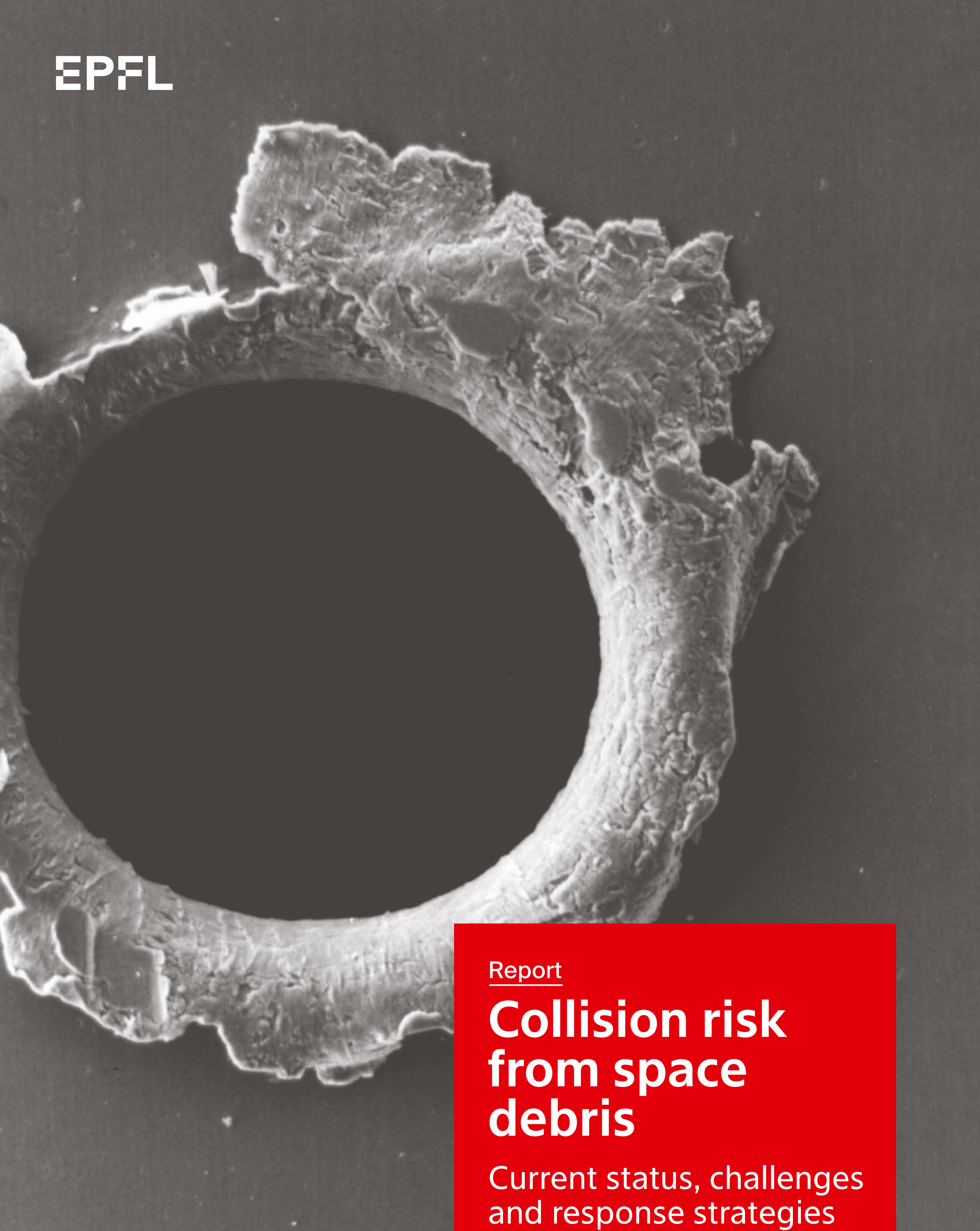

Report

Collision risk from space debris

Current status, challenges and response strategies

International Risk
Governance Center

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Cover: Space debris hole in a panel of the Solar Max satellite (source: NASA).

Executive summary

The space-based infrastructure on which our societies increasingly rely is threatened by the risk of collision between operational satellites and a growing amount of space debris — non-functional human-made objects. This risk is exacerbated by increasing and novel activities in space. Governance institutions and mechanisms have not kept up with the pace of change in space activities. Without increased efforts to improve the safety and sustainability of space activities, current and potential future benefits from space could be jeopardised.

In May 2021, the EPFL International Risk Governance Center (IRGC) convened a group of experts to consider the risk governance challenges posed by space debris. The group comprised individuals drawn from academia, industry, non-governmental organisations and policymaking institutions. An earlier version of this report was used to inform discussions at the workshop. This report describes the risks posed by space debris, explains the current response strategy and presents a range of possible strategies for the future. It serves as a foundation for deliberations about the policy options and next steps that are needed.

From the space age to the New Space era

Space activities are now conducted by numerous different actors, including private and governmental entities, complicating the management of orbits. The drop in manufacturing and launching costs have resulted in a surge of new satellites being launched. In the coming decade, the number of active satellites in orbit could increase tenfold with the planned launch of several large constellations comprising thousands of satellites. Although the space economy could soon be booming, there is a lot of uncertainty about how the space ecosystem will evolve. For example, it is not clear what activities will be conducted in low Earth orbit, nor how many large constellations will ultimately be completed.

Risks related to space debris

Space debris is a by-product of space activities and encompasses a wealth of objects with diverse sizes, generation processes and harm potential. Objects deposited in orbit can be as large as rocket bodies and defunct spacecraft or as small as paint flakes. With the current monitoring infrastructure, only space debris larger than 10 cm in low Earth orbit can reliably be tracked and catalogued. Fragments resulting from explosions and collisions represent the majority of the trackable space debris population.

Operational spacecraft face a collision risk from the space debris population. When equipped with manoeuvring capabilities, spacecraft can potentially dodge catalogued objects. However, not all spacecraft can manoeuvre and we only have limited knowledge of the positions of space debris.

A low-intensity collision can affect the performances of a spacecraft or disable some subsystems. If the collision intensity is higher, it can result in the disabling of the spacecraft or its complete fragmentation. Objects too small to be tracked cannot be dodged, but a collision with them can still result in the loss of a spacecraft. These lethal non-trackable objects dominate the risk profile of operational spacecraft as they are far more numerous and cannot be avoided. The large number of derelict objects abandoned in low Earth orbit have a significant risk-generating potential as they could create tens of thousands of lethal non-trackable debris if they were to collide or explode.

Loss of spacecraft can result in large disruptions on Earth due to the unavailability of critical satellite services. Space debris is also a threat to human spaceflight as a collision with an untrackable piece of debris can result in the loss of human lives.

Risk evaluation and the prioritisation of response strategies are complicated by two main factors: (i) uncertainty about the cost of damage to satellites and disruption of services that rely on them, and (ii) a lack of data to conduct cost-benefit analyses of mitigation and remediation approaches.

The current response strategy

At the technical level, ensuring both the near-term safety of operations and the long-term stability of the space environment relies on mitigation and remediation. Debris mitigation refers to technical procedures and requirements for operational spacecraft aimed at reducing the likelihood that they become or generate debris. It includes spacecraft shielding, collision avoidance manoeuvres, post-mission disposal and removing stored energy at end-of-life to limit the probability of an accidental explosion. Remediation refers to methods aimed at reducing risk once debris have been created. It includes actively removing derelict objects from orbit, lowering the probability of a predicted collision by affecting the trajectory of one of the two pieces of debris prior to the predicted collision time and upgrading derelict objects with collision avoidance capabilities.

At the governance level, the only binding instruments of public international space law are five United Nations treaties on outer space adopted in the 1960s and 1970s, which do not directly address the space debris problem. To address this gap, non-binding instruments such as guidelines, technical standards and industry-led best practices have been developed, with the aim of limiting the creation of new debris and reducing collision risk. International guidelines are often integrated as part of requirements in licensing procedures that are defined in national space regulations or laws. However, overall compliance with internationally agreed-upon guidelines is low.

Response strategies for the future

The current response strategy has a number of limitations. First, it mainly addresses the creation of new pieces of debris, without tackling the legacy of derelict objects. Second, national policies are non-uniform and do not always implement internationally agreed-upon guidelines. Third, national requirements prioritise ex-ante measures to minimise a mission's potential space debris creation; once in orbit, the policies in place only weakly incentivise operators to reduce the risk of debris creation.

Reinforcing the current strategy would involve: (i) strengthening monitoring and tracking capabilities with new infrastructure, enhanced collaboration and new requirements for operators, (ii) revising the international guidelines, (iii) devising mechanisms to incentivise countries to adopt national regulations aligned with internationally agreed-upon standards, (iv) adopting more stringent technical requirements at the national level, (v) possibly introducing ex-post sanctions for failure to implement space debris mitigation plans, and (vi) developing mechanisms to finance space debris remediation and to address the apportionment of costs.

Proposals for new response strategies include market-based solutions designed to incentivise risk-reducing behaviours in space. Insurance is a key example, but, given the uncertain legal framework and the remote nature of space, it is unlikely to reduce risk efficiently. Marketable permits and regulatory fees could be an efficient way of reducing risk, but there are major impediments to establishing them, such as defining the appropriate and acceptable unit of risk that would determine the fees or permit requirements. Other non-conventional response strategies for dealing with risks from space debris include allocating orbital space in low Earth orbit, limiting the number of satellites launched, and the disclosure of relevant and timely information about space missions' sustainability.

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Acronyms

ADR	Active debris removal
AMC	Advance market commitment
ASAT	Anti-satellite [weapon]
CAM	Collision avoidance manoeuvre
CPR	Common-pool resource
EMR	Energy-to-mass ratio
ESA	European Space Agency
GEO	Geostationary Earth orbit
IADC	Inter-Agency Space Debris Coordination Committee
ISO	International Organization for Standardization
ITU	International Telecommunication Union
JCA	Just-in-time collision avoidance
LC	Liability Convention
LEO	Low Earth orbit
LNT	Lethal non-trackable [object or debris]
MEO	Medium Earth orbit
NASA	National Aeronautics and Space Administration
ODMSP	[US Government] Orbital Debris Mitigation Standard Practices
OST	Outer Space Treaty
PMD	Post-mission disposal
PNT	Position, navigation and timing
SEM	Space environment management
SSA	Space situational awareness
SSN	[US] Space Surveillance Network
SSR	Space Sustainability Rating
STM	Space traffic management
TPL	Third-party liability
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space

Introduction

Human societies increasingly rely on space-based infrastructure across a wide variety of domains. Data provided by Earth observation satellites are instrumental in monitoring land use, atmospheric pollution, oceans' health and the climate. Global navigation satellite systems are crucial to the functioning of transportation and financial systems. Satellites are also increasingly used for communications with the advent of large constellations for broadband internet and the Internet of things.

This essential infrastructure — as well as the prospect of further benefits as the space economy develops — is threatened by growing levels of space debris. Decades of space exploration and exploitation have led to congestion in near-Earth orbital space. Space debris exists in a wide variety of shapes and sizes, ranging from rocket stages weighing several tons to tiny paint flakes. Low Earth orbit (LEO), the orbital region ranging from the upper atmosphere to an altitude of 2,000 km, is the most crowded region. At these altitudes, objects travel extremely fast. Thus, even collision with small objects can result in devastating damage. Operational spacecraft face the risk of such damage from space debris, which could result in large disruptions on Earth due to the unavailability of critical satellite services. Space debris also threatens astronauts and space tourists as a piece of space debris hitting a crewed spacecraft could result in severe injuries and the loss of human life.

