THE ECONOMICS OF SPACE DEBRIS IN PERSPECTIVE

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ABSTRACT

This paper identifies socio-economic impacts of a potential Kessler syndrome and discusses policy options to improve compliance with space debris mitigation measures. The accumulation of space debris in Earth's orbits is already proving costly to space actors, but the main risks and costs lie in the future. If the generation of debris spins out of control and leads to the disruption or loss of several important space applications, socio-economic impacts could be severe. Improving compliance among satellite operators is an indispensable first step towards long-term sustainability of orbits. A range of policy options and lessons learnt from other domains, such as environmental pollution abatement, could complement existing measures at the national level. Other avenues for action include the strengthening of space situational awareness systems, data reporting structures and further R&D in debris remediation, other hazards and risk assessment. All this will require close co-operation between public and private actors.

Keywords: space sustainability; regulatory compliance; space debris mitigation; socio-economic impacts of space activities; space economy.

1 INTRODUCTION

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 carried out extensive work on space debris, mainly concentrating on technical aspects of the congestion of low-earth orbits.

In order to complement the work of other organisations, the OECD Space Forum[i] has focused primarily on economic dimensions and launched a project on space sustainability in 2019 - guided and assisted by its members, in particular the UK and Canadian Space Agencies and the US National Aeronautics and Space Administration (NASA). The first part of the project focused on the economics of space debris, while 2021 activities aim to build more knowledge on the value and sustainability of space-based infrastructure.

This paper shares some of the preliminary findings from this project, notably on the socio-economic impacts of space debris and possible policy options from other policy domains.

2 THE ECONOMICS OF SPACE DEBRIS

Earth's orbits can be considered as a common pool resource, meaning that its use combines a low level of excludability (excluding potential beneficiaries is not possible), with a high level of subtractability (one actor's use of the resource diminishes other actors' use), similar to terrestrial natural resources such as forests or fisheries (Fig. 1).

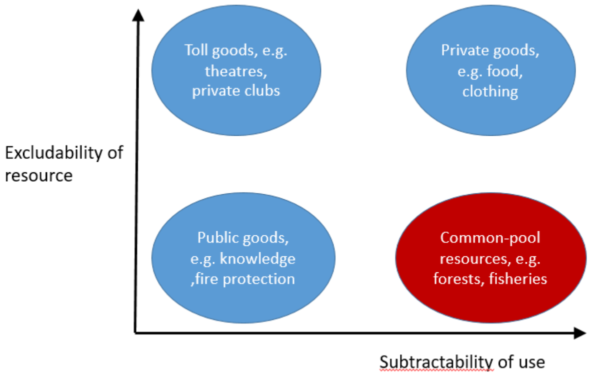

Figure 1: Concept of "subtractability of use" [1].

Overexploitation and pollution are frequent negative externalities associated with 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. For space activities, this translates for example into human activities potentially littering selected 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.

The management of common pool resources, for which market mechanisms are generally highly imperfect or

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completely absent, depends crucially on the existence and effectiveness of rules and institutions to govern their use (see for instance[2]).

3 THE GROWING CHALLENGE OF SPACE DEBRIS

In the last fifteen years, the challenge of space debris has become more pressing. First, because the use of Earth's orbits, in particular the low-Earth orbits, has intensified, and second, because of the increase in the orbital debris population.

3.1 More intensive use of Earth's orbits

The use of Earth's orbits has significantly increased in the last few years, following growing institutional applications and commercialisation of space activities (Fig. 1).

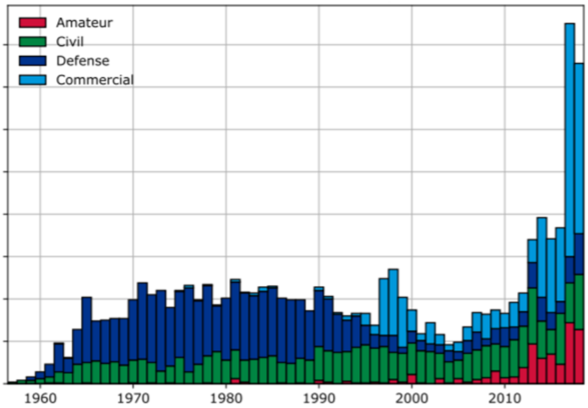

Figure 1. Global payload launch traffic in LEO (200-1750km altitudes) [3]

However, the real game changer will be the full deployment of several broadband mega-constellations that are under preparation.

With the deployment of several of the announced broadband mega constellations (e.g. SpacerX's Starlink, OneWeb), 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 (from today's 3000). 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 [4] and [5]).

