



# Small Satellite Constellations and End-of-Life Deorbit Considerations

Vitali Braun

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## Abstract

Space missions come with a huge potential to provide global services such as navigation or telecommunication. With decreasing cost to insert satellites into orbit and the further miniaturization, the currently observed launch traffic involves more and more small satellites. Global broadband Internet services delivered by large constellations consisting of thousands of small satellites have been proposed by several companies. Some of the first satellites were already launched. Space debris mitigation guidelines have reached international consensus more than a decade ago and are applied to current space missions. What do they imply for small satellites? And are they still valid for large constellations? If an increasing number of satellites are continued to be inserted into a constrained orbital region, would there ultimately be an issue with sustainability? Research over the past few years has provided some reassuring output that a way toward a sustainable use of outer space does exist – under the current mitigation guidelines and even with operational small satellite large constellations. But there are clear

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limits, and the international community is faced with an increasing level of responsibility to preserve the commonly shared resource space for future generations.

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**Keywords**

End-of-life · Sustainability · Long-term evolution · Mega-constellations · Disposal · Space debris

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## 1 Introduction

Having achieved the objectives of their satellite mission and barring any mishap before that, any owner or operator is facing the challenge in the inescapable transition from the operational to the disposal phase, assuming that any potential extension of the operational phase has already been applied before. The disposal phase is the time interval during which a satellite completes its disposal actions, with the main objective of permanently reducing its likelihood of a future accidental breakup and to achieve a required long-term clearance of the *protected regions* it had been crossing or operated in ISO (2019). Possible disposal actions range from doing nothing at all; maneuvering the satellite such that it doesn't interfere with any protected region in the near future; targeting a faster orbit decay, for instance, by maneuvering to a lower altitude orbit in the low Earth orbit (LEO) region; targeting an atmospheric reentry with a well-defined impact footprint on the Earth's surface (controlled reentry); to attempting a retrieval of the satellite and a subsequent recovery on Earth, the latter surely being the most expensive option.

Certainly, the *do-nothing-at-all* option after the operational phase results in the lowest direct cost associated with a single satellite mission and may even come with a strong incentive in an intensely competitive market or where missions are selected on a lowest price scheme only (Schaub et al. 2015; Adilov et al. 2013). This is also the case when a satellite is essentially operated until it no longer responds. But any satellite launched into Earth orbit will immediately find itself in company with other active missions, derelict spacecraft, spent upper stages, as well as space debris sharing the very same environment. Leaving a nonoperational satellite in that environment results in an additional potential collision partner for other active satellites, which would be perceived by them as a further operational burden. Even worse, a satellite, after end-of-life and remaining in space for years, or maybe even decades or centuries, may suffer a breakup resulting in hundreds to thousands of fragments lethal to other missions, with Titan Transtage breakups near the geosynchronous region being prominent examples. Left in orbit and potentially approaching an atmospheric reentry in an uncontrolled way, a satellite may also pose a risk to people or infrastructure on ground even many years after its operations have ceased.

In this chapter, today's space environment is described with a focus on orbital regions of interest based on certain applications satellite missions have been

designed for. The historic evolution of the space environment and the number of objects on orbit serves as an indication how individual actors, policy decisions, applications, and events (like explosive breakups) continue to shape that environment. With the proliferation of space debris, we put the safe operation of satellites in space and the valuable services they provide at risk. Space debris environment evolution models provide the means to study possible future scenarios. In many different recent studies, the impact of future launch traffic on the space debris environment, involving small satellites and potential large constellations thereof, has been addressed and will be summarized herein.

The rationale for space debris mitigation actions results from such analyses, and environment evolution models allow to evaluate the efficacy of different mitigation strategies. This ultimately leads to the discussion of methods to assess the impact of a given mission on the space debris environment. Perceiving the near-Earth space environment as finite, it is only reasonable to address the idea of a *capacity*, essentially leveraging a satellite-specific environment criticality index to a maximum number of objects a certain environment or orbital region can accommodate during a time period in a sustainable way.

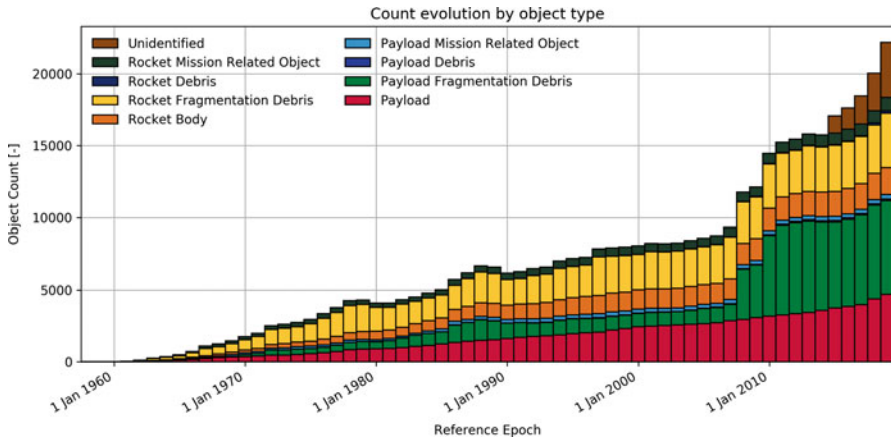
Given that our society today heavily relies on the complex infrastructure in space and assuming that this technological dependence is very likely to intensify in the future, we clearly have to address the sustainable use of the resource space in order to ensure that future generations may likewise benefit from space.

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## 2 The Space Debris Environment

In March 1958, the satellite Vanguard 1 was launched into low Earth orbit (LEO). Having a mass of only about 1.5 kg, the small satellite conducted a very successful scientific mission improving our knowledge in the areas of geodesy and atmospheric research. Operations ceased in May 1964 when Vanguard 1 turned to a derelict spacecraft in an 4000 km × 650 km orbit with a remaining orbital lifetime of a few centuries. Today, it is the oldest human-made object in Earth orbit, sharing that environment with about 19,800 objects (space-track.org 2019), which consist of active and derelict satellites, rocket bodies, and other space debris. But Vanguard 1 is not the only example of a historic signature in today's orbits, which is why understanding our current space environment and, maybe even more importantly, discussing any potential future scenarios are inevitably linked to events and decisions in the past which shaped that environment.

