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THE ECONOMICS OF SPACE DEBRIS IN PERSPECTIVE

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Space Sustainability: The Economics of Space Debris in Perspective

By Marit Undseth, Claire Jolly and Mattia Olivari
(OECD Directorate for Science, Technology and Innovation, OECD Space Forum Secretariat)

This OECD paper provides an original, first-time, economic analysis of the issue of space debris, identifying and discussing key sustainability challenges for current and future space activities, reviewing the most relevant socio-economic impacts linked to space debris and exploring policy recommendations. It intends to prepare the ground for future policy responses that are vital to ensuring continued human operations and presence in space. STI has a key role to play in space debris mitigation and remediation, with more work needed in research and development, international co-operation and collaboration with industry.

Keywords: Space sustainability; space debris.

JEL codes: F01; F55; F60; O30; Q55.

Summary and main findings

This paper explores selected long-term sustainability issues and the role of science, technology and innovation in the context of increasing activities in outer space, with a particular focus on the economics of space debris. Several international organisations and committees (e.g. United Nations' Committee on the Peaceful Uses of Outer Space, Inter-Agency Space Debris Coordination Committee), national administrations and space agencies have already carried out extensive work on some of these issues, mainly concentrating on the legal and technical aspects of space debris and the congestion of low-earth orbits. This paper brings in some original perspectives on space sustainability, by providing a fresh look at the economics of space debris, and by proposing some avenues for action, based on experiences in environmental pollution abatement from other policy domains.

Economic and societal vulnerabilities to space hazards, in particular space debris, are growing.

- The use of Earth's orbits, in particular the low-earth orbit, has significantly increased in the last ten years, following growing institutional uses and commercialisation of space activities. This evolution is expected to continue and accelerate with the deployment of mega-constellations for satellite broadband, some comprising several thousand satellites.
- One of the most pressing threats to the long-term sustainability of space operations is the accumulation of space debris in Earth's orbits, in particular in the low-earth orbit. Individual exceptional events (anti-satellite tests, collisions) can have disastrous consequences. The 2007 destruction of the FengYun-1C satellite doubled the amount of debris at 800 km altitude and led to a 30% increase in the total orbital debris population.

Space debris protection and mitigation measures are already costly to satellite operators, but the main risks and costs lie in the future, if the generation of debris spins out of control and renders certain orbits unusable for human activities.

- Space debris already generate associate costs, including satellite protection, mitigation and even replacement costs in some cases. To this must also be added the costs of debris surveillance and tracking. Operators in the geostationary orbit (GEO) have estimated protective and mitigation costs at some 5-10% of total mission costs. In the upper lower-earth orbits (LEO), these costs are much higher.
- However, the main cost and risk of collisions with debris is the generation of further debris, which could ultimately lead to the so-called Kessler syndrome of cascading, self-generating collisions. This ecological tipping point may render certain orbits unusable.
- Under this scenario, socio-economic impacts could be severe. Several important space applications could be affected or lost, in particular space-based observations for weather forecasting, climate monitoring, earth sciences, and potentially, satellite communications. Certain geographic areas and social groups would be disproportionally affected, in particular in rural areas with limited existing ground infrastructures and large reliance on space infrastructure.

Comprehensive national and international mitigation measures exist, but compliance is insufficient to stabilise the orbital environment.

- LEO and GEO orbit-clearance guidelines[1] provide a list of mitigation measures that would contribute to slowing down the accumulation of debris and eventually stabilise the space environment: This includes no intentional generation of debris (including anti-satellite tests), no accidental explosions in orbit, a 25-year deorbit rule in LEO and GEO, collision avoidance when feasible, as well as the minimisation of casualty risk on ground. Some studies also recommend the active removal of several large pieces of debris per year.
- Compliance with these measures is still insufficient. While most GEO operators comply with guidelines, compliance rates are much lower in LEO (less than 60% in all orbits and closer to only 20% in orbits above 650 kilometres). Several countries have conducted orbital anti-satellite tests over the years.

There are also legal and technological challenges, especially for active debris removal.

- The space environment is unique in that it is extremely difficult to attribute actions to specific operators. Effective monitoring depends on active co-operation from operators to identify and name space objects and technological progress in object detection and tracking.
- Traffic management measures are increasingly needed to avoid collisions and further debris generation. Current advanced systems of terrestrial and space-based sensors track some 20 000 debris and active satellites typically 10 cm and bigger in the low-earth orbit and 30-50 cm and bigger in the geosynchronous orbit. However, this covers less than 0.02% of the total estimated debris population in Earth's orbits bigger than 1 millimetre.
- Only a small share of satellites in LEO are insured in-orbit against malfunctions and accidents. Some satellites have liability insurance, generally because of legal requirements (e.g. mandatory in France and the United Kingdom).
- And finally, active debris removal technologies are in various stages of testing, involving both public and private actors. However, legal issues concerning debris ownership, liability and long-term funding of operations are far from being resolved.

Practices in other policy domains could contribute to finding ways to increase compliance and internalise the costs of orbital debris pollution, while partnerships with the private sector will be key to addressing these challenges.

- Improving compliance behaviour among satellite operators is an indispensable step to contribute to long-term sustainability of orbits. For this, a range of policy solutions and lessons learnt from other domains and sectors may serve as inspiration, particularly common pollution abatement measures, with instruments that include taxes, tradable permits, financial security mechanisms, and voluntary agreements.
- Relevant avenues for action could include the strengthening of space situational awareness (SSA) systems, data reporting structures, engaging in further R&D in debris removal in particular; and finally addressing debris mitigation guidelines compliance particularly at national levels. This will imply close co-operation with public and private actors. In order to support and improve decision-making, the development of new indicators should also be explored, as to monitor debris mitigation performance and environmental instability.

There is still a long way to go in improving space sustainability via space debris mitigation, with many promising areas for further science, technology and innovation (STI).

- Faced with a doubling or tripling of active satellites in LEO, it will become critical to strengthen current space situational awareness data processing and management capabilities. More research

[1] The International Inter-Agency Space Debris Coordination Committee Debris Mitigation Guidelines ((IADC, 2007[18]) and the UN COPUOS Guidelines for the Long-term Sustainability of Space Activities (UN COPUOS, 2018[2]).

is also needed in both active and passive deorbit technologies and techniques, as well as in the "greening" of the sector in general (e.g. spacecraft design and reuse, cleaner propulsion technologies).

- More broadly, the threat of space debris is just one of several hazards in the space environment, requiring further research. For instance, space weather research is still in its early stages, with many unknowns about the fundamental physical boundaries of space weather events, and many efforts needed in developing forecasts.

Continuité à long-terme des activités spatiales: Focus sur les impacts économiques des débris spatiaux

Résumé et principales conclusions

Ce document examine certains aspects de la viabilité à long terme des activités spatiales ainsi que le rôle de la science, de la technologie et de l'innovation dans le contexte de l'augmentation des activités menées dans l'espace extra-atmosphérique, sous l'angle spécifique des débris spatiaux. Plusieurs organisations et comités internationaux, dont le Comité des utilisations pacifiques de l'espace extra-atmosphérique (CUPEEA) de l'Organisation des Nations Unies (ONU) et le Comité de coordination interinstitutions sur les débris spatiaux (IADC), des administrations nationales et des agences spatiales ont déjà mené d'importants travaux autour de quelques-unes de ces questions, principalement les aspects juridiques et techniques des débris spatiaux et la congestion de l'orbite terrestre basse. Ce document apporte des éclairages inédits sur la viabilité de l'espace en portant un nouveau regard sur les impacts économiques des débris spatiaux et en proposant des pistes d'action inspirées du retour d'expérience des mesures de réduction de la pollution environnementale, appliquées à d'autres secteurs.

Les vulnérabilités économiques et sociales causées par les menaces pesant sur l'infrastructure spatiale, en particulier les débris spatiaux, sont en augmentation.

- Depuis dix ans, la croissance des utilisations institutionnelles de l'espace et de la commercialisation des activités spatiales s'est accélérée, recourant en particulier à l'orbite terrestre basse. Cette tendance devrait se poursuivre et s'accélérer encore avec le déploiement de gigantesques constellations de (parfois plusieurs milliers de) satellites haut débit.
- L'une des menaces les plus sévères pour la viabilité à long terme des opérations spatiales est l'accumulation de débris en orbite terrestre, en particulier l'orbite terrestre basse. Certains événements isolés exceptionnels (essais de missiles antisatellite, collisions) peuvent avoir des conséquences désastreuses. En 2007, la destruction du satellite FengYun-1C a doublé la quantité de débris à 800 km d'altitude et gonflé de 30 % la population totale de débris orbitaux.

Les mesures de réduction des débris spatiaux et de protection contre leurs effets, déjà coûteuses pour les opérateurs de satellites, le seront d'autant plus à l'avenir. De même, les risques seront d'autant plus importants, si la production de débris devient incontrôlable et rend certaines orbites inutilisables.

- Les débris spatiaux induisent déjà des coûts, notamment ceux liés à la protection des satellites, de l'atténuation des risques et même du remplacement des satellites touchés dans certains cas. À cela s'ajoutent les coûts de la surveillance et du suivi des débris. Les opérateurs de satellites en orbite géostationnaire estiment que l'atténuation des risques et la protection représentent entre 5 et 10 % du coût total d'une mission. Le chiffre est souvent plus élevé pour les opérateurs de satellites en orbite terrestre basse.
- Cependant, les principaux coûts et risques de collision avec des débris sont dus à la production de débris supplémentaires, laquelle pourrait finir par causer ce qu'on appelle le syndrome de

Kessler, c'est-à-dire la multiplication des collisions elles-mêmes causées par d'autres collisions. Au-delà de ce seuil, certaines orbites deviendraient inutilisables car trop encombrées.

- Dans un tel scénario, les impacts socio-économiques seraient graves. Plusieurs applications spatiales importantes pourraient être touchées ou perdues, en particulier les observations réalisées depuis l'espace pour les prévisions météorologiques, la surveillance climatique ou les sciences de la terre et, peut-être, les communications par satellite. Certaines régions et certains groupes sociaux seraient plus affectés que d'autres, en particulier dans les zones rurales dotées d'infrastructures terrestres limitées, qui dépendent beaucoup des infrastructures spatiales.

Il existe des mesures nationales et internationales exhaustives d'atténuation des risques, mais la conformité à ces mesures est insuffisante pour stabiliser l'environnement orbital.

- Les lignes directrices[2] relatives au désencombrement de l'orbite terrestre basse et de l'orbite géostationnaire établissent une liste de mesures de réduction qui contribueraient à ralentir l'accumulation de débris et, en définitive, stabiliser l'environnement spatial : pas de production intentionnelle de débris (y compris s'agissant des essais de missiles antisatellite), pas d'explosion accidentelle en orbite, règle de désorbitage au bout de 25 ans, limitation des risques de collision quand c'est possible, minimisation des risques de dégâts au sol. Certaines études ont également recommandé de procéder chaque année à l'enlèvement actif de plusieurs gros débris.
- La conformité à ces mesures est encore insuffisante. Si la plupart des opérateurs de l'orbite géostationnaire les respectent, les taux de conformité sont très inférieurs pour l'orbite terrestre basse (moins de 60 % toutes orbites confondues, et pas loin de seulement 20 % dans les orbites situées au-delà de 650 kilomètres). Plusieurs pays ont conduit des essais de missiles anti-satellite au fil des ans.

Il existe aussi des défis juridiques et techniques à relever, en particulier s'agissant de l'élimination active des débris.

- L'environnement spatial est unique dans le sens où il est extrêmement difficile d'attribuer telle ou telle action à des opérateurs spécifiques. Le surveiller efficacement suppose une coopération active des opérateurs pour identifier et nommer les objets spatiaux, et des avancées technologiques dans les domaines de la détection et du suivi des objets.
- Des mesures de gestion du trafic sont de plus en plus nécessaires pour éviter les collisions et la production de débris supplémentaires. Les systèmes avancés actuels de capteurs au sol et en orbite surveillent quelque 20 000 débris et satellites actifs de taille égale ou supérieure à 10 cm en orbite terrestre basse et de taille égale ou supérieure à 30 à 50 cm en orbite géosynchrone. Mais cette surveillance couvre moins de 0.02 % de la population totale estimée de débris orbitaux de plus de 1 millimètre.
- Un nombre très limité de satellites en orbite terrestre basse sont assurés en orbite contre les dysfonctionnements et les accidents. Certains satellites font l'objet d'une assurance de responsabilité civile, en général en application d'une exigence juridique (obligatoire en France et au Royaume-Uni, par exemple).
- Les techniques d'enlèvement actif de débris sont à divers stades d'essai, faisant intervenir tant des acteurs privés que des acteurs publics. Mais les questions juridiques liées à la propriété des débris, à la responsabilité civile et au financement à long terme des opérations sont loin d'être résolues.

[2] Lignes directrices relatives à la réduction des débris spatiaux du Comité de coordination interinstitutions sur les débris spatiaux (IADC, 2007[18]) et Lignes directrices du Comité des utilisations pacifiques de l'espace extra-atmosphérique aux fins de la viabilité à long terme des activités spatiales (UN COPUOS, 2018[2]).

Les pratiques issues d'autres domaines d'action pourraient donner des moyens d'accroître la conformité et d'internaliser les coûts de la pollution causée par les débris orbitaux, sachant que des partenariats avec le secteur privé seront essentiels pour relever ces défis.

- La viabilité à long terme des orbites passe impérativement par une amélioration des taux de conformité des opérateurs de satellites. Or, il existe une panoplie de moyens d'action et d'enseignements tirés d'autres domaines ou secteurs qui pourraient servir d'inspiration, en particulier les mesures courantes de réduction de la pollution, avec des instruments tels que taxes, permis négociables, mécanismes de sécurité financière et accords volontaires.
- Les pistes à suivre pourraient être le renforcement des dispositifs de veille spatiale et des structures de communication de données, avec davantage de R-D relative à l'enlèvement des débris notamment ; et une action pour la conformité aux lignes directrices relatives à la réduction des débris spatiaux, en particulier au niveau national. Cela nécessitera une coopération étroite entre les acteurs publics et privés. Afin de soutenir et d'améliorer le processus de décision, il devrait aussi être envisagé d'élaborer de nouveaux indicateurs, par exemple de suivi des performances de réduction des débris, ou de suivi de l'instabilité environnementale.

Il reste encore beaucoup à faire pour améliorer la viabilité de l'espace en y limitant les débris, ce qui ouvre de nombreuses voies prometteuses pour l'avancement de la science, de la technologie et de l'innovation (STI).

- Dans la perspective du doublement voire du triplement du nombre de satellites actifs en orbite terrestre basse, il deviendra vital de renforcer les capacités de traitement et de gestion des données collectées par la veille spatiale. Il convient également de consacrer davantage d'efforts de recherche aux techniques et technologies de désorbitage actif et passif, ainsi qu'au « verdissement » du secteur dans son ensemble (par exemple, conception et réutilisation des engins spatiaux, technologies de propulsion plus propres).
- Plus généralement, les débris spatiaux ne sont que l'un des dangers de l'environnement spatial auxquels il faut consacrer des recherches. Par exemple, la recherche sur la météorologie spatiale est balbutiante : on connaît encore très peu les limites physiques fondamentales des événements météorologiques de l'espace, et d'importants travaux sont nécessaires dans le domaine de l'élaboration des prévisions.

1 Introduction

The increasing use and cluttering of Earth’s orbits go hand in hand with the digital transformation of the economy and society (see OECD (2019[1])). Digital technologies have contributed to lowering launch costs and unleashing the full potential of space-generated data and signals, drawing investments to the sector and growing reliance on space-based infrastructures. In a similar vein, digital technologies will be instrumental in addressing the growing problem of accumulating space debris, which, if continuing unchecked, could put at risk the continued use of Earth’s orbits for societal benefit.

Defining space sustainability

The United Nations’ Committee on the Peaceful Uses of Outer Space (UN COPUOS) defines long-term space sustainability as:

> *“[…] the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations.” ((UN COPUOS, 2018[2]).*

This definition focusses on the outer space environment (e.g. Earth’s orbits, electromagnetic spectrum), and emphasises “equitable access” for both present and future generations. Equitable access has both geographic, social and intergenerational dimensions. In this paper, the OECD Space Forum Secretariat will use UN COPUOS' definition and scope of space sustainability.

However, it is important to keep in mind that space sustainability could have a much wider scope, including aspects such as environmental impacts of space activities on earth and beyond, social sustainability with public acceptance considerations, sustainability of recruitment and workforce composition, etc.