In addition to space debris, the intensifying use of the low-earth orbits raises a number of additional issues ranging from radio interference to light pollution for astronomic observations [6].

3.2 The accumulation of space debris in 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 [7].

The Inter-Agency Debris Committee (IADC) defines space debris as "all manmade objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere that are non-functional" [8]. The highest concentrations of objects can be found in the low–earth orbit between 800 and 1000 kilometres of altitude and towards the 1400 kilometres altitude. Other debris belts are close to the orbits of the existing navigation satellite constellations, between 19000 and 23000 kilometres of altitude, and of the critical geostationary orbit at 36000 kilometres, where many large telecommunications and weather satellites are positioned.

Atmospheric drag and other natural phenomena eventually pull debris closer to Earth where they mostly burn up upon entering the atmosphere. However, this process may take anything from a couple of years to several centuries depending on the orbit. 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 [9].

The amount of orbital debris has increased significantly in the last years (Fig. 2), in particular following the fragmentation events of FengYun-1C in 2007 and Iridium-33/Kosmos-2251 in 2009 [10].

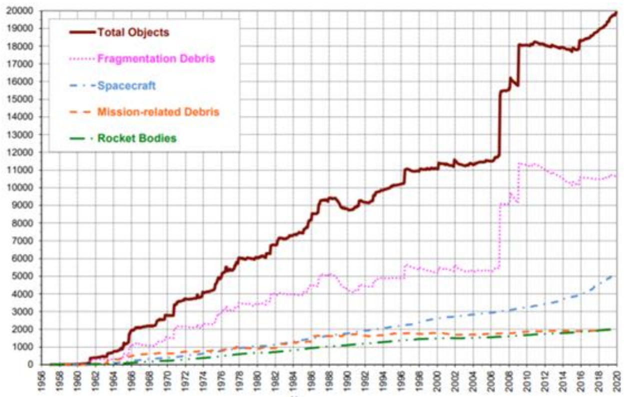

Figure 2: Evolution of the catalogued space object population: 10 cm and larger objects in Earth's orbits, including operational satellites [11]

Overall, more than 20000 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 (measuring between 10 cm and 1 mm) has been estimated to almost 129 million [12].

4 SOCIO-ECONOMIC IMPACTS OF SPACE DEBRIS

The protection against space debris and their mitigation leads to a series of costs for actors in the space community, ranging from loss of the payload to launch delays. These costs may grow dramatically in the next decades.

4.1 Current economic impacts of space debris

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 (often in the range of hundreds of millions of US dollars) [13]. Tab.1 provides a non-exhaustive list of current costs of space debris.

Type of cost/impact	Description
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.

Table 1: Current economic impacts of space debris [14]

Debris-related damage: This may lead to loss of functionality, mission life or even to the loss of the spacecraft. 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.

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: 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. Satellite operators report an increase in manoeuvres to avoid collisions with debris, as documented by the rise in conjunction warnings provided by the commercially hosted SOCRATES information service (Fig. 3).

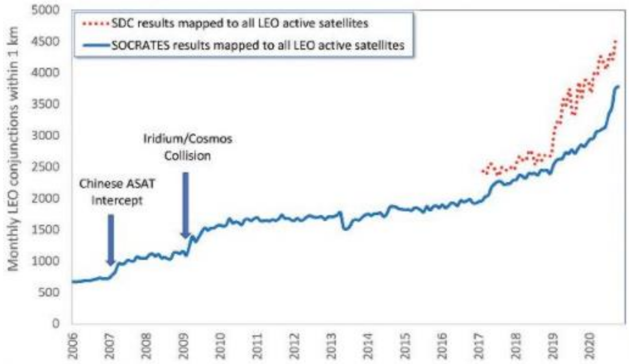

Fig. 3: Monthly conjunction warnings for active low earth orbit (LEO) satellites [15]

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 usually black out during the manoeuvre, which may last up to two days.

Volumetric assessments indicate that a future mega constellation would receive millions of conjunction warnings and have to conduct hundreds of thousands of avoidance manoeuvres. This would be unmanageable without the support of 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.

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 [16].

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 [17], [18].

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 [19]. A collision with space debris or other spacecraft is still considered a low-probability event and does not affect insurance premiums, at least not for the time being [20]. Still, a growing number of insurance actors are concerned. In 2020, the underwriter Assure Space declared it would no longer offer insurance policies covering collision risks in the low-earth orbit [21].

4.2 Potential future costs of space debris

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 (Kessler Syndrome). 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 space sector. The social costs would be unequally distributed, with lower-income and rural regions more hardly hit, in view of their growing dependence on satellite communications, in particular. These costs are listed in Tab. 2 and are further elaborated in the following paragraphs.