Collisions between large derelict objects cannot currently be avoided. Such collisions can result in a large number of smaller fragments, significantly increasing the subsequent collision risk for operational spacecraft. The long-term danger is a cascade of collisions, threatening the safety of future space operations. Modelling of the space debris environment has shown that the tipping point for this cascading effect might already have been reached in some orbital regions.

Collision risk is exacerbated by the current rapid growth of the space economy. Decreasing launch and manufacturing costs have resulted in a surge in the number of satellites launched. In the next decade, the number of operational spacecraft could increase by an order of magnitude. The planned launch of large constellations comprising thousands of spacecraft is a major concern. The development of space travel and exploration will also lead to greater risk exposure due to the increased presence of humans in space.

Responding to space debris collision risk is complicated by the high levels of uncertainty about the behaviour of the space ecosystem and future human activities in space. Interconnections between elements of the system are characterised by a high degree of complexity, the possibility of cascading events and tipping points, which are characteristic of systemic risks (IRGC, 2018). Although collision risk is currently small, it may slowly increase to the point where irreversible consequences materialise.

In our view, the rapid evolution of activity in space means that improved risk governance is now needed. There are signs of governance deficits, particularly related to: weak compliance with international guidelines concerning mitigation, the lack of a development path for remediation, the absence of common agreement on principles for space governance, and insufficient international collaboration.

This report was produced in advance of an IRGC multi-stakeholder expert workshop that we held in May 2021. We start in chapter 1 with a discussion of the space ecosystem and its evolution. In chapter 2, we provide an overview of the collision risk landscape, outlining both the physical and the economic characteristics of the risk, and addressing both its drivers and its consequences. In chapter 3, we review the current strategy for managing collision risk, detailing both the technical approaches used and the governance framework that has been established. In chapter 4, we present a number of options for reinforcing the current management strategy and complementing it with the introduction of novel approaches.

The objective of this report is to give a concise yet comprehensive overview of the current status of collision risk in low Earth orbit. We also want to draw attention to some of the major challenges, some of which are highlighted in boxes throughout the document. We hope that the report will increase awareness of this issue and prompt a wider community of policymakers and decision-makers to address it. The report also serves as a foundation for deliberations about the next steps that are needed, and we will shortly be publishing a companion policy brief setting out some of the key priorities.

↦ In IRGC's Spotlight on risk article, "Intensifying space activity calls for increased scrutiny of risks," we highlight the complexity of the risk landscape inherent to human activities in near-Earth space, and explain that this pattern of complex interconnections is characteristic of systemic risks, suggesting that a systems approach is needed to address risk in space. Some aspects of space debris collision risk may be dealt with using measures for individual risk, but because the risk develops in a complex adaptive system, feedback effects require addressing it as a systemic risk.

Chapter 1

From the space age to the New Space era

1.

Different orbits for different applications

On 4 October 1957, Sputnik I, the first human-made satellite, was launched into orbit. Since then, more than 6,000 rocket launches have brought over 11,000 satellites into space (ESA Space Debris Office, 2021). Although space is vast, most human activities in space take place in near-Earth orbital space, where satellites are best positioned for Earth observation and communication. Two regions of orbital space are of special interest for human activities: geostationary Earth orbit (GEO) and low Earth orbit (LEO). As both LEO and GEO have a significant value for human activities, they have been the most used orbital regions and are thus the most congested. There are currently about 2,600 operational satellites in LEO and 560 satellites in GEO (Union of Concerned Scientists, 2021).

These two regions have different physical characteristics that affect the activities that can be performed. GEO is a circular orbit at an altitude of 35,786 km above the equator. A satellite in GEO remains above the same point on the Earth's surface. Due to this particular feature, this orbit is used for television and radio broadcasting, as well as other communications.

LEO is the spherical shell that extends from the upper atmosphere to an altitude of 2,000 km. At these altitudes, satellites travel much faster than in GEO and take about 90 minutes to perform one revolution. Thus, a network of satellites known as a constellation is necessary for continuous coverage of a specific location on Earth. As satellites are far closer to the Earth's surface, communication with them is subject to lower latency and requires lower gain antennas. The closer view of the Earth is beneficial for remote sensing (e.g., environmental monitoring, meteorology) as it increases data resolution. Contrary to GEO, satellites in LEO have a wide variety of orbits with different inclinations and eccentricities. LEO is less costly to reach than GEO as less propellant is necessary.

The region between LEO and GEO, called medium Earth orbit (MEO), offers a trade-off in its physical characteristics between the two most used regions (see Figure 1). It is principally used for position, navigation and timing (PNT) services but also communications. Due to its large volume and relatively low number of satellites, MEO is less congested than LEO and GEO.

2.

New actors and business models

While at the start of the space age, activities in space were mostly conducted by governments, more and more private actors have become involved in space activities. Commercial launch activities and technological developments have drastically reduced the cost of launching satellites (Jones, 2018). These drivers have resulted in a burgeoning set of space companies – generally known as New Space – and opened the way for alternative applications and business models (Pelton, 2017).

The space sector revenues have increased steadily from about $176 billion in 2005 to about $360 billion in 2019, with the vast majority of the growth in commercial activities (Weinzierl, 2018). In 2019, the satellite industry accounted for 74% of the revenues of the global space economy (Satellite Industry Association, 2020). In 2018, the US had a 43% market share of the global satellite industry revenues (Satellite Industry Association, 2019). Most of the revenues of the satellite industry were realised across the satellite communications (50%) and navigation (48%) value chains, with only 2% of the revenues generated by the Earth observations value chain (Euroconsult, 2019). Currently, the vast majority of the revenue from the satellite industry comes from activities taking place in GEO and MEO, as TV and radio broadcasting, other communications, and PNT services are the dominating segments. However, this could change with the advent of LEO satellite internet constellations. Euroconsult (2019) estimates that the revenues of the commercial satellite industry could reach $485 billion by 2028. Recent reports by Goldman Sachs, Morgan Stanley and Bank of America Merrill Lynch project a $1–2.7 trillion space economy in the 2040s (OECD, 2019).

Two major trends are characteristic of New Space and shape the future space environment: small satellites and large constellations (Jakhu & Pelton, 2017b). Small satellites vary widely in terms of mass, volume, orbital characteristics and applications, but

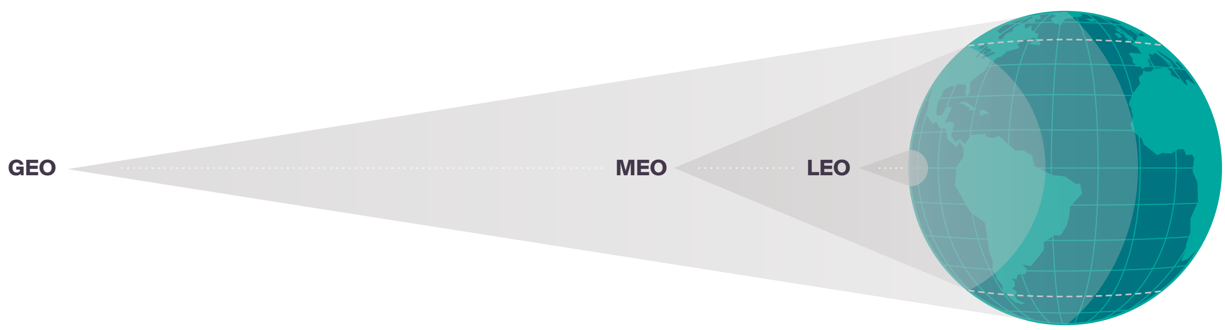

Figure 1: Schematic of orbital altitudes and coverage areas (adapted from SES, 2020).

the upper mass limit of small satellites is generally taken as 600 kg. They range from CubeSats[1] used for student experiments or launched by start-up companies, to larger 200–300 kg satellites that are often part of constellations. The trend to launch an increasing number of small satellites began in the early 1990s and is expected to surge in the coming years. In 2019, 79% of the 492 spacecraft launched into orbit were small satellites (Bryce Space and Technology, 2020). In the coming decade, the vast majority of deployments are expected to be part of large commercial constellations for remote sensing and communications.

The evolution of space activities since the 1970s has been characterised by a rapid growth in the size and performances of commercial satellites with a focus on large GEO satellites. Due to the transmission distance, there is high latency (or transmission delay) when communicating with a satellite in GEO, which is not optimal for broadband internet. In LEO, the latency is significantly diminished, and less powerful amplifiers are necessary for successful transmission, but a large number of satellites is necessary to provide global coverage. Moreover, as satellites are moving in the sky, they need to be tracked by the receiver. In the 1990s, small satellite constellations (50 to 70 satellites) were deployed into LEO to provide global communications (voice, messaging and data). The companies behind these constellations went bankrupt, mainly due to a lack of demand for the services proposed at the prices offered. After a financial restructuring, they became economically viable as they could offer lower prices. The increase in demand for internet-based services coupled with the decrease in launch and manufacturing costs, the miniaturisation of satellite components, and new architectures have revived the interest for LEO satellite internet constellations. At the same time, increased connectivity and computation capabilities enable new business models.

In the past five years, numerous commercial companies have proposed, funded, and in a few cases begun the deployment of large constellations of small satellites in LEO for remote sensing, the Internet of things and broadband internet. The largest proposed constellations, which can comprise thousands of satellites, are for broadband internet. While there are currently about 3,400 operational satellites orbiting Earth, companies have plans for placing over 60,000 satellites in orbit in the coming decade.[2]

Challenge: Uncertainty on space economy plans

There is high uncertainty as to when and if the proposed large constellations will be completed. Plans are ambiguous as constellations' settings (altitude, orbital planes, number of satellites, etc.) and deployment schedules constantly change. Moreover, these endeavours require a tremendous amount of capital which is difficult to secure, as there is a lack of certainty regarding the demand for satellite-based internet. The availability of low-cost technology for user terminals will be a necessary condition to enable those constellations to be successful (Daehnick et al., 2020).

[1] A CubeSat is a small satellite made of multiple standardised 10 cm^3 cubic units. They often use commercial off-the-shelf components for their electronics and structure.

[2] The number of proposed new satellites is constantly changing. While some recent estimates reach more than 100,000 additional satellites in orbit by 2030, the US regulator had received licence requests for more than 60,000 satellites as of March 2021 (Gleason, 2021).

Chapter 2

Risks related to space debris

1.

A balance of sources and sinks

Space debris, also referred to as orbital debris or space junk, is defined as “all artificial objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional” by the Inter-Agency Space Debris Coordination Committee (IADC, 2007, p. 5). Space debris is a by-product of space activities and encompasses a wealth of objects with diverse sizes, generating processes and harm potential.

The evolution of the space debris population is a balance of sources and sinks (Bonnal & McKnight, 2017). Sources of space debris can be grouped into four categories (Baker, 1989):

1. Inactive payloads[3] — Former active payloads which can no longer be controlled by their operators. This category includes satellites that have reached their end-of-life and cannot be de-orbited because they do not have any propulsion capabilities or remaining propellant, and satellites for which the operator has lost control.
2. Mission-related objects — Objects associated with space activities remaining in space. The major contributor to this category is rocket bodies, which have been left in orbit after serving their purpose. Other hardware released during operations includes lens

[3] A payload is a “space object designed to perform a specific function in space excluding launch functionality” (ESA Space Debris Office, 2020).

covers, bolts, fairings, multi-layer insulation and payload separation hardware.

3. Fragmentation debris – Debris generated when space objects break up through explosions and collisions.
4. Micro particulate matter – Debris ranging between 1 and 100 microns, including residues from solid rocket motor firings, ejecta material released through small-particles impacts, and degradation of space assets (e.g., paint flakes).