The accumulation of space debris in Earth’s orbits, in particular the low-earth orbit, is one of the most pressing threats to the long-term sustainability of space operations. Issues related to the allocation and use of electromagnetic spectrum are not covered in this paper, but they represent another growing concern, due to the intensification of space activities and to terrestrial competition for spectrum

The economic dimension of sustainability is particularly important for the space sector, and economic and environmental objectives will increasingly need to be balanced to fulfil this objective of meeting “*the needs of the present generations while preserving the outer space environment for future generations*”.

Space sustainability and the tragedy of the commons

When natural resources are degraded, economic growth can slow down or even become negative. This calls for adequate management to sustain growth without causing irremediable damages.

For space activities, the Outer Space Treaty of 1967 establishes the freedom of exploration and use of space for the benefit and interest of all countries, as well as the non-appropriation of outer space, including the Moon and other celestial bodies. In this context, Earth's orbits and electromagnetic spectrum are generally considered as limited natural resources (UN COPUOS, 2018[2]).

From an economic perspective, Earth's orbits and electromagnetic spectrum are "common pool resources", in the sense that they are characterised by:

- Low level of excludability: No single actor can establish control over the good;
- High subtractability of use: Use by one agent detracts from the amount available to others.

Table 1.1. Concept of "subtractability of use"

		Subtractability of use	
		High	Low
Difficulty of excluding potential beneficiaries	High	Common-pool resources: groundwater basins, lakes, irrigation systems, fisheries, forests, etc.	Public goods: peace and security of a community, national defence, knowledge, fire protection, weather forecasts, etc.
	Low	Private goods: food, clothing, automobiles, etc.	Toll goods: theatres, private clubs, day-care centres

Source: Ostrum (2009[3]), p. 413, cited in (Smith, 2017[4]), "Innovating for the global commons: multilateral collaboration in a polycentric world", https://doi.org/10.1093/oxrep/grw039

Overexploitation and pollution are frequent negative externalities of common pool resources, often referred to as the "tragedy of the commons", where the actions of individual users, motivated by short-term gains, go against the common long-term interest of all users. The management of common pool resources, for which market mechanisms are highly imperfect or completely absent, depends crucially on the existence and effectiveness of the rules and institutions (whether formal or informal) to govern their use (see for instance (Ostrom, 2009[3]) for important governance design principles).

For space activities, this translates for example into human activities potentially littering Earth's orbits beyond sustainable limits, creating space debris that could reduce the value of space activities by increasing the risk of damaging collisions and requiring mitigation actions.

Objectives and structure of the paper

This paper explores selected long-term sustainability issues related to increasing activities in outer space, with a particular focus on the economics of space debris.

Several international organisations and committees (e.g. United Nations' Committee on the Peaceful Uses of Outer Space, Inter-Agency Space Debris Coordination Committee), national administrations and space agencies have already carried out extensive work on some of these issues, mainly concentrating on the technical aspects of space debris and the congestion of low-earth orbits. This paper brings in some original perspectives on space sustainability, by providing a fresh look at the economics of space debris, and by contributing some illustrations of selected policy options on environmental pollution abatement from different domains.

The structure of the paper addresses the following points, as it aims to:

- Identify and discuss key sustainability challenges for current and future space activities;
- Review the most relevant socio-economic impacts linked to space debris, for current and future space exploration and exploitation;
- Identify potential policy responses from other domains and sectors, drawing mainly on OECD substance and recommendations;
- Explore policy recommendations specific to the space domain.

2 Selected challenges for sustainability of outer space activities

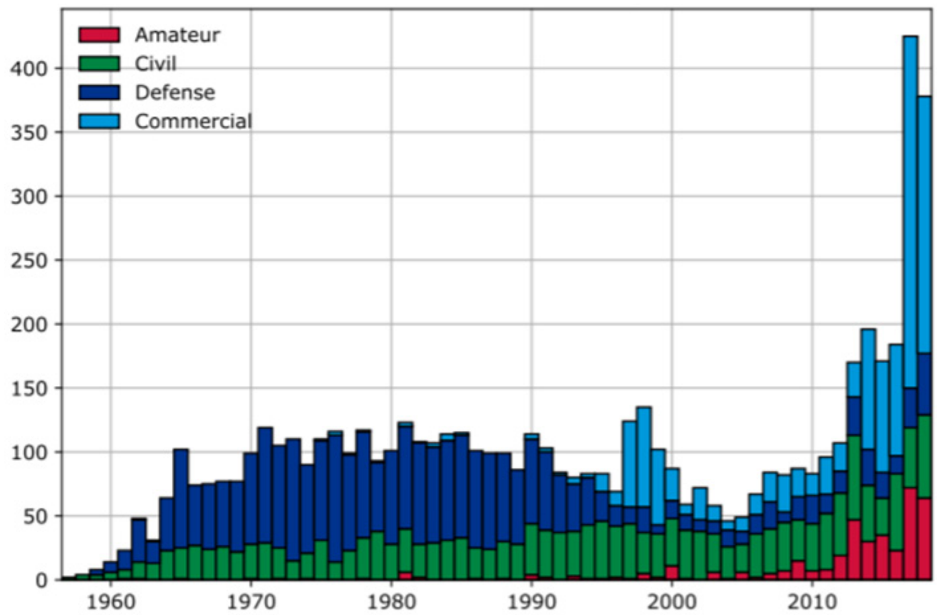
One of the (unexpected) effects of digitalisation is the increased use of Earth's orbits, for commercial, civil and military purposes. Activities, in particular in the low-earth orbit, have significantly increased in the last few years, following growing institutional applications and commercialisation of space activities, pulled by lower launch costs and high expected returns in the data-intensive downstream segments. This poses a range of challenges in terms of managing limited resources (orbital space, radio frequency spectrum) and addressing space infrastructure's vulnerabilities to natural and manmade events.

More intensive use of certain orbits

Earth's orbits, in particular the low-earth orbit (LEO), are becoming ever more crowded due a growth in the population of functional satellites, mainly for commercial activities (Figure 2.1). It is interesting to note the growth in "amateur" launches since 2000, which refers mainly to very small educational satellites built by students in higher education institutions, or even in middle or upper middle school.

Figure 2.1. Payload launch traffic in LEO

Global launch activity for payloads with perigee altitudes of 200-1 750 km



Source: ESA (2019[5]), *ESA's Annual Space Environment Report: Produced with the DISCOS Database*, http://www.esa.int (accessed on 13 March 2019).

The low-earth orbit totalled some 1 500 operational satellites by the end of 2019, two-thirds of all operational satellites, compared with 560 satellites in the geosynchronous orbit (Table 2.1). This number does not take into account the recent launches of SpaceX Starlink satellites (see below).

Table 2.1. Operational satellites by orbit

As of 14 December 2019

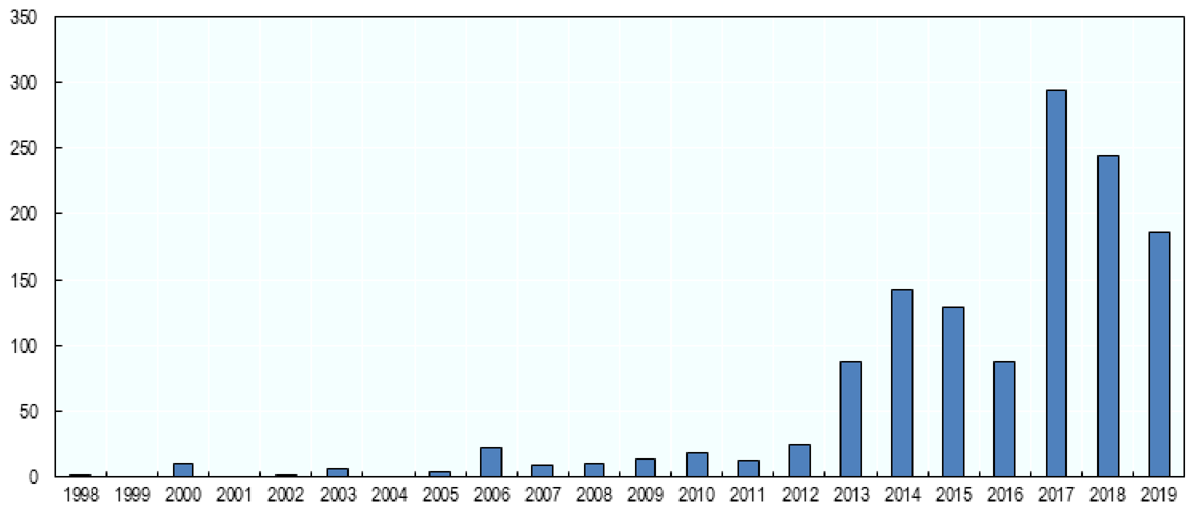
	Low-earth orbit	Medium earth orbit	Elliptical orbit	Geosynchronous orbit	Total
Total number of satellites	**1 468**	**132**	**56**	**562**	**2 218**
United States	754	34	31	188	1 007
China	236	26	1	60	323
Russian Federation	97	28	7	32	164

Note: This also includes bilateral and multilateral missions
Source: Union of Concerned Scientists (2019[6]), "UCS Satellite Database: December 2019 update", https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database

Cubesats and other very small satellites account for the lion's share of LEO satellites. Cubesats are a class of nanosatellites that use a standard size and form factor, originally developed in 1999 by California Polytechnic State University at San Luis Obispo and Stanford University to provide a platform for education and space exploration. The standard cubesat size is "one unit" or "1U", measuring 10x10x10 cm, and is extendable to larger sizes stacked lengthwise; 1.5, 2, 3, 6, etc. (NASA, 2015[7]). In the last five years, more than 900 cubesats have been launched into the low-earth orbit (Figure 2.2). Operators in the United States own about half of LEO operational satellites, mainly used for commercial activities, followed by China (16%) (Union of Concerned Scientists, 2019[6]). Many cubesats do not carry propulsion, either for mass reduction reasons or because their launch option (e.g. as secondary payload) prohibits it for safety reasons. This is problematic for debris mitigation, as cubesats in higher orbits cannot actively deorbit, and because they cannot carry out avoidance manoeuvres.

Figure 2.2. Yearly cubesat launches

Includes successful and failed launches



Note: Includes all cubesats (0.25U to 27U), nanosatellites (1-10 kg), picosatellites (0.01-1 kg) and femtosatellites (0.001-0.01 kg, e.g. pocketqubes and suncubes)
Source: Nanosatellite Database (2020[8]), *Nanosatellite and cubesat database*, Version 6 January 2020, https://www.nanosats.eu/.

However, the real game changer would be the full deployment of one or several of the broadband mega-constellations that are under preparation. In 2018, the US Federal Communications Commission approved SpaceX' plan of almost 12 000 satellites, and in 2019 the company submitted filings with the International Telecommunications Union for an additional 30 000 satellites (FCC, 2018[9]; 2018[10]). By early 2020, the company had more than 200 Starlink satellites in orbit, making it the largest commercial satellite operator. In July 2019, Amazon filed an application with the US Federal Communications Commission for its 3 000+ Kuiper System constellation. In 2019, OneWeb launched the first satellites in their planned 650+ satellite constellation. SpaceX, in its future Starlink constellation, foresees placing first about 1 600 satellites at 550 km, followed by ~2 800 satellites at 1 150 km and ~7 500 satellites at 340 km. The Amazon Kuiper System constellation would deploy three "shells" of satellites at 590 km, 610 km and 630 km, while OneWeb intends to use the 1 200 km orbit (OECD, 2019[11]; US FCC, 2019[12]). Other large constellations are being considered in North America and China in particular.

With the deployment of one or several of the announced broadband mega constellations, the number of operational satellites in orbit could double or even triple in the next five years. When taking into account all existing satellite filings, there could be several tens of thousands of operational objects in orbit by 2030 (around 2 000 today). With this level of orbital density, according to multiple modelling efforts, it is not a question of *if* a defunct satellite will collide with debris, but *when* (see for instance (IADC, 2013[13]) and (University of Southampton, 2017[14])). The increasing use of the low-earth orbit raises a number of additional issues ranging from space debris, radio interference to light pollution for astronomic observations (OECD, 2019[11]).

Growing demand for radio frequency spectrum and increased risk of interferences

Issues related to the allocation and use of electromagnetic spectrum is another growing concern for the long-term sustainability of space activities, due to the intensification of space operations and to terrestrial competition (OECD, 2019[11]).

Radio frequencies, used by spacecraft to communicate with other spacecraft and terrestrial ground stations, are often defined as a limited (albeit reusable) natural resource (ITU, 2015[15]). The International Telecommunications Union ensures equitable access to this resource by allocating frequency bands to individual countries and mitigates interference issues by reserving specific bands for specific uses (e.g. fixed satellite service up- and downlinks).

There are growing concerns of interferences from both terrestrial and space networks (e.g. deployment of 5G, the growth of mobile communications worldwide). Concerning the space networks, the sheer size of many planned constellations in low-earth orbit raises particular concerns about orbital interferences. Some satellite operators in the geostationary and medium-earth orbits worry that the increasing crowding of the low-earth orbit could eventually jam the link between higher-flying satellites and terrestrial satellite dishes (OECD, 2019[11]).

Many of these issues started to be addressed by the large World Radiocommunication Conference held in Sharm el-Sheikh in fall 2019, aiming at improving international co-ordination (ITU, 2019[16]).

The accumulation of orbital debris in certain Earth's orbits

Space debris have been accumulating in space since the launch of the first satellite in 1957, resulting from routine space operations, accidents and explosions. In the last 60 years, there have been more than 500 break-ups, collisions and explosions, so-called fragmentation events (ESA, 2019[17]).

Although there are no clear legal definition of space debris at the international level, space debris are technically defined as “all manmade objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional” (IADC, 2007[18]). The highest concentrations of objects can be found in the low–earth orbit between 800 and 1 000 kilometres of altitude and towards the 1 400 kilometres altitude. Other debris belts are close to the orbits of the existing navigation satellite constellations, between 19 000 and 23 000 kilometres of altitude, and of the critical geostationary orbit at 36 000 kilometres, where many large telecommunications and weather satellites are positioned.

Atmospheric drag and other natural phenomena eventually pull debris closer to Earth where they burn up upon entering the atmosphere (orbital decay)[3]. However, this process takes anything from a couple of years in orbits below 600 kilometres, to several centuries above 1 000 kilometres. In the geostationary orbit, there is no atmospheric drag, so that debris remain in orbit unless moved to dedicated “graveyard” orbits. Overall, the effects of some 62% of all breakups recorded since 1961 are still on orbit (Liou et al., 2018[19]).

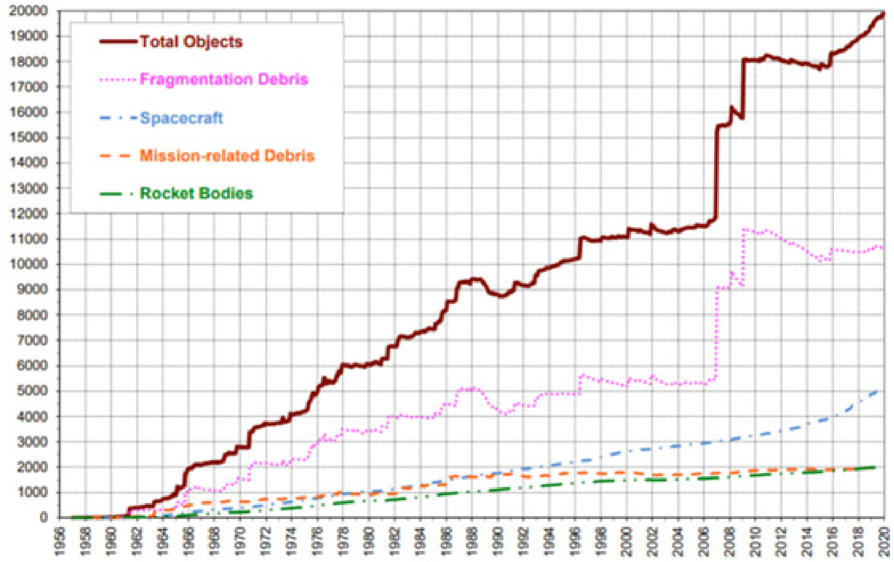
The amount of orbital debris has increased significantly in the last years. Figure 2.3 illustrates the evolution of tracked space objects (including satellites) in the low-earth orbit from the 1960s onwards, showing two marked increases in the debris population. The first increase followed the intentional destruction of the Chinese weather satellite FengYun-1C in an anti-satellite weapons test in 2007. The second increase occurred following the first documented collision between two satellites, Iridium-33 and Kosmos-2251, in 2009 (ESA, 2019[5]). The destruction of FengYun-1C doubled the amount of debris at 800 km altitude and led to a 30% increase in the total orbital debris population. Other countries have also conducted anti-satellite tests (e.g. the United States in 1985 and 2008), but at lower altitudes. India recently conducted an anti-satellite test in March 2019, creating a cloud of debris that could potentially pose a risk to the International Space Station.

