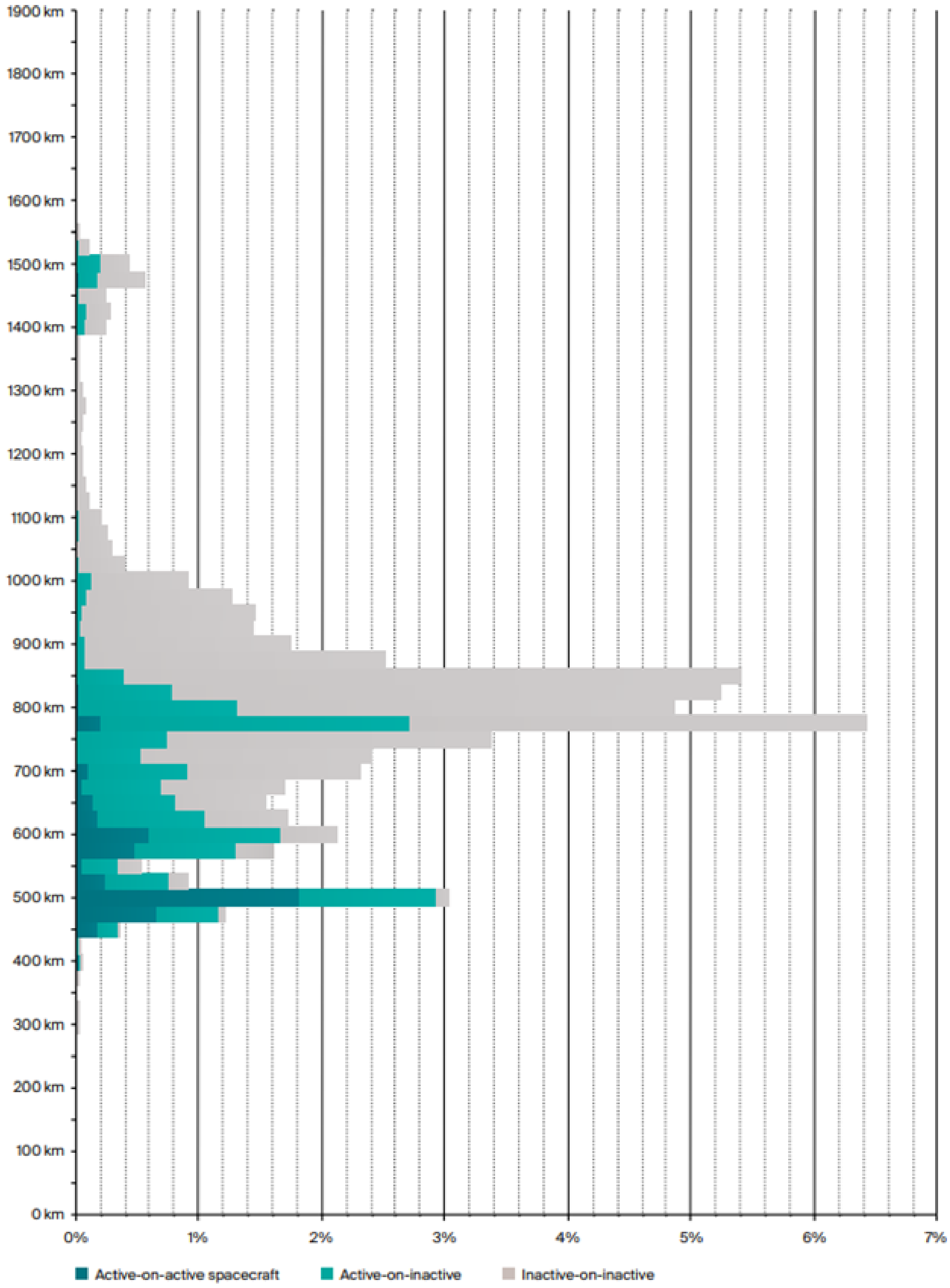


Figure 8 – Estimated annual collision rate as a function of altitude and types of tracked objects in LEO [11], 2019.

communications satellites, many of which are worth hundreds of millions of dollars.

As of 2021 there were about 560 operational satellites in GEO [11]. Once they reach the end of their operational lives, GEO satellites are generally moved to a 'graveyard' orbit 300 km above the GEO region for disposal. This is because the satellites are too far from Earth to be deorbited economically, and there is no natural orbit clearing mechanism such as atmospheric drag. As such, GEO satellites often include a disposal or 'reorbit' allowance in their propellant budgets. However it has been reported that only two thirds of operational GEO satellites successfully reach a graveyard orbit at the end of their lives, while a quarter fail after attempting the manoeuvre and a tenth do not even try [17] [18]. Therefore the graveyard orbit strategy only slows the developing problem of debris in GEO rather than solving it.

The general consensus is that the risk of collisions occurring in GEO is several orders of magnitude less than that in LEO [18]. As an example, the same study noted previously (Frey and Lemmens [17]) put the cumulative probability of collisions in GEO at 3.2×10^{-4}, equivalent to one collision every 3,000 years or so. Unlike LEO, objects in GEO are concentrated within a relatively narrow band of specific altitude and inclination. However the overall

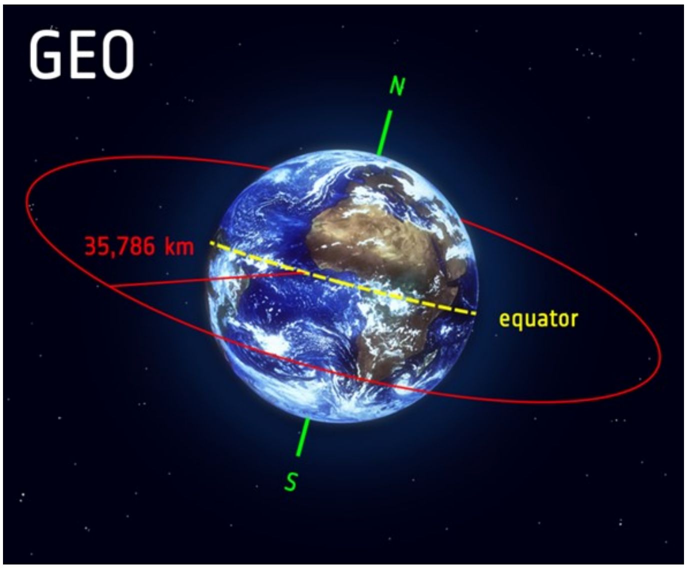


Figure 9 – The Geostationary Earth Orbit (GEO).

volume of this band is relatively large given its greater distance from Earth. Additionally, GEO satellites are orbiting in the same direction at the same speed and inclination, and so the probability of a high-speed collision should be reduced.

The general consensus is that the risk of collisions occurring in GEO is several orders of magnitude less than that in LEO.

Despite this consensus, a significant disparity exists between the probability of collisions in GEO as calculated by some researchers versus that calculated by others. For example, one study from 2018 (D. Oltrogge et al. [19]) suggests that collision likelihood in GEO is as much as four orders of magnitude higher than previously published by other researchers. The results of this study indicate that a collision is likely to occur every 4 years for one satellite out of the entire GEO active satellite population against a 1 cm object catalogue [19], as shown in Figure 10. The reasons proposed for this disparity are that other studies have used simplistic flux-based GEO collision likelihood assessment methods (i.e. stochastic models based on uniform probability distributions, such as *MASTER*) that fail to account for the synchronicity, high spatial variability (geopotential wells) and time-varying dynamics of the GEO orbit regime [19].

Also of note is that the probability of collision in GEO is not uniform by longitude. Concentrations of debris exist at two specific longitudes (referred to as 'geopotential wells') that serve to significantly increase the risk of collision at and near these locations (see section I.3.3 for further discussion). An additional risk is the interaction or 'coupling' of objects in graveyard orbits with the active GEO band.

While calculations based on stochastic models may ultimately be underestimating the probability of collision in GEO, for the purposes of this paper we accept the consensus view that collisions in GEO are less likely than those in LEO. Nevertheless, we note that the geopotential wells exhibit higher probabilities of collision, and that a clearer understanding of the relative probability of collision in GEO vs that in LEO is needed. Examples of GEO satellites that have experienced collisions with debris are presented in section III.2.

I.2.3 MEO

The region between LEO and GEO (from 2,000 km up to 35,000 km) is referred to as MEO (Medium Earth Orbit). The MEO region offers a trade-off in its physical characteristics between the two other regions. It is principally used for position, navigation, and timing services (e.g. GPS satellites), but also communications.

Due to its large volume and relatively low number of satellites, MEO is considerably less congested than LEO and GEO [11]. As a measure of comparison, there were approximately 52 operational payloads and 16 intact rocket bodies in MEO in 2017; versus figures of 2,300 and 822 respectively for LEO, and 708 and 67 respectively for GEO [17]. This low density of objects results in a low risk of collision with space debris in the MEO region, at least one order of magnitude less than that in GEO [17].

Despite this there are additional risks inherent to the MEO region, including the fact that unlike the disposal mechanisms of deorbit and natural decay in LEO and graveyard orbits in GEO, satellites in MEO do not always have a clear method of disposal. It is known however that gravitational resonances could be utilised to provide MEO satellites with a disposal solution. Paths through these resonances could direct satellites at the end of their lives back towards the Earth to burn up in its atmosphere [20].

I.3 Enhanced concentrations of debris

Higher than usual concentrations of debris exist at specific locations in Earth orbit; defined by either altitude, inclination, or longitude. These enhanced concentrations are described in the subsections below.

I.3.1 Clusters

A subset of the massive derelicts discussed in section I.1.3 are the clusters – high density concentrations of large objects at specific LEO

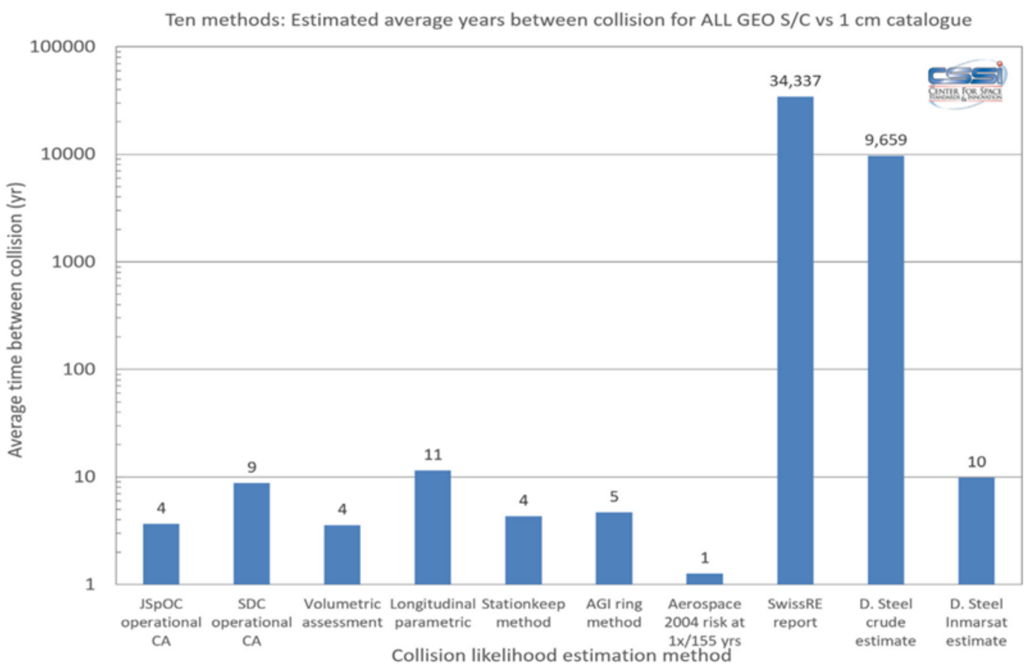


Figure 10 – Disagreement between methods of the average number of years between collisions for all active GEO satellites vs debris objects > 1 cm [19], 2018.

altitudes. Objects within these clusters have mainly been left in orbit between 1980 and 2000, before international guidelines were adopted. The debris-generating risk from these are significant as both the consequences and probability are larger than for a 'typical' collision event.

At least six clusters exist and are monitored via the Massive Collision Monitoring Activity (MCMA) [15]. The clusters of arguably greatest concern are C775, C850, and C975; centred at altitudes of 775 km, 850 km, and 975 km respectively. Each of these has an annual probability of collision between members of the cluster of greater than 1 in 1000. Further details of these three clusters are given in Figure 11.

Notably a collision in the C850 cluster would cause a near doubling of the trackable space debris population with the liberation of roughly 16,000 trackable fragments and 200,000 or more LNT (recalling that there are currently around 36,500 trackable and catalogued objects *in total*). The annual probability of such a collision is estimated at 1 in 800, or approximately 0.1%.