The evolution of the number of on-orbit objects is shown in Fig. 1. After more than 5800 launches and 530 debris-generating events (ESA Space Debris Office 2019), the catalogued orbital population today is clearly dominated by nonfunctional objects, with only about 10% thereof being active satellites (Union of Concerned Scientists 2019). While fragments from explosive breakups of rocket bodies have had the major share in the orbital population since 1961, the situation has distinctly changed after the Fengyun-1C anti-satellite test in 2007 and the collision between Kosmos-2251 and Iridium 33 in 2009, adding in total more than 5700 debris



**Fig. 1** Count of number of objects in orbit for different object types (<https://discosweb.esoc.esa.int>, as of August 23, 2019. ©ESA 2019)

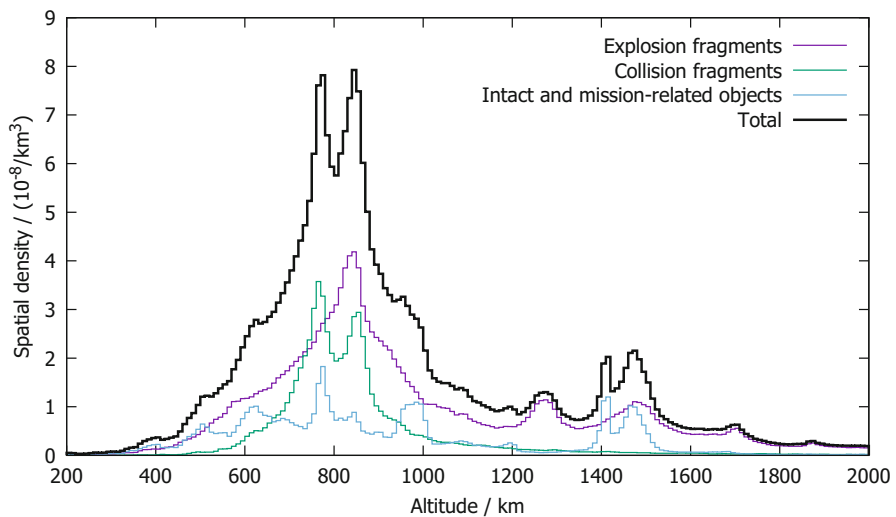
fragments. There is one more notable feature in Fig. 1, namely, the objects labelled as *Unidentified* which appear as part of the population since 2015. Those are not new objects but mostly the result of a combination of data coming from two different entities: the satellite catalogue (SatCat) maintained by the US Air Force’s 18th Space Control Squadron (18 SPCS) and the catalogue provided jointly by the JSC Vimpel Interstate Corporation and the Keldysh Institute of Applied Mathematics (KIAM). Many of the objects in the Vimpel catalogue are correlated to the ones from the SatCat, but there is a remaining subset of objects, mainly in higher altitude orbits, which have not found their way into the US catalogue. Moreover, as their origin could not be determined, they remain categorized as unidentified for the time being which, in fact, is also true for a few objects in the US catalogue.

Evidently, no single catalogue can ever claim completeness, and the object count evolution in Fig. 1 is only referring to the subset of objects we are able to monitor continuously via ground-based observations, limited by observability constraints and sensor sensitivity. The numbers in Fig. 1 are often referred to in literature as on-orbit objects larger than 10 cm, which more or less reflects on current sensor limits. Space debris models, such as ESA’s Meteoroid and Space Debris Terrestrial Environment Reference (MASTER), provide a comprehensive picture of the environment given the evidence we have. In its latest version (available from <https://sdup.esoc.esa.int>), the MASTER model counts about 34,000 objects larger than 10 cm at the reference epoch of November 1, 2016. By modelling known debris-generating events and calibrating them with actual measurements (Braun et al. 2019), MASTER provides us with estimated object numbers as if we were unaffected by observability and sensitivity limits.

Being designed to fulfil a specific mission, operational satellites have been launched to orbits that accommodate best for the given mission objectives. As those satellites and their associated rocket upper stages are the main source for any

debris generated, it does not come as a surprise that the distribution of space debris more or less follows the one of their progenitors, at least for larger objects sizes. Figure 2 shows the spatial density, that is, the number of objects per volume element of one cubic kilometer, as a function of the orbital altitude in LEO for objects larger than 10 cm according to MASTER. The most congested altitude band is between 700 and 900 km. It is the preferred region for Earth observation satellites and a typical choice for Sun-synchronous orbit missions. Clearly visible are the two distinct peaks in the collision fragments from the Fengyun-1C (at about 850 km) and the Kosmos-Iridium (slightly below 800 km) events, both of which occurred in the very same congested region. The spatial density shows a steep decline toward lower altitudes due to increased atmospheric drag which acts against the direction of motion, thereby lowering the objects' orbital altitude over time and effectively acting as a natural sink mechanism for the space debris environment.

The increasing number of objects in Earth orbits has a major impact on the operation of satellites. Over the past few years, collision avoidance has become a standard process for any maneuverable satellite in LEO, for example, ESA's Space Debris Office reports on 27 collision avoidance maneuvers (CAMs) in 2018 conducted by 8 satellites (Braun 2019). Taking the entire LEO satellite fleet operated by the European Space Operations Centre (ESOC) into account, an average number of one to two CAMs are required per year and per spacecraft (Braun 2019). An ESA study concluded that each avoidance maneuver can be associated with an overall cost of approximately EUR 25,000 (Krag et al. 2018). Extrapolating this number to about 580 alerts above the maneuver threshold, assumed to occur annually in LEO, results in a potential yearly damage of EUR 14.5 million (Krag et al. 2018).



**Fig. 2** Spatial density in the LEO region for objects larger than 10 cm according to the MASTER model on November 1, 2016. (©ESA)

The consequences of a collision can be manifold. A widely accepted criterion to assess whether an impacting object is lethal or not is the energy-to-mass ratio for that event: if the kinetic energy of the impactor divided by the mass of the target satellite is above 40 J/g, it is generally considered a catastrophic collision resulting in a complete fragmentation of the target satellite (McKnight 1991). For instance, an aluminum sphere of 10 cm diameter hitting a 1500 kg LEO satellite with a typical impact velocity of 10 km/s results in an energy-to-mass ratio of about 50 J/g. The higher the impact velocity, the smaller a lethal object can be. This became quite evident in August 2016, when Sentinel-1A was hit by an impactor of about 1 cm in size (Krag et al. 2017) into its leading solar array wing. A picture taken by an onboard camera confirmed a 40 cm impact feature that also explains the permanent power loss of about 5% for the mission. The MASTER model estimates about 900,000 objects larger than 1 cm, and a flux analysis for the Sentinel-1A orbit reveals that the annual probability of an impact with objects larger than 1 cm is about 6%. The Sentinel-1A mission survived this impact without major consequences. Certainly, if the main body would have been impacted, the outcome could have been significantly worse, ranging from the loss of components over subsystems up to the entire mission. However, it is not only the individual mission affected after such an event. The Sentinel-1A event resulted in a total number of seven tracked fragments, which also appeared as chasers (or secondary objects) in the regular collision avoidance screenings of other ESA satellites. With even higher numbers of fragments, the effects will be non-negligible in the operations of other missions: the fragments of the Fengyun-1C and the Kosmos-Iridium event combined make up about 40% of all conjunction events (where the collision probability went above  $10^{-6}$ ) for the satellites screened by ESA's Space Debris Office since 2015.