All in all, more than 20 000 objects larger than 10 cm are currently catalogued and tracked by the US Air Force Space Surveillance Network. Meanwhile, the total (untracked) amount of debris 1 millimetre and bigger cm has been estimated to almost 130 million (ESA, 2019[17]).

[3] As a side note, not all debris objects are destroyed when entering the atmosphere, and can also pose a casualty risk on the ground. Statistically, one large object (e.g. full satellite or upper stage) reenters the atmosphere per week (Bonnal, 2017[86]).

Figure 2.3. Evolution of the catalogued space object population

10 cm and larger objects in Earth's orbits, including operational satellites



Source: (NASA, 2020[20]), *Orbital Debris Quarterly News*, volume 24, issue 1, https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv24i1.pdf

The current tracked object population is mainly composed of fragmentation debris from satellites and rockets, followed by spacecraft (less than half of which are operational), rocket bodies and mission-related debris (lens caps, solid rocket firings) (ESA, 2019[5]; US Air Force, 2020[21]). However, whereas rocket bodies account for only about 10% of tracked objects, they account for almost 40% of mass and area (as measured in m^2), respectively (ESA, 2019[5]).

Table 2.2. Type and orbits of selected tracked space objects

January 2019, number of objects and their mass (in metric tons)

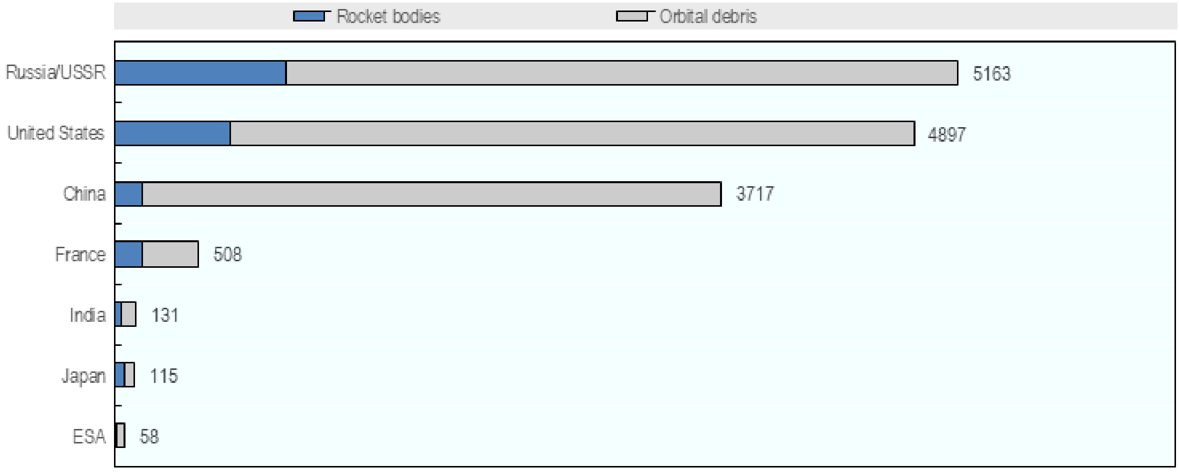
Selected orbits	Fragmentation debris	Mission-related debris	Rocket bodies	Payloads	Total (including other object types)
LEO	8 681 (1.5 tons)	769 (7.5 tons)	855 (1 271.7 tons)	2 943 (1 406.5 tons)	13 485 (2 688.5 tons)
GEO	3 (0.2 tons)	44 (1 tons)	65 (133.8 tons)	742 (646.3 tons)	842 (2 429.6 tons)
Total (including objects in other orbits)	10 525 (1.7 tons)	1 224 (136.3 tons)	1 884 (3 258.7 tons)	4 708 (5 096.1 tons)	22 014 (8 493.8 tons)

Note: Catalogued items come from the ESA DISCOS Database, with number of items slightly higher than those recorded by Space-track.org.
Source: Adapted from ESA (2019[5]), *Annual Space Environment Report: 2019.*

A small number of countries have produced the bulk of orbital space debris, proportional to the size of their space programme and years of activities. Assigning space debris ownership is a sensitive issue, as there is no clear legal definition of space debris at the international level, and furthermore, not all debris can be traced to a specific object or fragmentation event. Still, some databases, such as the US Air Force's Space-track.org, contribute to tracking and identifying debris ownership (Figure 2.4).

Figure 2.4. Space debris by country

Debris and rocket bodies in orbit, January 2020



Note: US Air Force definition of debris and ownership.
Source: US Air Force (2020[21]), Space-Track.Org.

The Russian Federation, the United States and China account for the vast majority of identifiable debris and rocket bodies, followed by France, India and Japan (US Air Force, 2020[21]).

It is important to note that several rockets currently in operation were designed at a time when space debris was not a critical issue, and the deorbiting of rocket bodies may prove difficult in some cases (Macaire, 2017[22]). In March 2019 for example, the upper stage of a discarded Atlas V disintegrated almost ten years after launch.

3 Socio-economic impacts of space debris and debris mitigation measures

The protection against space debris and their mitigation lead to a series of costs for actors in the space community, ranging from loss of the payload to launch delays, when waiting for specific launch windows. These costs are already growing, as this section will demonstrate, and may grow dramatically in the next decade.

What is the current economic impact of space debris?

Although some national and private operators may keep the information confidential for strategic or commercial reasons, the costs related to managing space debris in planning for missions and daily operations seem to be on the rise. While data are limited, some operators (in the geostationary orbit) have indicated that the full range of protective and debris mitigation measures (e.g. shielding, manoeuvres and moving into graveyard orbit) may amount to some 5-10 % of total mission costs, that often range in the hundreds of millions of dollars (National Research Council, 2011[23]).

On any orbit, spacecraft replacement costs and related delays and data loss is the most direct consequence of a fatal collision with space debris. However, there are also multiple other costs that can negatively affect spacecraft's mass and fuel consumption and hence launch costs and the length of the operational mission life. This includes impact avoidance or reduction measures (e.g. shielding, debris avoidance manoeuvres), as well as debris mitigation measures (e.g. orbit clearance, venting of residual fuel) and other considerations that alter the spacecraft's design (National Research Council, 2011[23]). There are also all the costs associated with debris surveillance, tracking and reporting.

Table 3.1 summarises the current and possible future costs and other impacts of space debris that are discussed in this section and the next one. The list is non-exhaustive.

Table 3.1. Overview of current and potential future impacts and related costs of space debris

Time frame	Type of cost/impact	Description
Current impacts	Debris-related damage	Loss of functionality or loss of entire satellites. Many incidents go unreported.
	Satellite and constellation design	Costs associated with satellite shielding, collision avoidance capabilities, safehold modes and redundancies (i.e. launch extra satellites as spares). Satellite constellations increasingly include spares for system resilience, but this solution often becomes part of the problem.
	Operations costs	Costs of Space Situational Awareness (SSA) activities, services and software. Data-blackouts when conducting avoidance manoeuvres.
	Orbit clearance costs	In the geostationary orbit: Relatively low, equivalent to about three months of station-keeping. In the low-earth orbit above 650 km altitude: Very high and requiring specific satellite subsystems (on-board computer).
	Insurance costs	Overall, limited use of in-orbit insurance by operators for space debris. Space debris collisions have historically been considered low-probability and not affecting insurance

		premiums.
Potential future impacts	Loss of unique applications and functionalities	Space observations from some of the orbits most vulnerable to space debris are often the best or the only source of data and signals in their domain. This applies in particular to polar-orbiting weather and earth observation satellites. The loss of polar-orbiting weather satellite observations would heavily affect the Southern hemisphere, where there are fewer terrestrial observations.
	Lives lost	The International Space Station is located at about 400 km altitude. Although debris at that altitude decays naturally, it still poses a real collision threat.
	Interrupted time series for earth science and climate research	Uninterrupted time series are crucial for the accuracy and reliability of weather prediction and climate models.
	Curbed economic growth and slowdown in investments in the sector	Satellite broadband is widely considered as a key driver of space activities and revenues in the coming decades. More than ten broadband satellite constellations are in different stages of development. Practically all LEO communication services would be affected, on orbit and/or during orbit-raising, as the majority of constellations are located near or above the thickest LEO debris belts. Reduced access to venture finance, with investors preferring more affordable and less risky terrestrial alternatives.
	Distributional effects	The loss or perturbation of certain low-earth orbits could be felt more heavily in rural low-density residential areas and low-income countries

Debris-related damage: Little is known about impact events with non-tracked debris objects (below 10 cm). In several cases, operators do not know the cause of the malfunction, or they choose not to report the event. Table 3.2 shows a list of possible and/or confirmed events in the low-earth orbit related to collisions with space debris over the last two decades.

Table 3.2. Possible debris impact events in LEO

Satellite/event	Country of operator	Altitude	Anomaly date	Details
SUNSAT	South Africa	400-838 km	19/01/2001	Irreversible multi-point physical failure
JASON-1	United States / France	1 336 km	03/2002	Impulse of 0.365mm/s from GPS residuals; hit left solar array from behind; lost 10% of array struck; orbit change of 30cm
Cosmos 539	Russia	1 340-1 380 km	21/04/2002	Decrease in period of 1 sec. with a 20cm x 50cm object created
JASON-1	United States/France	1 336 km	09/2005	Impulse of 0.182mm/s from GPS residuals; orbit change of 10cm
EOS-Terra	United States	705 km	13/10/2009	One battery cell in hexbay unit and heater failed simultaneously with attitude disturbance; 3mm impactor suggested
Aura	United States	685 km	12/03/2010	Panel #11 lost 50% of power and had 875 asec angular disturbance
Pegaso	Ecuador	650-654 km	22/05/2013	Close pass to rocket body but no hit
Iridium-47	United States	785-795 km	07/06/2014	Ten high velocity (80m/s) debris produced hinting at impact
Iridum-91	United States	785-795 km	30/11/2014	Four low velocity debris produced hinting on-board anomalous event
WorldView-2	United States	770 km	19/07/2016	Nine pieces detected, but WorldView says satellite is still working
Sentinel-1A	Europe	693 km	23/08/2016	6–8 pieces produced (6 catalogued) and visual verification of solar array damage; impactor of 1 cm and 0.2 gr at 11 km/s

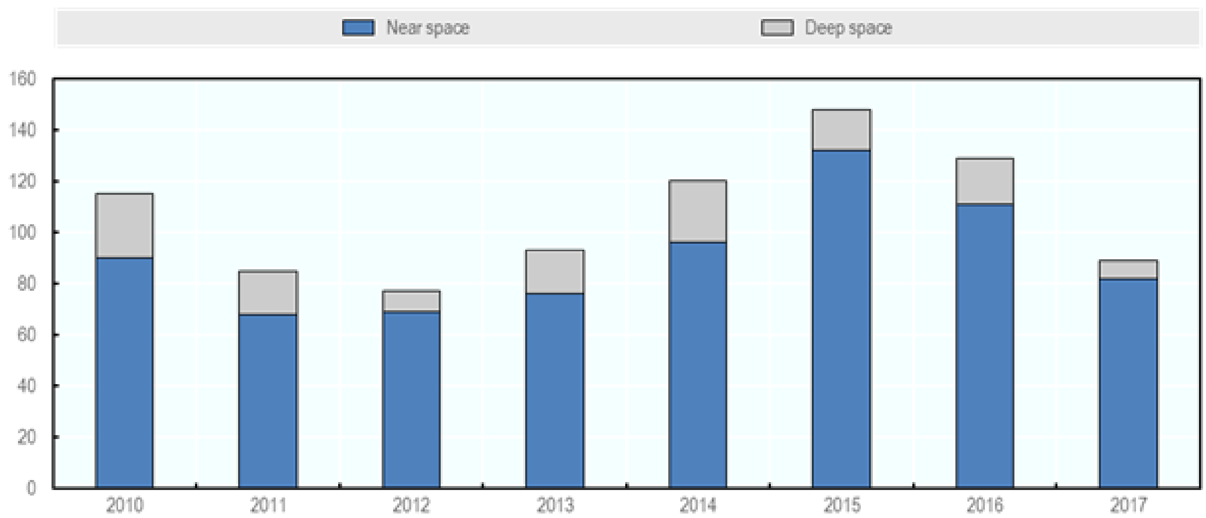
Source: Swiss Re Corporate Solutions (2018[24]), *New space, new dimensions, new challenges: How satellite constellations impact space risk*.

Satellite and constellation design costs: This includes for instance shielding, collision avoidance capabilities, safehold modes, redundancies to protect against space weather and jamming (IT security increasing issue). More generally, designing mission redundancies with spare satellites is becoming increasingly important to improve system resilience, but it is also part of the bigger problem of debris accumulation.

Operations costs: Satellite operators report an increase in manoeuvres to avoid collisions with debris. Operators need to take into account different types of data and sources with various formats to plan orbital trajectories. They may receive hundreds of warnings of impending close approaches (conjunction warnings) a year, several of which may be false or inaccurate, creating a significant burden on operators in terms of analysis and data management. Between 2015 and 2017, more than 8 000 conjunction data message (CDM) events were reported for one satellite mission alone, the European Sentinel-2A satellite (Braun et al., 2017[25]).

If the conjunction warning is considered critical, a collision avoidance manoeuvre is conducted. This consumes satellite propellant and in addition, some of the satellite instruments (e.g. cameras) usually black out during the manoeuvre, which may last up to two days. In 2017, the US Strategic Command issued hundreds of close approach warnings to their public and private partners, with more than 90 confirmed collision avoidance manoeuvres from satellite operators, as illustrated in Figure 3.1 (Weeden, 2018[26]).

Figure 3.1. Confirmed collision avoidance manœuvres of operators



Source: Weeden, B. (2018[26]), "Promoting cooperative solutions for space sustainability: US perspectives on SSA", presentation at the symposium "The SSA Strategic Challenges for India", 14-15 June, Bengaluru, https://swfound.org/media/206180/bw_us_perspectives_ssa.pdf.

Collision avoidance can affect every actor active in the space environment. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) has for example reported five avoidance manoeuvres between 2010 and 2014 for their Metop-A and Metop-B polar orbiting satellites, each manoeuvre quite small and expending only 70 g out 316 kg of hydrazine fuel (EUMETSAT, 2019[27]). ESA missions supported by the Space Debris Office conducted on average 1.8 avoidance manoeuvres between 2009 and 2016. Sentinel-1A had to conduct eight manoeuvres in 2014 (Braun et al., 2017[28]). Meanwhile, the International Space Station has seen a significant increase in debris avoidance manoeuvres, with seventeen manoeuvres taking place between 2009 and 2017, compared to eight manoeuvres in the 1999-2008 timeframe (Peters et al., 2013[29]; Liou, 2018[30])., Volumetric assessments indicate that a mega constellation such as SpaceX's Starlink would receive millions of conjunction warnings and have to conduct hundreds of thousands of avoidance manoeuvres. This would be unmanageable without the support of brand new artificial intelligence systems, and many warnings would go ignored. Improving and automating space situational awareness (SSA) detection and warning systems is one of several major challenges ahead.

Orbit clearance costs: Orbit-clearance costs include the fuel needed to clear satellites from orbit after the end of its operational life. For satellites in the geosynchronous orbit, this implies moving the satellite to a graveyard a few hundred kilometres above the operational orbit. The transfer manoeuvre requires about the same amount of fuel as three months of station keeping, some 11 m/s of delta-v (velocity needed) [4].

For satellites in the low-earth orbit, the fuel needed for orbit-clearing increases with the orbit altitude and the area-to-mass ratio of the spacecraft. For circular orbits below 600 km, no manoeuvres are necessary to respect the guidelines for an object to be deorbited or removed 25 years from its end of life. However, for higher-altitude LEO satellites, the necessary delta-v may constitute a significant share of total mission life. For 2 000 km orbits, the velocity needed may reach and surpass 450 m/s, and accounting for end-of-mission deorbit may significantly affect satellite design and mass, especially since an operating control system would also need to be installed (Janovsky et al., 2002[31]).