While a collision in the C975 cluster would not generate as many fragments, the annual probability of collision is much higher at approximately 1 in 90, or approximately 1%. It is also notable that the C975 cluster contains nearly four times the mass of the 588-satellite OneWeb constellation, at an altitude just below that of these satellites. Unlike the OneWeb constellation however, the objects within each of these clusters have no capability or intent to avoid collisions.

Each cluster of large objects in LEO has an annual probability of collision of greater than 1 in 1000.

I.3.2 High inclination orbits (applicable to LEO)

Satellites in LEO are spread over a wider range of angle of inclination (orbit tilt) than those in GEO (28°–115° vs 0°–15°). However satellites in LEO are not spread uniformly over this range of inclinations.

The majority of Earth observation, reconnaissance, and weather satellites (plus many of the satellites in new constellations such as OneWeb) orbit in *high inclination orbits* (i.e. those between 60° and 120°). A frequently-used example of such an orbit is the *Sun-Synchronous Orbit* (SSO) with an inclination of 98°–100°.

Multiple high inclination orbits, each with different ascending node longitudes (the longitude of the point in its orbit at which the satellite 'ascends' over the equator), pass over or near the poles – meaning that conjunctions between satellites and debris in such orbits happen frequently in the high latitude areas. As

Center of Cluster (Span)	# of Objects and Mass (kg)	PC/yr and Probability of First Collision by 2019	Mass Involved in Typical Collision	Debris Generated from Collision Trackable (LNT)	Comments
775 km (60)	101 ~100,000	~1/400 4%	~1,600 – 2,800 kg	~4,500 (~60,000)	**Most operational satellites affected**
850 km (45)	75 ~208,000	~1/800 1%	~6,000 – 18,000 kg	~16,000 (~200,000)	**Most consequential events**
975 km (115)	314 ~335,000	~1/90 11%	~1,600 – 2,800 kg	~4,500 (~60,000)	**Most likely events**

Figure 11 – Characteristics of the three clusters with the highest probability of collisions (2019) [16].

a result, the probability of collision for satellites in high inclination orbits is generally higher than for those at lower inclinations, possibly by as much as a factor of two or three [21], as illustrated in Figure 12. This situation has been compounded by the fact that several major debris-creating events have occurred in high inclination orbits including the intentional destruction of the Fengyun-1C satellite (inclination 99°), collision between Iridium 33 (86°) and Cosmos 2251 (74°), and explosion of DMSP-F13 (98.6°). There have been multiple debris impact events in high inclination orbits reported since these major events [22].

I.3.3 Geopotential wells (applicable to GEO)

Concentrations of debris exist at two specific longitudes in the GEO region, referred to as 'geopotential wells', that serve to significantly increase the risk of collision at and near these locations.

These wells are centred at 75°E and 105°W, as shown in Figure 13. Any satellites that end up drifting in their GEO orbit (e.g. those that have lost East-West station-keeping ability) will pass through these areas twice a year, while other debris is permanently captured within them [18]. Stochastic debris modelling such as that performed by the *MASTER* model (see section II.2) does not take account of this effect. Other analyses suggest that the probability of collision at the centre of the wells is a factor of 7 greater than at longitudes far from them [8] [18].

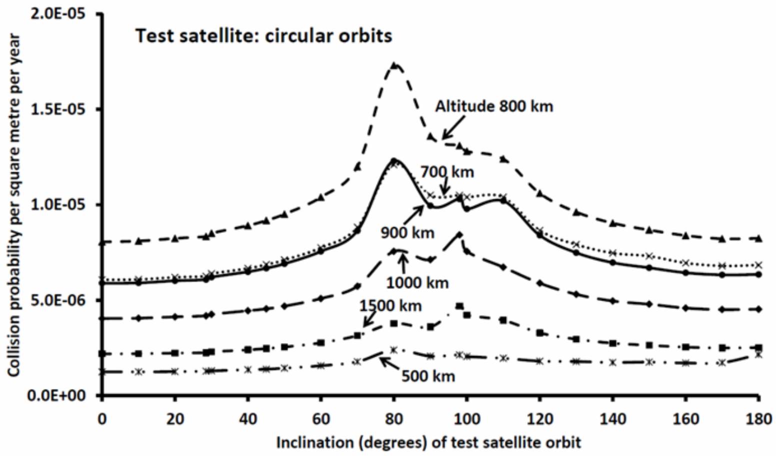


Figure 12 – Variation of the collision probability against orbit inclination, showing the effect of high-inclination orbits [21], 2015.

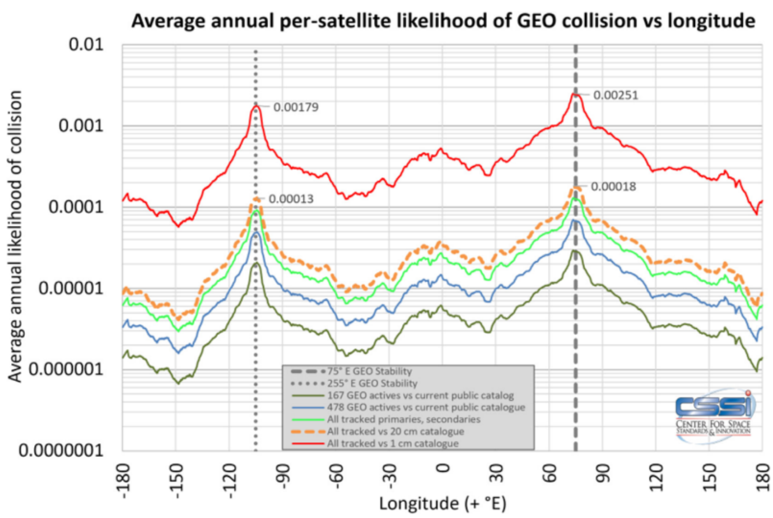


Figure 13 – Per-satellite likelihood of GEO collision by longitude, showing the effect of the geopotential wells [19], 2018.

II. Models and Space Debris Environment Projections

Models enable study of how the space debris environment will respond to future events and mitigation practices. They are also used by scientists and space organisations to determine the risk to current and future spacecraft. As such, the information provided by these models is of interest to the insurance community in providing relative measures of the risk posed by space debris. In this section some of the primary models in use today are described.

II.1 ORDEM and LEGEND

ORDEM (Orbital Debris Engineering Model) was developed by the NASA Orbital Debris Program Office (ODPO) to provide knowledge and estimates of the orbital debris environment (*debris spatial density, flux etc.*) for engineering solutions such as spacecraft design. The latest version, ORDEM 3.2, was released in 2022 and incorporates observational data to reflect the current and future debris environment up to the year 2050. The data encompasses LEO (Low Earth Orbit) to GEO (Geostationary Orbit) altitudes and debris objects from 10 µm (10 microns) up to 1 m in size [23].

LEGEND is a debris evolutionary model that is the NASA ODPO's primary model for study of the *long-term debris environment* and how it will evolve into the future. Covering all orbital regions up to 50,000 km in altitude, the model provides debris characteristics (number, type etc.) as functions of time, altitude, longitude, and latitude. The model includes both historical simulation and future projection components, and includes debris down to 1 mm in size [24]. LEGEND allows an examination of how various mitigation practices may help protect the environment, and provides estimates of future on-orbit collisions. An example of the model's future projection functionality is given in Figure 14.

As shown by this plot, even with 90% PMD (Post Mission Disposal) compliance (see section IV.4.1) and no future accidental explosions (blue line), the simulated LEO debris population is

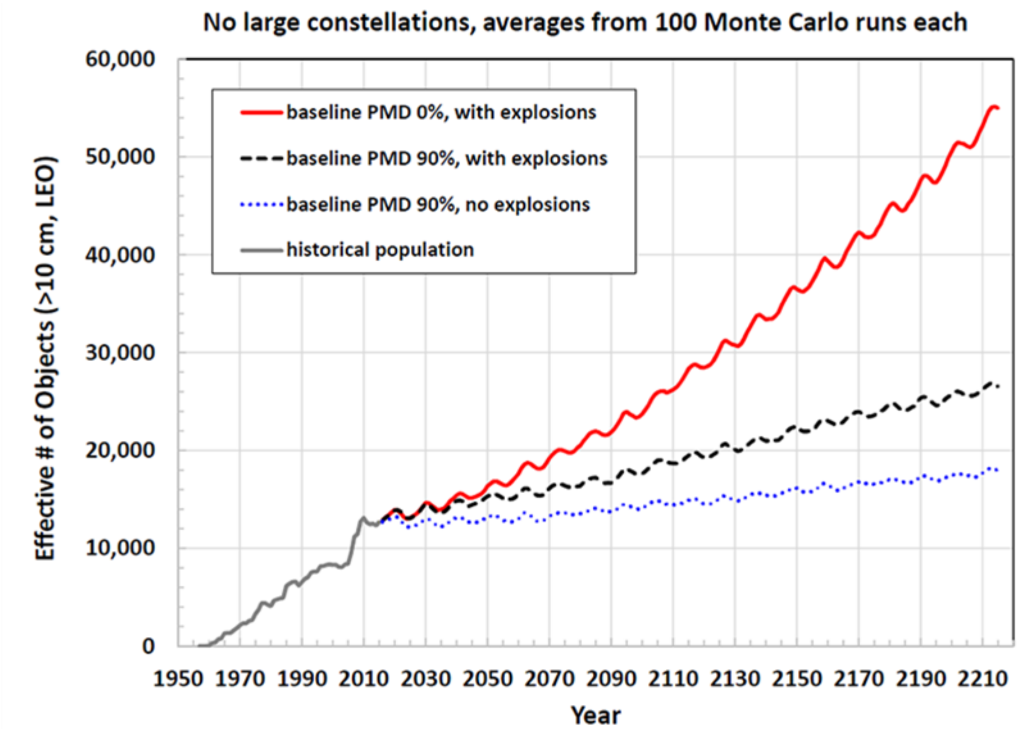


Figure 14 – LEGEND-simulated future projection scenarios for the effective number of debris objects >10cm in LEO, without large constellations but varying levels of Post-Mission Disposal (PMD) compliance, with or without accidental explosions [24], 2022.

predicted to increase by approximately 30% over the next 200 years. Notably the same outcome has been forecast by six different models in a study performed by the Inter-Agency Space Debris Coordination Committee (IADC) in 2013. The same study concluded that this population growth is primarily driven by *catastrophic collisions* (those involving large objects that result in the complete fragmentation of the objects involved and generate a significant amount of debris) between 700 and 1000 km in altitude and that such collisions are likely to occur every 5 to 9 years [25].

II.2 MASTER and DELTA

ESA's Space Debris Office maintains and distributes a number of models for the characterisation of the space debris environment and its evolution. The agency's most prominent debris and meteoroid risk assessment tool is MASTER (Meteoroid and Space Debris Terrestrial Environment Reference). MASTER covers debris and meteoroids from 1 µm (1 micron) up to 100 m in size [26]. The model uses mathematical techniques to determine *impact flux* information (number of impacts per square metre of satellite area per year), and predicts the space debris environment up to the year 2050.

ESA's DELTA tool (Debris Environment Long-Term Analysis) is similar to LEGEND (described above) in that it is used to study the *effectiveness of debris-mitigation measures* and provide *long-term debris population projections*. The tool covers all orbital regions and is able to examine the long-term effects of different future traffic profiles and debris mitigation measures, such as passivation and disposal at end-of-life, and also to take into account active remediation measures. DELTA uses an initial space-object population as input, usually extracted from MASTER.

II.3 Comparison of model outputs

ORDEM and MASTER are the two premier orbital debris models available today. In general both models are in agreement where there is good data on the orbital debris environment, for example where there is tracking of debris (1 cm upwards) and/or experiments that have provided evidence of debris impacts (e.g. on the Hubble Space Telescope). However there are also clear differences in the flux estimates given by the two models mainly in orbit and size regimes that are poorly covered by underlying measurement data, for example in the sub-centimetre (and particularly the sub-millimetre) category [27]. Additionally the data sources and methods of calculation can vary between models.

In this section some key outputs of these models are given and comparisons made to highlight areas of agreement and divergence.

II.3.1 Orbital debris fluxes

The orbital debris fluxes, representing the cumulative number of objects of a given size and larger that pass through each square metre of space per year, for two specific orbits are shown in Figure 15. Although this data is from 2014 (P. Krisko et al. [28]), more recent data from 2021 as presented in A. Horstmann et al. [27] is similar.

The plot on the left shows the orbital debris fluxes for a SSO (Sun-Synchronous Orbit) around 800 km in altitude (i.e. within the LEO orbital region) representing one of the most critical regions of space with the highest accumulation of objects (see sections I.3.1 and I.3.2). The plot on the right shows the fluxes for an orbit in the GEO region.