The effect of collision fragments triggering new collisions and potentially leading to a self-sustained growth in the object numbers has been described by Kessler and Cour-Palais (1978) and became known as the *Kessler syndrome*. It basically means that if in a certain region a critical density of objects is reached, the self-sustained cascading effect would further increase the density without even adding new objects into that orbital region through new launches. This has been confirmed by more recent long-term environment evolution studies (e.g., Liou 2011), where even a future no-launch scenario resulted in an overall orbital population growth due to mutual collisions. The time when this tipping point had been passed was estimated to be in the 1990s (Bastida Virgili and Krag 2011). It is therefore likely that the conditions for a self-sustainable growth are already met in the altitude band between 700 and 900 km and remediation measures, such as active debris removal, might be required to stabilize that region in the future.

The threat posed by the space debris environment, as outlined above, has been recognized as critical by the international community during the 1990s. With officially establishing the Inter-Agency Space Debris Coordination Committee (IADC) in 1993 and culminating in the adoption of the United Nations Technical Report on Space Debris in 1999 (United Nations (UN) 1999), the way toward an international consensus on space debris mitigation had been paved.

### 3 Space Debris Mitigation

The IADC Mitigation Guidelines (IADC 2007) have been endorsed by the UN General Assembly in 2007 and formed the required international consensus as the basis for subsequent standardization (e.g., ISO-24113:2011) and adoption into national laws (UNCOPUOS 2019a). The main intent is to reduce short- and long-term space debris generation via dedicated mitigation measures. As of today, the only discrimination made is between launch vehicles and spacecraft, which means that all mitigation measures apply equally, whether the mission is public or private, whether it is a large scientific satellite or a tiny *femtosat*.

For satellites in any orbital region, the mitigation guidelines entail to limit the release of debris and minimize the breakup potential during normal operations, to limit the probability of accidental collision with known objects, and, after end-of-life, to passivate the satellite and limit its presence in either the LEO or the GEO protected regions. The *LEO protected region* is defined as the spherical region that extends from the Earth's surface up to an altitude of 2000 km, whereas the *GEO protected region* is a segment of the spherical shell defined by the altitude band between 35,586 and 35,986 km (geosynchronous altitude  $\pm 200$  km) and latitudes between  $\pm 15$  degrees with respect to the equatorial plane (IADC 2007).

Even though there are some small satellites (<500 kg) that are launched into geosynchronous orbits, those typically have a few hundreds of kilograms of mass. The vast majority of satellites, especially with a mass below 100 kg, are launched into the LEO region. For instance, for the nano-/microsatellites in the range between 1 and 50 kg, less than 2% of those are expected to go beyond the LEO region in the projected period from 2019 to 2023 (SEI 2019). Therefore, the focus in the following will be on LEO missions.

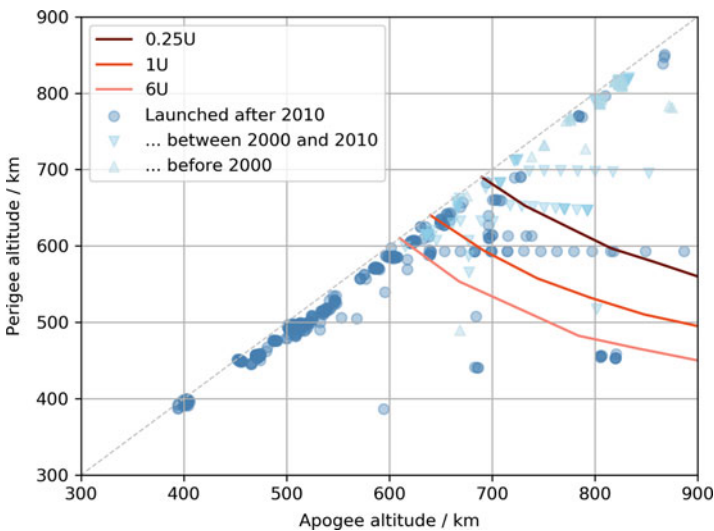
The disposal phase for any satellite mission in LEO consists of two major steps: limiting its presence in LEO to a maximum of 25 years followed by a passivation of the spacecraft. The so-called *25-year rule* has been accepted based on long-term environment evolution analyses (see also next paragraph) showing an acceptable future trend in the orbital population. For satellites without any maneuvering capability, and therefore lacking the means to avoid collisions, it is understood to set the starting point of that 25-year period already at the time the object is inserted into the environment, whereas for maneuverable satellites that period starts only after the end of the mission. Several options to accomplish the removal of a satellite from the LEO protected region exist and are given in order of preference in ISO (2019):

1. Retrieving it and performing a controlled reentry to recover it safely on the Earth
2. Maneuvering it in a controlled manner into a targeted reentry with a well-defined impact footprint on the surface of the Earth to limit the possibility of human casualty
3. Maneuvering it in a controlled manner to an orbit with a shorter orbital lifetime that is compliant with the 25-year rule
4. Augmenting its orbital decay by deploying a device so that the remaining orbital lifetime is compliant with the 25-year rule

5. Allowing its orbit to decay naturally so that the remaining orbital lifetime is compliant with the 25-year rule

Unless any of the first two options is selected, a passivation of the satellite is required. In general, this implies that the satellite design already foresees measures to permanently deplete all remaining onboard sources of stored energy, such as discharging batteries and making sure they do not recharge again, venting pressure vessels and safe or stop any moving parts like momentum wheels or flywheels.

With retrieval or targeted reentries being very uncommon disposal options for small satellites, the general approach is to launch them into sufficiently low orbits which would comply with the 25-year rule through natural orbital decay. Alternatively, if there is maneuvering capability or the option for orbital decay augmentation after end of mission, for instance, via drag sails, higher altitude orbits can be selected. A more detailed set of recommendations, specifically for small satellites, is provided by IAA (2019). Figure 3 shows the destination orbits (by perigee and apogee altitude) of small satellites with mass below 50 kg. Obviously, the more recent launches tend to put small satellites into lower orbits, but this cannot be attributed to the parallel development of space debris mitigation guidelines alone: it is rather the fundamental change in how small satellites are being launched. The first missions had to find opportunities for piggyback launches, where the primary payload would determine their orbit. It shouldn't come as a surprise that many of those first missions had been injected into typical orbits Earth observation satellites