Insurance costs: it is estimated that only six percent of satellites in low-earth orbit have in-orbit insurance, compared to nearly half of all GEO satellites (Foust, 2018[32]; AXA/XL Group, 2019[33]).

In-orbit insurance offers protection against different types of risk (e.g. spacecraft dysfunctions, space environment hazards, third-party liability), with average annual premium rates accounting for about 0.7% of the insured amount (AON, 2018[34]). A collision with space debris or other spacecraft is still considered a low-probability event and does not affect insurance premiums for the time being (Swiss Re Corporate Solutions, 2018[24]).

Future costs of space debris

According to many experienced satellite operators, the current costs of space debris are nothing compared with future prospects. In a worst-case scenario, certain orbits may become unusable, due to continued, self-reinforcing space debris generation. This would have significant negative impacts on the provision of several important government services and would most probably also slow down economic growth in the sector. The social costs would be unequally distributed, with some rural regions more hardly hit, in view of their growing dependence on satellite communications in particular.

Loss or perturbations of orbits

If the space debris situation is not collectively managed, collisions and continued debris creation could become self-generating. This situation would be very difficult to reverse, as certain orbits of significant socio-economic use and value, could be rendered unusable for future generations. Some modelling predict that this could occur as early as within the next couple of decades, as discussed below.

Debris objects and fragments constitute a significant collision hazard for other spacecraft that are on orbit or travelling through debris belts during orbit-raising. Even flecks of paint and other tiny debris fragments can cause damage because of their high velocity of up to 10 kilometres per second in the low-earth orbit. Furthermore, debris objects constitute an even higher collision risk for each other because they are not manoeuvrable, thus generating more debris (Swiss Re Corporate Solutions, 2018[24]).

[4] Delta-v (Δv), literally "velocity needed" and measured in the units of speed, is used to determine the mass of propellant necessary to perform specific manoeuvres (e.g. launch, orbital manoeuvres).

Modelling exercises suggest that the likelihood of a collision between an operational GEO satellite and a 1 cm debris object is once every four years, and once every fifty years for a collision with a 20 cm debris object (Oltrogge et al., 2018[35]). A study conducted by Swiss Re in 2018 estimated that a 200 kg broadband satellite in a 1 000 satellite constellation flying in an orbit at 1 200 km altitude (similar to OneWeb and SpaceX) would have a 11% risk of colliding with a 1-10 cm object, a risk that would increase to 90% over the next 20 years (Swiss Re Corporate Solutions, 2018[24]). Still, space debris is not considered a significant enough hazard to affect insurance premiums, neither in LEO nor in GEO.

However, collision risk is projected to increase quite significantly in the next decade. Modelling conducted by the Inter-Agency Space Debris Coordination Committee (IADC) in the 2009-12 timeframe (before the increase in cubesat launches and the announcement of mega-constellations) predicted an average 30% increase in the amount of low-earth orbit debris in the next 200 years, with catastrophic collisions occurring every five to nine years, factoring in a 95% compliance rate to mitigation rules (IADC, 2013[13]). A 2017 study at the University of Southampton found that adding one mega-constellation of several thousand satellites to the low-earth orbit space environment would increase the number of catastrophic collisions by 50% over the next 200 years (University of Southampton, 2017[14]).

In a worst-case scenario, researchers suggest that the low-earth orbit could be rendered unusable for future generations, because collisions and the continued generation of debris would become self-sustaining, the so-called Kessler syndrome (Kessler and Cour-Palais, 1978[36]). Exactly when and if this ecological tipping-point is reached, is subject to great uncertainty, with current modelling capabilities unable to provide an answer. A US National Research Council report found that this could take place within the coming two decades (National Research Council, 2011[23]), while Kessler himself, who in a 1978 paper suggested it would happen by year 2000, has later prolonged the forecast by a century (Kurt, 2015[37]). Either way, the economic tipping point, where operations in low-earth orbit become economically unsustainable, may be reached well before (Adilov, Alexander and Cunningham, 2018[38]). Human spaceflight operations in the lower earth orbits may also be considered too risky, due to the concentrations of cubesats and broadband satellites.

Potential socio-economic impacts of the Kessler syndrome

The loss of certain orbits would have wide-reaching, significant consequences, some of which are summarised below:

- Unique applications and functionalities may be lost
- Lives lost
- Interrupted time series for earth science and climate research
- Increased crowding and pressures on other orbits
- Curbed economic growth and slowdown in investments in the sector
- Distributional effects: Negative impacts could be felt more heavily in rural low-density residential areas and low-income countries

Most affected orbits and applications

The disruption or loss of certain low-earth orbits would, in some cases, have severe impacts on terrestrial applications, for which space observations (from these orbits) are either the best or the only source of data and signals. This applies in particular to polar-orbiting weather and earth observation satellites, which make unique contributions to weather forecasting and climate change observations and research.

The orbits most likely to be disrupted by the Kessler syndrome are found at 650-1 000 km and towards 1 400 km altitude in the low-earth orbit, where the thickest belts of debris are located. For instance, the 2009 collision between Iridium-33 and Kosmos-2251 satellites took place at 776 km altitude.

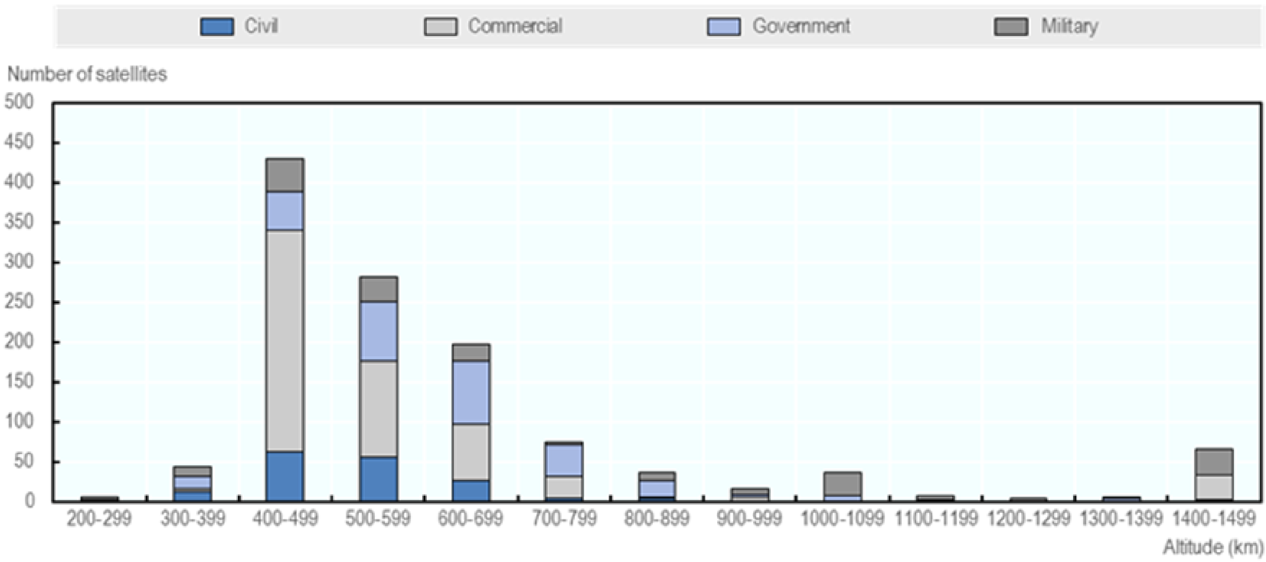
Table 3.3. Affected orbits and space applications

Application	Altitude	Examples of current missions
Human spaceflight	400 km	International Space Station
Weather forecasting	800-830 km	All polar-orbiting satellites in WMO's Global Observing System, belonging to China, Europe, Russia, United States (e.g. Metop, JPSS)
Earth observation	780-900 km	Several earth observation missions, e.g. Sentinel-2 / 3 / 5P (Europe), Megha-Tropiques and Saral (France / India), Resourcesat-2 (India). Majority of EO missions are in lower orbits (600-700 km)
Communications (telephony, broadband (future))	700-800 km and 1 200-1 400 km	Current LEO satcom providers include Iridium and Globalstar (United States). More than ten 100+ constellations planned in the next years, most of which would be located at 1 200-1 400 km altitude (e.g. Starlink (SpaceX, OneWeb, Telesat (Canada), Hongyan and Commsat (China), Astrome (India), Samsung (Japan)

Commercial activities: Commercial operators (mainly earth observation and communications) are currently mainly located at altitudes between 400 and 700 km, as shown in Figure 3.2 (Union of Concerned Scientists, 2019[6]). It should be noted that the value of commercial operations in the low-earth orbit is significantly lower than that of telecommunications activities in the geostationary orbit.

Figure 3.2. Operational satellites by type of operator and orbit altitude in LEO

As of March 2019



Note: Does not include dual-use missions.
Source: Union of Concerned Scientists (2019[6]), "UCS Satellite Database: March 2019 update", https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database

Current human spaceflight activities: The International Space Station is located at about 400 km altitude. Although debris at that altitude decays naturally, it still poses a real collision threat.

Placing satellites in sun-synchronous orbits (600-800 km altitude) makes it possible to pass over any given point on Earth at the same time every day, or to place the satellite's solar panels in constant sunlight. Sun-synchronous orbits are particularly useful for earth observation, weather and climate observation, and military intelligence. For instance, some seventeen polar-orbiting weather satellites (e.g. the US Joint Polar Satellite System and European Metop satellites) are located at between 820 and 830 km altitude (see Table 3.3 above).

UK estimates of benefits from satellite-based meteorological observations to the UK economy range between GBP 670-1 000 million annually (Innovate UK, 2018[39]). Polar-orbiting weather satellites provide essential inputs to numerical weather prediction models, reducing errors and improving forecast accuracy (EUMETSAT, 2014[40]). The European Centre for Medium-Range Weather Forecasts found that a simultaneous loss of both European and US polar-orbiting satellites would cause a 15-20% reduction in accuracy (EUMETSAT, 2014[40]). The loss of polar-orbiting weather satellite observations would heavily affect the Southern hemisphere, where there are fewer terrestrial observations.

Several weather and earth observation satellites in affected orbits also make unique measurements for climate observations. The Jason-2 and Jason-3 satellites, located at 1 336 km altitude, measure variations in sea surface height, which provide information about global sea levels, the speed and direction of ocean currents, and heat stored in the ocean.

LEO constellations for satellite communications: There are currently two commercial communications constellations in the low-earth orbit offering satellite telephony services: Globalstar (at 1 400 km) and Iridium (780 km). However, satellite broadband is widely considered as a key driver of space activities and revenues in the coming decades, although future profitability and viability of business models remain highly uncertain. More than ten broadband satellite constellations are in different stages of development, with two companies (OneWeb and SpaceX) having launched the first satellites in their constellation. SpaceX, as noted above, had by January 2020 more than 200 satellites in orbit, with plans to launch two dedicated Starlink missions per month until the end of the year.

Practically all LEO communication services would be affected by space debris, on orbit and / or during orbit-raising, as the majority of constellations are located near or above the thickest LEO debris belts.

Other possible impacts

- **Reduced access to finance for space ventures**: While the current financial climate is favourable for space sector investments, it is important to acknowledge that many space applications face growing competition from terrestrial applications (e.g. communications, earth observation). It is reasonable to expect that a growing space debris problem may deter investments into the sector, with investors preferring more affordable and less risky terrestrial alternatives.
- **Negative distributional effects of space debris**: The loss or perturbation of certain low-earth orbits would affect some groups and geographic regions more heavily than others. In some low-income countries, satellite systems may provide more reliable and accurate data and signals than terrestrial infrastructure. One of the big selling points for space broadband is its ability to connect hard-to-reach places, including rural regions in both developed and developing countries.

Debris mitigation and remediation measures

Some countries have had debris mitigation guidelines in place for several decades (e.g. NASA debris mitigation guidelines in place since 1995). However, the fragmentation events in 2007 and 2009 raised awareness of the issue and triggered a number of studies on the future evolution of the space debris environment.

A study conducted by the Inter-Agency Space Debris Coordination Committee identified a “good” implementation of international debris mitigation guidelines (e.g. 25-year LEO deorbit rule, avoid intentional destruction) as a key measure to stabilise the future low-earth orbit environment (IADC, 2013[13]): More specifically, some 90% of future launches would need to adhere to orbit clearance guidelines over the next 100 years, especially in the low-earth orbit. As for active debris removal, a NASA study has recommended the removal of about five “large, and intact” objects per year (Liou, Johnson and Hill, 2010[41]).

Space debris remediation and mitigation measures can be divided into three categories

- Debris limitation measures
- Active debris removal (or nudging)
- Space situational awareness (space object surveillance and tracking, collision avoidance ("traffic management"), data-sharing, etc.)

Debris limitation measures

The Inter-Agency Debris Coordination Committee developed the first set of international guidelines on debris mitigation in 2001-02, with a minor revision in 2007 (see Box 3.1). These guidelines recommend that post-mission GEO satellites be moved to a graveyard orbit and that spacecraft in the LEO orbit be deorbited or manoeuvred to an orbit from which natural decay occurs within maximum 25 years. Compliance with these guidelines would go a long way to stabilising the orbital environment.

Box 3.1. Debris mitigation guidelines and regulations

The Inter-Agency Debris Coordination Committee issued space debris mitigation guidelines in 2001 and updated them in 2007 (IADC, 2007[18]). These and similar space agencies' guidelines aim for the:

- Limitation of space debris released during normal operations: Payloads and rocket bodies should be designed not to release debris during normal operations. Where this is not feasible, any release of debris should be minimised in number, area and orbital lifetime. If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property.
- Minimisation of the potential for in-orbit break-ups: In all operational regimes, the potential for break-ups during operational phases should be minimised, e.g. increase (sub)system reliability, minimise the potential for post-mission break-ups resulting from stored energy (stored in tanks, batteries, etc.). This also includes the avoidance of intentional destruction and other harmful activities.
- Avoidance of intentional destruction and other harmful activities.
- Post mission disposal in LEO and GEO: Permanent or (quasi-) periodic non-functional man-made objects should be cleared from orbit. For payloads in LEO, this involves active or passive deorbiting within 25 years of mission completion. GEO payloads should be moved to a graveyard orbit.
- Prevention of in-orbit collisions: Mission projects should estimate and limit the probability of accidental collisions with known objects during the payload or rocket body's orbital lifetime.

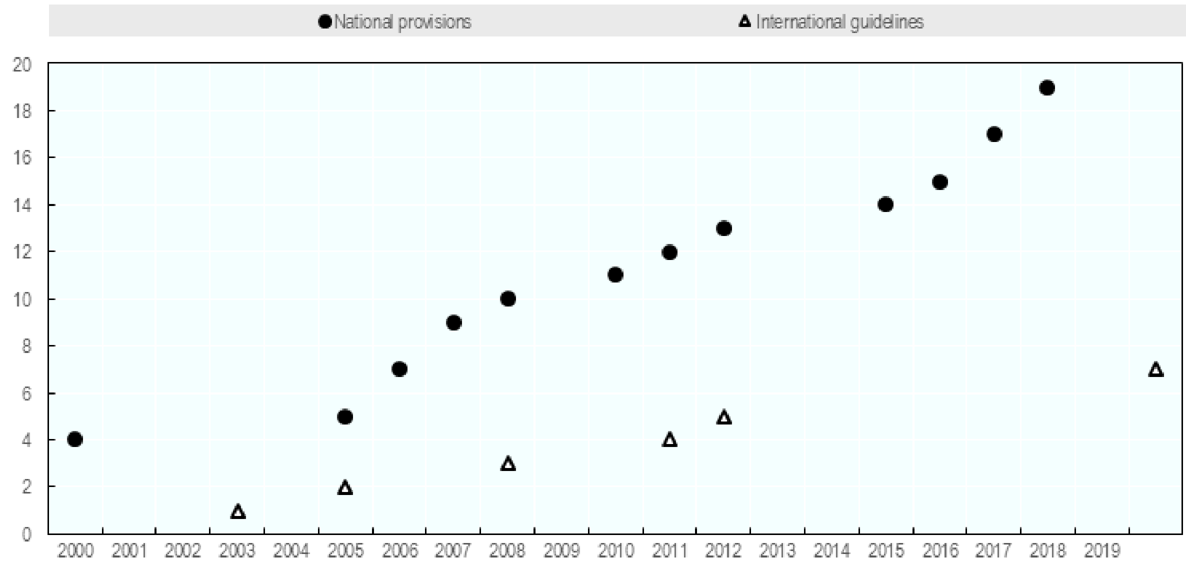
In 2018, the 92 members of the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS) approved a much wider set of 21 long-term sustainability guidelines (UN COPUOS, 2018[2]). The guidelines addressed a range of issues related to space sustainability (e.g. debris, radio frequency spectrum use, space weather) and called for improved registration and supervision of space objects and activities. The guidelines also underlined the importance of data collection, sharing and modelling for both space debris and space weather incidents.