Only two sinks are available to clear space debris from orbits: atmospheric drag and direct retrieval. The residual atmosphere slowly drags objects down. As altitude increases, atmospheric density decreases. Thus, objects at higher altitude take more time to come back to Earth. The density of the atmosphere is affected by the solar cycles, which last 11 years. The strength of these cycles and thus the resulting atmospheric drag are difficult to predict. The lifetime of a piece of debris depends on the ratio between its cross-sectional area and its mass, its altitude, and solar activity. This is illustrated in Figure 2, where the predicted orbital lifetimes for three different objects in circular orbits are shown. It is often assumed that objects below 600 km re-enter the atmosphere in less than 25 years, but this also depends on other parameters. Precise lifetime modelling prior to launch is therefore difficult. Direct retrieval of large pieces of debris from orbit is in its infancy (May, 2021), with first missions planned in the next five years (see *Remediation*, p. 20).

As the amount of space debris increases, the probability of a collision between them also increases. When a collision happens, it generates fragments that further increase the probability of other collisions. The secondary debris can then collide and generate even more debris. This cascading effect where space debris becomes self-generating is known as the Kessler Syndrome (Kessler & Cour-Palais, 1978). Past a tipping point, even without any new launches, the number of objects orbiting Earth could increase exponentially with time. The time scale on which such a cascading effect occurs can be large, and the tipping point is difficult to identify.

Orbital lifetime by initial orbital altitude

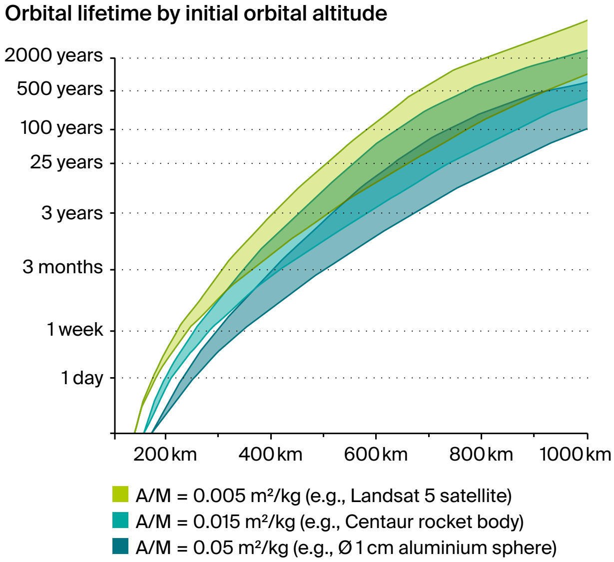

Figure 2: Orbital decay time versus altitude for circular orbits (adapted from National Research Council, 1995, Figure 1–6). The upper line is at solar minimum and the lower line is at solar maximum.

2. Space debris population

Current debris population

Due to the difficulty of monitoring space debris, there is uncertainty regarding the current number of debris pieces in orbit. The space debris population is monitored using radars and electro-optical sensors placed on the ground and in orbit. With current technology, some information on objects larger than 0.5–1 cm can be acquired. However, only objects approximately larger than 10 cm in LEO and larger than 80 cm in GEO can be reliably tracked and catalogued (Bonnal & McKnight, 2017).[4] The population of smaller objects is modelled based on periodic radar surveys, impacts observed on exposed surfaces from spaceflight that have been returned to Earth, and data on collisions and explosions. Modelling programs that detail the flux of debris particles in Earth orbit have been developed

[4] The deployment of the Space Fence, a radar system, could increase by an order of magnitude the number of debris tracked by the US Space Surveillance Network, as debris as small as 5 cm could be tracked (Gruss, 2019). In March 2020, the US Space Force has announced that the Space Fence is operational, but the impact on the number of catalogued objects has not yet been observed (Erwin, 2020). LeoLabs, a private company, is developing a network of radars aiming at cataloguing objects down to 2 cm in size (Stevenson et al., 2020).

to help operators assess the on-orbit collision risk faced by their spacecraft.[5]

The European Space Agency (ESA)'s statistical model of the debris population estimates that there are 128 million objects in the 1 mm to 1 cm size range, 900,000 objects in the 1 cm to 10 cm size range, and 34,000 objects larger than 10 cm (ESA Space Debris Office, 2021). The US Space Surveillance Network (SSN) tracks and maintains a public catalogue of more than 22,000 objects out of which more than 84% have orbits crossing LEO (Combined Force Space Component Command, 2021). The distribution of those catalogued objects across altitudes by object type is presented in Figure 3.

As depicted in Figure 4, the current population of space debris accumulated gradually over time as a by-product of space activities. Since the launch of Sputnik I, there have been more than 500 events resulting in fragmentation (ESA Space Debris Office, 2021). Fragmentation events represent

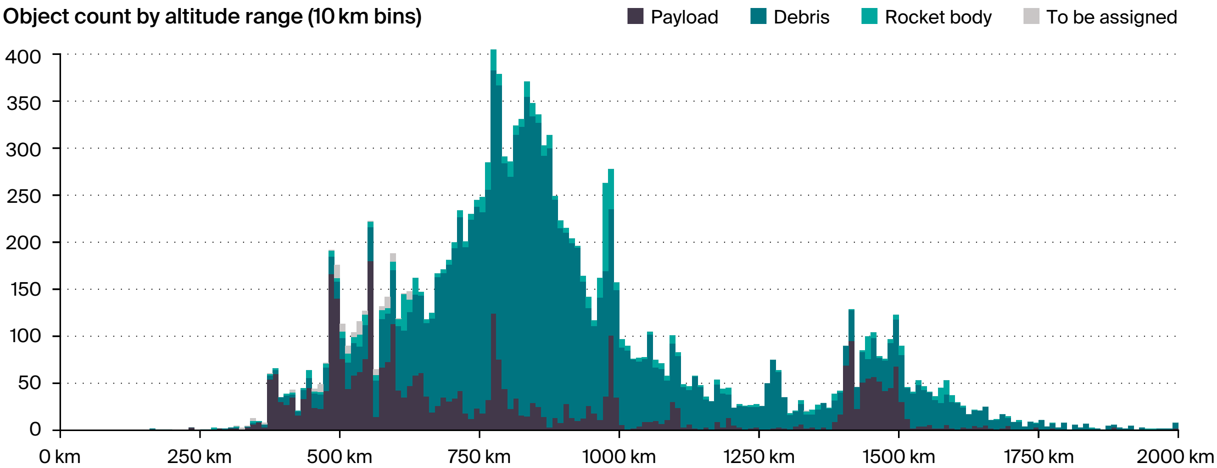

Figure 3: Publicly available catalogue of space objects tracked by the US SSN as of 22 May 2020 (Combined Force Space Component Command, 2021). The 'Payload' category comprises both operational and non-operational objects.

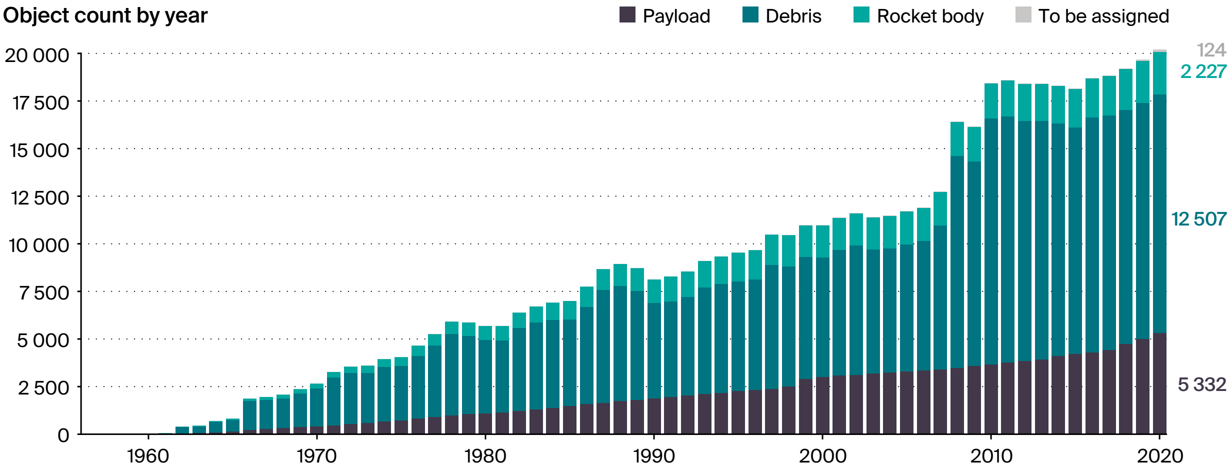

Figure 4: Evolution of the number of objects in orbit by type (Combined Force Space Component Command, 2021). For the evolution of mass and area in orbit, see ESA Space Debris Office (2020, Figure 2.1).

[5] For example, the National Aeronautics and Space Administration (NASA) has developed the Orbital Debris Engineering Model (ORDEM) and ESA the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model (see Krisko et al., 2015, for a comparison).

the most abundant source of the trackable debris population. The dominant causes of break-ups are deliberate destruction, propulsion-related explosions, battery explosions and accidental collisions (Bonnal & McKnight, 2017; Pardini & Anselmo, 2014). The deliberate destruction of the Chinese satellite Fengyun-1C orbiting at an altitude of 865 km in January 2007 accounts for the largest absolute growth of the debris catalogue. The Chinese anti-satellite (ASAT) missile test resulted in 3,433 trackable fragments. The second-largest generative event is the accidental collision between the active commercial satellite Iridium 33 and a derelict Russian military satellite Cosmos-2251, which generated 2,296 trackable fragments. Other collisions have only generated a limited number of trackable debris.

Challenge: Deliberate creation of space debris

The most consequential break-up event was the result of a deliberate destruction using an anti-satellite (ASAT) weapon. With the increasing militarisation of space, there are concerns that the deliberate destruction of satellites might become a repeating source of space debris. In 2019, India destroyed one of its own satellites orbiting at an altitude of 280 km, generating about 400 fragments (Henry, 2019b). In 2020, Russia conducted three ASAT tests albeit without reaching any target (Harrison et al., 2021). Mechanisms to prevent the deliberate creation of debris in space are lacking (Weeden & Samson, 2019).

Future debris population

Predicting the future debris population is arduous as there is uncertainty on both the current debris population and the future behaviour of space actors.[6] The postulation of a cascading effect whereby the generation of space debris via collisions could lead to an exponential increase in orbital debris (Kessler & Cour-Palais, 1978) led to efforts in modelling the space environment and its evolution.

The aim of modelling is to assess the impact of different mitigation and remediation measures on the space debris population rather than estimate absolute numbers. For these studies, Monte-Carlo methods are used to address the uncertainty and a time-span of 100–200 years is typically used.

Modelling studies of the orbital debris population in LEO suggest that the current environment has already reached the level of instability (Liou et al., 2013). Several studies have shown that even without new launches, the population of space objects would remain relatively constant for only about 50 years and would increase afterwards as the creation of new collision fragments would exceed the amount of decaying debris (Liou & Johnson, 2006, 2008). The predicted growth of the debris population is non-uniform across altitudes and is the strongest where the current debris population is the largest (800–1000 km). Subsequent studies have analysed the impact of the future launch traffic and various policy measures (e.g., active debris removal, post-mission disposal success rate) on the space debris population. Simulations of the future space debris population conducted by the Inter-Agency Space Debris Coordination Committee (IADC) using six different models were consistent:[7] even with a 90% compliance of the 25-years rule (see *International soft law instruments*, p. 22) and no future explosion, the simulated LEO debris population increased by an average of approximately 30% in the next 200 years and catastrophic collisions occurred every five to nine years (Liou et al., 2013).

Recently, the impact of the increase in launch traffic and of large satellite constellations on the space debris population has been studied (see, e.g., Bastida Virgili et al., 2016; Liou et al., 2018; Lucken & Giolito, 2019; Le May et al., 2018; Olivieri & Francesconi, 2020; Pardini & Anselmo, 2020; Somma et al., 2019). Overall, most studies concluded that high compliance with the current international mitigation standards was a prerequisite for keeping space activities sustainable in the long term.