**Fig. 3** Destination orbits according to ESA's DISCOS database for on-orbit satellites (as of September 2019) with mass below 50 kg. Altitude limits for a natural orbit decay within 25 years (simulated with ESA's DRAMA/OSCAR tool) indicated for 0.25 U, 1 U, and 6 U CubeSats, for randomly tumbling EOL attitude and a mass of 0.25, 1, and 6 kg, respectively. (©ESA)



occupy, for instance, in Sun-synchronous orbits around 800 km. With ride shares and especially dedicated small satellite launches becoming a reality in the last few years, the picture has clearly changed. From a space debris mitigation perspective, this can be called a positive trend (if launch providers apply the available mitigation standards and guidelines), which is also confirmed by ESA's latest environment report (ESA Space Debris Office 2019): for satellites with a mass below 10 kg, the LEO lifetime compliance has increased from 70.9% to 77.6% over the course of 10 years (2000 vs. 2010). Moreover, looking at the small satellites below 50 kg, as displayed in Fig. 3, it can be said that for all launches since the year 2000, about 26.4% of the satellites currently on orbit have a lifetime beyond 25 years. For those launched since 2010, that number drops to 16.0% and for objects launched since 2015 even to 6.7%. Figure 3 indicates the altitude limits for three different types of CubeSats below which a compliance with the 25-year rule through natural orbital decay can be expected. For near-circular orbits, this threshold is typically around 600 km but depends on the specific satellite design, its assumed attitude mode after disposal, and the applied solar activity forecast method the estimated lifetime is susceptible to. There are many uncertainties in the lifetime estimation process and thus in the compliance verification of any end-of-life disposal plan. Nevertheless, commonly accepted methods and processes on how to perform such analyses have been established, for instance, on ISO level (ISO 2016), and form the basis for tools used by agencies, industry, and academia worldwide in early mission design phases, such as NASA's DAS (Liou et al. 2019), CNES' STELA (CNES 2019), or ESA's DRAMA software (ESA 2019).

The preference of lower altitude orbits comes with another advantage in view of the small satellite failure rates that are still rather high with 42.6% of all launched small satellites between 2009 and 2016 showing either partial or total mission failure (Jacklin 2019). With access to space becoming more affordable, many new entrants come with a generally lower experience in space hardware compared to traditional entities. In addition, shorter design and development cycles do not necessarily imply a positive effect when it comes to reliability. It does not mean that granting everyone access to space is something bad – rather the contrary. But from a perspective of a sustainable space debris environment, it is preferred to have such missions in altitudes where they would naturally comply with guidelines and failure can thus be an option. In other words, if reliability is difficult to assess for any newly developed system, a recommendation could be to go to higher altitude orbits only after a certain design has been proven to work, for instance, via a precursor mission or a checkout in a low altitude orbit.

While the reported failure rates apply to single small satellite missions, the situation might be completely different for small satellite constellations. If a constellation operator can demonstrate a subset from the envisaged constellation working flawlessly, it might be reasonable to assume that the entire fleet would operate with a high success rate, given the identical satellite design. But what is a sufficiently high success rate given that today's mission to deploy large constellations typically targets orbital altitudes around 1000 km? Any satellite failing at those altitudes would remain in the environment for centuries or even millennia. It

is therefore crucial to address the environmental impact any large constellation deployment may have and to carefully design the required end-of-life strategy (IADC 2017).

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## 4 Small Satellite Constellations and the Future of the Environment

The concept of satellite constellations has been around since the beginning of space flight, where a group of similar satellites would be used to achieve a certain objective in areas including navigation, telecommunication, meteorology, Earth observation, and reconnaissance. While most of the historic and operational constellations would typically consist of dozens up to a few hundreds of satellites, a rather recent development is to provide low-latency global broadband Internet services through a space-based infrastructure consisting of thousands of small satellites. A very high number of satellites, in a large constellation, are required to obtain a global broadband coverage, whereas the low-latency requirement would demand a deployment in lower altitudes. The most prominent examples include:

- Project Kuiper by Amazon, proposing a constellation of 3236 satellites in LEO according to a filing with the FCC on July 4, 2019.
- The first six satellites were launched in February 2019, but this system has currently declared bankruptcy.
- SpaceX's Starlink constellation consisting of 4425 up to 11,943 satellites, with a first batch of 60 satellites launched in May 2019.

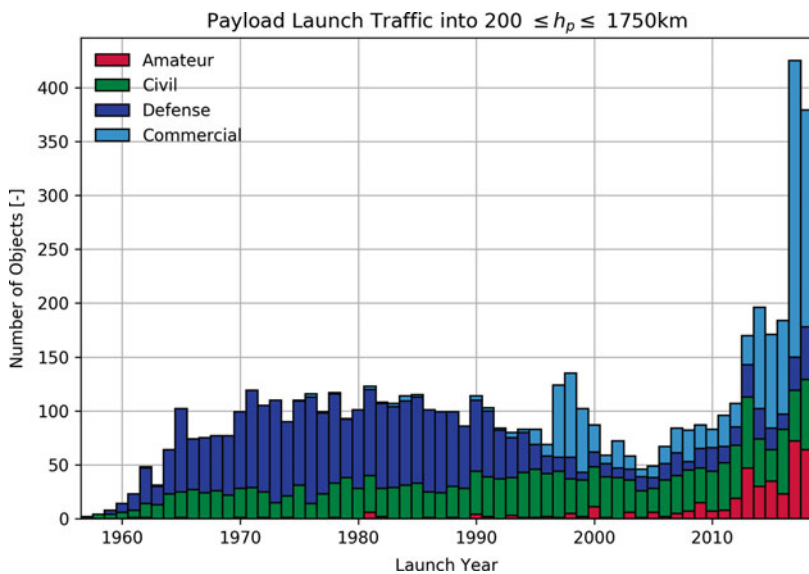
Even though the potential impact of satellite constellations on the space debris environment has been subject of study long before the announcement of any of the abovementioned large constellations (e.g., Anselmo 2001), the current space debris mitigation guidelines are based on the outcome of long-term environment evolution projections without foreseeing any distinct constellation deployment in the models. It was therefore only reasonable that concerns had been raised on whether the recommended mitigation practices were sufficient to limit the growth of the on-orbit population given that thousands of new satellites may become part of that environment very soon. Therefore, several investigations were initiated, mainly involving researchers with capabilities to run long-term environment evolution studies, and coordinated on IADC level, in order to show how a potential future with large constellations in orbit might look like and to provide further technical input to the ongoing policy and guidelines discussions on long-term sustainability. It is important to understand that one does not even get close to predicting the future of the environment with any of the available models. However, if reasonable assumptions are being made and there is an international consensus on the modelling approach, then it is possible (and in fact being done) to base policy decisions on the outcome of such studies. They do not provide credible estimates on the exact total number of objects the population is going to have at a certain point in time, but

they allow studying the relative effects when certain mitigation measures are introduced. As an example, the 25-year rule reached consensus after the simulation results obtained by different entities had shown a limited growth of the environment – compared to a reference scenario without disposals in LEO that showed an exponential increase in object numbers indicative of a collisional cascading runaway situation.