In the last ten years, the body of international and national guidelines, recommendations and standards has continued to grow and is becoming increasingly comprehensive, covering both government and commercial activities (see Annex B). ESA has developed the "European Code of Conduct for Space Debris Mitigation" (2004), in co-operation with the space agencies in Italy, United Kingdom, France and Germany. For debris mitigation in the geostationary orbit, the International Telecommunications Union (ITU) has produced the recommendation ITU-R S.1003-2 (2010). To bridge between primary space debris mitigation objectives and lower level standards and technical reports, the International Organisation for Standardisation (ISO) issued a reviewed set of engineering standards for space debris mitigation (ISO 24113:2019) in 2019.

At the national level, a growing number of countries have integrated provisions for debris mitigation into laws, technical standards, guidelines, etc. as shown in Figure 3.3. In 2019, the United States updated their *Orbital Debris Mitigation Standard Practices* for the first time since 2001, introducing for instance new quantitative limits on debris-producing events and addressing more recent issues such as the operation of cubesats, large constellations and satellite servicing.

Figure 3.3. Evolution of space debris provisions

Number of international guidelines and number of countries with provisions for space debris



Note: National provisions include legislations, guidelines, standards and other technical provisions in Austria, Australia, Belgium, Canada, China, Denmark, Finland, France, Germany, Greece, Japan, the Netherlands, New Zealand, Nigeria, Russia, Ukraine, United Arab Emirates, the United Kingdom and the United States.
Source: Adapted from UNOOSA (2019[42]), "Compendium: Space debris mitigation standards adopted by states and international organisations".

The level of detail, legal status and scope varies considerably. France is one of a few countries with a law that lists mandatory technical requirements for debris mitigation, while several other countries oblige space launch licence applicants to produce environmental impact studies, debris mitigations plans or payload disposal plans (e.g. Austria, Finland, New Zealand). France, Korea and the United Kingdom also require operators to carry third-party liability insurance. Table 3.4 provides an overview of selected national mechanisms.

Table 3.4. Selected national mechanisms for space debris mitigation

Mandatory environmental requirements (e.g. environmental impact study, debris mitigation plan, payload disposal plan)	Requirements addressing specific activities or actors	Mandatory third-party liability insurance	Agency guidelines, technical requirements and standards

Austria, Australia, Belgium, Denmark, Finland, France, Greece, New Zealand, Nigeria, United Kingdom	Canada (remote sensing, telecommunications), Germany (telecommunications), United States (remote sensing, telecommunications),	France, Korea, United Kingdom	Japan, China, Germany, Russia, Ukraine, United States

Source: Adapted from UNOOSA (2019[42]), "Compendium: Space debris mitigation standards adopted by states and international organisations".

The compliance with the different sets of voluntary guidelines to safely deorbit old satellites varies quite significantly today, and remains highly dependent on the orbits considered:

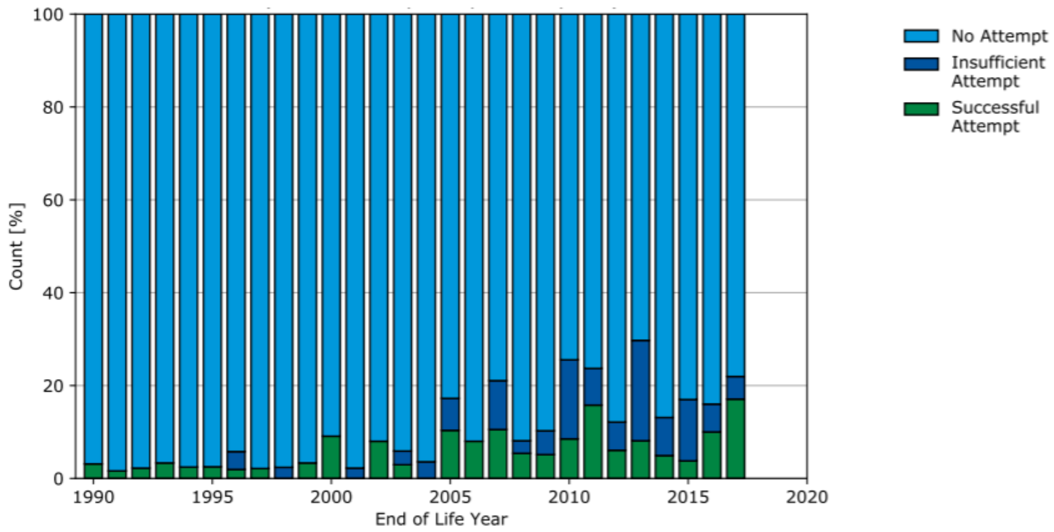
- In the GEO orbit, the satellite clearance compliance is high, at some 80%, especially for more recent satellites (e.g. with an end-of-life after 2000), this requires satellites to be moved to a safe "graveyard orbit" above 36 000 km;
- In LEO orbits, only around half of the satellites with an end-of-life in 2017 were cleared (naturally burning in the atmosphere by atmospheric drag or actively de-orbited);
- When excluding naturally compliant objects and only concentrating on objects in orbits above 650 km (where some of the busiest orbits concentrate), less than 20% of satellites with an end-of-life in 2017 were actually deorbited (ESA, 2019[5]) (see Figure 3.4). Still, the compliance rate for more recent satellites is higher than for older ones;
- France introduced legally binding debris mitigation requirements in 2011, and it is still too early to detect any impacts of the regulation. Some 20% of French-licensed satellites in LEO with an end-of-life in 2000-15 and with a de/re-orbit capacity have performed a deorbit manoeuvre (Cazaux, 2017[43]).

There are several reasons why compliance is higher for satellites in GEO than in LEO.

- **Different attitude to risk**: Individual satellites in LEO and GEO do not have the same value to the operator. Satellites in LEO are more affordable to manufacture and launch, having usually much lower mass and a shorter mission life (2-5 years) than satellites in GEO (15-20 years in orbit). Increasingly, spare satellites are also being included into LEO constellations to make them more resilient to launch failures, in-orbit failures and other incidents (a type of "self-insurance"). All this makes LEO operators relatively tolerant to in-orbit collisions. In contrast, satellites in GEO are typically worth hundreds of millions of US dollars, are expensive to launch in view of the high altitude they need to reach, and when considering large telecommunications satellites, they account for some of the most valuable revenue streams in the space economy.
- **Expensive deorbit manoeuvres**: LEO debris mitigation measures are also relatively more expensive than equivalent measures in the geostationary orbit. As a ratio of total mission costs, more energy (fuel) is needed for deorbiting or moving a spacecraft in LEO to a lower orbit than it is to move a spacecraft in GEO to a graveyard orbit.

Figure 3.4. Payload clearance in low-earth orbit excluding naturally compliant objects

Includes orbits above approximately 650 km altitude



Source: ESA (2019[5]), *ESA's Annual Space Environment Report: Produced with the DISCOS Database*, http://www.esa.int (accessed on 13 March 2019).

- **Lack of adequate compliance control measures**: The space environment is unique in that it is extremely difficult to attribute actions to specific operators. Therefore, any monitoring organisation still relies very much on data from satellite operators to identify and name space objects. There are also technological hurdles, especially in the low-earth orbit, where objects need to be tracked by radar. The recent trend of launching multiple satellites simultaneously further complicates the task of identifying individual satellites (see the section on Traffic management).
- **Insufficient data on actual risks**: although observations and modelling are improving in different parts of the world, the number and nature of objects recorded in existing debris catalogues do not reflect the reality. Operators do not yet have sufficient knowledge to calculate and address fully technical and commercial risks.

Overall, many commercial low-earth orbit operators lack economic incentives to adhere to voluntary guidelines. This stands in contrast to geostationary orbit operators, which have a common interest in keeping the orbit as debris-free as possible in order to avoid collisions, and for which the mitigation measures remain relatively affordable.

Active debris removal solutions

The strict application of space debris mitigation measures is inevitably needed to preserve the Earth's orbital environment. Besides that, active debris removal has been identified as a key measure to stabilise the orbital environment, but several technological, legal and geopolitical barriers remain.

From a purely technological point of view, active debris removal is challenging. It involves far- and close-proximity operations, relative navigation, as well as rendezvous and docking with (non-co-operating) space platforms moving at speeds of several kilometres per second, capturing the payload and removing it from orbit. While (parts) of this technology is mastered by space agencies in Canada, China, Europe, United States, and the Russian Federation, it would need to become much more affordable than what is currently the case. Several public and private actors are working to identify potential removal solutions. ESA's Clean Space initiative is looking at the required technology developments, including advanced image processing, complex guidance, navigation and control and innovative robotics to capture debris. In 2018-19, the

European RemoveDebris mission, funded by the European Commission, is testing several active debris removal technologies on orbit, including nets and harpoons.

There are however numerous legal and geopolitical challenges, when exploring active space debris removal. First, from a legal point of view, the Outer Space Treaty (1967) and the Liability Convention (1973) establish a strong property ownership regime of "space objects", which states that no nation may salvage, or otherwise collect, the space objects of other nations that are in space without the formal consent of the object's registered national owner. The retrieval of debris would involve sharing potentially sensitive data about the object's design that could involve national security, foreign policy, intellectual property rights, etc. (National Research Council, 2011[23]). "Reverse engineering" could also be possible. From this perspective, countries would realistically be limited to removing their own satellites.

Then there is the question of who should pay for the debris removal. In terms of third-party liability, the Liability Convention can theoretically be invoked to recover compensation for damages due to the "fault of the state responsible for the launch of the space object". However, it remains unclear whether space debris can be considered part of a space object, in the absence of a formal definition (it also remains a question whether this would be desirable). In any case, many pieces of debris are not traceable to a specific space object or fragmentation event, making it very difficult to hold any country or firm responsible. The Liability Convention has been invoked only once since its creation, when, in 1978, the nuclear-powered satellite Kosmos 954 scattered radioactive material over northern Canada upon re-entry.

Alternative solutions currently under discussion include "just-in-time" collision avoidance (JCA) approaches, which could be employed in case of an imminent collision between derelict objects. The use of space- or ground-based lasers could potentially "nudge" one of the objects out of harm's way (but it remains in orbit). Alternative solutions envisage the insertion of an artificial atmosphere in front of one of the colliding debris objects to induce a drag and modify its orbital parameters (Bonnal et al., 2019[44]). All legal, technological and economic hurdles aside, these approaches depend on a much more accurate capability of space situational awareness and space tracking than what exists today.

Space situational awareness

The shear vastness of Earth's orbits makes it impossible to keep track of all space objects at all times. Therefore, effective space situational awareness (SSA or space tracking) and space traffic management relies on the co-ordination and joint efforts of military, civilian and commercial operators and space object trackers, all of which hold essential, but incomplete, data and information about the position of their own and others' space assets.

The United States Air Force has the largest government tracking and surveillance system in place and provide conjunction warnings to both private and government operators worldwide. Other countries (e.g. the Russian Federation, China, France) also have space tracking radars and telescopes, and commercial capabilities are rapidly growing, both in the geostationary and low-earth orbits. Some data-sharing exists at the international level. In Europe, the European Union is providing funding to a Consortium of Member States (EUSST) including Germany, France, the United Kingdom, Italy, Spain and more recently Poland, Portugal and Romania, to join their efforts in observational and data processing capabilities for SST. The United States Air Force has agreements with some seventeen countries (Australia, Belgium, Brazil, Canada, Denmark, France, Germany, Italy, Israel, Japan, Korea, the Netherlands, Norway, Spain, Thailand, the United Arab Emirates and United Kingdom), the European Space Agency and EUMETSAT. This also includes more than seventy commercial satellite owners, operators and launch providers (US Strategic Command, 2018[45]).

The US Department of Defence's Space Surveillance Network (SSN) is a global network of ground- and space-based radars, lasers and telescopes that tracks all catalogued space objects, including objects 10cm and larger in LEO and 1m and larger in GEO (Liou, 2018[30]). Other agencies also contribute data.

For instance, NASA radars, telescopes and in-situ measurements characterise objects that are too small to be tracked by the Space Surveillance Network, but still large enough to cause a threat to space missions (Liou, 2018[30]). The Space Surveillance Network will soon be reinforced by the deployment of the "Space Fence", a powerful ground-based radar designed to detect unusual activity on orbit. Objects detected by the Space Fence will be gradually added to existing debris catalogues.

However, current space tracking capabilities have some shortcomings.

- The system remains relatively imprecise, with operators sometimes choosing to ignore warnings.
- The close to 20 000 pieces of debris currently catalogued and tracked by the United States Air Force is deemed to represent less about 0.02% of total estimated debris population. The deployment of the Space Fence will improve the situation, but not resolve it, as it will increase the number of catalogued objects, but not the observational accuracy.
- Space tracking organisations entirely rely on the co-operation of space operators to identify space objects.

Added to this are the issues of space traffic management. Collision avoidance processes are currently often manual and ad-hoc (ESA, 2019[46]). This is illustrated by the September 2019 low-earth orbit incident involving the European Space Agency earth observation satellite Aeolus and Space X' Starlink 44 satellite. Starlink 44 was temporarily lowered to near 320 km altitude to conduct deorbit tests, thus entering a region already occupied by the Aeolus satellite. When the US Air Force issued a close proximity warning (surpassing the Agency's safety threshold of 1 in 10 000 collision probability), ESA operators conducted an avoidance manoeuvre (ESA, 2019[46]). Operators for both satellites were in contact before and after the manoeuvre, but SpaceX has later communicated that a communications bug prevented the Starlink operator from seeing the correspondence with the probability increase.

To address some of these challenges, the United States is taking a new approach to commercial space traffic management, moving it from the Department of Defense to the Department of Commerce. The US Space Policy Directives 2 and 3, issued in 2018, establish the Department of Commerce as the lead civil agency for commercial space situational awareness (SSA) and space traffic management (STM). Whereas military-to-military SSA data-sharing agreements will continue as before, the Office for Space Commerce in the Department of Commerce will provide services to commercial stakeholders. One important initiative, as set out in the Space Policy Directive 3, is an open-architecture data-sharing platform, including data from international government and private operators. Some basic services will be provided free of charge, with commercial providers able to provide add-on services. In July 2019, the Department of Defense sent the first sets of satellite and tracking data to this new repository, dubbed the Unified Data Library. The Office for Space Commerce has also been tasked with co-ordinating activities across US agencies to create and update standards, practices and guidelines related to debris mitigation and space traffic management (e.g. update government debris mitigation standard practices, establish new guidelines for commercial satellite design). This will be integrated into respective licensing processes.

The industry itself is also taking steps. The Space Data Association was created in 2009 and includes both incumbent and more recent satellite operators. The organisation shares operational data and promotes industry best practices, while also working to improve the accuracy and timeliness of collision warning notifications. More recently, the Space Safety Coalition was formed in 2019 to promote space safety through the voluntary adoption of international standards, guidelines, and practices. The coalition, which includes more than twenty space operators, space industry associations and space industry stakeholders, has published a set of "Best Practices for the Sustainability of Space Operations", building on international guidelines (SSC, 2019[47]).

In-orbit insurance

While not strictly a debris mitigation measure, in-orbit insurance, in particular third-party liability insurance could play an important in shaping operator behaviour and contribute to covering remediation costs.

In-orbit insurance typically covers the first year in space of a mission, including the commissioning phase and some months of the remaining mission life, and can be renewed on a yearly basis. In the last years, insurers have proven increasingly willing to extend coverage to several years or even the entire mission life. In 2018, some 93 satellites in LEO and 216 satellites in GEO, or 6% and 43% of the total number of satellites in the respective orbits, had in-orbit insurance, representing some USD 5.5 and 27.5 billion in insured in-orbit exposure (Swiss Re Corporate Solutions, 2018[24]; AXA/XL Group, 2019[33]). In-orbit insurance protects against physical loss, damage or failure.