[6] Assumptions on anthropogenic variables such as the launch traffic, compliance with post-mission disposal guidelines and passivation success rates must be made.
[7] The observation that different models obtain similar results is not a proof of their validity. Similar results might be obtained because similar (and potentially incorrect) methods or assumptions are used.

A collision among the nearly 2,000 large-derelict objects abandoned in LEO would result in the creation of thousands of trackable pieces of debris and many more lethal non-trackable (LNT) debris pieces (Rossi et al., 2020). When these objects are clustered, they have a significant probability of colliding. Thus, clusters of large-derelict objects pose a significant debris-generating risk (McKnight et al., 2019). A quarter of the large-derelict objects in LEO are contained within four concentrated clusters centred at 775, 850, 975 and 1500 km (Rossi et al., 2020). The annual probability of collision within these four clusters ranges from 1/90 to 1/1200. Conjunctions with a miss distance smaller than 1 km occur on average 1,000 times a year between objects of these clusters. Objects within these clusters have mainly been left in orbit between 1980 and 2000, before international guidelines were adopted.

Challenge: Comparing different risks

Comparing the risk posed by large-derelict objects and large satellite constellations is difficult as the characteristics of proposed constellations evolve rapidly, and high uncertainty about their realisation, reliability and capabilities prevail. While failed uncontrolled satellites are a significant risk for a constellation, this risk can be mitigated by an efficient management of the constellation (see Petit et al., 2021). In contrast, for clusters of large-derelict objects, no manoeuvre can be performed. These large-derelict objects are far larger and heavier than constellation satellites. Thus, a collision among them would result in the creation of more debris (Rossi et al., 2020).

For LEO orbits above 600 km, the major contributors of large-derelict objects are Russia[8] (68%), the US (20%), and China (2%) (McKnight et al., 2019). In recent years, China and India have started to contribute to the debris-generating potential in certain orbits. Of the 16 launches conducted by India in LEO above 600 km between 2012 and 2019, half of them have left a rocket body. Between 2011 and 2019, China has been the primary contributor of derelict objects in those orbits.

The debris-generating threat posed by large-derelict objects has triggered studies aimed at establishing priority lists for active debris removal missions (see, e.g., Kebschull et al., 2014; Letizia et al., 2018; Rossi et al., 2015). Recently, an international team used 11 different approaches to identify the top 50 statistically-most-concerning derelict objects in LEO (McKnight et al., 2021). The first 20 objects on this list are rocket bodies weighing 9,000 kg launched by Russia or the former Soviet Union. While none of the objects are American, four are Japanese, one Chinese, one French and one from ESA.

3. Risks to operational spacecraft and human spaceflight

Operational spacecraft face a collision risk from other spacecraft and the space debris population. A low-intensity collision can affect the performances of a spacecraft or disable some subsystems (e.g., damaging small parts such as solar panels or sensors). If the collision intensity is higher, it can result in the disabling of the spacecraft (lethal collision) or its complete fragmentation (catastrophic collision).[9] Loss of spacecraft can result in large disruptions on Earth due to the unavailability of critical satellite services.

LEO has the highest collision probability of all orbital regions, at least three orders of magnitude greater than in any other region (Bonnal & McKnight, 2017). This is due to the higher density of debris and higher orbital speeds. Satellites have an orbital speed of about 3 km/s in GEO and 7–8 km/s in LEO resulting in collisions with significantly greater impact velocities in LEO. Figure 5 depicts the annual collision probability for catalogued objects as a function of altitude. Above 650 km, the collision probability among space debris is greater than the one involving operational spacecraft.

[8] Russia includes countries of the Commonwealth of Independent States (CIS) as many objects were deposited during the Soviet Union era.
[9] A commonly used measure of a collision intensity is the energy-to-mass ratio (EMR). Collisions with an EMR exceeding 40,000 J/kg are assumed to be catastrophic (McKnight et al., 1995).

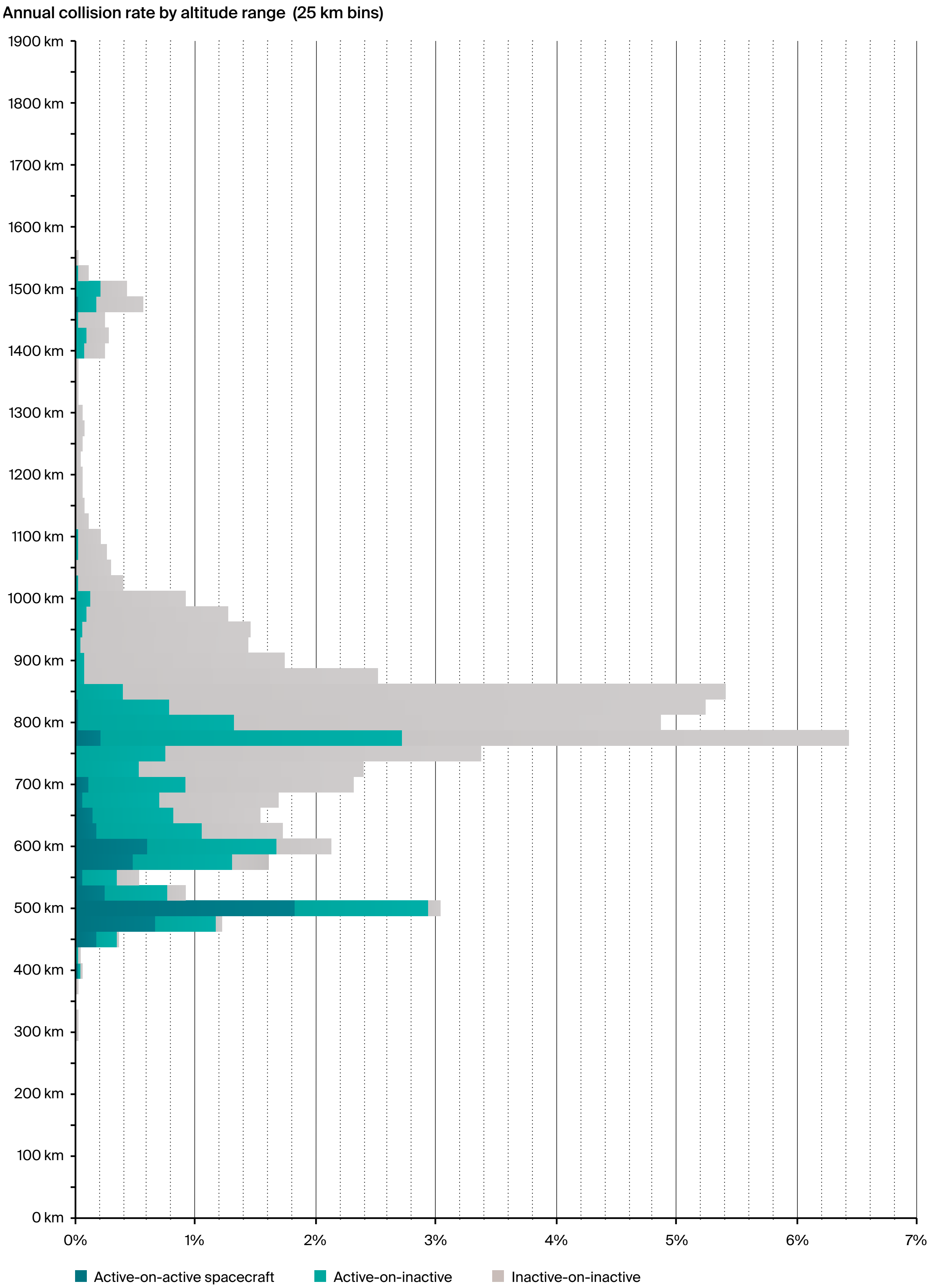

Figure 5: Estimated annual collision rate as a function of altitude and types of objects involved in a conjunction for currently tracked objects (adapted from Oltrogge & Alfano, 2019).

Radtke et al. (2017) estimate that the threshold for catastrophic collisions for a 150 kg satellite (e.g., a OneWeb satellite) is reached for impactor debris with diameters of about 3 cm in LEO.[10] Debris below the catastrophic collision threshold can still damage an operational spacecraft, but spacecraft shielding can protect it from high impact velocity debris for objects smaller than about 5 mm. Collision with larger debris will result in the loss of spacecraft capabilities, and in the worst case, the loss of the entire spacecraft. As disentangling technical failures from impacts with small debris is difficult, the cause of a loss of a spacecraft is often unknown (SwissRe, 2018).

When equipped with manoeuvring capabilities, spacecraft can potentially dodge catalogued objects. However, we only have limited knowledge of the positions of these objects. The probabilistic measurement of positions implies that encounters with low probability can still lead to a collision, and close encounters are sometimes identified too late to make a manoeuvre (Peterson et al., 2018).[11] Some operational satellites, such as CubeSats, lack manoeuvring capabilities and thus cannot move in the event of a conjunction (see *Collision avoidance manoeuvres*, p. 19).

Objects too small to be tracked cannot be dodged but can still cause lethal collisions (and even catastrophic ones in certain cases). These LNT objects dominate the risk profile of operational spacecraft. As they are far more numerous than trackable objects and cannot be avoided, LNT objects make up more than 95% of the mission-terminating collisional risk for a typical LEO satellite (Maclay & McKnight, 2020). The large number of derelict objects abandoned in LEO have a significant risk-generating potential as they could generate tens of thousands of LNT debris (see *Future debris population*, p. 10). Spacecraft fragmentations are not localised events solely affecting spacecraft in the vicinity of the event. They can adversely affect space operations across all orbital regimes (Oltrogge & Alfano, 2019).

Space debris is also a threat to astronauts and space tourists as a collision with an untrackable piece of debris could result in the loss of human life.

4.

Costs related to space debris

Data on the current economic impacts of space debris is scarce. The most prominent economic impact caused by space debris is losing an operational spacecraft following a collision with space debris. Costs to build, launch and maintain a spacecraft in LEO vary significantly between different applications. The Hubble Space Telescope, which is probably the costliest single satellite program in LEO, cost $4.7 billion at its launch (Ballhaus et al., 2010) and $9.6 billion by its last servicing mission in 2009 (Overbye, 2009). In comparison, the reported manufacturing cost per OneWeb satellite was $1 million (Henry, 2019a), and launch cost per satellite was around $2 million (de Selding, 2015). When a satellite is lost, not only is the asset lost, but also the value from the services derived from the data generated or transmitted by the satellite. Evaluating the costs of the resulting disruptions on Earth is extremely difficult and has not yet been conducted. Efforts to mitigate the effect of space debris through the design of the spacecraft (e.g., shielding, collision avoidance and post-mission disposal capabilities, and redundancies), the monitoring infrastructure, the operations (e.g., analysis and management of conjunction warnings, loss of service and fuel when conducting collision avoidance manoeuvres), the clearance of orbits at end-of-life, and insurance are also significant costs (OECD, 2020).

The current economic impact of space debris is largely unknown because: (i) damage due to untracked debris is unreported, (ii) satellite operators are not transparent regarding the costs of protecting against debris they face, and (iii) investments in space debris monitoring and tracking not only benefit space debris mitigation but also have defence purposes. However, the current direct cost of space debris appears to be low because the perceived risk is too low to trigger active responses from operators. As the perceived risk increases, stricter mitigation measures will be taken (voluntarily or through regulation), which will create a set of recurring costs

[10] Note that this depends on the impact velocity and density of impactor debris.
[11] For large debris, the current typical accuracy is in the order of ± 1 km along the velocity vector and ± 200 m in the radial direction (Bonnal et al., 2020).

that will be difficult to reduce as stabilising the debris population will require the continuation of those measures. Once the perceived risk increases above a threshold, remediation activities will start to be implemented (Schaub et al., 2015). However, the earlier remediation is implemented, the lower the costs for reducing the risk, as removing thousands of small fragments is significantly less cost-efficient than removing a large object (McKnight, 2010).