Before discussing the outcome of the recent studies on the effects of large constellations, it is important to understand the modelling approach and the assumptions typically made in such simulations in order to ease the interpretation of the results and to be aware of the various uncertainties and the sensitivity of certain parameters.

The first step is to select a reference population representing the current space debris environment. At IADC, as an input to the studies on large constellation, it was agreed to select the MASTER reference population from January 1, 2013 for all objects larger than 10 cm (about 20,000 objects in LEO). The size threshold means a trade-off between those objects relevant for the simulation, i.e., being lethal in a sense of potentially causing catastrophic breakups, and the required computational resources. For the selected objects in that population snapshot, the orbital evolution can be computed until any given point in the future. Typically, projection spans between 100 and 200 years are foreseen.

As new satellites are certainly going to be launched in the future, the next inevitable step consists of defining a launch traffic model. Figure 4 shows the launch traffic to the LEO protected region until 2018. While civil and defense missions were



**Fig. 4** Payload launch traffic to the LEO protected region (ESA Space Debris Office 2019). ©ESA 2019)

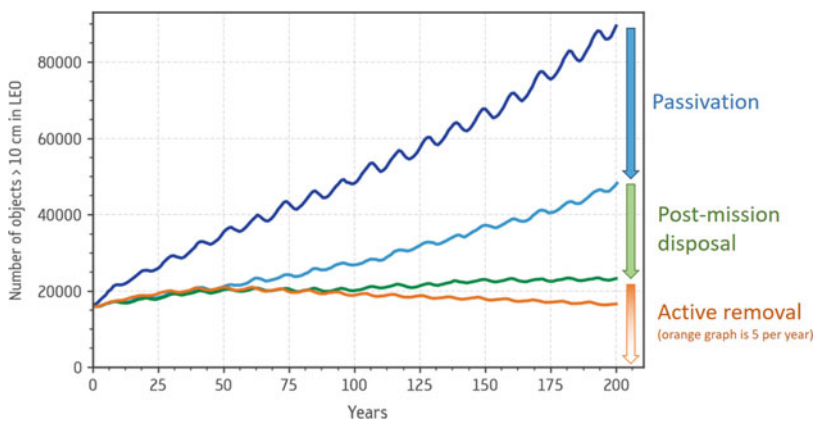
predominant until the early 1990s, amateur and especially commercial missions initiated the paradigm change toward what is referred to as *NewSpace* today. A researcher in 1985 might have perceived a very comfortable situation observing that there was a launch record of roughly 100 satellites per year into LEO for the past 15 years and even a more or less stable share between defense and civil missions. It would have been a reasonable assumption back then to say that things might remain like this for quite some time and therefore to assume a stable launch rate of 100 satellites per year for the future evolution studies they had envisioned. The same researcher 30 years later would be faced with a certain issue: seeing the commercialization, the trend toward smaller satellites, new launch opportunities (ride shares and dedicated small satellite launches), and the announcements made on a possible deployment of large constellations, it is a rather daunting task to make any launch traffic projections, especially for a 100-year time horizon. In past IADC activities, it was generally assumed that the launch record of 8 years may be concatenated to cover the projection span. For instance, when using the IADC 2013 population, the launch record from 2005 to 2012 would be taken such that all launches in the future resembled the very same activity, with only a decent jitter applied to the orbital elements of each payload newly added to the simulation. However, the launch activity between 2005 and 2012 was substantially different from what we see today, especially if market forecasts (e.g., SEI 2019) are taken into consideration, which rather confirm the trend of several hundreds of satellites launched into LEO in the coming few years. In order to account for this effect, many researchers have augmented their models to follow the 2005–2012 cycle and superimpose a trend derived from recent small satellite launches and current market forecasts.

The launch traffic model adds objects to the environment generally assumed to be operational for a certain period, where either they would have no orbit control and thus follow a natural orbit evolution due to external perturbations or they would perform station-keeping and/or collision avoidance maneuvers. In the latter case, it can be assumed that a satellite would successfully avoid any potential collision while it is operated. After its operational phase, that satellite would join the set of objects that are susceptible to collisions and at any simulation step be evaluated by the breakup event model. As an example, the model would check whether at any given time step two objects share the same volume element in space. If this is the case, a collision probability for that encounter would be obtained, and, based on the result, a collision may be triggered or not. In the former case, a breakup model (very common is NASA's Standard Breakup Model EVOLVE 4.0 (Johnson et al. 2001)) would generate fragments of a given size, area-to-mass ratio, and velocity increment, which are subsequently added to the population. The breakup event model would also be used to trigger explosive fragmentations, generally applied to the subset of on-orbit rocket bodies. Again, one may take the history of on-orbit explosions and extrapolate a trend for the future, but then it is also reasonable to assume that passivation would be successfully applied to all future launchers and at a certain point no explosive breakups would occur any more. The latter approach is sometimes preferred to better isolate and compare mitigation measures in a collision-driven growth of the environment.

With the assumptions made above, one simple reference scenario can already be created without any post-mission disposal (PMD) measures so that both satellites and rocket bodies are left on their orbits after their mission. Mitigation activity is added to the model and includes passivation, PMD, and active debris removal (ADR) measures. An exemplary simulation output is shown in Fig. 5. Without any mitigation measures, a nonlinear increase in the number of objects in LEO can be observed, which effectively means that catastrophic collisions would occur more frequently over time – a prerequisite for a collisional cascade. With passivation alone, the number of objects after 200 years is already halved, but a nonlinear trend is still discernible. Adding PMD (with a success rate of 90%) on top leads to a still growing population. Finally, a complete remediation of the environment could, in theory, be achieved by ADR depending on the rate of objects being actively removed from the environment. In Fig. 5, an example is given for five satellites being actively removed per year.

Having established a reference scenario for the background population without any deployment of large constellations, the effect of inserting thousands of small satellites into distinct altitude bands can now be studied relative to that scenario. A generic large constellation was devised in Bastida Virgili and Krag (2015), with a total of 1080 active satellites at 1100 km altitude, and distributed in 20 orbital planes with an inclination of 85 degrees. The full set of model parameters from that study is given in Table 1.