As can be seen, the flux of debris in the critical size range (defined as debris between 1 mm and 1 cm in size) is higher for the SSO orbit, ranging between approximately 10^0 (1 object / m2 / year) and 10^{-4} (0.0001 objects / m2 / year, equivalent to one object per ten-thousand square metres per year) depending on the debris size. For comparison the flux in the GEO orbit is between approximately 10^{-4} and 10^{-7} (0.0000001 objects / m2 / year, equivalent to one object per ten-million square metres per year). This data also highlights some divergence between the two models, shown as a gap between the red and blue lines. As shown, there is generally high divergence at the very small debris sizes, some divergence within the critical region, and generally low divergence at the larger debris sizes.

II.3.2 Impact of large constellations

Models also allow the impact of large constellations on the space debris environment to be simulated. In one such example, LEGEND was used to quantify the potential debris-generating effects of large constellations (LCs) on the LEO environment for the NASA ODPO Large Constellation Study performed in 2018. Some of the modelling results from this study are shown in Figure 16.

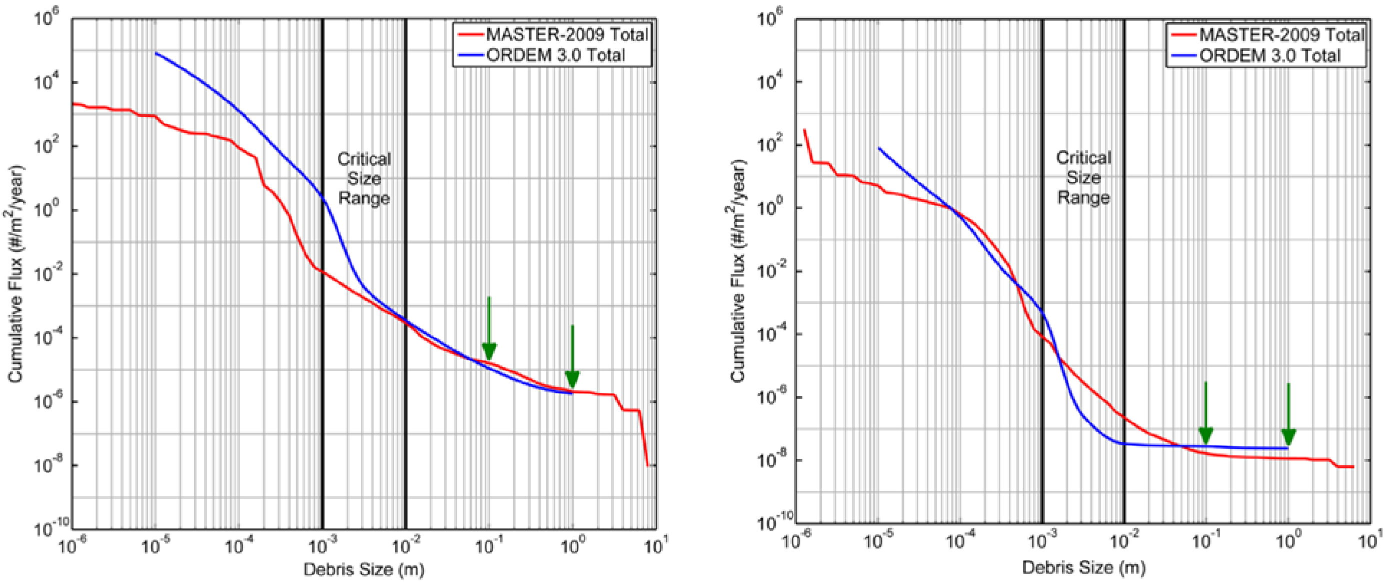


Figure 15 – ORDEM 3.0 and MASTER-2009 orbital debris fluxes for a SSO orbit around 800km altitude (left) and a GEO orbit (right), based on data from 2014. Arrows highlight the cumulative fluxes for 10cm and 1m debris [28].

The plot on the left shows the development of the *effective number of debris objects >10cm in LEO* over the next 200 years; considering three LCs within the 1000-1325 km altitude range, a total of 8,300 satellites within the three LCs, and that the operations and routine spacecraft replenishment of the LCs are assumed to continue for 20 years. The plot on the right shows the *cumulative number of catastrophic collisions* over the same 200 years following the same considerations.

Three scenarios are shown by the coloured lines in addition to the background level (i.e. a debris environment with no constellations, Post Mission Disposal (PMD) compliance of 90%, and with accidental explosions), shown by the black dashed line in Figure 14. All scenarios include accidental explosions within the LC population, however *varying levels of PMD compliance*: 90% (red), 95% (blue), and 99% (green).

As can be seen, the projections suggest that the impact of the LCs over the next 200 years is an *increase in both the effective number of debris objects in LEO and the cumulative number of catastrophic collisions*. Depending on the PMD scenario, the former is expected to increase anywhere between +22% and +290% while the latter is expected to increase from a baseline of 27 to between 34 and 260.

Models suggest that the impact of large constellations will be an increase in both the number of debris objects and the number of catastrophic collisions.

While these are only the results of one study into the effects of three notional constellations, the potential impact that LCs could have on the LEO debris environment is clear. Notably most studies performed to look at the impact of LCs have concluded that compliance with current international mitigation standards (see section IV.3) is a prerequisite to keep space activities sustainable in the long-term [11].

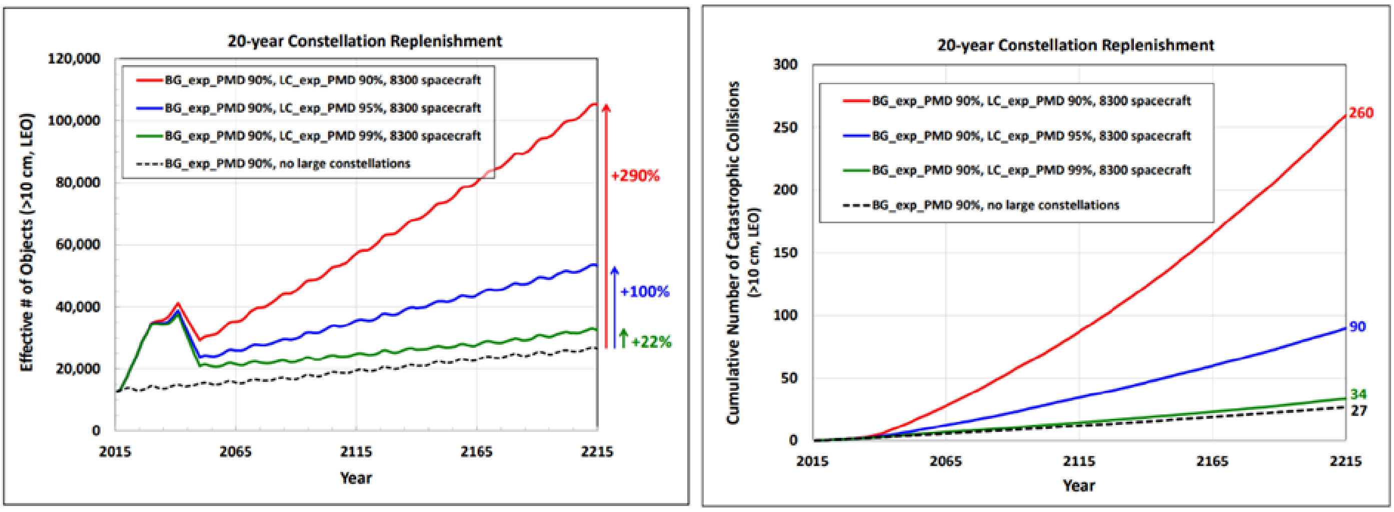


Figure 16 – LEGEND results from projected LC scenarios where the LCs maintain full operations with spacecraft replenishment for 20 years; showing the effective number of debris objects in LEO for each scenario (left) and the cumulative number of catastrophic collisions (right) [29], 2018.

III. Case Studies

Space debris has been accumulating since the dawn of the space age, however most debris-creating events have occurred within the last 20 years. This section presents a selection of events that have been significant, resulting in either dramatic increases in the space debris population and/or damage to active satellites.

III.1 Major debris-creating events

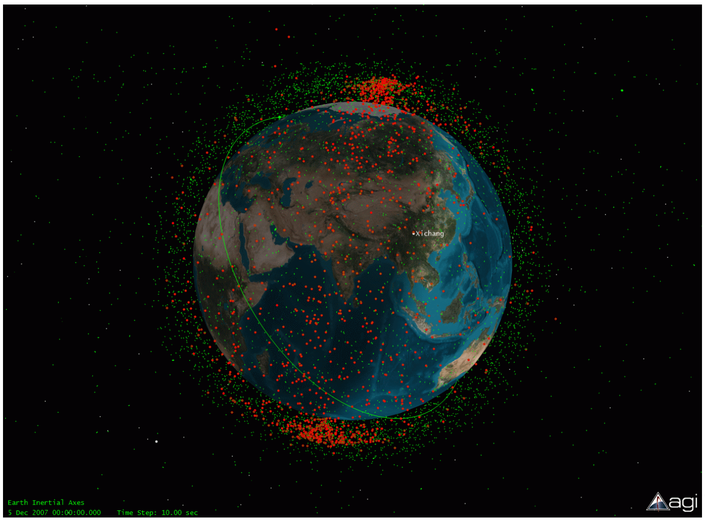
There are several examples of major debris-creating events that have occurred as recently as 2021. Some of these are deliberate actions referred to as ASAT (Anti-Satellite) weapons tests, while others are accidental collisions involving large intact spacecraft.

III.1.1 Fengyun-1C (2007)

One of the worst events in the growth of the space debris population (see Figure 17) was the deliberate destruction of the defunct Chinese Fengyun-1C (FY-1C) weather satellite via an ASAT test on 11th January 2007. This event created an estimated 300,000 objects of 1 cm or larger – each large enough to be fatal to a satellite mission. Of these, approximately 3,300 objects were 10 cm or greater in size, large enough to be tracked and added to the resident space object catalogue [10]. The majority of these objects remain to this day orbiting close to the orbit of the original satellite, *approximately 850 km in altitude at a high inclination of 99°*. As a high inclination Sun-Synchronous Orbit (SSO) this is one of the most popular orbits for Earth-observation missions, used by all spacefaring nations. At the time of the event in 2007, 1,893 of the 2,833 payloads for which data was available passed through the debris cloud shown in Figure 17, causing at least some increase in the overall risk to each satellite [30].

> The majority of Fengyun-1C debris remains in-orbit, approximately 850 km in altitude at an inclination of 99°.

The debris cloud created by FY-1C poses significant and ongoing risks to satellites that share orbits at similar altitudes and inclinations. Moreover, the altitude of the FY-1C debris cloud also coincides with the C850 cluster of massive derelicts (see section I.3.1). Because of the relatively high 850 km altitude (within the 'LEO high' region), it will require many decades if not centuries for atmospheric drag to naturally deorbit the debris. Analysis has shown that over 79% of the trackable pieces of debris are predicted to remain in orbit 100 years after the event [30].



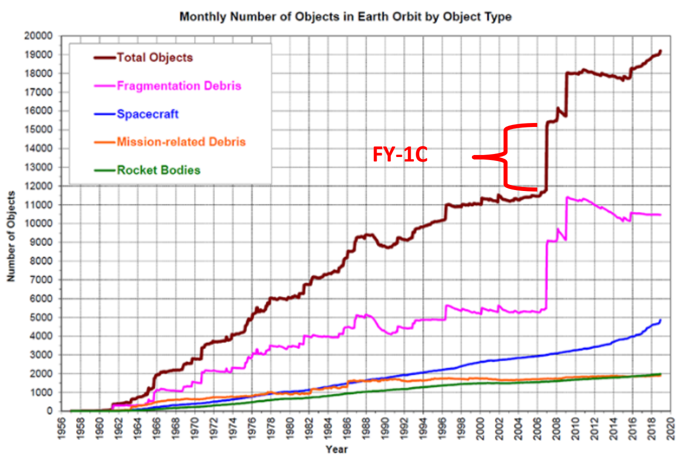


Figure 17 – Left: Fengyun-1C ASAT test debris in red relative to the other debris in Earth orbit in 2007 (green). The green line shows the orbit of the International Space Station [30] [31]. Right: growth in the number of objects >10 cm in LEO, with the impact of the Fengyun-1C ASAT test highlighted in red [5].

III.1.2 Iridium 33 and Cosmos 2251 (2009)

The collision of the satellites Iridium 33 and Cosmos 2251 on 10th February 2009 marked the *first accidental collision of two large, intact resident space objects; one of which was an active satellite*. The active Iridium 33 was part of a constellation providing mobile phone service, while the inactive Cosmos 2251 was a Russian military satellite that had been taken out of service several years earlier. In the event, the two satellites collided at nearly right angles to each other at a relative speed of over 11 km/s, resulting in the destruction of both satellites [10].