Economic inefficiencies in orbit are not solely caused by space debris, as operational spacecraft also induce a collision avoidance burden on other spacecraft. Higher densities of active spacecraft result in more conjunctions and thus greater collision avoidance costs (see p. 19). Although new technologies and better coordination can drastically reduce the costs associated with collision avoidance manoeuvres among operational spacecraft, those costs are unlikely to vanish in the near future.

Challenge: Estimating the future economic impact of space debris

The future economic impact of space debris is hard to predict. It depends on strong assumptions used for modeling and on the total economic value countries, or humanity as a whole, derive from near-Earth orbital space. Both are subject to uncertainty and ambiguity. The impact could include the loss of unique capabilities and applications (e.g., weather and Earth observation), the loss or reduction of new capabilities and applications (i.e., preventing the space economy to grow), human casualties, and space debris remediation (OECD, 2020).

5. The tragedy of the space commons

Orbital space in LEO is scarce but can be freely accessed. It is rivalrous as one's use of a particular orbit prevents other space actors from using it. Moreover, its use is non-excludable, i.e., it is costly to exclude actors from enjoying the benefits of orbital space. These two characteristics – subtractability of use and excludability – renders orbital space in LEO a common-pool resource (CPR). This type of good faces a management problem known as the tragedy of the commons (Hardin, 1968). Individuals' failure to integrate the costs they impose on others when consuming the resource leads to an overconsumption of the resource, potentially leading to its depletion. At the same time, efforts from one space actor to maintain the resource accrue to all. This disincentivises resource preserving activities, resulting in their underprovision.

Two traditional remedies are often proposed to the tragedy of the commons: government control or private property rights. The former usually takes the form of a Pigouvian tax (Pigou, 1932), which raises the private cost such that actors generating space debris consider both their private cost and the social cost in taking their decisions. Examples of Pigouvian taxes include launch and orbital-use fees (see *Regulatory fees*, p. 29). However, this solution faces two obstacles: lack of knowledge and incentive problems. The public sector might not have sufficient knowledge to implement an optimally sized tax, and even if it has the knowledge, solving the problem might not be in its interest. The second solution commonly applied to the tragedy of the commons is private property rights. Coase (1960) pointed out that externalities emerge from imperfect or absent property rights. When property rights are clearly defined, it is possible to determine which party must bear the cost of conducting a particular activity. Provided that negotiations and enforcement costs are negligible, the resulting pollution level will maximise efficiency. In other words, the tragedy of the orbital commons stems from its open-access nature. By assigning property rights, space actors would have an incentive to maintain and keep their property uncluttered. However, how could property rights be allocated in space? The Outer Space Treaty (OST; 1966), which is the main instrument of the international legal regime (see *Binding public international law*, p. 21), states that "the exploration and use of outer space shall be the province of all mankind" (Article I) and prevents "national appropriation by claim of sovereignty, by means of use or occupation, or by any other means" (Article II), rendering attempts at establishing property rights in space difficult.[12] The allocation of orbital space (see p. 30) would be close to assigning private property rights.

Aside from the legal obstacles, defining property rights in space faces physical obstacles. Satellites use different combinations of eccentricities and inclinations, making the allocation of a certain volume of space difficult. Defining the appropriate volume to allocate would also be a challenge (Salter, 2016). Reaching an international agreement regarding the scope and the allocation of property rights seems intractable. If the cost of defining and enforcing property rights is higher than the gains generated by those property rights, it is more efficient not to create them (Demsetz, 1967). Government control and private property rights are extrema in the spectrum of institutions available to manage CPRs. Work by Elinor Ostrom (2015) and colleagues have unveiled many empirical examples of successfully managed CPRs that do not rely on those two options. By observing the self-governing institutions created by communities around the globe to manage their CPRs, Ostrom (2015) has devised a set of conditions that are instrumental in the sustainable management of CPRs. However, fostering these conditions in the management of a global CPR such as orbital space in LEO is challenging. The institutions and mechanisms in place do not include relevant appropriators, do not define rights and responsibilities according to capabilities, and decision-making institutions and enforcement mechanisms are lacking (Johnson-Freese & Weeden, 2012; Weeden & Chow, 2012).

Challenge: Appropriation of orbital space

As constellations can have difficulty coexisting at the same altitude, there is some form of appropriation of space by constellation operators. For example, once Starlink is completed, it is unlikely that another operator will be able to launch a constellation at the same altitude without taking an unbearable level of risk. It is unclear how the Outer Space Treaty provision on non-appropriation by means of use or occupation should apply to constellations in near-Earth orbital space (see Johnson, 2020, for a discussion on this topic).

[12] Note that liability rules could induce a property rights regime without the need for explicitly defining those rights. If liability rules were to systematically favour one type of party (e.g., the first operator in a given orbital volume), this would have a similar result as creating private property rights.

Chapter 3

The current response strategy

Three sets of activities are aimed at reducing the space debris growth and the negative impact debris has on space operations: space situational awareness (SSA), space traffic management (STM) and space environment management (SEM).

SSA is the foundation of all debris related action. It "includes perceiving orbital anomalies or threats, maintaining an inventory of objects as completely as possible, and developing and providing timely information for collision avoidance and safe operation" (Bonnal & McKnight, 2017, p. 43). Without the required data on the space environment, STM and SEM cannot be conducted. SSA consists of detecting and tracking space objects using networks of geographically distributed sensors.[13] It also includes pooling and fusing data, as well as the algorithms and computer resources necessary to determine orbits. The US SSN, which includes radars and telescopes, is the main source of orbital data. The Combined Space Operations Center (CspOC) maintains a publicly available catalogue of orbital data on unclassified objects based on the observation of the SSN.[14] Many other countries, such as Russia, France and Germany, have SSA capabilities, but their products are not as widely distributed (*Space Situational Awareness*, 2020). Our increased dependence on space assets resulting in vulnerabilities to disruptions has led to growing interest in and need for SSA capabilities (Lal et al., 2018). Higher expectations from operators (public

[13] Note that monitoring of near-Earth asteroids and space weather are sometimes included in SSA.
[14] The catalogue is available at www.space-track.org.

and private) regarding the quality of SSA products and a desire to increase self-reliance have pushed countries to increase funding for SSA. Recently, the private sector has also developed capabilities in sensors and software systems for SSA with different services already available to the space operator community.

STM is "the planning, coordination, and on-orbit synchronisation of activities to enhance the safety, stability, and sustainability of operations in the space environment" (The White House, 2018). The aim of STM activities is to operate safely within the existing space environment by avoiding collisions with known objects. At the core of STM is collision avoidance.

Challenge: Most trackable debris cannot be manoeuvred

Collision avoidance manoeuvres can only be performed by manoeuvrable spacecraft, but only about 7.5% of the trackable population of space objects is manoeuvrable (Bonnal et al., 2020). Collisions involving large-derelict objects would generate a large number of debris pieces greatly increasing the collision risk for operational spacecraft (see *Future debris population*, p. 10). This risk cannot be addressed through STM as these large-derelict objects are non-manoeuvrable.

SEM encompasses activities aimed at ensuring both the near-term safety of operations and the long-term stability of the environment (Maclay & McKnight, 2020). It comprises mitigation, aimed at preventing the creation of new debris, and remediation, aimed at reducing risk once debris have been created.

Figure 6 summarises the relationships between SSA, STM and SEM. As there is no commonly agreed-upon definition, the boundaries between these three sets of activities can differ among actors. Overall, they comprise technical elements embedded in an overarching governance environment. For the purpose of detailing the existing response strategy to address risks related to space debris, we first look at the technical elements and then discuss the regulatory context.

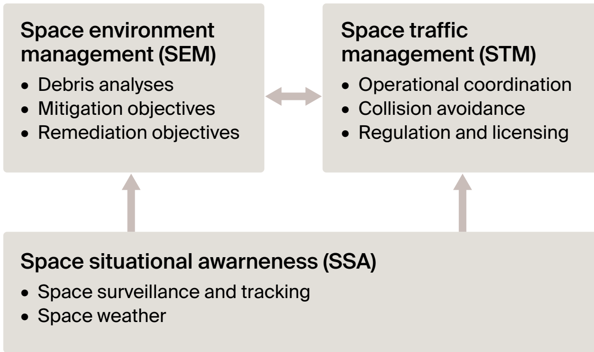

Figure 6: Relationships between space debris related actions (adapted from Bonnal et al., 2020, Figure 1).

1.

Technical approaches

Mitigation

Debris mitigation refers to technical procedures or requirements for operational spacecraft aimed at reducing the risk that they become debris or generate debris. Bonnal and McKnight (2017, p. 115) observe that "because of the time and cost necessary to modify designs and operations practices, the debris problem has a significant time lag between the recognition of the issues and the effect of changes." If mitigation actions are taken too late or are insufficient, remediation becomes necessary. The predictions of the future space debris population (see p. 10) highlight the need for compliance with strict mitigation standards.

Shielding

Spacecraft can be protected from hypervelocity impacts of small pieces of debris using shielding. Adding shielding is costly and adds weight to the spacecraft. Space debris models are used to estimate satellite structure penetration rates. Critical parts of spacecraft are more heavily shielded, but external parts such as solar panels cannot be protected. Thus, impacts from small pieces of debris can degrade satellite performances.

Collision avoidance manoeuvres

A collision avoidance manoeuvre (CAM) consists of modifying the orbit of a spacecraft to avoid a predicted collision with a piece of debris or another active spacecraft. It requires the ability to manoeuvre, which some active spacecraft lack. Operators assess the risk of a conjunction based on data provided by other operators, government systems and private services. As the trajectories of catalogued objects have uncertainties, only a probability of collision can be derived. Operators then decide if a CAM should be conducted (a typical probability threshold used by operators is 10^{-4}).

When a predicted collision involves two active spacecraft, it requires coordination to avoid conflicting actions. Rules and communication protocols for these situations are currently lacking. Procedure to detect conjunction events, perform a collision risk assessment and decide which manoeuvre to perform differ among operators.

Challenge: Collision avoidance in the New Space era

- The increase in active spacecraft and debris results in increased conjunction alerts, which cannot be treated manually.
- Rules and procedures to coordinate manoeuvres are lacking.
- The relatively high uncertainty on satellite positions results in many false alerts.
- Different data providers can have different measurements of satellite positions making decisions difficult.

CAMs are costly as they require staff to monitor the conjunctions, assess the risk and conduct the manoeuvres. For a typical satellite in LEO, an operator can receive hundreds of conjunction alerts per week. After processing these alerts, there are still about two actionable alerts requiring detailed follow-up analysis per spacecraft per week (Bastida Virgili et al., 2019). ESA estimates that it needs to perform more than one CAM per satellite per year. Efforts are currently being made to automate these processes, reducing the need for staff and confusion over who performs manoeuvres. Given the planned increase in active satellites, automation of CAMs will be necessary. Improved SSA capabilities will also be instrumental in reducing collision risk, as they will increase the efficiency of collision avoidance manoeuvres because: (i) better knowledge of satellite positions can drastically reduce the number of false alerts and the probability of detecting an encounter too late, and (ii) tracking of smaller debris allows for dodging them.

When a manoeuvre is conducted, the service or experiment is momentarily interrupted. CAMs can sometimes be integrated into maintenance but often require using scarce fuel, reducing mission duration.