Several operational and end-of-life options were considered to see what the impact on the environment might be, measured in the total number of objects and the cumulative number of catastrophic collisions after 200 years. In addition, the obtained graphs provide additional information whether there is an indication of a runaway situation or not. It was observed that the PMD success rate appears to be the most sensitive parameter, as shown in Fig. 6 for the mean environment evolution trends from a detailed Monte Carlo analysis. The impact of a large constellation can



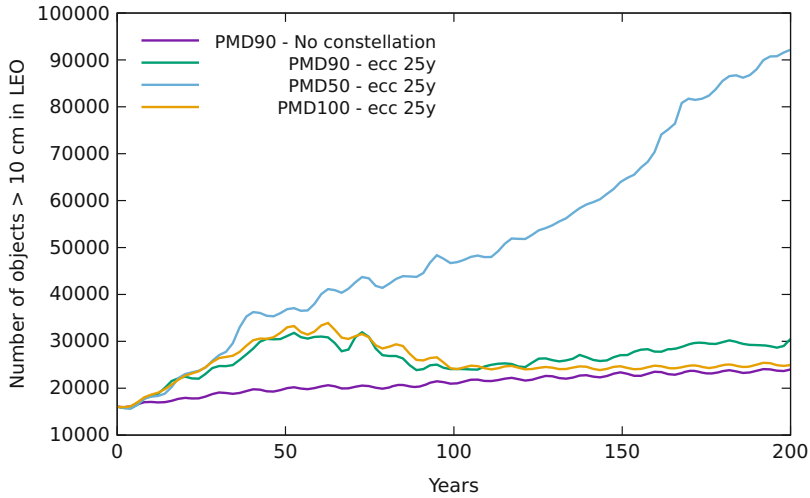
**Fig. 5** Example for the evolution of object numbers (> 10 cm) in LEO over 200 years for different mitigation strategies. (©ESA)

**Table 1** Simulation parameters for a generic small satellite mega-constellation in Bastida Virgili and Krag (2015)

Parameter	Value
No. of satellites	1080
Orbital altitude	1100 km
No. of orbital planes	20
Orbit inclination	85 deg
Mass per satellite	200 kg
Average cross section	1 m <sup>2</sup>
Full operational capability	2021
First launch	2018, with 20 launches/year until 2021
Operational lifetime	5 years
Replenishment	12 launches/year
No. of satellites per launch after 2021	18
Upper stage behavior	Immediate reentry after satellite release
Mission-related objects released	None
Collision avoidance	Yes
Constellation lifetime	50 years
End-of-life strategy	Lowering only perigee altitude such that remaining lifetime is <25 years
Background population	MASTER reference population from May 1, 2013; launch traffic 2005–2012
Background population PMD success rate	90%
Explosions	None

essentially be separated into three parts: a steep increase in the on-orbit object population during the constellation buildup and replenishment phases; followed by a period of a decreasing population while the remaining satellites after disposal are still on their decaying orbits; and, finally, a long-term, gradual increase in the population due to collisions involving long-lived, failed constellation satellites.

Assuming a 100% success rate for the disposal of constellation satellites, it is even possible to return to an environment where there would be basically no sign that a constellation ever existed (magenta graph). Applying the same PMD success rate as for the background (90%), a notable difference is observed after 200 years, but the trend (green graph) is very similar to the background population, and also the growth rate is on the same order, so that one could call such a scenario acceptable. In fact, later studies (e.g., Bastida Virgili et al. 2016a) introduced a Wilcoxon rank sum test to show that the null hypothesis of a nonexistent long-term impact had to be rejected (at a 5% significance level) for PMD success rates below 95%. Further reducing the PMD success rate leads to an increase of the object growth rate in LEO after the constellation lifetime, as shown for the 50% case in Fig. 6 (blue graph). In that case, it is already very obvious that the constellation has a long-term impact on the environment. It should be emphasized that Fig. 6 is only showing the mean trends.



**Fig. 6** Evolution of the number of objects in LEO varying the PMD success rate for constellation satellites. (Bastida Virgili and Krag 2015. ©ESA, 2015)

Other representations included the assessed uncertainty from the different Monte Carlo runs and showed that variations from that mean can be quite high, even though they do not contradict the interpretation given here (Bastida Virgili et al. 2016a). A high PMD success rate is therefore required, as otherwise many failed satellites will end up stranded in the constellation’s operational altitude and suffer from collisions at some point. Another finding was a positive correlation between the constellation lifetime and the PMD success rate: increasing the former demands to be more successful in the disposal phase in order to end up in similar scenarios after the constellation has ceased.

More detailed analysis followed later, after the initial identification of significant parameters for the long-term impact on the environment had been made, e.g., (Bastida Virgili et al. 2016a, b). Combining the results of different environment evolution models, it was confirmed that the highest priority for any large constellation should be on the PMD success rate. The effect of further reducing the remaining orbital lifetime after disposal, for instance, from 25 years to 10 years, was discernible, as the interaction with lower altitude satellites and the potential for a collision would be reduced. A trade-off between PMD success rate and the residual lifetime would be always biased toward the former. As an example, a 90% PMD success rate combined with a 25-year remaining lifetime strategy resulted in the same number of objects in LEO over the projection period as a scenario with 85% PMD success rate and disposal orbits with a 5-year remaining lifetime (Lewis et al. 2017). However, the failure rate is typically not selectable by the constellation operator and may be even unknown at the beginning when the constellation is being built up. One option is to insert the first satellites into low orbital altitudes and have an initial checkout phase followed by a transfer to the operational orbit. In that case, any early orbit

failure will leave a satellite stranded at altitudes that are highly affected by residual drag, thereby leading to a quick natural removal from the environment.

Satellites being part of the background population would experience a non-negligible impact of such a large constellation operated at much higher altitudes, as the disposed constellation satellites would start crossing their operational orbits. The efforts in terms of collision avoidance would clearly increase, with an example being the five- to tenfold increased flux estimated for the International Space Station (ISS) during the constellation's operational lifetime (Lewis et al. 2017; Peterson et al. 2016). Adding high numbers of small satellites into lower altitudes below 600 km only exacerbates this effect (Bastida Virgili et al. 2016b).

Similar results for slightly different constellation parameters were also obtained by other researchers (e.g., Kitajima et al. 2016). In essence, one may conclude that the more general results obtained for the space debris environment evolution in earlier studies, e.g., (Anselmo 2001), were confirmed by the more recent analyses that put a focus on the impact large constellations may have: a full adherence to the currently existing mitigation guidelines (incl. the 25-year rule) may avoid a destabilization in the long-term evolution of the environment, if accepted PMD failure rates for constellation satellites would be limited even further. This would also be in line with the currently recommended end-of-life disposal reliability of 90% in ISO-24113 as a bare minimum. Further measures that have an influence on the environmental impact already during the design phase are to decrease the constellation satellites' cross section and to increase the individual constellation satellite's lifetimes (Lewis et al. 2017). Nevertheless, an impact on the environment will always exist, at least on the short-term during the operational phase of the constellation with an increase in collision avoidance efforts for all other operators.