Type of cost/impact	Description
Loss of unique applications	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.
Lives lost	The International Space Station is located at about 400 km altitude. A Chinese Space Station at a similar altitude is under preparation.
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 in the sector	Many future LEO communication services would be affected, on orbit and/or during orbit-raising, as several planned constellations are located near or above the thickest LEO debris belts.
Reduced access to finance	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

Table 2: Potential future impacts of space debris [22]

Loss of unique applications and functionalities: The orbits most likely to be disrupted by the Kessler Syndrome are found at 650-1000 km and towards 1400 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.

In some cases, the disruption or loss of certain low-earth orbits would 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. (Tab. 3).

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. Polar-orbiting weather satellites provide essential inputs to numerical weather prediction models, reducing errors and improving forecast accuracy [23]. The European Centre for Medium-Range Weather Forecasts has found that a simultaneous loss of both European and US polar-orbiting satellites would cause a 15-20% reduction in accuracy [24]. For instance, estimated benefits from satellite-based meteorological observations to the UK economy amount to between GBP 670-1000 million annually [25]. The loss of polar-orbiting weather satellite observations would also heavily affect the Southern hemisphere, where there are fewer terrestrial observations.

Lives lost: The International Space Station is located at about 400 km altitude. The planned Chinese Space Station will have a similar location. Although debris at that altitude decays naturally, it still poses a real collision threat. 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 [26], [27].

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. Several weather and earth observation satellites in affected orbits make unique measurements for climate observations. The Jason-2 and Jason-3 satellites, located at 1336 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.

Curbed economic growth in the space sector: Current commercial operators (mostly earth observation and telecom) are mainly located at 400-700 km altitudes [28]. Although the current value of commercial operations in the low-earth orbit is significantly lower than that of telecommunications activities in the geostationary orbit, satellite broadband is widely considered a key driver of space activities and revenues in the coming decades, despite uncertainty concerning business models and viability. Many LEO communication services would be affected by space debris, on orbit and/or during orbit-raising, as several of the planned constellations are located near or above the thickest LEO debris belts. This could have knock-on effects on other industry segments, such as manufacturing and launch.

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: The loss or perturbation of certain low-earth orbits would affect some groups and geographic regions more heavily than others, depending on the coverage and quality of existing terrestrial infrastructure. In some low-income countries, satellite systems may provide more reliable and accurate data and signals than terrestrial alternatives. 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.

5 DEBRIS MITIGATION AND REMEDIATION MEASURES AND THEIR CHALLENGES

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 about the issue and triggered a number of studies on the future evolution of the space debris environment.

Space debris remediation and mitigation measures that are currently in use or under development, can be divided into three categories:

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

5.1 Debris limitation measures

IADC developed the first set of international guidelines on debris mitigation in 2001-02, with a minor revision in 2007. 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.

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. Examples include the European Code of Conduct for Space Debris Mitigation; ITU-R S.1003-2 for the geostationary orbit; and ISO 24113:2019, which provides a bridge between primary space debris mitigation objectives and lower level standards and technical reports.

At the national level, a growing number of countries have integrated provisions for debris mitigation into laws, technical standards, guidelines, etc. 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.

However, current levels of compliance with the different sets of voluntary guidelines to safely deorbit old satellites varies quite significantly, and remain highly dependent on the orbits considered:

- In the GEO orbit, the satellite clearance compliance is high, at some 80%, especially for more recent satellites (with an end-of-life after 2000), this requires satellites to be moved to a safe "graveyard orbit" above 36000 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, less than 20% of satellites with an end-of-life in 2017 were actually deorbited

[29]. 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 [30].

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 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. An on-board computer is also required.

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.

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 fully address 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 this unique GEO orbit as debris-free as possible, in order to avoid collisions, and for which mitigation measures remain relatively affordable.

5.2 Space situational awareness and traffic management

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 (Space Surveillance Network – SSN) 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. The United States Air Force has agreements with some seventeen countries and international organisations. This also includes more than seventy commercial satellite owners, operators and launch providers [31].

The Space Surveillance Network is a global network of ground- and space-based radars, lasers and telescopes that tracks all catalogued space objects, including objects 10 cm and larger in LEO and 1 m and larger in GEO [32]. 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 [33]. 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 20000 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.

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 Office of Space Commerce in the Department of Commerce. Whereas military-to-military data-sharing agreements will continue as before, the Office for Space Commerce will provide services to commercial stakeholders. One important initiative is the Open Architecture Data Repository (OADR), a data-sharing platform that will include data from international and private operators and allow for the commercial development of add-on services.