> The collision of Iridium 33 and Cosmos 2251 was the first accidental collision of two, large, intact objects; one of which was an active satellite.

The collision had a significant impact on the space debris environment (clearly visible alongside the jump attributable to FY-1C in Figure 3 and Figure 17), creating approximately 200,000 objects of 1 cm or larger, of which over 2,000 were 10 cm or greater in size. The majority of these objects remain orbiting in shells centred on the parent orbits shown in Figure 18, *780 km in altitude and at high inclinations of 86° (Iridium 33) and 74° (Cosmos 2251)* [10].

Although no warning had been issued of a potential collision between the two satellites, a close approach of 584 m had been predicted prior to the event by the *SOCRATES* satellite conjunction report [32]. Such reports however do not provide a yes/no answer as to whether or not two objects will collide, they can only determine a probability of collision, which in this case was estimated to be 1 in 500,000 [10]. As shown by this event, uncertainties in knowing the positions of objects in orbit because of limited data (at least in 2009) meant that some conjunctions were actually much closer in reality than predicted by the SOCRATES report.

Analysis by NASA and outside experts indicates that more than half of the Iridium debris will remain in orbit for at least 100 years, and much of the Cosmos debris will remain in orbit at least 20 to 30 years [32]. This debris poses a hazard to other space-based assets (again in the LEO high region, and at high inclinations) through either direct collision, or indirectly via impacts with other debris, increasing the number of debris objects and thereby increasing the hazard.

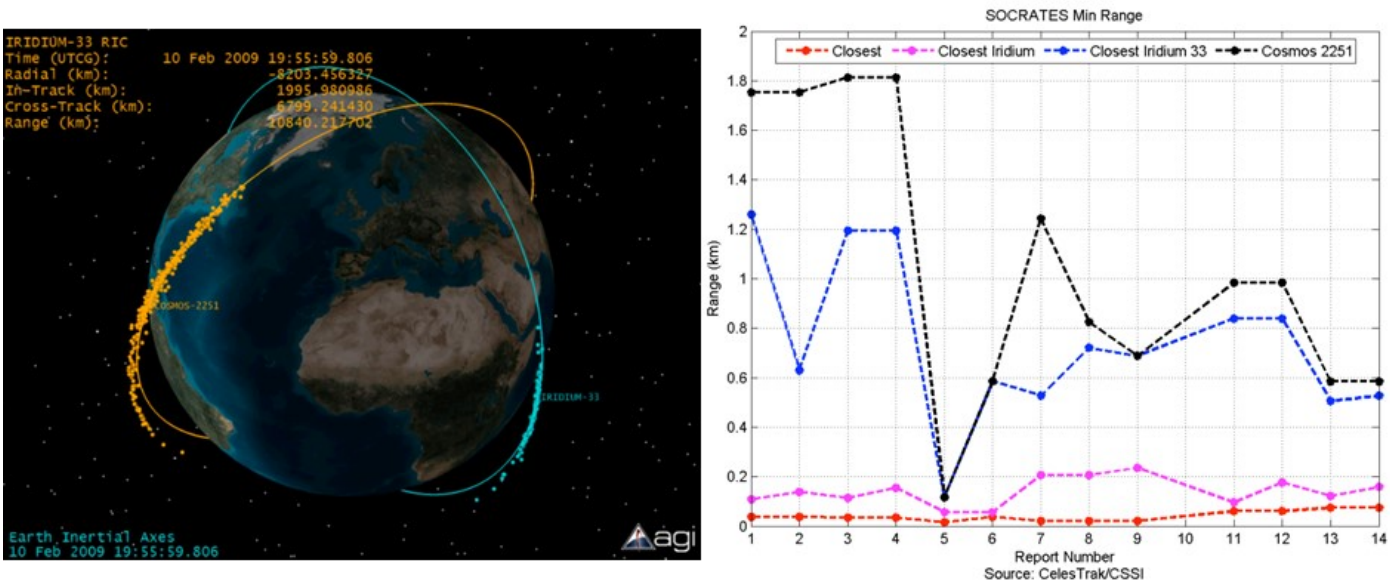


Figure 18 – Left: View of the Iridium 33 and Cosmos 2251 debris clouds three hours after the collision [32]. Right: SOCRATES approach distances for the closest conjunctions involving Iridium and Cosmos 2251 satellites in 14 reports over the week prior to the collision.

III.1.3 Cosmos 1408 (2021)

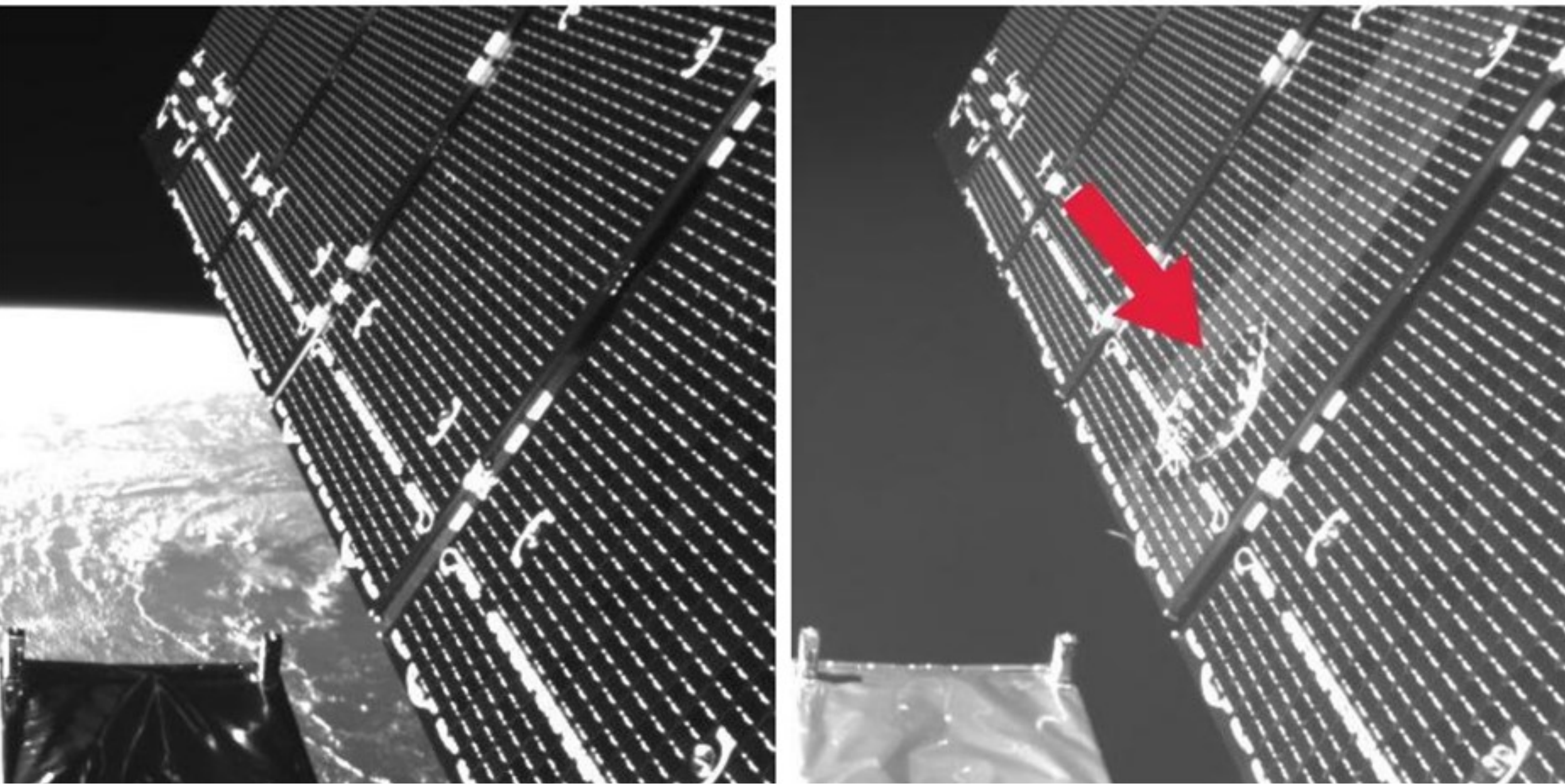
The most recent major debris-creating event was the deliberate destruction of the defunct Russian Cosmos 1408 military satellite via an ASAT test on 15th November 2021. The event created an estimated 1,500 trackable objects and several hundred thousand smaller objects [33]. The majority of these objects remain orbiting in a band *between 300 km and 1,100 km in altitude and at high inclinations* (at the time of impact the satellite was in an orbit of around 480 km and 82° inclination) [34].

Shortly after the event it was reported that astronauts on board the International Space Station (ISS) were instructed to take shelter inside the docked Dragon and Soyuz capsules for several hours because of the proximity between the cloud of debris and the ISS. With much of the debris passing through or near the ISS orbit at 400 km it has been suggested by NASA administrator Bill Nelson that astronauts now face a risk from debris four times greater than normal [35].

Not only does the debris caused by this event pose an ongoing risk to astronauts aboard the ISS and China's Tiangong space station, it further increases the risk of collision with many of the growing number of satellites in LEO. In early 2022 it was reported that debris from the event was creating surges of close approaches, referred to as "conjunction squalls", with active satellites in these orbits. The space situational awareness company *COMSPOC* predicted that in the first week of April there would be 40,000 conjunctions (defined as approaches within 10 km) purely as a result of the Cosmos ASAT test [36].

While spacecraft in SSOs such as the *Dove* imaging CubeSats operated by the company *Planet* will feel some of the strongest effects, those outside of SSO will also be affected. It was reported in August 2022 that the latest series of SpaceX Starlink satellites to have been launched ("Group 3") were orbiting in SSO in the path of the Cosmos debris, and that on one day there were 6,000 conjunctions within 10 km involving 841 Starlink satellites. It is unclear how many, if any, of the satellites had to manoeuvre to avoid collisions [37].

Figure 19 – Solar panel before and after debris collision on Sentinel 1A [40].



III.1.4 Envisat (potential future event)

The satellite Envisat is a prime example of a massive derelict (see section I.1.3) orbiting in the 'LEO high' region at an altitude of 800 km. It is therefore an example of a major debris-creating event waiting to happen.

Launched in 2002, the satellite was the largest Earth observation spacecraft ever built weighing approximately 8 tonnes [38]. The mission ended in 2012 following the unexpected loss of contact with the satellite, itself possibly the victim of a small debris impact. As a result, Envisat now represents one of the largest pieces of space debris in orbit, and one of the most concerning given its large mass and therefore its potential to significantly contaminate the LEO environment if it were to be involved in a major collision. Studies have shown that the collision of a small satellite or rocket body with Envisat would substantially increase the LEO debris population, with an increase in spatial density of 400% at the altitude where the collision occurs [39].

Envisat is not expected to deorbit naturally for more than 150 years [39]. Adding to the risk profile is the fact that the satellite is located in a Sun-Synchronous Orbit (SSO) and therefore has a high inclination, meaning that conjunctions between other satellites and debris (including the debris produced by other major events) happen frequently. Because of the risk associated with its presence in orbit, Envisat has been and remains a candidate for Active Debris Removal missions (see section IV.5.1).

Image credit: ESA

III.2 Other events involving collisions of debris with active satellites

Besides the major debris-creating events described above, there are many other events involving the collision of debris with active satellites. Table 2 below provides details of several examples.

Notably, the Iridium 91 and Iridium 47 events occurred in orbits where there is already a higher than normal density of debris due to the Chinese ASAT test (see section III.1.1) and Iridium 33–Cosmos 2251 collision (see section III.1.2). Furthermore the exact time of the Iridium 91 event put the satellite in a debris convergence zone near the South Pole, where object density is significantly higher [44]. These factors highlight the additional risk posed to satellites in orbits close to existing debris and/or in orbits that pass through the polar convergence zones.