Post-mission disposal

Satellites left in orbit at end-of-life are a major source of collision risk. For this reason, the post-mission disposal (PMD) has been identified as a key action to reduce risk. However, PMD has a cost, as it requires propellant to lower the orbit of a satellite to re-enter the atmosphere.[15] If the control of a spacecraft is lost or if it has no more propellant, its PMD cannot be completed. Satellites are often used past their design life, as they generate revenue or benefit science, but this increases the risk of losing control of them and often results in the use of the remaining propellant.

The international standard regarding PMD is to de-orbit no more than 25 years after the end of operations (hereafter 25-years rule; see *International soft law instruments*, p. 22). This number was derived more than 20 years ago based on a cost-benefit analysis. However, many actors argue that this is too long given the increase in space traffic. Proposals to reduce this duration to 1, 5 or 10 years have been made. Some observers argue that 25 years is still a good cost-benefit duration but that the problem is the compliance level with respect to this rule (Foust, 2020).

[15] Passive methods such as augmenting the atmospheric drag (e.g., using a sail) or electrodynamic tethers can also be used to reduce the altitude. These methods are not fully mature yet and appear more suited to small spacecraft (NASA, 2020; Sánchez-Arriaga et al., 2017).

A high PMD success rate is instrumental in reducing large constellations' impact on the space environment. For large constellations above 1000 km, Liou et al. (2018) showed that a 99% success rate was required to limit the long-term growth of the space debris population.

Operators of satellites without any manoeuvrability capabilities who want or need to abide by the 25-years rule can launch their spacecraft in orbits where they will naturally re-enter the atmosphere within this time.

Companies developing the technologies for active debris removal — such as Astroscale and ClearSpace — are also planning to offer end-of-life services. Removing failed spacecraft from orbit at their end-of-life would enhance the overall PMD success rate of an operator.

Passivation

Passivation consists of limiting the probability of accidental explosion by removing internal energy contained in a spacecraft at the end of its mission or the end of its useful life. To avoid explosions, the remaining propellant should be vented and batteries completely discharged. New technologies are developed to maximise the probability of success of these actions (ESA, 2016).

Remediation

Remediation activities can take two broad forms: removing debris from orbit and slightly changing debris trajectories before predicted collisions (Kessler et al., 2010). The former is a strategic approach that consists of actively removing a certain number of derelict objects to reduce the probability of major collisions. In contrast, the latter is a tactical approach that consists of lowering the probability of a predicted collision by affecting the trajectory of one of the two pieces of debris prior to the predicted collision time (Bonnal et al., 2020). An extension of the tactical approach consists of upgrading derelict objects with collision avoidance capabilities.

Active debris removal

Active debris removal (ADR) consists of removing space debris from orbit to reduce collision risk for operational spacecraft and the growth of the space debris population. Its use to stabilise the debris population has been studied using modelling (e.g., Bastida Virgili & Krag, 2009; Liou, 2011; Liou et al., 2010; Liou & Johnson, 2009). Liou et al. (2010) showed that the debris population in LEO could be stabilised in the next 200 years with an ADR rate of five objects per year. However, this landmark study was done before the advent of New Space and assumed a future launch traffic similar to the historical one. Given the risk-generating potential of large-derelict objects (see *Future debris population*, p. 10), there is growing agreement that the removal of large debris will be necessary.

In 1984, the space shuttle brought two satellites, which had been placed into incorrect orbits, back to Earth. The capture was performed by astronauts during a spacewalk.[16] This type of crewed mission is extremely costly and would not make commercial sense. Numerous methods that do not require humans to perform ADR missions have been envisioned (see Mark & Kamath, 2019; Shan et al., 2016, for a review).

Challenge: Paying for removing derelict objects

Although removing derelict objects from orbits faces legal and political challenges, the larger challenge to overcome is economic. ADR is costly and the willingness from spacefaring nations to finance remediation appears limited.

Two companies — Astroscale and ClearSpace — are currently working towards the first uncrewed ADR missions. In March 2021, Astroscale launched its End-of-Life Service by Astroscale demonstration (ELSA-d) mission, with the aim of testing the technologies necessary for debris docking and removal (Astroscale, 2021; Forshaw et al., 2019).

[16] In this instance, the satellites could be controlled: their altitude and rotation was lowered from the ground.

Astroscale has also been selected for the first phase of the Commercial Removal of Debris Demonstration (CRD2) project, an ADR mission funded by the Japan Aerospace Exploration Agency (JAXA), which consists of sending a spacecraft to inspect a discarded Japanese rocket upper stage (Henry, 2020). This first phase, which should be completed before 31 March 2023, is the first step towards removing the rocket upper stage. The first uncrewed removal of a derelict object is planned to be conducted by the ClearSpace-1 mission, scheduled for launch in 2025. This mission is led by the Swiss start-up ClearSpace and has received about €120 million in funding from ESA in November 2019. The target of the mission is a Vega Secondary Payload Adapter (VESPA) weighing 120 kg with an 800 km by 660 km altitude orbit (ESA, 2019).

Just-in-time collision avoidance

Just-in-time collision avoidance (JCA) consists of lowering the collision probability between non-manoeuvrable objects by acting on one of them. Prior to the predicted collision time, the trajectory of one of the objects involved is deflected to reduce the probability of collision. To conduct JCA, the accuracy of objects' ephemerides would have to be one or two orders of magnitude higher than observed today (Bonnal et al., 2020).

Various JCA methods have been proposed and are currently under study. They include using radiation pressure from ground-based lasers to nudge debris, generating a cloud of gas and particles using a sounding rocket to deflect a debris trajectory, and using a space-based laser to vaporise the surface of a piece of debris, generating a recoil effect (e.g., Bonnal et al., 2020; Phipps & Bonnal, 2016).

Nano-tugs

Instead of nudging non-manoeuvrable objects just before a close approach, derelict objects could be upgraded with collision avoidance capabilities (McKnight et al., 2020). One or more nanosatellite would be deployed close to a derelict object and attach to its surface. These nano-tugs could cooperatively determine their orientation and then use their propulsion system to detumble the object and perform CAMs. This method would bring derelict objects in the space traffic realm by giving them position determination and collision avoidance capabilities.

2.

Regulatory approaches

The deployment of supporting conditions and technical measures must be mandated or encouraged by international and national regulatory instruments, both public and private. In this section we look at the current situation and conclude with a discussion on compliance.

Binding public international law

The only internationally binding instruments of public international space law are five UN treaties on outer space adopted in the 1960s and 1970s. They were negotiated through the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS), a UN body created in 1958 which operates on consensus. Due to the compromises required to achieve consensus, "the language of the five treaties is not always clear and leaves room for varied interpretation" (Jakhu & Pelton, 2017a, p. 21). The UN treaties are legally binding on the states who have signed and ratified them. However, enforcement mechanisms are weak.

Challenge: Lack of shared conception of space

The former US administration declared that outer space should not be viewed as a global commons (Exec. Order No. 13914, 2020). Observers have argued that this view undermines safety and predictability (Panda & Silverstein, 2021). Although UN outer space treaties do not specifically define space as a global commons, there is much debate around this terminology. Hertzfeld et al. (2015) suggest moving beyond this term and similar ones as they do not fully capture the full legal and economic conditions of space, and do not provide an adequate framework for its future handling. However, a common conception among major spacefaring nations regarding the status of outer space is probably a stepping stone for its global management.

None of the UN treaties on outer space specify rules regarding space debris or even mention it. Nevertheless, two treaties impact the space debris issue: the Outer Space Treaty (OST; 1966) and the

Liability Convention (LC; 1971). The extent to which the provisions of those treaties apply to space debris is subject to interpretation (e.g., Baker, 1989; Dennerley, 2018; Nelson, 2015).

Article I of the OST states that "[t]he exploration and use of outer space [...] shall be carried out for the benefits and in the interests of all countries [...] and shall be the province of all mankind." The treaty guarantees the freedom of access, exploration, and scientific investigation of space. Although commercial activities were not prevalent when the treaty was drafted, Article VI ensures that states "bear international responsibility for national activities in outer space [...] whether such activities are carried on by governmental agencies or by non-governmental entities." Moreover, when conducted by non-governmental entities, space activities "shall require authorisation and continuing supervision by the appropriate State." The treaty also provides that the state of registry of a space object "shall retain jurisdiction and control" over it (Article VIII) and that states shall avoid activities that could lead to "potentially harmful interference with activities of other States" (Article IX).

Challenge: The Liability Convention (LC)

- The LC neither defines the fault nor establishes a standard of care for actors conducting space activities. The absence of precedent at both the international and domestic level leaves the ability of a victim to recover its losses uncertain (SwissRe, 2018).
- As the liability regime is stronger for damage on the ground or in the air compared to in orbit, space actors are disincentivised to de-orbit their spacecraft.
- As states retain jurisdiction and control over their space objects, removing space debris from a foreign country requires its approval.

The LC creates two separate liability regimes depending on where damage occurs. The LC provides that a "launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight" (Article II). However, for in-orbit activities, it creates a fault-based liability regime. Due to a lack of definition of fault, there is uncertainty as to the circumstances under which a state would be liable for the damage caused by its space debris (Dennerley, 2018). Even if such a standard were to be defined, the remote nature of space activities, which are difficult to monitor or inspect closely, would still make it complicated to establish fault (Degrange, 2018).

International soft law instruments

Since the adoption of the Moon Agreement in 1979 (which has been ratified by only 18 states, none of which is a major space power), multilateral negotiations on a binding agreement under the auspices of the UNCOPUOS have failed. The lacunae in the binding space governance regime regarding space debris have been addressed through non-binding instruments such as guidelines, technical standards and industry-led best practices.

In 1995, NASA was the first national space agency to take action by issuing a set of orbital debris mitigation guidelines. The US government followed in 2001 by establishing the US Government Orbital Debris Mitigation Standard Practices (ODMSP), which are applicable to government-operated or procured space systems (Liou et al., 2020).[17] At the international level, the Inter-Agency Space Debris Coordination Committee (IADC), comprised of the space agencies of 10 countries and ESA, was formed in 1993. In 2002, IADC adopted the first international guidelines on space debris, which were revised in 2007 (IADC, 2007). The IADC guidelines cover the overall environmental impact of space missions and define two protected regions with regard to the generation of space debris: the LEO region and the Geosynchronous region. They focus on four areas:

1. Limitation of debris released during normal operations.
2. Minimisation of the potential for on-orbit break-ups.
3. Post-mission disposal.
4. Prevention of on-orbit collisions.

[17] The ODMSP were revised in 2019.

The guidelines recommend that a feasible space debris mitigation plan be established and documented for each space mission. For post-mission disposal, the guidelines recommend that the orbital lifetime of spacecraft or orbital stages, after completion of operations, should be limited to 25 years.

The IADC guidelines formed the basis of the guidelines adopted by UNCOPUOS in 2007 and endorsed by the UN General Assembly in 2008 (UNCOPUOS, 2007). The UNCOPUOS guidelines are very similar to the IADC guidelines but without the 25-years rule. Both sets of guidelines show the willingness to address space debris on the global stage. Still, they are limited in their reach as they are not legally binding under international law, not retroactive and seem not to apply to military activities (Su, 2016).

In 2019, UNCOPUOS approved a set of 21 Guidelines for the Long-term Sustainability of Outer Space Activities. These guidelines are high-level recommendations not only concerned with space debris. They provide guidance on four broad topics: (i) the national policy and regulatory frameworks for space activities; (ii) safety of space operations; (iii) international cooperation, capacity-building and awareness; and (iv) scientific and technical research and development (UNCOPUOS, 2019).

Challenge: International guidelines change slowly

The internationally agreed-upon space debris mitigation guidelines have only slightly evolved since the first adoption of the IADC guidelines in 2002, but space activities and actors have significantly changed.