In-orbit insurance may also include third-party liability insurance, which is required by some countries for the entire mission life (e.g. United Kingdom, France, but not the United States). According to the 1972 Liability Convention countries are ultimately responsible for all space objects launched from their territories. In 2018, the UK Space Agency introduced a new “sliding scale” policy for in-orbit third-party liability, under which insurance requirements for low-risk activities may be reduced or waived, whereas operators planning a higher-risk mission may need to hold a greater level of insurance. A low-risk mission includes for instance satellites that fly at low, sparsely populated, altitudes, with a short orbital lifetime (less than a year) and with few high-value assets nearby (UK Space Agency, 2018[48]). It is important to note that for third-party liability to be effective, it must be possible to reliably attribute actions to specific operators. This is in many cases not possible with current space-tracking capabilities.

It is also uncertain whether the current financial health of the space insurance sector permits it to carry out its intended function. The industry is still adapting to the disruptions of the space sector, with growing commercial activity in the low-earth orbit where operators are less prone to insure their payloads. Markets premiums have decreased steadily since 2010 and in 2018, incurred losses were higher than gross premiums. Furthermore, since 2016, market premiums have been insufficient to pay peak insured value claims, a situation unseen in the last twenty years (AXA/XL Group, 2019[33]). In 2019, the reinsurer Swiss Re announced that it would stop underwriting new space policies.

Little of this can be directly attributed to space debris. In-orbit insurance remains rare, accounting in 2018 for only 23% of premiums. Since 2000, the main causes of insurance losses have been launch-related or failures associated with the satellite’s power supply (each accounting for about a third of losses) (AXA/XL Group, 2019[33]).

4 Policy learning from other sectors

Introduction

The international community has come a long way in space debris mitigation in the last ten years (for a full overview of existing national and international policies and guidelines, see Annex B), but there are still remaining challenges, as presented in Table 4.1. Some of these challenges are of a technological nature, while others are more policy-oriented.

In particular, three policy challenges can be identified:

- Raising compliance with existing international guidelines and national provisions for debris limitation
- Addressing the issue of remediation and third-party liability
- Co-ordinating the activities and needs of military, civilian and commercial stakeholders in an increasingly crowded spatial environment.

Table 4.1. Overview of debris mitigation measures and remaining challenges

Type of measure	Description	Challenges
Debris limitation	Efforts to limit space debris released during normal operations; minimise of the potential for in-orbit break-ups; carry out post mission disposal in LEO and GEO; and prevent in-orbit collisions. This also includes the avoidance of intentional destruction and other harmful activities.	**Compliance with national and international guidelines is insufficient, in particular among LEO operators (public and commercial).** Growing concerns about impacts of weaponisation of space.
Active debris removal	Debris limitation is not enough to stabilise the orbital environment. A minimum removal of five objects (mainly large rocket bodies) annually would also be necessary. Removal involves technologically challenging close proximity operations (e.g. rendezvous, docking, different types of object capture and deorbit). Alternative approaches, such as just-in-time collision avoidance, are currently being discussed, but rely, among other things, on a much more accurate capability of space situational awareness and space tracking than what exists today.	These technologies are under development, with affordability being a big challenge**. Also unresolved legal questions of ownership and liability as well as the coverage of remediation costs.**
Space situational awareness	Space situational awareness involves networks of terrestrial and space-based sensors that monitor the orbital environment, track objects and issue warnings to operators. The most complete government space object catalogue includes some 20 000 objects, with changes expected with the deployment of the US Space Fence. Capabilities are mainly public (US Air Force), but commercial actors are increasingly important. Governance for US systems is changing, with the US Department of Commerce playing a more important role.	Big technological challenges in terms of object detection (potentially destructive objects below 10 cm generally go undetected), accuracy and reliability of warnings and processing and analysis of huge amounts of data. **The system is dependent on inter-agency and international co-operation and data sharing with operators**. Attributing actions in space is extremely difficult, and is further complicated by the trend of having multiple payloads per launch.

Several countries are therefore considering different options for policy intervention in this area. Such actions also seem to be widely supported by the private sector, expressed in responses to an OECD Space Forum survey circulated to satellite operators in 2019 (see Box 4.1).

Box 4.1. OECD Space Forum survey among commercial operators: Debris mitigation practices and policy preferences

In June-October 2019, the OECD Space Forum conducted a small survey among twenty selected satellite operators, active in satellite communications and earth observation, with questions on debris protection and mitigation practices, possible policy responses and market forecasts for specific in-orbit activities (satellite-extension services, active debris removal). Their responses are summarised below:

- All respondents are already engaged in different types of space debris mitigation measures, as part of their missions and satellites' design and by adhering to IADC guidelines.
- They also use space situational awareness (SSA) services, mainly by being a part of CoSpoc (US Airforce) and the commercial Space Data Association data-sharing initiative. Several respondents also have or plan to have in-house capabilities and/or use commercial SSA services. In-orbit insurance is much less common among respondents, and is only used in the geostationary orbit.
- Respondents welcome government action in the area of space debris mitigation, notably by developing further guidelines with the private sector and providing operational information. The majority also would like to see new regulations in the low-earth orbit, although some would prefer industry-self regulations.
- In terms of possible new regulatory tools, respondents prefer financial incentives for post-mission disposal, followed by charges on polluting practices. Some respondents find that public authorities should endure the costs as licensing authorities. Respondents further suggest the levying of an "eco-tax" adapted to the level of guideline compliance; "discounts" to compliant operators; and restricting noncompliant operators from future access to space (through licencing).
- The majority of respondents believe there could be a commercial market for on orbit servicing within the next five years, but opinions about the commercial prospects for space debris removal are mixed. A few respondents believe a market could exist in five years, while others are more pessimistic (never).

This section presents a selection of policy practices in other domains (pollution abatement, transport management) that can provide relevant policy lessons for outer space, in particular on the issue of dealing with commercial actors.

Space debris mitigation shares many commonalities with environmental regulatory and voluntary approaches at the national and international level for pollution abatement. In this domain, mitigation policies such as taxes, subsidies and different types of fees and charges directed to firms and individuals, have been in place for several decades. Numerous lessons learnt could potentially be applied in the space sector to tackle orbital debris. In terms of governance, it would also be useful to review measures covering transboundary pollution and other issues (e.g. ocean, climate change).

Similarly, several policy arrangements exist for enforcing environmental liability, requiring different types of financial security mechanisms (e.g. liability insurance, bonds, deposits) to ensure rehabilitation and/or clean up (e.g. marine oil spills, land rehabilitation at landfills or mining sites).

A last section looks at the management of the transportation in constrained spatial environments (e.g. airspace), both in terms of addressing externalities and multi-user organisation.

Finally, it is useful to discuss the potential impacts of environmental stringency, specifically distributional effects and impacts on competitiveness. One concern is that space debris regulation may increase the cost of space activities and in that way limit certain actors' access to space (e.g. low-income countries, small firms). Another concern is that strict national regulations may negatively affect competitiveness, with 'lenient' international guidelines creating a race to the bottom or regulation-hopping. OECD research has identified a positive correlation between stringent national regulations and exports in environmental goods (Sauvage, 2014[49]).

Regulative and voluntary approaches for pollution abatement

National policies

OECD maintains many databases, including an original Policy Instruments for the Environment (PINE) database. It includes some 3 000 instruments in more than 60 countries, providing a comprehensive overview of policy solutions for different environmental domains (OECD, 2019[50]). These policy solutions are part of both national frameworks and international environmental agreements, which depend on national ratification and enforcement.

It distinguishes six categories of instruments:

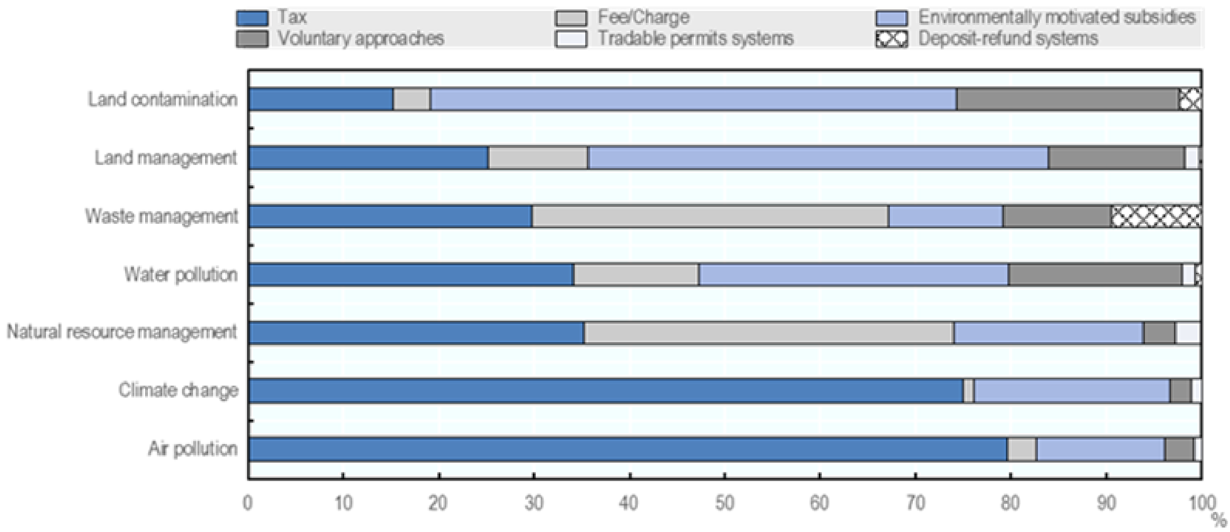
- Environmentally related taxes: Includes taxes on energy products, motor vehicles and transport service and mainly targets carbon dioxide emissions and other greenhouse gases. They encourage industries to shift to less greenhouse gas-intensive ways of production, either by improving their efficiency or by switching to low-carbon substitutes.
- Fees and charges (used interchangeably): Similarly to taxes, fees and charges increase the cost of polluting products or activities and consequently discourage their consumption and production. A charge varies with the consumption of a product, whereas a tax varies according to the pollution generated.
- Tradable permits: Used to allocate emission or resource exploitation rights. Increasingly used around the world to mitigate climate change, air pollution, water scarcity or fisheries over-harvesting (e.g. RGGI).
- Deposit-refund systems: Places a surcharge on the price of potentially polluting products. When pollution is avoided, by returning the products or their residuals, the surcharge is refunded (cover bottles, lead-acid batteries, motor vehicles or scrapped tyres).
- Subsidies: Subsidies can take many forms and include payments from government to producers, preferential tax treatments, grants, subsidised loans, loan guarantees, etc. They are environmentally motivated if they reduce directly or indirectly the use of something that has a proven, specific negative impact on the environment.
- Voluntary approaches: Commitments by firms or industries to improve their environmental performance beyond legal obligations. Voluntary approaches are often supported by legal oversight to verify that environmental performance actually improves. This includes measures such as unilateral commitments, negotiated agreements or voluntary programmes (OECD, 2000[51]).

Figure 4.1 shows how these policy instruments are distributed across the most relevant environmental domains for this analysis.

Taxes are by far the most common policy instrument, followed by fees/charges, environmentally motivated subsidies and voluntary approaches. The following section will discuss the application of these instruments and how they may be relevant to space debris mitigation.

Figure 4.1. Selected policy instruments by type and different environmental domain

Share of instruments listed in the PINE database



Source: OECD (2019[50]), Policy instruments for the environment (PINE) database, http://oe.cd/pine.

Taxes and fees

- The levying of taxes or fees is sometimes mentioned as a possible solution to internalise the environmental costs associated with to space activities (see for instance (Macauley, 2015[52])), and to reduce the use of polluting materials (e.g. a tax linked to the design of the satellite).
- The downside with taxes is a relatively heavy administrative burden, in particular in a system with many exemptions and case-by-case considerations. Also, the application of taxes is in some cases considered detrimental to competitiveness, which is why energy-intensive industries benefit from tax exemptions in many OECD countries (OECD, 2018[53]).
- In the space sector, such competitiveness concerns would not only be related to competitions between countries, but also competition with terrestrial industries.

Tradeable permits

- Different types of tradeable permits have proven relatively effective in the management of natural resources, such as fisheries and water, as well as in pollution abatement.
- In 2005, the European Union (EU) created the world's first international cap and trade programme with the goal of reducing carbon emissions. OECD research shows that the programme has led to 10-14% cuts in emissions and that there was no negative economic impact on participating firms (Dechezleprêtre, Nachtigall and Venmans, 2018[54]). California introduced its own cap and trade programme in 2013.

- However, the introduction of tradeable permits is generally associated with the granting of property rights, which in an orbital environment context would be prohibited from a legal perspective as well as hard to implement (see for instance (Salter, 2016[55])).

Environmentally-motivated subsidies

- Another approach that may be considered are environmentally-motivated subsidies, including for instance VAT exemptions on specific technologies (e.g. electric cars), feed-in tariffs, tax credits for environmentally relevant investments, etc.
- Unlike environmental taxes, environmentally-motivated subsidies do not internalise environmental costs, but, instead, provide support for positive externalities, i.e. contribute to delivering more social benefits than would otherwise be the case, such as R&D tax incentives (Greene and Braathen, 2014[56]).
- When designing policies, there are several pitfalls to avoid, including technology lock-in, rebound effects, windfall gains and freeriding. Consequently, eligibility criteria should ideally be based on technology-neutral performance measures and represent behaviour that goes beyond "normal" practices. Furthermore, thresholds would need to be reviewed regularly and tightened if necessary, following the development of new technologies (Greene and Braathen, 2014[56]).

Voluntary approaches

- Voluntary approaches are sometimes used as a complement to other instruments or to introduce new policies. They are relatively affordable and flexible from the enforcing agency's point of view. The current space debris mitigation guidelines fall into the category of voluntary approaches.
- For firms, adhering to voluntary approaches may make economic sense for "no regret" actions, creating savings on inputs and lower compliance costs and increased sales due to improved public image.
- These approaches generally generate "modest" environmental effects, because of the risk of free-riding, poor monitoring, non-enforceable commitments, lack of transparency, etc. (OECD, 2000[51])
- They are much more likely to generate major "soft" effects, such as collective learning, generation and diffusion of information and consensus building.
- Policy design needs to address the significant risk of industry capture and should, if possible, secure the presence of third parties for objective setting, require transparent performance monitoring, clearly establish penalties for non-compliance, and include information-oriented provisions (e.g. support for activities in technical assistance, workshops, best practice guides, etc.) (OECD, 2000[51])

International treaties

There are hundreds of global, regional, multilateral and bilateral environmental agreements and protocols concerning the atmosphere, marine environment, marine living resources, hazardous substances, etc. The majority of these agreements and protocols are legally binding for the countries that have formally ratified them, and set minimum pollution thresholds, establish liability, introduce compulsory insurance, etc., sometimes with considerable success.

- The 1979 Geneva Convention on Long-Range Transboundary Air Pollution has contributed to a 40-80% decrease in the emissions of harmful substances (e.g. sulphur, nitrogen, lead) in Europe, coinciding with economic growth.
- The International Convention on Civil Liability for Oil Pollution Damage (CLC 69) has contributed to a notable drop in oil tanker spills, despite an increase in the transported volume. Under this

convention, the registered ship owner has strict liability for pollution damage, with the amount generally determined by the size of the ship.

- Still, enforcement remains a challenge in many cases. In the case of marine pollution, some violations leave no verifiable trail (e.g. the dumping of litter or plastics); and violations committed in high seas are referred to flag stages, which often take no action (GAO, 2000[57]). Indeed, the International Convention on Civil Liability for Oil Pollution Damage does not cover pollution incidents in high seas.
- For transboundary air pollution, the principle of no-harm is established for neighbouring countries (in cases with a clear causal link), but is much more tenuous in longer-distance pollution, which is harder to prove. Furthermore, there is no agreement on state liability or the principle of common but differentiated responsibilities of countries (Yamineva and Romppanen, 2017[58]).
- In the domain of air pollution, there are indications that further international co-operation may follow non-treaty-based approaches (guidelines, knowledge exchange platforms). The implementation of the Paris Agreement on climate change is likely to involve co-operative agreements among smaller groups of countries (van Asselt, 2017[59]).

While not legally binding, "soft law" approaches may permit a more flexible and adaptable implementation and can be built on a more solid consensus among stakeholders, beyond states (Yamineva and Romppanen, 2017[58]).

Environmental liability and financial security mechanisms

An important principle in pollution abatement is to hold the polluter liable for environmental damage. The Polluter Pays Principle was first formally articulated in 1972 by the OECD Council, and is often applied as a liability and compensation mechanism that can also contribute to preventing future pollution.