Satellite	Orbit	Event date	Description
Express 80	GEO	15/08/2020	Damage to satellite antenna and heaters due to a suspected debris strike. The satellite remains fully operational and no claim for damage was made.
AMC-9	GEO	17/06/2017	A mechanical strike event took place which caused a loss of satellite control and telemetry as it slightly changed its orbit and shed debris. Following the event, operator SES regained control and transferred the satellite to a graveyard orbit. The satellite was declared a total loss. This was one of several events occurring in GEO in 2017 (also *Echostar 3* and *Telkom-1*) [18].
Sentinel 1A	LEO SSO	23/08/2016	The satellite was struck by a 1 cm (0.2 kg) particle of debris which caused damage to a panel of one solar array (0.4 m diameter crater, see Figure 19). There was no impact on the mission, however a momentum change / change in orbit was detected as was a partial (5%) loss of power [40]. At the time of the event the satellite was in a 98.2° inclination, 723 km altitude orbit [41].
Worldview 2	LEO SSO	19/07/2016	The satellite was observed to shed debris however remained fully operational. Most of the debris produced is in longer-period orbits, indicating a fragmentation event (i.e. caused by an external impactor as opposed to an internal explosion) [42]. At the time of the event the satellite was in a 98.5° inclination, 768 by 767 km orbit.
Iridium 91	LEO Polar	30/11/2014	The satellite shed four pieces of debris at low velocity. The satellite remained in full operation and did not show any obvious changes in its orbit at the breakup time. Suspected cause was a collision with a small debris object. Notably Iridium 91 was the satellite moved into *Iridium 33's* slot after the collision with Cosmos 2251. At the time of the event the satellite was in an 86.4° inclination, 780 km orbit [41].
Iridium 47	LEO Polar	07/06/2014	The satellite shed 10 fragments at high velocity (80 m/s) but remained in full operation with no obvious changes in its orbit at the time of breakup. In the absence of evidence of an explosion on board the spacecraft, a collision with a piece of untracked debris is the most likely culprit [43]. At the time of the event the satellite was in an 86.4° inclination, 780 km orbit [41].

Table 2 – Examples of collisions between space debris and active satellites.

IV. Responses to Space Debris

The accumulation of space debris is a growing problem that demands action if the future use of Earth orbits is to be safeguarded. This section provides an overview of current response strategies, tracking capabilities, and the existing space debris guidelines; and an examination of select activities that deal with either the mitigation or remediation of space debris.

IV.1 Overview of strategies (SSA, STM, and SEM)

Responses to space debris can broadly be broken down into three strategies as shown in Figure 20: Space Situational Awareness (SSA), Space Traffic Management (STM), and Space Environment Management (SEM).

SSA is the foundation of all debris response strategies, and consists of *providing information on orbiting space objects*:

- Space object discovery, tracking, and characterisation;
- Distribution of this information to enable collision avoidance and safe operations.

Without this information, STM and SEM cannot be conducted. Several providers of such information are given in Table 3. The U.S. SSN (Space Surveillance Network) remains the main source of orbital data, maintaining a catalogue of over 20,000 objects. However there is growing commercial interest in SSA services, and a number of companies in the private sector have developed capabilities in sensors and software systems that are now available to the space operator community. Notably it is only within the last three years that improvements have been made in SSA capabilities to enable the tracking of objects in the medium sized category (1-10cm).

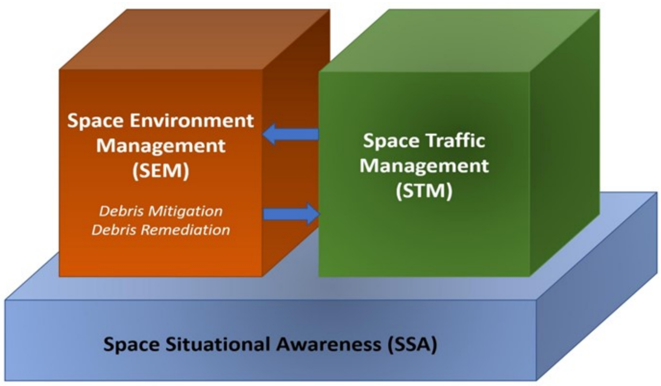


Figure 20 – Overview of the three space debris strategies: SSA, STM, and SEM [16].

STM provides the following functions:

- Management of interactions between space operators and the catalogued debris population;
- Coordination of collision avoidance manoeuvres between space operators.

STM relies on SSA information for orbit predictions and conjunction notices, and when the conjunction involves another operator, STM calls for the coordination of collision avoidance manoeuvres [14]. STM organisations such as the *Space Data Association (SDA)* and *Slingshot Aerospace* bring together satellite operators to facilitate operator-operator coordination. SDA membership includes many of the world's major satellite communications companies, including Eutelsat, Inmarsat, Intelsat, and SES [45].

SEM incorporates two main sets of activities:

- *Mitigation activities* that aim to prevent the creation of new debris through responsible design and operational practises i.e. "not making the environment worse";
- *Remediation activities* that aim to reduce the risk from debris once it has been created i.e. "actively making the environment better".

Collectively these activities aim to reduce growth of the debris population. Sections IV.4 and IV.5 explore some of these activities in more detail.

IV.2 Tracking

The tracking of space debris provides actionable intelligence, allowing certain mitigating and remediatory actions to be taken. As previously noted in section I.1.1, a portion of the total space debris population including intact satellites and large to medium sized objects (down to ~ 1 cm in size) is trackable with current technology. The main providers of tracking capabilities include national space surveillance systems such as the U.S. SSN (run by the Combined Space Operations Center 'CSpOC') and the European Space Surveillance & Tracking (EU SST) programme, and private sector companies including *LeoLabs* and *COMSPOC*. A summary of these providers and the services offered by each is given below.

Despite the improving availability of space object tracking there are at least two clear limitations that remain relevant:

- The vast majority of the space debris population and that which is of greatest concern, the Lethal Non-trackable (LNT) debris i.e. that between 5 mm and 1 cm in diameter, is not currently tracked. Put another way, the public catalogue of over

Provider	Functions	Capabilities (sensors, catalogue, object size etc.)
National i.e. governmental providers		
U.S. SSN	• Detects, tracks, catalogues, and identifies artificial objects orbiting Earth. • Maintains a public catalogue of over 20,000 objects. • Provides conjunction warnings to both private and government operators.	• Largest tracking system worldwide. • Global network of over 30 ground- and space-based radars, lasers, and optical telescopes. • Existing catalogue tracks all objects ≥ 10 cm in diameter in LEO, and all objects ≥ 1 m in GEO [4]. • Recent deployment in 2020 of the S-band *Space Fence* radar on the Kwajalein Atoll allows tracking of objects down to 5 cm in diameter.
EU SST (est. 2014)	• Detection, cataloguing, and orbit prediction of space objects. • Provision of STM services including collision avoidance, re-entry analysis, and fragmentations analysis [46].	• Global network of sensors consisting of radars, telescopes, and laser ranging stations. • Tracking of objects in all orbital regimes from LEO to GEO. • Currently reliant on the U.S. SSN, however data is processed to feed a joint database and a future European catalogue. • Full coverage of objects > 35 cm in GEO & MEO by 2023. • Aim to cover 100% of objects > 50 cm in LEO.
Private i.e. commercial providers		
LeoLabs (est. 2016)	• Builds and operates a network of radars to provide tracking of LEO objects. • Operates a commercial platform that provides SSA and STM services.	• Network of 4 phased array radars with plans to expand this to 6+ radars. • Provide tracking data for objects in LEO only. • Two S-band radars ('Kiwi' and 'Costa Rica') operating since 2020 are capable of tracking objects down to 2 cm in size and are aiming to expand the LEO catalogue to over 100,000 objects [13] [47]. • Radars are capable of revisiting satellites many times per day and most objects at least once per day.
COMSPOC	• Deliver SSA products and services via proprietary software packages.	• SSA off-the-shelf packages. • High-accuracy positional knowledge services. • Screening of Resident Space Objects (RSOs) against all other RSOs of interest. • Collision avoidance manoeuvre planning.

Table 3 – Space object tracking providers and services offered.

20,000 trackable objects represents less than about 0.02% of the total estimated debris population [4].

- Tracking for the GEO region is significantly less capable than that for the LEO region, both in terms of the regularity of measurements and in object resolution.

Therefore whilst tracking (and more broadly speaking the wider strategies of SSA and STM) is necessary to assure mission safety, it is far from being a sufficient response alone to the growing challenges of operating in a congested space environment.

IV.3 Space debris guidelines

To counter the accumulation of space debris, space debris mitigation guidelines in the form of the U.S. Government *Orbital Debris Mitigation Standard Practices* (ODMSP) and the *Inter-Agency Space Debris Coordination Committee* (IADC) *Space Debris Mitigation Guidelines*, were first published in 2001 and 2002 respectively.

The ODMSP lists five objectives followed by the U.S. government in all of its space operations to limit the generation of new, long-lived debris [48]. The IADC guidelines provide four debris 'mitigation measures' that are targeted at space organisations and operators involved in the design and operation of spacecraft and launch vehicle orbital stages [49]. These measures aim to minimise or eliminate the generation of debris during and after space missions.

The four IADC debris mitigation measures can be summarised as follows:

1. **Limit debris released during normal operations.**

   Spacecraft should be designed not to release debris during normal operations. Where this is not feasible any release of debris should be minimised in number, area, and orbital lifetime.

2. Minimise the potential for on-orbit breakups

   a. Minimise the potential for post mission break-ups resulting from stored energy.

   b. Minimise the potential for break-ups during operational phases.

   c. Avoidance of intentional destructions (ASAT tests) and other harmful activities.

3. Post Mission Disposal (PMD) – see following discussion.

4. Prevention of on-orbit collisions.

   Avoidance manoeuvres for spacecraft during all operational phases and co-ordination of launch windows for launch vehicles should be considered.

Guidelines such as these provide a framework for 'what' needs to be done, however they are not legally binding and compliance levels since their introduction have been low (see discussion of PMD compliance in section IV.4.1). 'How' mitigation measures can be implemented has also been specified via some international standards such as ISO 24113 (Space systems – Space debris mitigation requirements); however the next step, the transfer of guidelines into *internationally binding regulations*, is largely still pending [50]. Some progress towards binding regulations has recently been made, see note under section IV.4.1.

Space debris guidelines are not legally binding and compliance levels since their introduction have been low.

IV.4 Mitigation activities

Mitigation activities aim to prevent the creation of new debris through responsible design and operational practises. As such, these activities can be applied to spacecraft either before they are launched (as in the case of spacecraft shielding) or while they are orbiting in an active and controlled state. Many mitigation activities have been formalised in the form of the space debris guidelines described previously. The following subsections go into more depth on the most widely-used examples.

IV.4.1 Post Mission Disposal

Post Mission Disposal (PMD) is of great importance as a mitigation activity given the strong influence it has on preventing growth of the space debris population. This has been recognised by space agencies such as ESA who have stated that strong compliance with PMD is the most effective *long-term* means of stabilising the space debris environment [50].

Both the ODMSP and the IADC established the now widely accepted guidelines on PMD that can be summarised as follows:

- Geosynchronous (GEO) region
  - Spacecraft should be ‘reorbited’ at End of Life (EOL) i.e. they should be moved to a ‘graveyard’ orbit that will remain above the GEO region for at least 100 years.
- LEO region
  - Spacecraft should be ‘deorbited’ at EOL i.e. they should be moved to either immediately re-enter the Earth’s atmosphere, or where appropriate manoeuvred into an orbit with an expected residual lifetime of 25 years or shorter *.
- Other orbits
  - Spacecraft should be manoeuvred to reduce their orbital lifetime, commensurate with LEO lifetime limitations, or relocated if they cause interference with highly utilised orbit regions.

Strong compliance with Post Mission Disposal is the most effective long-term means of stabilising the space debris environment.

Unfortunately not all spacecraft are compliant with the PMD guidelines, with one study suggesting that over the course of 10 years between 2006 and 2016, only 53.3% of payloads and 71.6% of rocket bodies in LEO were compliant, while 66.1% of payloads in GEO were complaint [17]. As such, even more than a decade after their introduction there were still high rates of non-compliance with PMD guidelines, particularly in terms of payloads in LEO. The most promising results showing increasing levels of compliance were for payloads in GEO. Efforts are being made to improve the level of compliance, for example regulations in France now explicitly require observance of the 25 year orbit clearance rule by satellites in LEO [4].

As of September 2022 the FCC has adopted a new rule that shortens the time allowed for LEO satellites to deorbit from 25 to 5 years.

As discussed in section II.3.2, the development of large constellations will likely increase the number of debris objects in LEO, even with much higher rates of PMD compliance (i.e. >90%) than those discussed above. Despite this, PMD will remain one of the most effective space debris mitigation measures well into the future. Proposals have been made to significantly reduce the 25 year limit for PMD in LEO, and advances made in the capability and affordability of compact electric propulsion may help enable this for even the smallest of satellites.

> * Note that as of 29th September 2022, the Federal Communications Commission (FCC) has adopted a new rule that shortens the time for satellite operators to deorbit satellites in LEO from 25 to 5 years following EOL [51]. This rule applies to both U.S.-licensed satellites as well as entities seeking to access the U.S. market using a non-U.S.-licensed satellite or satellite system [52]. This is the first

concrete rule on PMD, replacing the longstanding 25 year guideline. The new rule will afford companies a transition period of two years, meaning that it only comes into force for satellites launched from 29/09/2024 onwards.

IV.4.2 Collision avoidance

Collision avoidance can be employed as a space debris mitigation activity during preparations for the launch of new spacecraft, and throughout the in-orbit lifetime.