In Europe, the Space Surveillance and Tracking (EU SST) Support Framework was established by the European Union in 2014. The consortium currently consists of seven EU Member States (France, Germany, Italy, Poland, Portugal, Romania and Spain). The Consortium's Member States provide, through the SST Service Provision Portal operated by the European Satellite Centre, a set of SST services to all EU countries (and the United Kingdom), EU institutions, spacecraft owners and operators, and civil protection authorities.

The industry itself is also taking steps. The Space Data Association was created in 2009 and it 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 [34].

5.3 Active debris removal

The strict application of space debris mitigation measures is needed to preserve Earth's orbital environment. In addition, active debris removal has been identified as a possible measure to stabilise the orbital environment,

Several technology demonstration missions are underway, including ESA's ClearSpace-1 and the Japanese CRD-1 missions, but it remains a highly challenging exercise, for technological, legal and geopolitical reasons.

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 currently testing different removal solutions, including for instance nets, tethers and harpoons.

Furthermore, there are 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. [35]. "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 is unclear whether space debris can be considered part of a space object. 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 [36].

5.4 In-orbit insurance

While not strictly speaking 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 [37]; [38]. 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 [39]. 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 [40]. 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) [41].

In summary, the international community has come a long way in space debris mitigation in the last ten years, but there are still remaining challenges (Tab.3.)

Type of measure	Challenges
Debris limitation	Compliance with national and international guidelines is insufficient, in particular among LEO operators.
Active debris removal	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	Big technological challenges in terms of object detection, 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.

Table 3: Overview of debris mitigation measures and remaining challenges [42]

Some of these challenges are of a technological nature, while others are more policy-oriented. In particular, two policy challenges can be identified:

- Raising compliance with existing international guidelines and national provisions for debris limitation;
- Addressing the issues of remediation and third-party liability.

The next section will look at possible ways to address this, inspired by practices in the environmental domain.

6 POLICY LEARNING FROM OTHER SECTORS

Environmental pollution abatement policies such as taxes, subsidies and different types of fees and charges have been in place for several decades. Similarly, several policy arrangements exist for enforcing environmental liability, requiring different types of financial security mechanisms to ensure clean up and/or rehabilitation.

These instruments could provide relevant policy lessons for space debris mitigation and management, in particular on the issue of dealing with commercial actors. The following paragraphs discuss in greater detail the relative effectiveness of these measures in changing polluting behaviour, in remediation costs and/or raising government revenue and, importantly, how well, or if at all, they can be applied to the space sector.

6.1 Pollution abatement policies

These policies aim to increase the cost of polluting products and activities and/or encourage the introduction of less harmful alternatives. Among policy instruments registered in the OECD database on Policy Instruments for the Environment (PINE), the most common policy measures include

- Environmentally related taxes
- Charges/fees
- Tradable permits
- Subsidies
- Deposit-refund systems
- Voluntary approaches

Environmentally related taxes typically include 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 polluting ways of production, either by improving their efficiency or by switching to less harmful production substitutes.

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 [43]), 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. In addition, 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 [44]. In the space sector, such competitiveness concerns would not only be related to competition between countries, but also competition with terrestrial industries.

Tradable permits are used to allocate emissions or resource exploitation rights and are increasingly applied around the world to mitigate climate change, air pollution, water scarcity or fisheries over-harvesting.

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, with limited economic costs. OECD research shows that the world's first international cap and trade programme, introduced by the European Union in 2005 to curb carbon emissions, has led to 10-14% cuts in emissions and that there was no negative economic impact on participating firms [45].

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 [46]).

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. Examples include for instance value-added tax exemptions on specific technologies (e.g. electric cars), feed-in tariffs, tax credits for environmentally relevant investments, “scrap-and-build” subsidies, etc. The use of subsidies could be considered to incentivise space systems operators.

However, it is important to note that, unlike environmental taxes, environmentally motivated subsidies do not internalise environmental costs. Instead, subsidies 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 [47]. 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 [48].

Deposit-refund schemes combine a tax on consumption with a subsidy for the product’s recycling or appropriate disposal (e.g. packaging and beverage containers, batteries, tyres).

As with taxes, the scheme could change space operator behaviour and generate government revenues to address space debris. However, long mission lives (often extending ten years), could be a challenge for implementation.

Voluntary approaches refer to commitments by firms or industries to improve their environmental performance beyond legal obligations. They are often supported by legal oversight to verify that environmental performance actually improves. It includes measures such as unilateral commitments, negotiated agreements, voluntary programmes, certification and labelling schemes. 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.