Even though these findings provide some reassurance that the environmental impact of small satellite large constellations can be addressed and significantly reduced through careful mission design, there is an important caveat: the conclusions drawn from the investigation of the environmental impact of a single constellation do not always lend themselves to be applied if multiple large constellations are being operated. Moreover, even the increase of the number of intra-constellation satellites beyond the about 1000 satellites (as used in most analyses) may lead to different conclusions. For instance, in a constellation of 4000 satellites, the influence of whether conducting operational collision avoidance for the constellation satellites or not is much more pronounced than in a 1000 satellites case (Kitajima et al. 2016). This is understandable, as quadrupling the number of satellites in the constellation and applying the same PMD success rate mean that after any given time interval, the expected number of failed satellites at the constellation's operational altitude is four times higher. In other words, a linear increase in the constellation size may result in a nonlinear increase in the number of self-induced catastrophic collisions (Lewis et al. 2017). This finding has been also confirmed for non-constellation traffic: the expected increase in small satellites being launched into near-Earth space requires us to rethink the "big space" paradigm. Certain altitude bands (around 800 km) appear to show a future increase in spatial density even if no further launches would occur (Somma et al. 2019). Also other altitudes, as the ones proposed for large



constellations, show the tendency of a limited capacity in terms of a maximum number of satellites that could be inserted for a given time interval. A notion of the need to control the growth of the number of objects in the environment is thereby attained.

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## 5 Environment Control: The Concept of Capacity

The current set of space debris mitigation guidelines apply to single satellites and launch vehicles. Although their formulation is based on technical input gathered from long-term environment evolution studies, there is no dynamic way of accounting for significant changes in the environment that were not foreseen in those studies, like the substantial transformation of launch traffic with increased commercialization of the space sector or the current adherence levels to mitigation guidelines as opposed to expected ones. Moreover, it was noted earlier that a linear change in the behavior of an individual object has a nonlinear response when the number of individuals is high enough. Recognizing that each satellite may leave a certain footprint during its presence in the space debris environment, it seems only reasonable to come up with a metric or index formulated such that relevant aspects of the satellite's mission affecting the environment evolution are captured. Applying such an index globally, one may take this approach one step further and come up with the concept of environment capacity: if a certain environment evolution trend for a given period appears to be acceptable to the international community, one can compute the cumulated index and thus obtain the available resources to the community over the same period.

Several authors have studied ways of classifying intact satellites with respect to their environmental criticality. The *Figure of Merit* (FOM) developed in Utzmann et al. (2012) allows ranking objects according to their preference for active debris removal. Similar ranking schemes have been devised and extended to be applied in other areas such as the *Criticality of Spacecraft Index* (CSI) in Rossi et al. (2015), which has been later modified to assess parameter sensitivities of certain large constellations designs (*Criticality of Constellation Index* (CCI) Rossi et al. 2017); the ranking scheme to evaluate the Italian satellites' disposal strategy compliance in (Anselmo and Pardini 2015); the *Environment Criticality* (EC) index in (Kebeschull et al. 2017); or the *Environmental Consequences of Orbital Breakups* (ECOB) in (Letizia et al. 2017). Most of those formulations are based on a very simple relationship for the index:

$$\text{Index} = \text{Probability} \times \text{Severity},$$

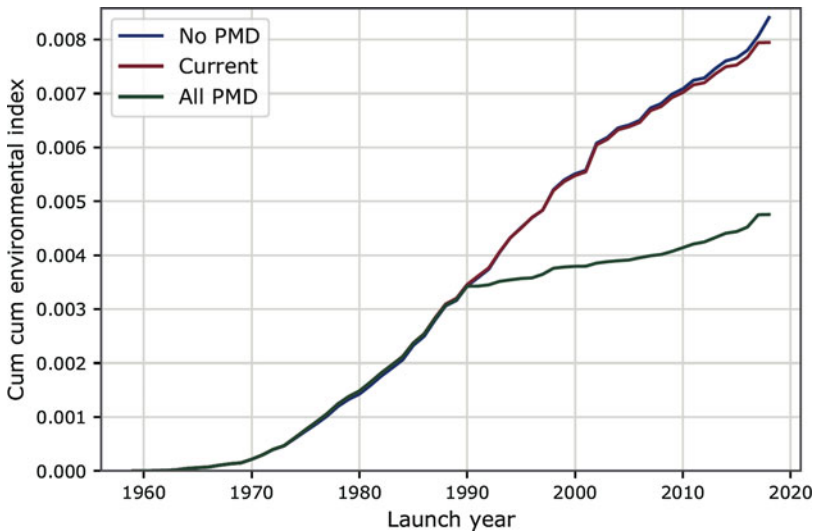
where the *probability* quantifies the likelihood of a collision (and subsequently a catastrophic breakup) for a given orbit subject to the background space debris population, whereas the *severity* provides an estimate of the potential breakup consequences.

Providing flux estimates for any given target orbit, the MASTER model has been used in many formulations, e.g., for the EC or the ECOB index, to come up with a value for the probability at distinct epochs but also to compute an integrated value over the mission lifetime (or the entire on-orbit time) capturing both the evolution of the target orbit and the background population.

The severity term generally quantifies the impact a fragmentation of the target satellite would have on the environment, including active satellites. For instance, if a breakup is likely to occur in densely populated orbital regions, the severity term will correspondingly be higher compared to cases with breakups in regions with low activity. More complete solutions, like for the ECOB index (Letizia et al. 2019), take also into account that fragment clouds evolve over time and thus affect different orbital regions and active satellites in the future.

The application of an index, or any other comparable risk metric, will capture the impact of a single mission on the environment. It will discriminate between large and small satellites, it will favor missions in naturally compliant orbits over high altitude ones, etc.

Having established the formulation of the index for single satellites, it is straightforward to compute the *cumulative index* for the entire on-orbit population of intact satellites. The strength of this cumulative index, when carefully constructed, is that it quantifies the notion of space as a limited resources discussed earlier. In such a representation, the state of the environment can be evaluated, and different mitigation strategies may be compared with respect to each other. An example for the cumulative ECOB index is shown in Fig. 7. It compares three



**Fig. 7** ECOB cumulative index as a function of time for different mitigation scenarios. (©ESA, 2018)

different strategies that were assumed to be applied since 1990 in order to see how the environment would have evolved until today. The *No PMD* scenario would see satellites just left in their operational orbits after the end of mission; in the *Current* scenario, the actual environment as it evolved until today can be found, whereas the *All PMD scenario* shows an evolution where all satellites launched after 1990 would have been disposed of after their operational lifetime. In essence, if end-of-life mitigation measures would have been applied since the 1990s as they are recommended today (of course, they did not exist back then), the cumulative index would have been only half of what it is now. Interestingly, the current situation is very close to the *No PMD* scenario. In other words, a low level of adherence to the mitigation guidelines does not differ too much from a scenario where operators just do not dispose of satellites after their end of mission. It may also indicate that the satellites being disposed are not necessarily the most critical ones in the environment.