In the first case, before a launch vehicle can lift off its trajectory must be checked against the trajectories of tracked and catalogued objects. This form of collision avoidance may be performed by the launch vehicle provider and other organisations (e.g. *The Aerospace Corporation*) who provide collision avoidance reports based on the launch window selected for a mission. Collision avoidance screenings for every possible lift-off time throughout the window are conducted to ensure that launched objects, both rockets and payloads, have an acceptably low risk of collision with catalogued objects on orbit [10]. As space has become more crowded, analysts have developed tools and methods to screen close approaches between launch objects and catalogue objects based on a probability of collision rather than on maintaining a strict separation distance. This has enabled a better assessment of the risk posed by debris during the launch phase and more efficient usage of launch window opportunities.

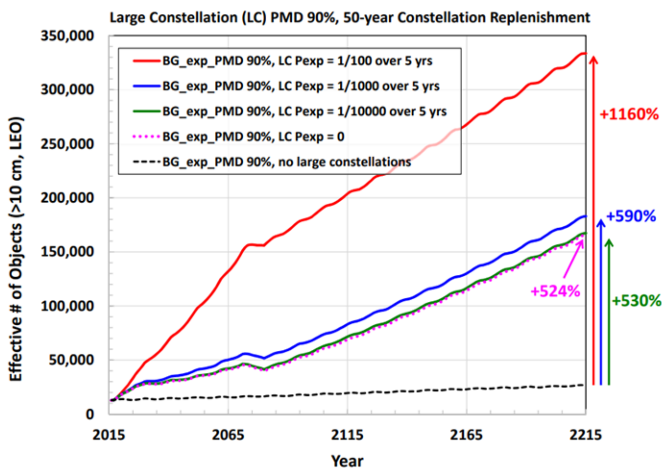


Figure 21 – Projected LC scenarios showing the increase in the effective number of debris objects in LEO for a range of different accidental explosion probabilities [29], 2018.

In the case of collision avoidance during the spacecraft lifetime in-orbit, operators continually need to take into account the risk posed by other spacecraft and space debris (at least that from tracked debris) and be ready to take action in the event of a close approach, referred to as a 'conjunction'. Warnings of such events may be given by the providers discussed in section IV.2 alongside other services such as the *SOCRATES* conjunction report.

If a particular conjunction warning is considered critical (a typical probability threshold used is 10^{-4} [11]), a Collision Avoidance Manoeuvre (CAM) is conducted by the operator. Depending on the timeliness of the warning (several days in advance might be considered typical), the operator will plan an appropriate manoeuvre to reduce the probability of collision. These manoeuvres often take the form of a short burn of a satellite's on-board thrusters to bring it out of conflict with the other object. As such, satellites need to budget a certain quantity of propellant to ensure they can perform several such manoeuvres if needed over their lifetimes. ESA estimates that it needs to perform more than one CAM per satellite per year [11]. It is pertinent to note that some satellites do not have propulsion systems (e.g. some very small satellites in LEO), for which CAMs may not be possible.

When *two active satellites* are involved in the same conjunction the situation is more complex given that coordination between two sets of operators may be necessary to avoid conflicting actions. Rules and communication protocols for these situations are currently lacking, and different operators have differing CAM procedures, as illustrated by a recent conjunction between a Starlink and OneWeb satellite in April 2021. In this example the Starlink satellite (operated by SpaceX) was operating using an automated collision avoidance system while the OneWeb satellite was being operated manually. Coordination between SpaceX and OneWeb resulted in SpaceX disabling the automated system so that the OneWeb satellite could perform its CAM safely [53]. Further development of protocols for the coordination of CAMs between operators will be needed as the space environment becomes more congested.

Depending on the satellite orbit and the warning thresholds defined, operators may receive anywhere from hundreds of conjunction warnings a year [4] to hundreds per week [11]. Clearly this can present a significant burden in terms of manual analysis and data management, particularly for satellites in the more crowded LEO region. With an increase in the numbers of satellites being launched, particularly as a result of constellations, the numbers of these conjunctions are expected to increase considerably. New companies such as *Neuraspace* (founded 2020) are developing STM solutions utilising Artificial Intelligence to help predict the probability of collisions and provide an automated collision avoidance service to operators, reducing the need for staff and confusion over who performs manoeuvres.

IV.4.3 Spacecraft passivation

Spacecraft passivation has been recognised alongside collision avoidance as being one of the most effective *short-term* means of reducing the space debris growth rate [50]. Passivation of spacecraft involves limiting the probability of post-mission accidental explosions by depleting internal 'stored' energy at the end of the spacecraft's life. This stored energy includes residual propellant stored in tanks, and power stored in the batteries. The process of passivation involves the venting of any residual propellant and depressurisation of tanks, the complete discharge of any batteries, and the inhibiting of any pyrotechnic devices.

The NASA ODPO Large Constellation Study performed in 2018 suggests that the rate of *unsuccessful* passivation (referred to in the study as 'accidental explosion probability') is expected to have a significant impact on the number of debris objects >10cm in LEO over the next 200 years. As shown in Figure 21, accidental explosion probabilities of 1/100 for large constellation (LC) spacecraft leads to a more than tenfold increase of the debris population in 200 years (top red curve), assuming a 90% rate of PMD compliance. However, when the accidental explosion probability is reduced to 1/1000 the population growth is approximately cut in half [29]. Once the probability is limited to this level, the debris population increase is primarily driven by the PMD compliance rate.

Notably, if large constellation spacecraft can achieve a combination of 1/1000 accidental explosion probability and 99% PMD compliance (not shown in Figure 21), their contribution to the future debris environment appears to be limited and acceptable.

Alongside collision avoidance, spacecraft passivation is one of the most effective short-term means of reducing the space debris growth rate.

IV.4.4 Spacecraft shielding

Impact resilience can be enhanced through the use of shielding that protects spacecraft from high velocity impacts of small debris. This shielding protects the spacecraft from damage and helps prevent fragmentation and creation of further debris. On manned spacecraft where resilience to impacts is of greater importance, dedicated shielding may be effective at

Figure 22 – Example of spacecraft shielding utilising a double-honeycomb panel design [54].

protecting against objects up to 1 cm in diameter [54]. This shielding can take the form of multiple thin bumper layers in front of the spacecraft structure, often referred to as a 'Whipple shield'. Such a design is intended to break up and disperse the incoming object, spreading its energy over a larger area which is then more likely to withstand it.

On unmanned spacecraft such as satellites, shielding is often restricted (for reasons of mass, volume, cost etc.) to simply enhancing the design of structural honeycomb panels and/or Multi-Layer Insulation (MLI) as shown in Figure 22. In this case the protection offered may be limited to objects up to several millimetres in diameter. Nevertheless, given the high number of objects within this size category, shielding can still be worthwhile.

Shielding is particularly recommended for the most vulnerable spacecraft surfaces e.g. those facing the direction of travel. Impact risk assessments may be performed during the spacecraft design phases using computer models to examine the benefits of different shielding options and to estimate structure penetration rates. Spacecraft survivability can also be improved by relocating vulnerable components and placing sensitive equipment behind existing structural components [54].

IV.5 Remediation activities

Remediation activities aim to reduce the risk from debris once it has been created, either by removing the debris from orbit or by changing debris trajectories before predicted collisions occur. The need for these activities is largely motivated by the potential for massive derelicts (see section I.1.3) to collide and create rapid increases in the space debris population (and particularly Lethal Non-Trackable 'LNT' debris). The three clusters of these objects in LEO each present a unique potential for LNT-generating events that are not being addressed by SSA, STM, or debris mitigation efforts [14]. Remediation activities however, such as those described in the following subsections, have the potential to reduce the risk associated with this

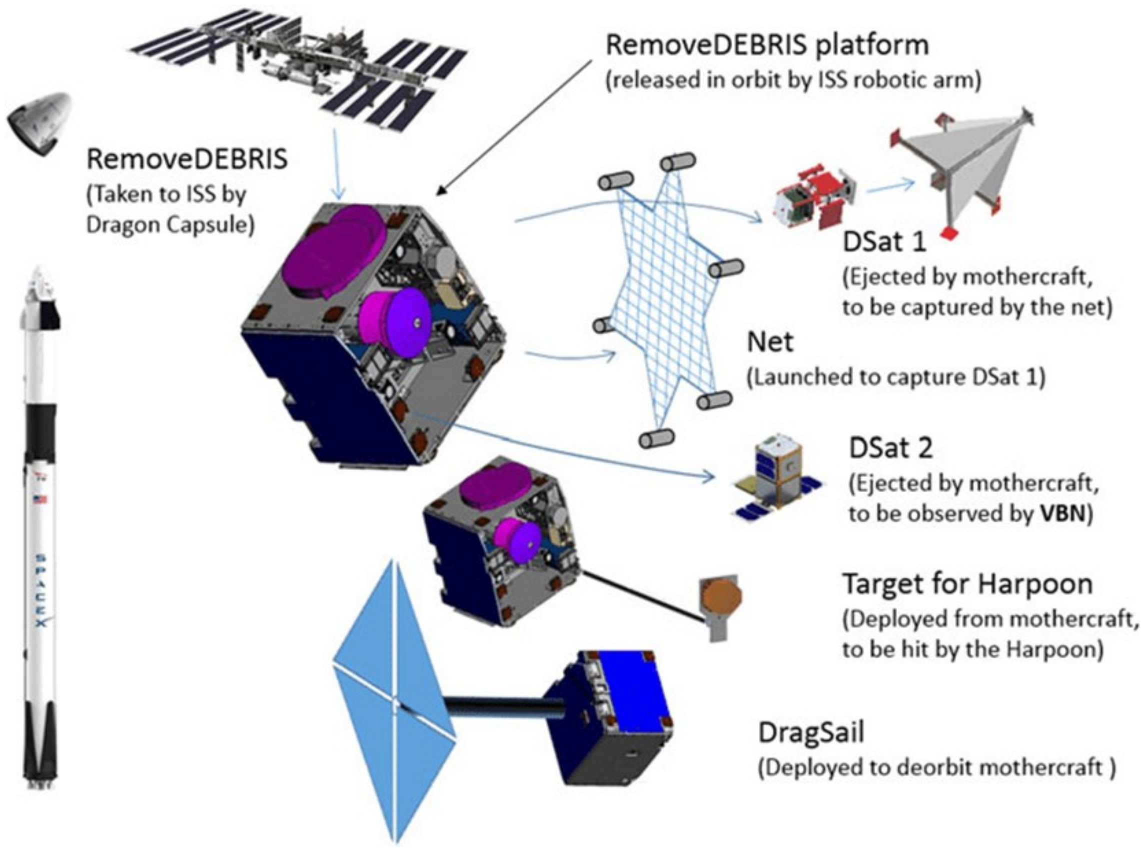


Figure 23 – Infographic of the RemoveDebris mission [55].

uncontrolled debris.

As of 2023 none of these activities are currently operational, however a number of companies are exploring their technological and commercial viability via demonstration missions.

Remediation activities are largely motivated by the potential for large objects to collide and create rapid increases in the debris population.

IV.5.1 Active Debris Removal

Active Debris Removal (ADR) involves the removal of debris from the space debris population using dedicated spacecraft that have been designed expressly for this purpose. Such spacecraft if commercialised would utilise a method of capturing a piece of space debris in-orbit before deorbiting it. Numerous methods of capture have been envisioned including the use of nets, harpoons, robotic arms, and magnetic docking plates.

The first mission to successfully demonstrate in-orbit some of these technologies was the *RemoveDEBRIS* mission in 2019; a collaboration between Surrey Space Centre, Surrey Satellite Technology Ltd. (SSTL), and Airbus Defence & Space amongst other partners. The mission consisted of a mini satellite platform that hosted the demonstration of four technologies (see Figure 23): a deployable net, vision based navigation system, space harpoon, and a drag sail. Both the net and the harpoon are technologies for the capture of debris, the vision based navigation is used for the observation of debris and determination of distance and spin rates, and the drag sail for accelerating the deorbit process at the end of life. Once in-orbit the platform released two CubeSats that acted as space debris targets for the net capture and vision based navigation demonstrations [55]. The mission was both a technical and PR success, raising awareness of the issue of space debris in the general public.