However, these approaches generally generate modest environmental effects, because of the risk of freeriding, poor monitoring, non-enforceable commitments, lack of transparency, etc. [49]. 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.) [50].

6.2 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, there are also other types of financial security instruments, such as performance bonds, bank guarantees, deposits, mutual funds, etc. [51]. For instance, hazardous waste operators in OECD countries are typically required to provide different types of financial security to prove their ability to meet potential clean-up responsibilities.

6.2.1 Environmental liability insurance

Some OECD countries (e.g. the United States) have comprehensive environmental liability legislation in place that mandates unlimited retroactive, strict, joint liability [52], with compulsory financial security requirements for operators. Strict enforcement create high economic risks, which drives the demand for environmental insurance.

It is worth noting some of the constraints of environmental liability insurance [53]:

- The market needs a certain level of maturity and competition among insurers to avoid overpricing.
- 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 voluntary environment insurance, because of high costs, fear of regulatory repercussions, etc.
- Insurers have the discretion to refuse insurance to individual operators.

6.2.2 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, waste management and resource extraction sectors.

Operators of activities susceptible to cause significant environmental damage (e.g. hazardous waste disposal sites, mining sites) are routinely obliged to provide different types of financial security, such as cash deposits, performance bonds and guarantees, to obtain licenses of operations. 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.

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

- A recurrent problem is that financial securities only partially cover the estimated environmental liabilities.
- In several OECD countries, mines continue to be abandoned, despite legal requirements for financial security [54]).
- In the United States, waste site clean-up and rehabilitation is increasingly paid for by taxpayers, despite financial assurance requirements. Government agency staffing issues and lacking resources affect oversight and enforcement, in addition to financial assurances not keeping pace with actual rehabilitation costs [55].
- Audits in Canadian federal states have found significant shortcomings with government

compliance and enforcement control and have recommended the transfer of these activities to a different ministry [56].

6.3 Summarising environmental policy options

Tab. 4 provides an overview of the policy instruments and measures discussed in this section, their effectiveness, in terms of shaping behaviour and the potential for generating government revenues, as well as their applicability to the space sector. Green and yellow shading in the table indicates higher applicability or effectiveness.

Selected approaches	Applicable to space?	Effectiveness?	
		Changing behaviour?	Covering remediation costs/ raising govt. revenue?
Subsidies	**Yes**, favoured by industry actors	Medium, reliant on policy design and frequent revision	Low, cost of pollution not internalised
Voluntary approaches	**Yes**, most common approach at national and international level	Low/ medium, **oversight and transparent reporting can improve compliance**	n.a.
Taxes and charges	**Yes,** but competition and trade issues	High, **if alternatives exist**	High, but complete coverage of costs not guaranteed
Liability insurance	**Yes**, but heavily reliant on statistical data	Medium, reliant on **effective monitoring**	Medium, govts. often end up covering the bill
Other types of financial security (deposits, bonds…)	**Yes**, but competition and trade issues	Medium, reliant on stringency of govt. oversight and **effective monitoring**	Medium, govts. often end up covering the bill
Tradable permits	No, requires granting of property rights	n.a.	n.a.

Table 4: Selected pollution abatement and liability instruments and their applicability to the space sector

As shown in Tab. 4, subsidies and voluntary approaches are the most easily applicable to the space sector. The space debris guidelines currently in use can be considered a voluntary approach. The problem is that these measures are not very effective, neither in inducing change in behaviour or in making funds available for remediation. Careful policy design could enhance effectiveness.

- In domains with small or no costs of non-compliance, other incentives can be provided, such as administrative "rewards" and public recognition. Public disclosure of enforcement and compliance records can also prove effective.
- Public agencies need to have the necessary skills and resources to carry out inspections and reach out to operators.
- Industry capture is a valid risk. It could be useful to secure the presence of third parties for objective setting and performance monitoring.
- Labels and certification schemes can have positive effects.

The next three policy measures in the table have proven to be effective measures in other domains, and there are no formal obstacles for their application to space debris mitigation. However, there are considerable challenges involved with the implementation.

- In the case of taxes, the fear of international competition as well as competition from terrestrial industries means that it is rarely considered as a viable stand-alone policy response.
- As for environmental liability insurance, it is to a certain extent applied today – indeed, on-orbit liability insurance exists. However, questions can be raised about the maturity of the space insurance market, in terms of the number of insurance providers and their ability to accurately calibrate insurance premiums. The sector would strongly benefit from more statistical data on risks and probabilities. Also, as previously discussed, current space tracking systems struggle with attributing actions or debris to specific operators.
- Other financial security measures, such as bonds and deposits, can also be applied to space, but there are concerns about their effectiveness. Indeed, experience shows that the financial security often only partially covers the liability and that in many cases, the government ends up covering most of the bill. The effectiveness of these measures therefore heavily relies on the quality of government oversight and enforcement.