These three sets of guidelines recommend that states implement them through relevant national mechanisms. The legal obligations provided by the UN outer space treaties to authorise and supervise space activities conducted by non-governmental entities, as well as their liability as a launching state, gave rise to national space legislation (Froehlich & Seffinga, 2018). The guidelines are often integrated as part of requirements in licensing procedures that are defined in national space regulations or legislations.

Technical and industry standards

The IADC and UNCOPUOS Guidelines have been completed by various technical standards developed by national space agencies, international organisations and industrial consortiums or associations. The International Organization for Standardization (ISO) has developed a family of standards addressing debris mitigation, which have been used to guide several countries in their space activities. The ISO 24113 is the top-level standard defining “the primary space debris mitigation requirements applicable to all elements of unmanned systems launched into, or passing through, near-Earth space, including launch vehicle orbital stages, operating spacecraft and any objects released as part of normal operations” (International Organization for Standardization, 2019).

The European Code of Conduct for Space Debris Mitigation (2004), which has been adopted by the Italian, British, French and German space agencies, as well as ESA, is consistent with the IADC Guidelines but provides greater technical details and explanations. More recently, the Space Safety Coalition, a group of satellite operators and other organisations, has adopted a set of Best Practices for the Sustainability of Space Operations, which go beyond the internationally agreed-upon guidelines.[18] The Best Practices state that “spacecraft should strive for a disposal process providing a probability of successful disposal of 95%” (Space Safety Coalition, 2019, p. 11) and that “operators of spacecraft that use chemical or electric propulsion to deorbit should strive to complete the deorbit phase within five years of end-of-mission” (p. 12).

[18] The Best Practices of the Space Safety Coalition have been endorsed by 48 entities (as of 24 March 2021) including operators, manufacturers and insurers.

Compliance with guidelines

Analysis of the post-mission disposal of spacecraft shows a low level of compliance with the 25-years rule (ESA Space Debris Office, 2020). The level of compliance has increased over the years and reached about 85% for rocket bodies and 75% for payloads with end of life in 2019 and 2018, respectively. However, for non-naturally compliant objects,[19] about 60% of the payloads and 30% of the rocket bodies do not even attempt to comply. Unfortunately, more detailed data on compliance with the guidelines is lacking. A fine-grained view of the space actors' behaviour would be helpful in both tailoring the policy response and incentivising compliance with the guidelines.

Challenge: Compliance with guidelines is low

Compliance with the internationally agreed-upon guidelines is low. Large-derelict objects are still deposited in orbit: 57% of the rocket bodies used in the past 10 years are still in orbit (McKnight et al., 2019).

[19] Due to their physical characteristics and orbital altitude, naturally compliant objects re-enter the atmosphere in less than 25 years without requiring any action from their operator (e.g., a de-orbit manoeuvre).

Chapter 4

Response strategies for the future

1.

Reinforcing the current response strategy

The current response strategy consists of non-binding internationally agreed-upon guidelines and standards which are often integrated into national laws or licensing requirements. The mechanisms established thus far only address the creation of new pieces of debris, but do not address the legacy of derelict objects. National requirements only address space debris by mandating the use of certain procedures or by requiring an ex-ante evaluation of a mission's potential space debris creation. Once in orbit, the policies in place at the national level only weakly incentivise operators to reduce the risk of debris creation.

Many observers have called for the development of a new binding multilateral agreement on space debris to prevent some spacefaring nations freeriding on the efforts of other ones. However, such an agreement is out of sight as the political agendas of major spacefaring nations are diverging. Rules regarding debris affect the space domain as a whole. As such, other space matters are usually included in the discussions and often impede agreement. Even reaching agreement on more stringent non-binding internationally agreed-upon guidelines on space debris currently seems out of reach.

Although coordinated international action would theoretically be preferable to avoid debris-related risk leakage from jurisdictions with stronger rules to jurisdictions with weaker rules, the extent of forum shopping is debated. As a first step, unilateral action by one or a few major spacefaring nations (especially the US) could be effective because the same requirements can be applied to foreign entities requiring market access. This mechanism could prevent operators from seeking a license in countries with weaker regulations and could help drive regulatory change abroad. Smaller states often base their regulations on the ones of larger states. Reciprocity among states can thus help adopt common rules.

At the international level, reinforcing the current strategy could include the following:

- Strengthening the commonly agreed-upon guidelines of IADC and COPUOS by adopting more stringent requirements.
- Devising mechanisms to incentivise countries to adopt national regulations aligned with internationally agreed-upon standards.

At the national level, it could include:

- Adopting new technical requirements.
- Introducing ex-post sanctions for non-compliance with the submitted space debris mitigation plan.

New technical requirements

A range of new technical requirements to reduce debris-related risks have been proposed. Without getting into details, we list in Table 1 the ones that have been most often cited as an effective way of reducing risk. The cost-benefit analysis of these requirements is unfortunately lacking and has prevented the adoption of some of them.

New monitoring and tracking capabilities

As we have seen throughout this report, the ability to characterise, monitor and track objects in space is instrumental in reducing risk. Reducing the uncertainty about space objects' positions and the detectability threshold would reduce costs associated with space debris. This requires better sensors and supporting infrastructure. On-board technologies such as global navigation satellite system (GNSS) receivers, beacons or laser retroreflectors can also help improve trackability of objects.

Comprehensive assessment of the cost-effectiveness of SSA technologies and trackability requirements is lacking. To what extent efforts

Table 1: New technical requirements.

When	Requirement	Key questions
During the mission	Reduce the probability threshold for on-orbit collision with LNT and trackable debris throughout the mission	• Should launching in some orbits be forbidden as a result? • Should these metrics be calculated in the aggregate for constellations?
	Require all satellites to be manoeuvrable	• Should there be exceptions? • Which technologies should be allowed? • Should a performance-based metric be used?
	Forbid any intentional release of debris	• Should there be exceptions?
Post-mission disposal	Shorten the time an object can stay in orbit after its end-of-life (from 25 years to 10, 5, or 1 year) or require de-orbiting immediately at end-of-life	• How should the threshold be set? • Should there be exceptions? • Should there be sanctions for non-compliance?
	Require a high post-mission disposal success rate	• Should there be sanctions for non-compliance? • Should this metric be calculated in the aggregate for constellations? Or should they be subject to a different rate?

in improving SSA capabilities is more or less cost-effective than improvement in space debris mitigation is unknown.

Financing programs or mechanisms for remediation

Mechanisms or programs for financing space debris remediation are limited. Research and development of the technologies necessary for remediation have been privately and publicly funded, albeit with limited budgets (see *Remediation*, p. 20). The largest spacefaring nations have for the moment failed to finance programs to develop and implement the technologies necessary for remediation.

Most derelict objects accumulated in orbits were deposited before the enactment of the international guidelines (see *Current debris population*, p. 8). Responsibility for their clean-up is thus debated. Mechanisms for sharing the burden among spacefaring nations have been developed but require agreement among nations (e.g., Muñoz-Patchen, 2018). Apportionment of the costs is a difficult task which could be bypassed using market-based mechanisms that generate funds. Management of the funds could take the form of bounty payments to regulated commercial entities that conduct remediation actions (Carroll, 2019). Fair and stable bounty payments (e.g., for the removal of an object or the deflection of its trajectory prior to a predicted collision) could encourage the development and deployment of cost-effective technologies.

Another proposed mechanism to develop commercial remediation capabilities is an advance market commitment (AMC), which is a type of demand-pull policy initiated for vaccines (Lifson & Linares, 2021). An AMC is a binding commitment to purchase a certain quantity of a product at a premium price coupled with a guarantee by the seller to offer subsequent quantity at near marginal cost. This mechanism would pull technology development by reducing demand uncertainty thus incentivising market entry.

2. Other possible response strategies

The only existing international governance mechanisms are non-binding, and space actors have only limited incentive to respect the rules, as they would incur all the costs of mitigation without reaping all the benefits. When current international guidelines are translated into national mechanisms, only ex-ante requirements are implemented. Operators are required to submit a space debris mitigation plan to obtain a license. However, the lack of ex-post monitoring and sanctions result in weak incentive to commit to the plan and a low adherence to existing guidelines. Instead of, or in addition to, the command-and-control approach commonly used, which consists of prescribing what is or is not allowed, economic incentives could be used. This section details market-based and other non-conventional response strategies that could be devised to address risks from space debris.

Insurance

Two types of satellite insurance are available on the market: first-party (property) and third-party liability (TPL) insurance. Both types of insurance can be bought for launch, in-orbit operations, or both. Satellite first-party insurance insures against the loss of performance of a satellite (i.e., it insures the asset), while TPL insurance insures against damage caused by a space operator's asset to third-parties.

In the space domain, first-party insurance is more common than TPL insurance. Operators often cover the risk of losing their satellites during the launch and the first months of operations (up to a year). In-orbit first-party insurance can then be bought on a yearly basis. In LEO, only about 3% of the satellites are covered by a first-party insurance (Kunstadter, 2020).[20] First-party insurance policies cover all risks, unless expressly excluded. Although the probability of a collision with a piece of space debris in LEO has significantly increased in the past 20 years, this

[20] Generally, governments do not insure their satellites. The growth of commercial activities should therefore result in the growth of the share of satellites insured. However, a significant share of the newly launched commercial satellites will be part of constellations, which often manage risk by using in-orbit spares rather than by purchasing insurance.

probability is still about two orders of magnitude smaller than the one of technical failure. As collision probability accounts for a small share of the overall probability of losing a spacecraft, premium rates are not driven by collision probabilities (Weeden & Christensen, 2019). Insurers encourage operators to follow best practices and international guidelines, but they neither require compliance nor economically penalise operators for non-compliance.

Due to the strong liability regime for damage on the ground or to aircrafts in flight under the LC (see *Binding public international law*, p. 21), launching states often require operators to purchase a TPL insurance for launch and/or re-entry. As the likelihood of a claim is lower for in-orbit activities, due to the fault-based regime, not all major launching states require an in-orbit TPL insurance. For example, while the US does not require an in-orbit TPL, France, the UK and Japan require it (with varying limit and scope).

A well-functioning liability insurance market can be, under certain conditions, an alternative to regulations. A prerequisite for insurance markets to achieve their risk-reduction potential is the availability of a clear legal framework regarding liability rules, which is lacking in the space debris context. The premium rates are priced according to the risk of a claim and not the probability of a collision. As the likelihood of a claim in case of a collision is low, the pricing mechanism of TPL insurance premium rates cannot induce risk-reducing behaviours. The historical absence of claims for TPL impedes the pricing of insurance premium rates commensurately with the collision probability. Although some risk classification is performed to price TPL insurance, premiums appear to be mostly driven by the cost of capital. This precludes TPL insurance from acting as a surrogate regulation.

Even with a more certain legal framework and efficient enforcement mechanisms, the remote nature of space would still render the assertion of liability difficult. Determining from the ground if a spacecraft has been lost due to a technical failure or due to a collision with space debris is often not possible. The uncertain legal framework and the remote nature of space have led the space industry to rely on first-party insurance, which provides coverage for all risks, rather than TPL. First-party insurance offers a much quicker and easier solution for operators than TPL when they lose an asset. TPL is thus likely to function at best inefficiently, as an operator whose insured space asset is damaged by a piece of space debris will be indemnified by its insurer. Although the latter could potentially recover its losses by suing the entity responsible for the damage (right of subrogation), there is much uncertainty about the legal framework on which such a recovery would rely (see *Binding public international law*, p. 21). The first-party insurance only covers the book value of the satellite lost (including launch), but the damage could include, e.g., reputation deficit and loss of customers. As the first-party insurance does not cover those types of damage, the operator might still seek indemnification through courts or its launching state.