Founded in 2013, *Astroscale* is one of the first private companies dedicated solely to on-orbit servicing, EOL (End of Life) and ADR services. A distinction is made here between *EOL services* concerning the removal of objects that have been launched with a docking plate (DP) for semi-cooperative removal, while *ADR services* concern the removal of objects that do not have a DP and are fully non-cooperative [56]. In March 2021 the company launched its ‘End-of-Life Services by Astroscale demonstration’ (ELSA-d): the first demonstration of the full suite of capabilities necessary for a customer debris removal mission. These capabilities include client search, inspection, approach and rendezvous, capture (of both non-tumbling and tumbling targets), and disposal. ELSA-d consists

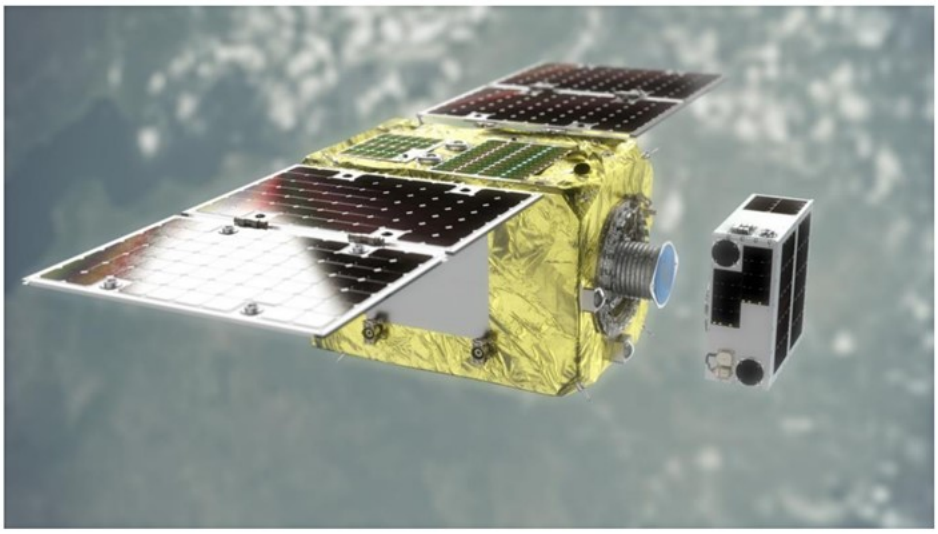


Figure 24 – ELSA-d recapture of client with servicer capture system extended [56].

of a 'servicer' and 'client' satellite, launched together. The servicer is equipped with proximity rendezvous technologies and a magnetic capture mechanism, while the client has a docking plate which enables it to be captured magnetically [56], see Figure 24. While ELSA-d aims to be the first such mission to demonstrate a full suite of EOL and ADR capabilities, it is also notable for having obtained a mission licence specifically for a debris removal mission, and for having pursued insurance for a mission of such complexity.

Beyond ELSA-d, Astroscale has also been selected for the first phase of an ADR project funded by the Japan Aerospace Exploration Agency (JAXA), which consists of sending a spacecraft (ADRAS-J) to inspect a discarded Japanese rocket upper stage [11]. This first phase is expected to be completed in 2023. If Astroscale is awarded a follow-on contract, the company will have until 2026 to capture and deorbit the upper stage.

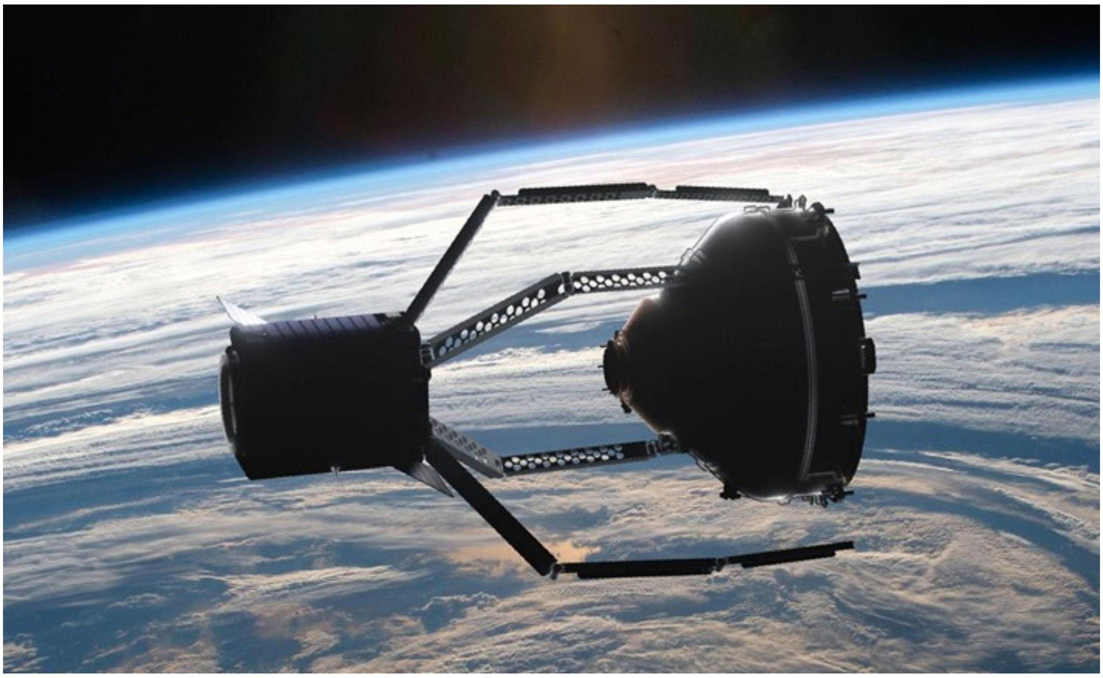


Figure 25 – ClearSpace-1 capturing the Vespa [58].

The first uncrewed removal of a derelict object is planned to be conducted by the *ClearSpace-1* mission, scheduled for launch in 2025 [11]. Led by the Swiss start-up *ClearSpace* that was founded in 2018, the mission was procured by ESA in 2019 to help establish a new market for in-orbit servicing and debris removal. The target is a 'Vespa' (Vega Secondary Payload Adapter) that was left in orbit following a Vega launch in 2013. Weighing approximately 100 kg, the Vespa is close in size to a small satellite. The ClearSpace-1 'chaser' will be launched into a 500 km orbit for commissioning and critical tests before being raised to the target orbit for rendezvous and capture using a quartet of robotic arms as shown in Figure 25. The combined chaser plus Vespa will then be deorbited to burn up in the atmosphere [57].

While each example of ADR development discussed in this subsection is focused on debris removal in the LEO region, studies have also been made of ADR in the GEO region, the 'Necropolis' study conducted in 2016 being one such example. This study was based on the premise that the current practice of relocating geostationary satellites to an unregulated 'graveyard' orbit (around 300 km above geostationary altitude) would in the long-term be unsustainable, given that as debris accumulates in this region itself the risk of collision increases. Instead, a system is proposed that collects uncontrolled satellites from the GEO and graveyard orbit environments and re-locates them to a permanently controlled storage facility in an inherently safe location, thereby removing them as a collision risk [18]. While the conclusions of the Necropolis study were very early and provisional it is clear that further development of ADR technology is needed, as solutions that work in LEO are not directly applicable to GEO.

IV.5.2 Just-in-time Collision Avoidance

Just-in-time Collision Avoidance (JCA) involves the deflection of debris trajectories in order to reduce the probability of a collision from occurring. As such, JCA is intended as a remediation activity when a collision between two space objects has been predicted and is deemed imminent. Various JCA methods have been proposed and are currently under study. These include the following:

Use of lasers to impart momentum on debris objects

Either ground or space-based laser systems would be used to target the debris with intense laser radiation. Exposure to this radiation would impart the necessary momentum to slightly modify the orbit of the debris and therefore avoid a collision. Alternatively, the lasers could be used to 'ablate' or vaporise the surface of the debris which in turn would generate a recoil effect. This again would modify the orbit sufficiently to avoid a predicted collision.

Generating a cloud of gas or particles in the orbital path of the debris

A small rocket launched from the ground or from an aeroplane would inject a cloud of gas or fine particles into the orbital path of the debris. On passing through this cloud a drag on the debris would be induced, and after a period of several orbits the trajectory of the debris would be sufficiently modified to avoid a predicted collision.

Upgrading derelict objects with collision avoidance capabilities via the use of "nano-tugs"

One or more nanosatellites referred to as "nano -tugs" would be deployed close to a derelict object and attach to its surface [11]. These nano-tugs could then use their own attitude control and propulsion systems to detumble the object and perform collision avoidance manoeuvres. In effect, such a system would enable massive derelicts to be "brought back to life from a collision avoidance and self-awareness perspective" [59].

In summary, it remains the case that none of the proposed JCA methods discussed above has yet moved to a demonstration phase. While each is expected to be a feasible method of providing a JCA service, technical and operational challenges remain. One of these is that most JCA methods assume that the accuracy of the ephemerides (tables giving the trajectories of the debris objects) is much better than observed today, typically by one or two orders of magnitude [59]. The current accuracy of large debris orbits is on the order of ±100's of metres in each dimension, while JCA systems may require much better accuracy on the order of metres.

V. Present Insurance Standpoint

There are two types of satellite insurance available on the market: First-Party, and Third-Party Liability (TPL). First-Party covers the value of the satellite (i.e. the asset) and is provided by the majority of space insurers. This insurance includes coverage for damage caused by collisions (whether it be with space debris or naturally occurring micrometeoroids) within the terms of a conventional all-risk policy. TPL on the other hand insures against damage caused by a space operator's asset to third-parties. Both First-Party and TPL are necessary to provide full coverage against all potential losses attributable to space debris, however as of 2023 many satellites are not insured and collisions with space debris are still considered a low-probability event.

V.1 First-Party insurance

Today's First-Party policies (also referred to as *launch and in-orbit* insurance) typically cover loss of or damage to the satellite due to collisions with space debris within the regular terms of the policy. Although the risk of collision with space debris has increased significantly over the last 20 years, this risk is still considered by the majority of insurers to remain low (and especially so in GEO). The main causes of insurance losses are either launch related or failures associated with satellite subsystems (e.g. power supply). An indication of the relative level of risk is that the probability of collision is still about two orders of magnitude smaller than that of technical failure [11]. As a result, premium rates are not currently driven by collision probabilities.

V.1.1 Recent events and specific risk considerations

Although the relative risk posed by space debris remains low, recent events (accidental collisions and intentional destructions, see section III) set against a backdrop of dramatic increases in the number of operational satellites (e.g. via constellations) have led many insurers to reassess their potential exposure. Some insurers have curtailed their exposures while others have withdrawn from insuring satellites in LEO altogether. Notably, the annual Lloyds RDS (Realistic Disaster Scenarios) specification lists space debris as one of four satellite risks to be considered by insurers for exposure management purposes.

Specific risk factors deserve consideration by insurers. For example, particular attention can be given to insureds operating in the most exposed orbital locations (see Figure 7 and section I.3). In common with single satellites, the First-Party policies for satellite constellations are all-risk; covering physical loss, damage, and failure. For LEO constellations however with multiple satellites orbiting the Earth multiple times a day, and with potential areas of concentration (e.g. over the poles, see section I.3.2), the collision risk can be more significant, warranting particular scrutiny from insurers.

It is pertinent to note that the majority of First-Party insurance exposure (in-orbit) is currently in GEO where the risk from space debris collisions is lower. Estimates suggest that only 6% of spacecraft in LEO have in-orbit insurance compared to nearly half of all GEO satellites [4]. Nevertheless, any significant worsening of the space debris population is expected to result in increased in-orbit insurance premium rates. A catastrophic incident incurring multiple losses may lead to rates being driven by collision probabilities, and potentially trigger the exit of insurers from the market.

> The risk of collision with space debris is still considered by the majority of insurers to be low.

V.2 Third-Party Liability

TPL is designed to address liability arising in two main areas:

1. *Damage to persons or property on the*

ground as the result of a failed launch or unexpected satellite re-entry.

2. *Damage occasioned in space*, such as the impact of self-generated debris on, or collision with, another satellite in-orbit.

While TPL covering the first of these areas is of most concern to the launch provider and in most cases will be required by law, TPL covering the second area is of more concern to the satellite operator and the requirement for it varies on the basis of the mission licence granting country (i.e. the 'launching state') and mission type.

V.2.1 Requirement for TPL

Some countries including the United Kingdom require most satellite operators to purchase TPL for the entire mission life while other countries such as the United States do not [4]. Notably the UKSA (UK Space Agency) introduced a new 'sliding scale' policy for in-orbit TPL in 2018, under which insurance requirements for low-risk missions (from the space debris point of view) may be reduced or waived, whereas operators planning a higher-risk mission may need to hold a greater level of insurance [4].

- Low-risk missions include smallsats deployed from or below the altitude of the ISS (International Space Station) at 400 km. Satellites at these very low, sparsely-populated altitudes (refer to Figure 7), with orbital lifetimes of less than a year and with few high-value assets nearby, would in most cases carry a negligible risk of third party damage [60].
- 'Standard' missions such as traditional GEO satellites or LEO satellites with proven propulsive systems are subject to an indicative TPL insurance requirement of EUR 60 million *per occurrence*. After an operator has launched a certain number of satellites, the UKSA may offer the operator the option to add an aggregate to their per-occurrence TPL policy [60].
- The highest risk missions such as a satellite launching into an orbit above 650 km with no propulsion or proven deorbit technologies, or a mega constellation without a robust and credible sustainability plan, would not be licensed by the UKSA given the threat they might pose to third parties in space.