Tradable permits are not applicable to space debris mitigation, as property rights cannot be granted in space.

As indicated, none of these measures offers a perfect solution to address space debris, but they open up some avenues of action for policy makers to improve the existing situation. These will be further reviewed in the following, final, section.

7 WAYS FORWARD FOR POLICY MAKERS

Based on the analysis in the previous sections, it may be useful for policy makers to direct some of their efforts to reinforcing space debris mitigation and compliance measures at the national level and addressing a number of remaining research challenges.

7.1 Reinforcing space debris mitigation and compliance measures at the national level

Although long-term solutions need to be sought at the international level, short- to medium-term policy solutions in space debris mitigation and compliance will require implementation nationally.

There are several recent examples of national efforts to address space debris. For example, 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.

When it comes to compliance with existing regulations and guidelines, this paper has already noted that several steps could be taken, for instance by involving neutral third parties in objective-setting, public disclosure of operator performance, financial incentives and creating dedicated activities for support and information exchange. Rewards for compliant behaviour, such as regulatory discounts or accelerated administrative procedures could also be considered. A recent promising initiative is the "Space Sustainability Rating" scheme, originally conceived by teams from the MIT Media Lab, the European Space Agency and the World Economic Forum. The objective is to promote mission designs and operational concepts that mitigate debris creation, and create a label that can encourage public and private operators to behave more responsibly.

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 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 (e.g. information-sharing agreements within the Combined Space Operations Center - CSpOC, EUSST and the Space Data Association) need support and promotion, while deeper and broader co-operation and data sharing should be encouraged.

7.2 Addressing remaining technological challenges and grasping emerging opportunities

At the same time, adequate public resources need to be channelled to the most urgent research questions, which are critical for supporting governments in monitoring and enforcing the existing policy framework as well as formulating sustainable future policies.

In that regard, stronger technological capabilities are needed in

- Space situational awareness (SSA): This is key to avoiding collisions and to enforcing mitigation measures. Better future capabilities are expected with growing numbers of actors and more sensors.
- 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 systems: More research is needed in both active and passive deorbit technologies and techniques to create more reliable and affordable systems.
- Debris mitigation and remediation: Continued work on developing affordable and reliable debris removal and nudging technologies, etc.

More broadly, the threat of space debris is just one of several hazards in the space environment to an increasingly important space-based infrastructure. Space weather research is still at a relatively early stage, with many unknowns about the fundamental physical boundaries of space weather events. Researchers may still be decades away from making solid forecasts. Capabilities will also need to be developed to better mitigate risks of collision with near Earth objects (NEOs), such as meteorites.

Finally, more knowledge is needed about the actual value and benefits of space infrastructure, as well as the costs and risks of space debris incidents. Decision makers need more evidence to underpin sustainable space policies. The OECD Space Forum is currently exploring some of these questions in collaboration with universities and research institutes from across the world, in a project on the value and sustainability of space-based infrastructure, with the first findings expected by the end of 2021.