Depending on the domain, the polluter pays principle may hold operators responsible for direct pollution costs, emergency response and clean-up costs, or even compensation to victims of pollution. In some cases, polluters may also be held liable in the absence of fault (strict liability).

The effectiveness of any liability mechanism depends on the solvency of the responsible parties. Some OECD countries have introduced mandatory financial security requirements for environmental liability to ensure that the public does not pay to remediate environmental damage caused by a company or other person that does not have adequate funding to carry out the remedial actions. While environmental liability insurance is the most widely used mechanism (particularly in the United States), there are also other types of financial security instruments, such as performance bonds, financial guarantees, deposits, funds, etc. (OECD, 2012[60]). Mining operators in several OECD countries (e.g. Australia, Canada, United States) are typically required to provide different types of financial security to prove their ability to meet potential clean-up responsibilities.

Environmental liability insurance

Among OECD countries, the United States has the most mature environmental liability insurance market, with environmental liability legislation dating back to the 1980s which mandates unlimited retroactive, strict, joint liability (OECD, 2012[60]). It has financial security requirements for a large range of activities susceptible to cause significant environmental damage (e.g. hazardous waste disposal sites). Due to strict enforcement, the regulations have created high economic risks for potentially liable operators, which drives the demand for environmental insurance.

In Europe, The environmental insurance market is less mature, and insurance is often voluntary. For instance, France and Germany considered that the limited number of insurers could result in high premiums. Furthermore, many insurance companies in Europe were opposed to mandatory schemes, due to their inexperience in estimating potential damage and potential claims (OECD, 2012[60]). Countries that have introduced mandatory insurance (e.g. Spain, Portugal, Czech Republic) sometimes exempt lower-risk activities based on certain criteria (e.g. certified environmental management systems).

It is worth noting some of the constraints of environmental liability insurance (OECD, 2012[60]):

- Insurance is only able to perform its function correctly if a certain amount of information on the probability and possible extent of the damage is available. An important barrier to the development of more far-reaching insurance products is the lack of statistical data on the frequency and severity of environmental damage and proven methodologies for ex ante risk assessment and ex post damage assessment.
- Existing environmental insurance policies function only in strict liability regimes and commonly do not cover damage resulting from intentional acts, and the insurer usually has the right to reduce the compensation for damage arising from gross negligence.
- Firms, in particular small and medium-sized enterprises (SMEs), are often unwilling to buy environment insurance, because of high costs, fear of regulatory repercussions, etc. Mandatory insurance may be a solution.
- Insurers have the discretion to refuse insurance to individual operators.

For maritime oil spills, the 1992 Civil Liability Convention (1992 CLC) attributes strict liability to ship owners for pollution damage in territorial waters and economic exploitation zones (not in high seas). The liability amount is normally determined by the size of the ship, with a ceiling set at SDR 89.8 million[5] (IOPC Funds, 2019[61]). This system, introduced in the late 1960s and establishing a cost-sharing scheme between the ship owners and their protection and indemnity insurers on one side, and the oil receivers on the other (see next section), has been praised as one of the contributing factors to the drop in oil tanker spills, despite an increase in the transported volume.

Other financial security mechanisms

Other financial security mechanisms include for instance performance (surety) bonds, cash guarantees and industry-financed funds, used for example in the maritime and extractive sectors.

One example at the international level is the International Convention on the Establishment of an International Fund for Compensation for Oil Pollution Damage (1992 FUND), which operates in tandem with the 1992 Civil Liability Convention (1992 CLC). The 1992 Fund pays compensation to those suffering oil pollution damage who do not obtain full compensation under the 1992 Civil Liability Convention (1992 CLC) for different reasons (liability exemptions, insufficient insurance, inability to pay, etc.). The fund is financed by contributions levied on any person who has in one calendar year received an amount of crude oil/heavy fuel oil above a specific threshold (150 000 tonnes), reported by Member States. The maximum compensation payable by the 1992 Fund is 203 million SDR for incidents occurring on or after 1 November 2003, irrespective of the size of the ship, and 135 million SDR for incidents occurring before that date. These maximum amounts include the sums actually paid by the ship owner under the 1992 CLC (IOPC Funds, 2019[61]).

[5] SDR: Special drawing rights, supplementary foreign-exchange reserve assets defined and maintained by the International Monetary Fund (IMF). The value of the SDR is based on a basket of key international currencies reviewed by IMF every five years. The weights assigned to each currency in the basket are adjusted to take into account their current prominence in terms of international trade and national foreign exchange reserves.

Mining operators in OECD countries are routinely obliged to provide different types of financial security to obtain licenses of operations, such as cash deposits, performance bonds and guarantees. In the United States, such regulations have been in place since the 1980s (GAO, 2005[62]).

- A performance bond is a surety bond issued by an insurance company or a bank to guarantee satisfactory completion of a project by a contractor. Unlike cash deposits and bank guarantees, surety bonds boosts liquidity and financial flexibility and allows other investments or paying down on debt. In 2018, one of the world's biggest mining companies, Peabody, in co-operation with Australian insurers, issued some USD 115 million worth of third-party surety bonds to rehabilitate mines operated by the company. (Ker, 2018[63]).
- A recurrent problem (found in Australia, Canada and the United States) is that financial securities only partially cover the estimated environmental liabilities. In Western Australia, performance bonds represented approximately 80% of the total cost of rehabilitation in 1999, but by 2008 this had dropped to less than 25% (Western Australian Auditor General, 2011[64]). Similarly, audits in Canadian British Columbia have found that the level of obtained financial securities covers less than half of the estimated environmental liabilities at major mines (British Columbia Auditor General, 2016[65]).
- To address the significant financial risk of the government, Western Australia introduced a Mining Rehabilitation Fund in 2013, which imposes an annual levy of 1% of the rehabilitation liability estimate. Under a fidelity fund, operators pay less than the full rehabilitation cost, but the funds can be used according to need rather than being tied to specific pieces of land (Western Australian Auditor General, 2011[64]). A five-year review of the fund concludes that the fund is growing according to plan (in the absence of any large payments). The scheme is also considered less prohibitive on small and medium-sized enterprises than performance bonds (Western Australia Department of Mines, Industry Regulation and Safety, 2018[66]).

The effectiveness of these financial security mechanisms has been questioned, due not only to instrument design issues but also to government capability to enforce them (e.g. lack of funds and possible industry capture).

- In Australia, mines continue to be abandoned, despite legal requirements for financial security (OECD, 2019[67]).
- In the United States, mining site clean-up and rehabilitation is increasingly paid for by taxpayers, despite financial assurance requirements. A 2005 investigation by the General Accountability Office (GAO) found that government agency staffing issues and lacking resources affected oversight and enforcement, in addition to financial assurances not keeping pace with actual rehabilitation costs (GAO, 2005[62]).
- Audits in Canadian British Columbia have found significant shortcomings with government compliance and enforcement control and recommended the transfer of these activities to a different ministry (British Columbia Auditor General, 2016[65]).

Managing increasingly crowded transportation routes and multiple needs of users

While pollution is one of the externalities of increasing space activities, crowding and congestion is another. Both airspace, ocean and surface transportation routes are increasingly crowded, with economic costs derived from infrastructure repairs, losses of productivity and wasted fuel, to name just a few. Furthermore, in particular in the case of airspace, there is also the national security dimension, and the increasing need to accommodate the interests of multiple users.

In some respects, the growth in commercial space transportation is comparable to the growth in commercial aviation in the last fifty years. To liberate capacity, many OECD countries have over the decades moved from segregated civil and military airspace activities to a jointly managed airspace, often referred to as "flexible" or "joint" use of airspace. This requires considerable civil-military co-operation and co-ordination at both the national and international level, and several existing practices may serve as an inspiration for space traffic management.

- Air traffic managers underline the importance of ensuring trust and good civil/military communication and collaboration. This entails data-sharing, joint planning and management, personnel exchanges between military and civil air traffic organisations, full inter-operability of systems, etc. Both Germany and the United Kingdom have reached an advanced level of integration, including the co-location of civil and military controllers and interoperable systems and infrastructure for communications, navigation and surveillance (ICAO, 2011[68]). Germany lists multiple benefits of their integrated system, such as a high level of safety and more than a doubling in capacity (ICAO, 2011[68]).
- At the international level, the International Civil Aviation Organisation (ICAO) hosted the Global Air Traffic Management Forum on Civil/Military Co-operation in 2009, gathering some 67 states, international organisations, air navigation services providers and industry organisations (ICAO, 2009[69]). ICAO has been recognised as the international facilitating platform for civil-military co-operation and co-ordination efforts, with the ensuing production of guidance documents and good practices. There are also examples of regional and smaller multilateral co-operative structures, such as the European EUROCONTROL or the Functional Airspace Block Europe Central (FABEC). FABEC has been operational since 2013 and includes more than twenty civil and military stakeholders from seven countries (Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland), with two permanent bodies that ensure close collaboration (FABEC, 2019[70]).

Promoting compliance

Compliance behaviour is primarily shaped by the regulatory cost of non-compliance, but also psychological and cultural factors. Other elements may also play a role, such as the provision of direct or indirect financial incentives or the fear of negative publicity. Compliance promotion refers to activities directed towards firms that educate and increase awareness about regulations, or that encourage voluntary changes in compliance behaviour. A 2009 OECD study on environmental compliance trends and good practices (OECD, 2009[71]) identified a set of measures that can be effective.

- Dissemination of information to the regulated community: This may include inspector visits, thematic workshops, best practices guidance with the help of industry associations, dedicated studies and plans on environmental management co-financed with industry. Benchmarking of environmental performance can be a useful tool (e.g. UK Spotlight on Business Environmental Performance).
- Promotion of compliance through administrative "rewards" and public recognition: Several OECD countries actively promote compliance using public recognition, expedited permitting and other regulatory flexibility. In the United States, the Environmental Protection Agency (EPA) sometimes requires the establishment of such systems as part of their corrective actions, while the existence of such systems may result in a waiver of penalty. In Europe, the EMAS standard can give operators certain privileges in permitting processes (e.g. in the Netherlands and the United Kingdom).
- Role of public pressure: The fear of adverse publicity can act as a strong deterrent for non-compliance with environmental requirements. Public disclosure can therefore be a powerful tool. In the United States, EPA and state agencies systematically issue press releases and news stories

about enforcement actions. EPA also discloses all enforcement and compliance records. In the European Union, the European Pollutant Release and Transfer Register provides information about industrial emissions into air, water and land as well as waste transfer (OECD, 2009[71]).

- Financial incentives: The use of financial incentives is generally related to the investment in innovative environmental technologies, and often includes tax incentives, low-interest loans and grants (e.g. in Finland, France and Japan).

Impact of environmental stringency on competitiveness and trade

The impact of stringent environmental regulation on competitiveness and trade is a real concern in the space sector. The sector already faces a range of constricting factors as compared to terrestrial industries, in terms of high launch costs, long lead-times, delays to book and schedule launches, safety regulations, trade regulations, etc. Adding extra costs may redirect investments to other activities and curb growth.

Furthermore, in the absence of international treaties and minimum environmental standards, stringent environmental policy may negatively affect exports, with customers preferring more affordable but also more polluting products and services.

Over the last 20 years, the OECD has studied the linkages between trade and environmental policies, covering OECD and BRIICS countries. This research is mainly based on industrial production, but some of the findings are also transferrable to other economic activities.

- Main findings indicate no effect of environmental policies on aggregate trade and overall competitiveness, and in any case modest compared with those induced by trade liberalisation. However, there are significant composition effects on specialisation patterns, i.e. more polluting actors are penalised, with "dirty" industries seeing a higher rise in production costs, while goods produced in a "cleaner" process will be less affected. At the same time, the country's comparative advantage shifts towards cleaner processes (Koźluk and Timiliotis, 2016[72]).
- Porter's hypothesis assumes that well-designed environmental policies could spur productivity and competitiveness gains in concerned companies, which could potentially spark first-mover advantages in specific "clean" sectors (Porter and Linde, 1995[73]). This hypothesis has inconclusive empirical evidence (Koźluk and Timiliotis, 2016[72]).
- More stringent environmental regulation can also lead to economic opportunities (Sauvage, 2014[49]). Stringent environmental regulation positively affects countries' specialisation in environmental products, even in sectors such as solid-waste management or wastewater treatment.

5 Space sustainability: What way forward?

The previous sections have explored key issues related to space debris, particularly the growth in orbital activity and the increasing societal vulnerability to orbital hazards; as well as future scenarios of continued space debris accumulation in Earth's orbits. It has further identified some of the main types and sources of space debris and discussed policy instruments used in sectors facing similar issues.

Based on this analysis, possible future avenues of action in the domain of space debris mitigation are proposed. They include a reinforcement of space debris mitigation and compliance measures at national levels, a needed focus on promising areas for further science, technology and innovation, and the development of new indicators to monitor debris mitigation performance and environmental instability.

Managing expectations while going in the right direction

- When considering possible solutions for space debris mitigation, it is important to keep in mind that non-compliance with existing guidelines remains the major source of debris creation.
- Building on existing best practices and guidelines, the creation of internationally binding minimum requirements in space debris mitigation would therefore represent a huge step forward. At the same time, this would not be a panacea. A review of international agreements in other environmental domains show that enforcement can be a problem, particularly in areas outside national jurisdiction (e.g. international waters), and that issues of liability are often not addressed. In space, this is an even bigger challenge.
- Short- to medium-term policy solutions in space debris mitigation and compliance would therefore require implementation ***at the national level***, with several existing examples. Recent regulatory frameworks and amendments in France, New Zealand and United Kingdom all address debris mitigation, with France explicitly requiring observance of the 25-year orbit clearance rule. New Zealand has launched the pilot "Space Regulatory and Sustainability Platform", to track space objects launched from the country and monitor compliance with permit conditions. France and the United Kingdom are requiring satellite operators to have in-orbit third-party liability insurance. The UK's *Space Industry Act* and New Zealand's *Outer Space and High-altitude Activities Act* focus on adherence to international debris mitigation guidelines.
- A positive step is that several regulatory frameworks increasingly take into account contemporary risks and business demographics (the "new space" actors). One example is UK's "sliding scale" requirements for third-party liability insurance, reducing or waiving insurance premiums for low-risk activities, providing more flexibility for small operators. The US Federal Communications Commission is equally drafting new regulations aiming to make the licensing process for small satellites with short mission lives faster and cheaper.
- Several steps could be taken to increase the environmental effectiveness of voluntary agreements, for instance the involvement of respected third parties in setting objectives, public disclosure of firm/organisation performance, financial incentives and creating dedicated activities for support and

information exchange. Rewards for compliant behaviour, such as regulatory discounts or accelerated administrative procedures, are used by other agencies, such as the Environmental Protection Agency.

- Space agencies play a key role in space debris mitigation and remediation, as funders and promoters of R&D, and as procurement agencies and licensing authorities in many countries. They often play as well the role of formal or informal advisory bodies and information hubs for space sector firms. Space agencies are well suited for compliance promotion activities, such as information dissemination and the promotion of good environmental management.
- Extended partnerships with the private sector and between countries will be essential to reach durable solutions. Existing public and commercial initiatives (information-sharing agreements within the Combined Space Operations Center - CSpOC, EUSST and the Space Data Association) need support and promotion, while deeper and wider co-operation and data sharing should be encouraged.

Remaining STI challenges

There is still a long way to go in improving space sustainability via space debris mitigation and remediation, with many promising areas for further science, technology and innovation (STI):

- Space situational awareness (SSA) and data management: Faced with a doubling or tripling of active satellites in LEO, it will become critical to strengthen current SSA data processing and management capabilities. Digital technologies improving computing capacity and automated response will need to be systematically integrated into SSA response and analysis.
- Deorbit technologies and research: More research is needed in both active and passive deorbit technologies and techniques. Orbital (gravitational) resonances from the Sun and the Moon can in certain cases be exploited to destabilise orbits and deorbit satellites (Witze, 2018[74]; Daquin et al., 2016[75]). Small changes in trajectories and launch windows can be amplified by the orbital environment and contribute to cost-efficient orbit clearance.
- More broadly, the threat of space debris is just one of several hazards in the space environment. Space weather research is still in its infancy, with many unknowns about the fundamental physical boundaries of space weather events and researchers may still be decades away from having solid forecasts. Currently, the NOAA Space Weather Prediction Center has only a few minutes to alert the US Space Command about incidents and protect space assets from damage. The most important source of data for space weather research and forecasts are space-based observatories (e.g. SOHO, DSCOVR) at the first Sun-Earth Lagrange point, with ESA considering a first-ever mission to the fifth Lagrange point. Capacities will also need to be developed to better mitigate risks of collision with near Earth objects (NEOs), such as meteorites.