In this sense, the formulation of an index can be used as a metric to describe the environment capacity. Without loss of generality, an example is being discussed in Letizia et al. (2019), where it is assumed that the international community could agree on a long-term environment evolution trend with a rigorous implementation of space debris mitigation guidelines and an associated PMD success rate of 90% corresponding to what they could define as a sustainable use of the resource space. It is possible to compute the cumulative index for such a scenario, which had a value of 2.4 over 100 years in Letizia et al. (2019). All missions that are supposed to be launched over the next 100 years are thus thought to consume at most an index of 2.4. If started in 2020, a certain index for all satellites launched in that year could be obtained, along with what remains for the subsequent 99 years by just subtracting what was consumed in 2020. This way, an important feedback mechanism could be introduced, where mitigation measures were directly translated to lower consumption and thus an increased capacity to launch more satellites.

Even though such an approach does not currently exist, it does not seem unrealistic that consensus might be reached in the future. In fact, the International Telecommunications Union's (ITU) registration process for frequency allocation works in a similar fashion, where registration is expected between 7 and 2 years before the date of *bringing into use*, and may serve as an inspiration for a capacity register (Letizia et al. 2019). Any mission designers might check their satellite's index estimate via a publicly available service and compare to similar missions followed by the capacity allocation for a possible launch.

Recognizing near-Earth space as a valuable resource where a sustainable consumption is desired, and given the free access to space according to the *Outer Space Treaty*, the space debris problem is another area that relates to the *tragedy of the commons*. One important aspect in this context is in which order entities would be allowed to harvest from that resource. In Letizia et al. (2019), the *first-come, first-served* approach is elaborated in analogy to the ITU registration process, but discussions have just begun, and the outcome remains to be seen. The likely slowdown in the deployment of smallsat constellations as a result of the Covid-19 virus, may help to resolve the issue of the equitable use of the global commons.

## 6 Conclusion

Many important services modern society relies on are delivered by satellite technology from near-Earth orbits. It is noble common goal to maintain these benefits or even to further expand for generations to come, but then issues related to sustainability need to be addressed. The increasing traffic in Earth orbits has given rise to concerns of a potential instability due to a collisional cascading effect, also referred to as the Kessler syndrome. This is not an issue in the far future – it needs to be addressed now, observing that research indicates repeatedly that a certain tipping point condition may have been already reached in altitudes around 800 km.

International consensus on space debris mitigation has been reached on UN level more than a decade ago, followed by an ongoing process of the adoption of those guidelines into standardization processes and national laws. In order to minimize the potential to generate space debris, any satellite or launch vehicle needs to limit its presence in the LEO and GEO protected regions. While current levels of adherence to post-mission disposal (PMD) guidelines are at about 60% for payloads (excluding naturally compliant ones, the PMD adherence level drops to merely 20% (ESA Space Debris Office 2019)) and about 80% for rocket bodies (ESA Space Debris Office 2019), it is encouraging to observe that especially small satellites are being increasingly inserted into sufficiently low orbits, where the remaining on-orbit lifetime is below 25 years.

For small satellite constellations, where plans to launch thousands of satellites into significantly higher altitudes at about 1000 km have been announced, a strict adherence to mitigation guidelines is required. Many researchers have confirmed that any impact of such a single large constellation on the environment can be minimal to negligible, if a high PMD success rate (>95%) would be attained. In case of multiple large constellations, also this could not be sufficient. Moreover, this is clearly beyond what is observed in LEO today and may serve as a serious constraint in a competitive market. Even though a certain trade-off may be possible when reducing the remaining on-orbit lifetime way below the required 25 years, the PMD success rate would still be the driving parameter: an exemplary analysis showed that 5 years remaining lifetime could allow for a trade-off with the PMD success rate to 85%. It has also been shown that a careful design of the constellation operations may address end-of-life issues already at relatively low additional cost, including the minimization of the satellite's cross section or the insertion into low altitude orbits. While there are ongoing discussions on whether more stringent requirements are required for large constellations or whether small satellites should be treated differently, the current analyses indicate that the existing set of guidelines need to be strictly applied by everyone.

Satellite collisions, which are expected to be the main driver of the object population growth in the future, are not only a subject of matter after the end-of-life measures have been taken. With increased space traffic in a highly dynamic environment, where there are difficulties to track and catalogue all potentially lethal objects, it is in the self-interest of any satellite operator to become even more responsible toward safe operations in space including collision avoidance measures.

The recent case of the close approach between ESA's Aeolus and SpaceX's Starlink satellite (Foust 2019) was indicative of the common need for more accurate data and methods but also procedures and protocols being established and exchanged within the community. Addressing this need, the recent adoption of the *Guidelines for the Long-term Sustainability of Outer Space Activities* by the UN's Committee on the Peaceful Uses of Outer Space (UNCOPUOS 2019b ) can only be reassuring.

Given that responsible space operations and full adherence to mitigation guidelines are granted, potentially with a few large constellations in space with sufficiently low environmental impact, this may nevertheless be insufficient to keep space sustainable. With too many satellites being launched, as can be the case with space infrastructure being commercialized and maintained to a high degree by profit-maximizing firms (Adilov et al. 2013), runaway conditions may still be reached. One example is in the launch of multiple large constellations, where not all of them find their business case achieved. A worst-case scenario in a potential bankruptcy could mean that all of the already launched satellites of that failed constellation would remain in space for centuries.

In a constrained environment, such as the LEO region, traffic needs to be controlled in order to guarantee sustainability. Where that limit is may be debatable, but the recent proposals to establish a rating scheme appear promising. With the likelihood of a collision and the impact such an event would have on operators and the environment in general factored into a single index, any space mission can be evaluated already before its launch. Moreover, a cumulative index could support the establishment of a capacity register for any given orbital region and thus limit the number of missions launched in a given time period as a consequence. This may be perceived as a step to constrain the freedom to access space guaranteed by the *Outer Space Treaty*, but recognizing space as a limited resource, noting that the Outer Space Treaty also calls to avoid harmful interference, and acknowledging that any satellite operated in space is actually consuming part of that commonly shared resource, it seems only reasonable to agree with Hegel: freedom is the recognition of necessity.

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## 7 Cross-References

- ▶ [Flight Software and Software-Driven Approaches to Small Satellite Networks](#)
- ▶ [High Altitude Platform Systems \(HAPS\) and Unmanned Aerial Vehicles \(UAV\) as an Alternative to Small Satellites](#)
- ▶ [Hosted Payload Packages as a Form of Small Satellite System](#)
- ▶ [Network Control Systems for Large-Scale Constellations](#)
- ▶ [Overview of Small Satellite Technology and Systems Design](#)
- ▶ [Power Systems for Small Satellites](#)
- ▶ [RF and Optical Communications for Small Satellites](#)
- ▶ [Small Satellite Antennas](#)
- ▶ [Small Satellites and Structural Design](#)
- ▶ [Spectrum Frequency Allocation Issues and Concerns for Small Satellites](#)
- ▶ [Stability, Pointing, and Orientation](#)

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