8 REFERENCES

1. Smith, K. (2017), "Innovating for the global commons: multilateral collaboration in a polycentric world", Oxford Review of Economic Policy, Volume 33, Issue 1, 1 January 2017, Pages 49–65, https://doi.org/10.1093/oxrep/grw039.
2. Smith, K. (2017), ibid.
3. ESA (2019), *Annual Space Environment Report*, European Space Operations Centre, Darmstadt, http://www.esa.int.
4. IADC (2013), *Stability of the Future LEO Environment*, Inter-Agency Debris Coordination Comittee, https://www.iadc-online.org/Documents/IADC-2012-08,%20Rev%201,%20Stability%20of%20Future%20LEO%20Environment.pdf.
5. University of Southampton (2017), "Biggest ever space debris study highlights risk posed by satellite 'mega-constellations' | University of Southampton", in *News releases website*, 19 April, https://www.southampton.ac.uk/news/2017/04/space-debris-mega-constellations.page.
6. OECD (2019), *The Space Economy in Figures: How Space Contributes to the Global Economy*, OECD Publishing, Paris, https://dx.doi.org/10.1787/c5996201-en.
7. ESA (2019), "Space debris by the numbers", webpage, European Space Operations Centre, http://m.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Space_debris_by_the_numbers.
8. IADC (2007), *IADC Space Debris Mitigation Guidelines*, Inter-Agency Space Debris Coordination Committee.
9. Liou, J. et al. (2018), "History of on-orbit satellite fragmentations: 15th edition", in *NASA Technical Memorandum*, NASA Orbital Debris Management Office, National Aeronautics and Space Administration, Houston, Texas, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180008451.pdf.
10. NASA (2020), "Orbital Debris Quarterly News", Vol. 24/1, https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv24i1.pdf.
11. NASA (2020), ibid.
12. ESA (2019), ESA (2019), "Space debris by the numbers".
13. National Research Council (2011), *Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs*, National Academies Press, Washington, DC, http://dx.doi.org/10.17226/13244.
14. Undseth, M., Jolly, C. and Olivari, M. (2020), "Space sustainability – The economics of space debris in perspective", OECD Science, Technology and Industry Policy Papers, n. 87. http://doi.org/10.1787/a339de43-en.
15. Werner, D. (2020), "Average monthly conjunction rates surge from 2017 to 2020, *Space News*, 3 November, https://spacenews.com/space-traffic-management-idling-in-first-gear/.
16. Janovsky, R. et al. (2002), "End-of-life de-orbiting strategies for satellites", in *Deutscher Luft- und Raumfahrtkongress 2002*, DGLR-JT2002-028, https://www.dlr.de/portaldata/55/Resources/dokumente/sart/dglr-2002-028.pdf.
17. Foust, J. (2018), "Do smallsats even need insurance?", in *Space News*, 4 October, https://spacenews.com/do-smallsats-even-need-insurance/.
18. AXA/XL Group (2019), "Space insurance update", Space Risks Study Group Plenary Session, International Union of Aerospace Insurers, Bordeaux.
19. AON (2018), "Aon ISB Space Insurance Fundamentals", AON plc, https://www.inst-aero-spatial.org/wp-content/uploads/2018-Space-Insurance-Training-IAS-PART-1.pdf.

20. Swiss Re Corporate Solutions (2018), *New space, new dimensions, new challenges How satellite constellations impact space risk*, Swiss Re Corporate Solutions, Zurich, https://www.swissre.com/dam/jcr:8bb6ac1d-a158-4b46-b32e-903ae5f89964/how-satellite-constellations-impact-space-risk.pdf.
21. Werner, D. (2020), "Assure Space won't cover collision risk in low Earth orbit", *Space News*, 11 March, https://spacenews.com/assure-space-leaves-leo/.
22. Undseth, M., M. Olivari and C. Jolly (2020)
23. Ibid.
24. EUMETSAT (2014), *The case for EPS/Metop Second Generation: Cost Benefit Analysis - Full Report*, European Organisation for the Exploitation of Meteorological Satellites, Darmstadt, https://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-3_Doc_11-04_MetOP-SG.pdf.
25. EUMETSAT (2014), ibid.
26. Innovate UK (2018), *Value of Satellite-Derived Earth Observation Capabilities to the UK Government Today and by 2020: Evidence from Nine Domestic Civil Use Cases*, Study carried out by London Economics, Innovate UK, London, https://londoneconomics.co.uk/wp-content/uploads/2018/07/LE-IUK-Value-of-EO-to-UK-Government-FINAL-forWeb.pdf.
27. Peters, S. et al. (2013), "Research issues and challenges in autonomous active space debris removal", *Proceedings at the 64th International Astronautical Congress*, https://www.researchgate.net/publication/259899538_Research_Issues_and_Challenges_in_Autonomous_Active_Space_Debris_Removal.
28. Liou, J. (2018), "US space debris environment, operations, and research update", in *55th Session of the Scientific and Technical Subcommittee Committee on the Peaceful Uses of Outer Space*, United Nations, Vienna, http://www.unoosa.org/documents/pdf/copuos/stsc/2018/tech-14E.pdf.
29. Union of Concerned Scientists (2019), "UCS Satellite Database: December 2019 update", Data as of 14 December, https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database.
30. ESA (2019), *Annual Space Environment Report*.
31. Cazaux, C. (2017), "Overview of 2016 space debris activities in France", CNES presentation at UN COPUOS Scientific and Technical Subcommittee, Vienna, http://www.unoosa.org/documents/pdf/copuos/stsc/2017/tech-13E.pdf.
32. US Strategic Command (2018), "Thailand sign agreement to share space services, data", *Press releases website*, 11 October, http://www.stratcom.mil/Media/News/News-Article-View/Article/1659776/usstratcom-thailand-sign-agreement-to-share-space-services-data/.
33. Liou, J. (2018), "US space debris environment, operations, and research update", in *55th Session of the Scientific and Technical Subcommittee Committee on the Peaceful Uses of Outer Space*, United Nations, Vienna, http://www.unoosa.org/documents/pdf/copuos/stsc/2018/tech-14E.pdf.
34. Liou, J. (2018), ibid.
35. SSC (2019), "Best Practices for the Sustainability of Space Operations", Space Safety Coalition, https://spacesafety.org/wp-content/uploads/2019/11/Endorsement-of-Best-Practices-for-Sustainability_v28.pdf.
36. National Research Council (2011), *Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs*, National Academies Press, Washington, DC, http://dx.doi.org/10.17226/13244.
37. Bonnal, C. (2017), "Sustainable activities in space: Space debris problematic in a nutshell", presentation at IZEST fall meeting, Orsay, https://gargantua.polytechnique.fr/siatel-web/linkto/mICYYYTHjyY6.
38. Swiss Re Corporate Solutions (2018), *New space, new dimensions, new challenges How satellite constellations impact space risk*, Swiss Re Corporate Solutions, Zurich, https://www.swissre.com/dam/jcr:8bb6ac1d-a158-4b46-b32e-903ae5f89964/how-satellite-constellations-impact-space-risk.pdf.
39. AXA/XL Group (2019), "Space insurance update",
40. Ibid.
41. Ibid.
42. Ibid.
43. Undseth, M., M. Olivari and C. Jolly (2020), ibid.