An emerging “space debris economy”?

- Will we see a more intensive use of cubesats and miniaturised technologies in lower orbits? Cubesats have been the fastest-growing category of launched satellites in the last years and, when launched at lower altitudes, are naturally compliant with debris mitigation guidelines. They are also ever more performant and affordable, and dedicated launch opportunities become more widespread. Furthermore, they increasingly receive preferential treatment in risk-based national legislations (e.g. introduction of sliding scale in the UK Outer Space Act for insurance requirements).

- Space surveillance and tracking capabilities, in both GEO and LEO: New (private) sources of situational awareness data are becoming increasingly important, with data analytics and modelling fuelled by advances in digital technologies. Private sector debris catalogues and tracking capabilities for the geostationary orbit may now be almost as good as government capabilities (IDA, 2016[76]), while solutions for the low-earth orbit are emerging. Start-ups such as LeoLabs provide data and services based on low-cost ground equipment and sophisticated data analysis. The company, which in October 2019 had three radars in the United States and New Zealand, has developed a cloud-based "Space Regulatory and Sustainability Platform" for the New Zealand Space Agency, a first of its kind, destined to track objects launched from New Zealand to ensure compliance with permit conditions (MBIE, 2019[77]). A novel project called TruSat intends to use blockchain technology to crowdsource and validate satellite orbital positions worldwide via open source software (TruSat, 2019[78]). The US Air Force Research Laboratory has signed agreements with several commercial space situational awareness data providers (e.g. Numerica, LeoLabs, ExoAnalytics) to get access to sensor networks and algorithms (Numerica, 2019[79]). The Space Situational Awareness (SSA) open-architecture data-sharing platform under development by the US Department of Commerce, including data from different government agencies, is also expected to spur innovative value-added products and services.
- In-orbit servicing solutions: Several governmental agencies and commercial companies have developed, or are in the process of acquiring, some capabilities for in-orbit servicing (e.g. NASA, DARPA, ESA, JAXA). In-orbit servicing involves a number of complex operations in space: the servicing of space platforms (e.g. satellite, space station) to replenish consumables and degradables (e.g. propellants, batteries, solar array); replacing failed functionality; and/or enhancing the mission through software and hardware upgrades. This is a major challenge as, when on orbit, space platforms can move at speeds of several kilometres a minute. The first commercial in-orbit servicing mission was launched in 2019, by a MEV-1 spacecraft developed by Orbital ATK for an Intelsat geostationary satellite. The main short-term market is seen in the life extension of geostationary satellites, with some 300 potential candidates, at least in theory (Kennedy, 2018[80]). However, the key benefits of in-orbit servicing are expected in the future. Satellite design is currently heavily restricted by extreme launch conditions, but the possibility of servicing could enable a much more flexible and modular satellite design, able to take advantage of the latest advances in materials and electronics, beyond software upgrades (Jaffart, 2018[81]). Market forecasts estimate a USD 3 billion market for in-orbit servicing over the 2017-27 period, mainly driven by life extension services (Northern Sky Research, 2018[82]).
- Active debris removal solutions: Active debris removal is at a less mature technological level, but several firms are preparing demonstration missions (e.g. Astroscale in 2020). Potential candidates for removal include more than 200 critical debris objects (3-9 tonnes); mainly rocket bodies, but also the European Envisat satellite. JAXA, has formally launched a project to remove a large piece of debris by 2025 (a Japanese rocket body) in a public-private partnership (Japanese Delegation to UNCOPUOS, 2019[83]). Both Airbus and Thales Alenia Space are developing in-orbit servicing vehicles with debris removal functions, some of which have been tested on the RemoveDEBRIS mission (Surrey Space Centre, 2019[84]; OECD, 2019[11]).
- "Green" satellite design and technology: The demand for space-environment friendly satellite design is picking up. This includes features to reduce or avoid debris creation (explosion-safe batteries, deorbit technologies) and/or facilitating active removal (e.g. markers or grapple fixtures). One example is OneWeb, which is installing grapple fixtures on their satellites. In Europe, all future Sentinel satellites will be designed for demise. Affordable deorbit technologies are already being tested on orbit. Canada's three-kilo CanX-7 satellite was launched in 2016 and is currently using its four 1 m^2 drag sails to deorbit at a significantly faster rate than it would have without the sails. Amazon's Kuiper constellation intends to use unpressurised and non-explosive propellant to mitigate accidental explosions, and satellites losing contact with ground control would automatically

deactivate themselves, first by self-passivation and orbit-lowering, then depleting all energy reservoirs and switching off charging circuits (FCC, 2019[85]). SpaceX' Starlink satellites are equipped with automated collision avoidance systems (although it is unclear which role the system played in the near-collision with the ESA Aeolus satellite).

A recent promising initiative is the "Space Sustainability Rating" scheme, originally conceived by teams from the MIT Media Lab, European Space Agency, and World Economic Forum. The initiative intends to be similar to the most widely used green building rating system in the construction industry, called the LEED certification for Leadership in Energy and Environmental Design. The objective is to promote mission designs and operational concepts that mitigate debris creation, and create a label that can encourage operators to behave more responsibly.

Indicators for monitoring debris mitigation performance and environmental instability

Indicators are needed to monitor the enforcement of debris mitigation guidelines and to serve as proxies for estimating the level of physical instability of the space environment. Some indicators already exist at the national and/or international level and have been used throughout this paper, while others need to be developed and sustained by systematic and co-ordinated data collection, as presented in Table 5.1 below. In the end, the indicators used altogether would contribute to better quantifying the risks and possible impacts of taking certain decisions (e.g. choosing potential candidates for de-orbiting).

This scoreboard would include indicators that track:

- Launch activity and satellites on orbit, in particular activities and objects that may increase risk of collisions, such as satellites without orbit control capacity or mega constellations.
- The accumulation of space debris by orbit, number, mass and size, etc., in particular big objects such as rocket bodies that pose particular risks in terms of collision and fragmentation, as well as the number and nature of fragmentation events;
- Space traffic-related warnings and incidents.

Table 5.1. Selected indicators for "orbital stability" and debris mitigation monitoring

Indicator	Dataset	Description	Data sources
Launch intensity and crowding of orbits	Annual launch activity	Number of failed and successful launches, by country, type of operator (public, private), destination orbit, type of spacecraft, mass, etc.	Multiple, e.g. UN COPUOS, US Federal Aviation Administration, etc.
	Number of operational satellites/spacecraft on orbit	Number of operational satellites by orbit, country, type of operator, spacecraft, etc.	Multiple, e.g. UN COPUOS, US Air Force
"Higher-risk" space object population, constellations	Number of non-manoeuvrable satellites (e.g. cubesats)	Number of satellites without propulsion and orbit control functions by orbit	Licencing authorities, cubesat directories
Space debris accumulation	Number, mass and size of space debris objects	Number, mass (tons) and size (m^2) of space debris objects by type, orbit, country, operator, etc. With a particular focus on high-mass, high-volume objects (e.g. rocket bodies)	ESA Environment Report, US Air Force
	"Higher-risk" debris objects	Number, size and mass of failed satellites, rocket bodies and other larger space objects	ESA Environment Report, US Air Force
	Number of fragmentation events	Number, mass and event cause of fragmentation events per year	ESA Environment Report, US Air Force

	Number of debris incidents and collisions	Number of confirmed and probably satellite incidents and malfunctions linked to space debris	Proprietary, insurance industry
Space traffic management issues	Number of conjunction warnings	Number of conjunction warnings per year, per orbit	Government agencies
	Number of collision manoeuvres	Number of collision manoeuvres per year, spacecraft, orbit	Government agencies, public and private operators
	Number of collisions with other satellites	Number of collisions per year, per orbit	Government agencies, public and private operators
Space debris mitigation	Space legislation	Number and type of space legislation provisions addressing debris mitigation (e.g. orbit removal, in-orbit liability)	UN COPUOS, national administrations
	Insurance premiums	Amount of premiums related to in-orbit insurance and in-orbit liability in a given year	Proprietary, insurance industry
	Insurance payouts	Amount of insurance payouts related to in-orbit insurance in a given year	Proprietary, insurance industry
	Main causes of insurance payouts	Main causes of insurance payouts (e.g. launch, types of satellite failure, other incidents), per year	Proprietary, insurance industry
	Number of insured and uninsured satellites in-orbit	Number and share of satellites with and without in-orbit insurance in LEO, GEO (and other orbits)	Proprietary, insurance industry
	Debris mitigation policies	List of (non-legal) international and national policy solutions addressing space debris mitigation	UN COPUOS, national administrations
	Compliance behaviour	End-of-life operations per year, object type, mass, orbit	ESA Environment Report
	Satellite failure rates	Number and share of failed satellites launched, per year and per constellation	Government agencies, public and private operators

Annex A. Survey on space debris sent to selected satellite operators

1. Are you factoring in space debris challenges when planning your activities as an operator? (several boxes can be ticked)

- By implementing debris mitigation strategies:

  ☐ In your mission design and operations (e.g. redundancies, choice of specific orbits to ease post-mission disposal)

  ☐ In your satellite design (e.g. shielding, design for demise)

  ☐ By adhering to IADC guidelines (e.g. post-mission disposal)

- By using Space Situational Awareness (SSA) services :

  ☐ Public

  ☐ Commercial

  ☐ In-house

  ☐ By using space insurance in case of accidents, loss of spacecraft or reduced satellite functionality ad-hoc (depending on the mission)

- Other (please specify):

2. Which actions should public authorities pursue to ensure long-term sustainability of earth orbits for all? (Several boxes can be ticked)

☐ Do nothing

☐ Develop new debris mitigation and space sustainability guidelines with the private sector

☐ Develop and enforce new regulations (e.g. minimum standards)

☐ Develop new lability rules (e.g. introduce mandatory in-orbit liability insurance)

☐ Provide operational information (e.g. SSA services)

Comments:

3. A number of public and private actors are developing R&D and demonstration projects to address space debris remediation or on orbit servicing (click when applicable)

- Do you think there could be a commercial market for active debris removal?

  ☐ In five years

  ☐ In ten years

☐ Never

Comments:

- Do you think there could be a commercial market for on orbit servicing to extend satellite lifetime?

☐ In five years

☐ In ten years

☐ Never

Comments:

- If debris remediation is sought out, how should the financial burden be distributed to ensure the long-term sustainability of earth orbits? (you can tick several boxes)

☐ This is a public mission, so public authorities and taxpayers should endure the costs of any remediation

- Other approaches that you think would deserve exploring:

☐ Financial incentives for post-mission disposal (e.g. tax credits, VAT exemptions)

☐ Charges on polluting practices (e.g. on non-compliant missions, on specific rocket and/or satellite design)

☐ Financial security mechanisms (bonds)

☐ Other (please specify)

Comments:

Annex B. List of space debris guidelines, best practices, standards and other documentation

This list provides an overview of selected international guidelines and national provisions for space debris mitigation. A further number of countries adhere to the principles of international guidelines.

International guidelines:

- Interagency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines (2002 and revised 2007)
- European Code of Conduct for Space Debris Mitigation, including (Italian Space Agency (ASI), the British National Space Centre (BNSC), the French Space Agency (CNES), the German Aerospace Agency (DLR) and the European Space Agency (ESA) (2004)
- UN COPUOS Space Debris Mitigation Guidelines (2007)
- International Telecommunications Union (ITU) Recommendation ITU-R S.1003.2 (12/2010) Environmental Protection of the Geostationary-Satellite Orbit
- UN COPUOS Guidelines for the Long-term Sustainability of Outer Space Activities (2019)
- International Organisation of Standardisation ISO 24113 :2019 Space Systems : Space Debris Mitigation Requirements (2011, updated 2019)
- Space Safety Coalition Best Practices for the Sustainability of Space Operations (2019)

Selected national initiatives:

Australia

- Space (Launches and Returns) Act 2018, articles 34 and 46C: An application for the grant of a domestic launch permit or an overseas payload permit must include a strategy for debris mitigation.

Austria

- National Outer Space Act 2011, Art. 5: “Mitigation of Space Debris”.

Belgium

- Law of 17 September 2005 on Activities of Launching, Flight Operation or Guidance of Space Objects, Art. 5: Conditions for granting authorisations determined with a view to protect “the environment, ensuring the optimal use of air space and outer space” […].

Canada

- Canada Remote Sensing Space Regulations – 2007: A remote sensing satellite disposal plan must be provided in order to obtain licence.
- Canadian Space Agency adoption of IADC Guidelines, 2012.
- Canadian Client Procedures Circular (CPC) for Licensing of Space Stations: Section 3.3.3 Space Debris Mitigation Plan of CPC-2-6-02 requires that applicants for space station spectrum and radio licences submit a space debris mitigation plan as part of their applications.

China

- China National Industry standard QJ3221-2005 Requirements for Orbital Debris Mitigation (put into effect in 2006, and revised in 2015).

Denmark

- The Danish Outer Space Act of 2016: Pursuant to section 6(1) no. 4 of the Act, approval of space activities requires that the operator has taken appropriate measures with regard to space debris management.

Finland

- Act on Space Activities, 2018: Section 10 of the act contains provisions for environmental protection and space debris According to the first paragraph, space activities shall be carried out in a manner that is environmentally sustainable and promotes the sustainable use of outer space. In its application for authorisation, the operator shall assess the environmental impacts of the activity on the Earth, in the airspace and in outer space and present a plan for measures to counter or reduce any possible adverse environmental impacts

France

- Decree on Technical Regulation issued pursuant to Act n°2008-518 of 3rd June 2008, 31 March 2011: The Technical Regulation is composed of a first part dedicated to launch systems and of a second part dedicated to orbital systems. Both parts contain provisions related to the mitigation of space debris.

Germany

- Product Assurance and Safety Requirements for DLR Space Projects: April 2012 (Issue 7.0): 5.7.7 Space Debris Mitigation Assessments

Greece

- Law 4508/2017 on "Authorization of space activities”: Necessary conditions for the licensing of space activities include and “adequate provision for the mitigation and management of space waste or residues according to technological developments and international practices” and “the non-contamination of space or celestial bodies or adverse changes in the environment”.

Japan

- JAXA management requirements 003 (JMR-003), issued in 2003 and revised in 2011

Netherlands

- Space Activities Act 2007, subsection 3, paragraph b. Activities in outer space may only be performed with the requisite licence. Areas to be covered in regulations designed to protect the environment in outer space include the disposal of space objects.

New Zealand

- Outer Space and High-altitude Activities (Licences and Permits) Regulations 2017, Art. 13: Requirements for orbital debris mitigation plan

Nigeria

- National Space Research and Development Agency Act 2010 No.9 A 1255: A licensee is “required to conduct its operations in such a way as to prevent the contamination of outer space or cause any adverse changes in the environment of the Earth, to avoid interference with the activities of others states involved in the peaceful exploration of outer space and, to govern the disposal of the pay load in outer space on the termination of operations.”

Russian Federation

- Russian Federation Federal Law "On the State Corporation for Space Activities ROSCOSMOS" dated July 13, 2015 N 215-FZ: One of the activities of the State Corporation ROSCOSMOS is the management of activities to reduce the debris in near-Earth space.
- Technical documentation GOST R 52925-2018 "Space Technology Items. General Requirements for Space Vehicles for Near-Space Debris Mitigation."

Ukraine

- Industrial standard URKT-11.03 "Limitation of the Near-Earth Orbital Debris Making at Operation of Space Technical Equipment", entered into force in on 19 July 2006: Elimination or minimisation of space debris during standard operations, etc.

United Kingdom

- Outer Space Act 1986: The licensee is required to conduct his operations in such a way as to "prevent the contamination of outer space or adverse changes in the environment of the Earth".

United States

- US Government Orbital Debris Mitigation Standard Practices (adopted 2001 and revised 2019)
- NASA Procedural Requirements for Limiting Orbital Debris (NPR 8715.6)
- NASA Standard 8719.14, Process for Limiting Orbital Debris
- NASA Handbook 8719.14, Handbook for Limiting Orbital Debris
- Department of Defense Instruction 3100.12 (2000)
- Department of Defense Directive 3100.10 (2012)
- Air Force Instruction 91-217 implements Air Force Policy Directives 13-6: Space Policy, and 91-2: Safety programs

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