Requiring operators to hold in-orbit TPL insurance cannot incentivise them to reduce the amount of debris generated due to the decoupling between risk and premium rates. However, if such a requirement applies as long as a satellite is in orbit, this would act as a kind of orbital fee (see *Regulatory fees*, p. 29), incentivising the timely de-orbiting of spacecraft (see, e.g., Reesman et al., 2020). It would incentivise operators to take less risk once a technical failure occurs or when extending the life of a spacecraft. From the perspective of the regulator, this requirement is easier to implement than a fee. Also, it does not require the regulator to price and justify the pricing of the fee. However, contrary to a fee, this mechanism would not provide funds for actively removing spacecraft. Moreover, it would imperfectly internalise the externality as it would not result in a fee level commensurate with risk, and debris released during normal operations would probably not be accounted for.

Marketable permits

Marketable permits (see, e.g., OECD, 1998; Schwartz, 2017, for an overview) are government-created licenses or obligations for a specific level of a particular activity. In other words, a marketable permit is a right or duty to take a defined action. It is a tool to incentivise certain desired behaviours. Such permits have been most prominently used in environmental and energy policies for natural-resource and pollution management. Such permits have typically been established to ration the use of common-pool resources, such as controlling air pollution and GHG emissions, but have also been used to favour the production of under-supplied goods or actions, such as renewable energy (Engel, 1999; Tietenberg, 2006). Two broad categories of marketable permits exist: cap-and-trade and credit trading. In a cap-and-trade system, the regulator sets an absolute budget — the cap — for the activity regulated, while in a credit trading system, the regulator sets the relative amount of an activity that can take place.

Marketable permits could be used to limit the creation of space debris and internalise the costs of managing collision risk with active spacecraft (David et al., 2019; Pecujlic & Germann, 2015). For these permits to be applicable to a CPR problem, the compliance costs (i.e., the abatement cost in the case of reducing debris creation) across the regulated entities should differ and the activity to be regulated must be fungible (i.e., its individual units must be interchangeable, and each of its parts must be indistinguishable from another part). It can reasonably be assumed that the cost of reducing debris generation differs across space actors. Technological innovation, which is likely to be uneven across actors, can yield further compliance costs differentials.

Challenge: Financing remediation

Remediation is addressed at neither the international nor the national level. Under the current strategy, resource-preserving investments are not internalised, thus remediation is not incentivised. Apportioning the costs of remediation among actors is particularly challenging. Financing space debris clean-up in LEO requires the development of imaginative and attractive mechanisms, perhaps based on successful schemes put in place in other sectors. Market-based mechanisms that generate funds for remediation could be a solution.

The unit of exchange of the activity regulated – the currency – must be carefully designed to maximise fungibility and prevent the externalities from escaping the trading market. Space debris is not fungible, as pieces of debris have diverse masses, cross-sections and orbits, thus generating a different collision risk. It is theoretically feasible to design a fungible unit of space debris related risk. However, designing a simple and implementable unit of space debris related risk that can be monitored is a challenge. A comprehensive unit of collision risk, which internalises all external costs generated by human-made objects in space, would also need to take into account the external costs imposed by active satellites on other space users (e.g., manoeuvring costs). Salzman and Ruhl (2000) argue that while theoretically attractive, comprehensive currencies designed to account for non-fungibility across type, space and time impose a heavy informational burden on the entities responsible for designing and supervising the trade program. This increased complexity results in increased transaction costs and reduces the potential efficiency of the program.

Regulatory fees

Regulatory fees, or Pigouvian taxes, are similar to marketable permits. A regulatory fee is a per-unit compliance cost that is guaranteed and independent of the amount of activity performed. Under the condition of certainty, the level and pattern of activity reduction, as well as the abatement cost incurred by the actors are the same in both regulatory schemes. If the regulator faces uncertainty regarding the abatement costs of the entities regulated, the outcome of these two approaches will differ. Marketable permits ensure that a certain amount of the activity is performed, but at uncertain abatement cost, while a regulatory fee places an upper bound on the abatement cost, but does not guarantee a certain amount of activity performed (see, e.g., Wiener, 1999). Firms facing high abatement costs can always opt to pay the fee. If more firms than expected by the regulator choose this option, the reduction of the regulated activity will not achieve its target. The uncertainty over economic growth can also impede the fee's ability to meet the policy goal, as firms can always choose to pay the tax if demand for their products or services rises.

Setting a regulatory fee involves two components: defining the unit of regulated activity that would drive fee liability and setting an efficient fee level. The considerations for designing a fungible currency for a marketable permit scheme also applies in defining the unit of risk for a regulatory fee. In the case of space debris, determining the efficient fee level is difficult as the regulatory authority is lacking information regarding the current and future abatement costs of the regulated actors. For example, in the near future, services to actively remove derelict satellites will probably be available, but a significant uncertainty regarding their cost remains. An important point is the trigger of the fee payment. Would regulated actors be required to pay the fee ex-ante based on disclosures of the predicted amount of debris-related risk created by their mission? Or would the fee be triggered on an ongoing basis based on the actual debris created?

Different forms of regulatory fees, often tied to a recycling mechanism, have been proposed in the literature (see, e.g., Dunstan & Szoka, 2009; Evans & Arakawa, 2012; Garber, 2017; Pusey, 2010; Rao et al., 2020; Roberts, 1992; Scheraga, 1986). Some of the schemes proposed, such as a launch or orbital parking fee, are not directly tied to the risk generation. Other schemes include discounts for risk-reducing design features or operating practices, or a deposit and refund mechanism. The most concrete example of a deposit and refund scheme is the recent proposal of a performance bond for successful disposal by the Federal Communications Commission (2020). With such a scheme, operators would have a strong monetary incentive to do everything possible to achieve the post-mission disposal of their spacecraft and to avoid the creation of any unplanned debris.

Challenge: Developing an effective and acceptable tax

Many forms of regulatory fees aimed at internalising debris creation have been proposed. They include taxes collected on launch, for orbital use or for debris generation. Proposed mechanisms include deposit and refund, and performance bond schemes. However, most proposals have only been developed at the abstract level and do not provide details on how they would be implemented. In particular, discussions about the unit of risk driving liability, the trigger of the fee liability or its calculation period, and the enforcement mechanism are lacking. More research and concrete proposals in this area are needed. Although research can help clarify the trade-offs in approximation errors between different implementations, acceptable options will likely be determined by actors' preferences.

Allocation of orbital space

Allocation of orbital space is a potential response strategy. Acknowledging the scarcity of radio frequencies and orbital space in GEO, the international community has devised mechanisms to allocate the electromagnetic spectrum and positions for satellites in GEO (Matignon, 2019). The International Telecommunication Union (ITU) is responsible for avoiding harmful radio interference and ensuring equitable access to radio frequencies and associated orbits (Jakhu, 2017). The ITU manages a cooperative system, where ITU member states collaborate to allow satellite systems to operate in outer space free from radio interference.

In LEO, some operators have acknowledged the difficulty in safely coordinating different constellations at the same altitude and have recommended avoiding overlapping altitudes (Maclay et al., 2019). However, creating "orbital slots" in LEO is much more difficult than in GEO as satellites have different altitudes and eccentricities. Complex methods have been developed to design orbits that preserve minimum separation between satellites of different constellation at all times and thus generate so-called "LEO slots" (Arnas et al., 2021).

The recognition that LEO is a limited shared resource has led to the development of indexes measuring the carrying capacity, or environment capacity, of orbits and the resource consumed by a spacecraft throughout its lifetime (Lemmens & Letizia, 2020; Letizia et al., 2019, 2020). This kind of space traffic footprint might be instrumental in assessing missions and could help develop market-based solutions such as regulatory fees or marketable permits, or be integrated into licensing processes.

Moratorium on launch and similar proposals

Some observers have proposed a moratorium on licensing or launches until further evidence on the risks involved is gathered and appropriate regulations are adopted (Boyle, 2021; Eder, 2021). Other observers have questioned the usefulness of having many satellite constellations providing a similar service, arguing that cooperation could help avoid the duplication of the infrastructure. Following the same perspective, the idea of capping the number of satellites per constellation has also been mentioned (Patel, 2019).

Corporate reputation and social responsibility

Corporate reputation and brand identity could be a driver of sustainability and social responsibility in space. If customers of satellite-based services have information regarding operators' practices and their level of sustainability, they might be willing to integrate this information into their provider selection. However, such information is currently unavailable. The development of the Space Sustainability Rating (SSR) by the Global Future Council on Space Technologies of the World Economic Forum is aimed at bridging this gap (Rathnasabapathy et al., 2020). The SSR is a composite indicator of a satellite footprint on the space environment.[21] Participation in the SSR will be voluntary and operators will have to provide mission data to the rating organisation.

The SSR could encourage satellite operators to improve the sustainability of their activities through increased transparency of operators' debris mitigation efforts. The challenge of such rating is defining the dimensions to be included and their respective weights. An over-complex rating calculation methodology can also impede effective communication of its results and their rationale.

To what extent reputation can help reduce risk in space is questionable. Maclay and McKnight (2020) argue that such rating could be an aspirational target, which would help space actors go beyond the legal requirements and the expected adherence to norms and guidelines.

[21] Other aspects of sustainability will be included in the SSR in the future. Design and development of the first iteration of the SSR and selection of a hosting organisation are currently finalised. The first ratings are expected to be conducted by the end of 2021.

Conclusion

Collision risk in low Earth orbit is on the rise. More satellite launches, combined with our societies' growing reliance on space assets, result both in a higher likelihood of collisions and more severe consequences in case of an accident. Much of the discussion regarding space safety is concerned with coordinating and managing increasing levels of space traffic. Although increased efforts are required in this area, the risk profile of an operating spacecraft is dominated by lethal non-trackable objects which cannot be dodged. Addressing this risk is of paramount importance and is becoming increasingly urgent. Moreover, the risk posed by large-derelict objects deposited in orbit since the start of the space age, which could generate tens of thousands of lethal non-trackable debris, is not currently being addressed.

Our objective in this report has been to provide a brief overview of the current status of collision risk in low Earth orbit and highlight the challenges we face in addressing the risk. We detailed the current response strategy at both the technical and governance levels and presented a range of possible response strategies that could be pursued in the future. The strategies presented in this work are not exhaustive, but we hope they will help to broaden the options being considered and highlight areas where further analysis and research are required.

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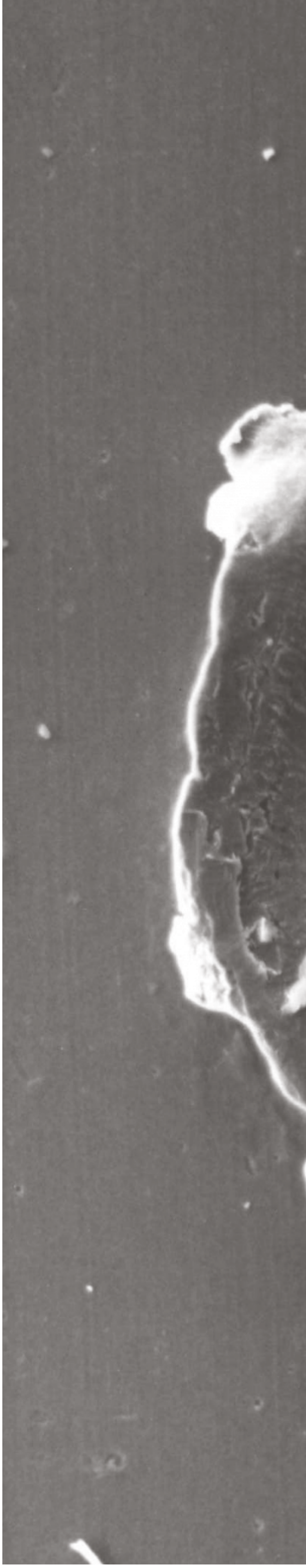

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