44. Macauley, M. (2015), “The economics of space debris: Estimating the costs and benefits of debris mitigation”, *Acta Astronautica*, Vol. 115, pp. 160-164, http://dx.doi.org/10.1016/j.actaastro.2015.05.006.

45. OECD (2018), *Taxing Energy Use 2018: Companion to the Taxing Energy Use Database*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264289635-en.

46. Dechezleprêtre, A., D. Nachtigall and F. Venmans (2018), “The joint impact of the European Union emissions trading system on carbon emissions and economic performance”, *OECD Economics Department Working Papers*, No. 1515, OECD Publishing, Paris, https://dx.doi.org/10.1787/4819b016-en.

47. Salter, A. (2016), “Space Debris: a Law and Economics Analysis of the Orbital Commons”, *Stanford Technology Law Review*, Vol. 19/2, https://law.stanford.edu/publications/space-debris-a-law-and-economics-analysis-of-the-orbital-commons/.

48. Greene, J. and N. Braathen (2014), “Tax Preferences for Environmental Goals: Use, Limitations and Preferred Practices”, *OECD Environment Working Papers*, No. 71, OECD Publishing, Paris, https://dx.doi.org/10.1787/5jxwrr4hkd6l-en.

49. Greene, J. and N. Braathen (2014), ibid.

50. OECD (2000), *Voluntary Approaches for Environmental Policy: An Assessment*, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264180260-en.

51. OECD (2000), ibid.

52. Fogleman, V. (2020), “Improving financial security in the context of the Environmental Liability Directive”, Study No 07.0203/2018/789239/SER/ENV.E.4, European Commission, https://ec.europa.eu/environment/legal/liability/pdf/Final_report.pdf.

53. OECD (2012), “Liability for environmental damage in Eastern Europe, Caucasus and Central Asia (EECCA): Implementation of good international practices”, Task Force for the Implementation of the Environmental Action Programme for Central and Eastern Europe, Paris, http://www.oecd.org/env/outreach/50244626.pdf.

54. OECD (2012), ibid.

55. OECD (2019), *OECD Environmental Performance Reviews: Australia 2019*, OECD Environmental Performance Reviews, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264310452-en.

56. GAO (2005), *Hardrock Mining: BLM Needs to Better Manage Financial Assurances to Guarantee Coverage of Reclamation Costs*, GAO-05-377, Government Accountability Office, Washington, DC, http://www.gao.gov/cgi-bin/getrpt?GAO-05-377.

57. British Columbia Auditor General (2016), *An Audit of Compliance and Enforcement of the Mining Sector*, Office of the Auditor General of British Columbia, Victoria, http://www.bcauditor.com.

[i] The OECD Space Forum has eleven partnering organisations: Canadian Space Agency (CSA); French Space Agency (CNES); German Aerospace Center (DLR); Italian Space Agency (ASI); Korea Aerospace Research Institute (KARI); Netherlands Space Office (NSO); Norwegian Space Agency (NOSA) and the Ministry of Trade, Industry and Fisheries; Swiss Space Office (SSO); UK Space Agency (UKSA); National Aeronautics and Space Administration (NASA); and European Space Agency (ESA).