While some large GEO satellite operators purchase TPL, many other GEO operators do not since they assess the risk of collision and resulting liability to other operational satellites as very low. The largest market for TPL therefore is in LEO, where the risk of collisions in-orbit is higher, and where satellites are normally deorbited at end of life. The requirements imposed by the launching state on LEO constellation operators in particular often include TPL with a 'deorbiting endorsement' to cover the deorbiting of the constellation up to a maximum insured sum. Again, this requirement is normally a response to the threat of liability being assumed by a government in its role or capacity as a launching state which it acquires under the terms of the Liability Convention of 1972 [8]. UK mission licences include an insurance requirement against TPL and separate indemnification of the UK Government for any claims which arise from the mission.

V.2.2 Challenges associated with TPL

From the perspective of many insurers, TPL for damage occasioned in space poses various challenges and as a result many chose to focus solely on First-Party insurance. These challenges include the lack of a clear legal framework regarding liability rules in the space debris context, a historical lack of claims, and the problem of assertion of liability. The historical lack of any claims under TPL due to space debris has kept premium rates low, and so insurers often need to write large numbers of policies in order to make it worthwhile. Given the low likelihood of claims and associated low rates, TPL pricing cannot induce risk-reducing behaviours. Assertion of liability in the event of a claim is difficult given the remote nature of space and challenges in determining the sources of debris and which of the two colliding objects should be held responsible.

These challenges have led the space industry to predominantly rely on First-Party insurance rather than TPL. Since an operator whose insured satellite is damaged by space debris will be protected by their own First-Party insurer, there is an element of justifying the need for TPL, particularly in light of the lack of claims. Although said First-Party insurer could potentially recover their losses by suing the entity responsible for the damage (right of subrogation), there is again the issue of assertion of liability. In addition there is much uncertainty about the legal framework on which such a recovery would rely [11]. First-Party only covers the value of the satellite, but an operator may also suffer from reputation damage and loss of customers. Therefore without TPL alternative sources of indemnification would need to be pursued.

Image credit: University of Warwick

Summary

The aim of this study has been to provide an overview of the state of knowledge in 2023 surrounding space debris. The bullet points below provide a summary of the key points of each section.

- In section I the classification and distribution of space debris was discussed.
  - The number of small objects in orbit far surpasses the number of large objects, a fact of some concern given that the small objects (and specifically Lethal Non-Trackable debris) are not trackable with today's technology.
  - Massive derelicts, pose a significant long-term risk given their high mass and therefore their potential to drive growth of the debris population and the future collision hazard.
  - LEO (Low Earth Orbit) has the highest collision probability of any orbital region, however absolute probabilities are uncertain, and there is disagreement amongst researchers particularly with regards to collision probability in GEO (Geostationary Earth Orbit).
  - Enhanced concentrations of debris exist in clusters of massive derelicts at specific altitudes, high inclination orbits in LEO, and geopotential wells in GEO.
- The models used by space organisations to simulate the space debris environment were described in section II.
  - NASA's *ORDEM* and ESA's *MASTER* are generally in agreement where there is good data (i.e. for large and medium debris), however there are differences in the flux estimates for smaller debris. These models suggest there is a higher flux of debris in LEO than there is in GEO by several orders of magnitude.
  - Other models such as *LEGEND* and *DELTA* show that the LEO debris population is expected to grow significantly in the long -term, with the rate of growth strongly dependent on factors including the level of PMD (Post Mission Disposal) compliance, occurrence of accidental explosions, and deployment of large constellations.
- In section III several examples of events involving space debris were presented.
  - Major events include deliberate actions (Anti-Satellite weapons tests) such as the destruction of Fengyun-1C in 2007 and Cosmos 1408 in 2021, while a prime example of the accidental collision of two large spacecraft is that involving Iridium 33 and Cosmos 2251 in 2009. Each of these events resulted in sharp increases in the space debris population, specifically in the LEO region and at high inclinations.
  - Many other events have occurred involving the collision of debris with active satellites, with impacts ranging from very minor (e.g. attitude disturbances) to severe (e.g. total loss of satellite).
- An overview of the varied responses to space debris was given in section IV.
  - Responses can be broken down into three main strategies: Space Situational Awareness (SSA), Space Traffic Management (STM), and Space Environment Management (SEM); the implementation of all three of which is necessary to effectively tackle space debris.
  - SSA includes the tracking of debris, however current tracking capabilities are limited and the public catalogue of trackable objects represents a tiny fraction of the total debris population.
  - Space debris guidelines lay out measures

that should be implemented to help minimise the generation of debris, however these are not legally binding and have seen limited levels of compliance.

- SEM incorporates both mitigation and remediation activities. Mitigation activities such as PMD, collision avoidance, and spacecraft passivation aim to prevent the creation of new debris. Remediation activities such as Active Debris Removal aim to reduce the risk from debris once it has been created.

• Finally in section V the present insurance standpoint on space debris has been discussed.

  - Two types of insurance are applicable: First-Party insurance, and Third-Party Liability (TPL).

  - Today's First-Party policies include cover for loss or damage as a result of collisions with space debris. Although the risk of collision has increased over the last 20 years, it is still considered low in relation to launch and component failure risks. Nevertheless, specific risk factors deserve consideration (e.g. the most congested altitudes in LEO), and some insurers are reassessing their exposure.

  - TPL is generally under-utilised by satellite operators, unless the launching state demands that it is purchased. TPL for damage occasioned in space poses various challenges including liability rules, a historical lack of claims resulting in low rates, and assertion of liability. These challenges have led the space industry to predominantly rely on First-Party insurance rather than TPL.

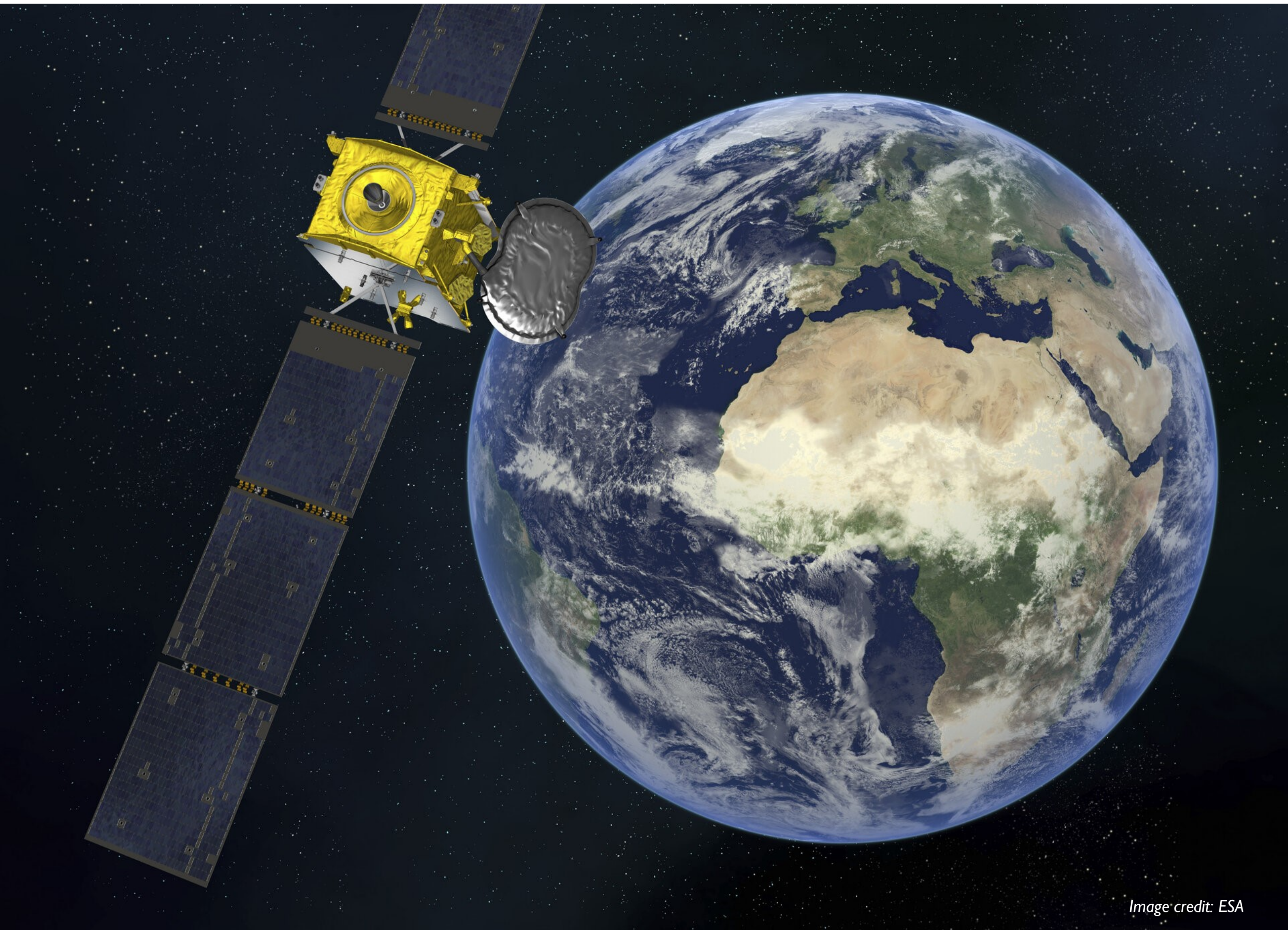


Image credit: ESA

Conclusion

The unhindered use of Earth orbits by satellites and other spacecraft is crucial for modern society. However the ever increasing space debris population threatens the future viability of these orbits. All stakeholders (regulators, manufacturers, operators, insurers etc.) must work together to implement actions that will stabilise the space environment and reduce the risk of catastrophic collisions. The need for a unified international policy is pressing given the rapid and continued growth in the number of spacecraft being launched, particularly as the result of LEO (Low Earth Orbit) constellation deployments.

While it is clear from this study that the risks to satellites from space debris are of growing concern, it is also evident that collision probabilities currently remain low. The probability of a collision involving a satellite in LEO is still about two orders of magnitude smaller than that of technical failure.

The consensus view is that collisions in GEO (where most First-Party insurance exposure is held) are less likely than those in LEO, probably by at least two orders of magnitude. However there is disagreement amongst researchers as to the absolute probability of collision in GEO, and hence uncertainty over *how much* less likely collisions in GEO really are. A clearer understanding of this is therefore needed, especially given that the majority of insurers exposure is via GEO satellites.

Simulations consistently predict that the LEO debris population will continue to increase into the future even with high levels of compliance with debris mitigation measures, and that the number of major collisions will also increase. The impact of large constellations has been studied by multiple groups, with most concluding that compliance with the current mitigation standards is a prerequisite to keep space activities sustainable in the long-term.

Notably, PMD has been identified as the most effective *long-term* means of stabilising the space debris environment, while spacecraft passivation has been identified as one of the most effective *short-term* means of reducing the space debris growth rate.

Risk factors that should be considered by insurers when evaluating their exposure to space debris related losses include the following:

- LEO
  - Satellites at an altitude with high levels of congestion such as those centred around 500 km and 800 km (see Figure 8), while at the same time being in a high inclination orbit. Each of these factors in isolation results in higher probabilities of collision.
  - Large constellations – these provide more opportunities for collisions and could in themselves be a source of future debris. Particular attention should be paid to PMD compliance, passivation, and collision avoidance procedures.
  - Clusters of massive derelicts that have the potential to generate large quantities of new debris. These objects have no capability and no intent to avoid collisions.
- GEO
  - Satellites located near or passing through the geopotential wells at 75°E and 105° W. Higher probabilities of collision exist at these locations and satellites that have lost East-West station-keeping ability are at risk of passing through them.
  - Inadequate levels of compliance with EOL reorbit guidelines (only two thirds of GEO satellites successfully reach a graveyard orbit).

- The relative lack of study that has been devoted to space debris in the GEO region, and the comparatively limited capabilities to track objects in GEO.

Recent years have seen technological progress in SSA tracking capabilities and remediation technologies such as ADR. Further progress however is required to address the tracking of smaller debris, and to demonstrate the feasibility of remediation activities. From the regulatory point of view, positive steps are being made at the national level in implementing policy solutions (e.g. the recent FCC 5-year PMD rule in the U.S., and requirement for TPL in the UK). Ultimately however, cooperation between states will be required to ensure all space debris guidelines are transformed into internationally binding regulations. In today’s world such cooperation may be in short supply, however it is for the benefit of all people that Earth orbits remain usable for commercial and scientific endeavours.

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