Policies for incentivizing orbital debris assessment and remediation

Carson Bullock^{1,*} and Robert T. Johanson^{2,3}

Edited by Thomas G. Roberts and Friederike M. C. Benning

HIGHLIGHTS

- Advances in tracking have clarified the risk orbital debris proliferation poses to satellites, but no system for risk assessment of individual space objects has yet been universally accepted. Consensus has been reached about a few broad classes of space objects that are high-priority targets for removal.
- Progress has been made in slowing the creation of new debris, but it is likely insufficient to ensure safe scientific and commercial activity in space without also removing existing debris. Several methods of active debris removal have been demonstrated and more are on the horizon, but how they will be funded, how to incentivize their use, and the legal regime around their deployment remains uncertain.
- Changes to federal policy can incentivize responsible behavior through a variety of mechanisms, each with benefits and drawbacks.

Space debris threatens to destroy valuable space infrastructure, but damages from debris are not an inevitability. The scientific community has ideas for how to prevent the creation of new debris and limit the impact of pre-existing debris, but it will take government action to see that vision through. This essay unpacks how we know what we know, in service of ultimately discussing how policy-makers can use predictions of the long-term risks posed by satellites and debris on the orbital environment to more effectively prescribe behavior for operators. Financial incentives for sustainability, including taxation and cap-and-trade systems, have the potential to greatly benefit the safety and reliability of space missions, but they carry a variety of political and economic challenges, particularly at the international level. Now is a critical time to determine a policy strategy for debris management, because negotiations in the near-term may set valuable precedents

for controlling the next century of debris proliferation.

Foundations

Kosmos-2251 is ready for liftoff. It is June 16, 1993, and 2251 is strapped atop a Kosmos-3M rocket, sitting on the pad at the Plesetsk Cosmodrome in Russia. The Strela-class communication satellite and its rocket have decades of heritage, so it is no surprise that the launch goes off without a hitch. Placed into a nearly circular orbit 500 miles above the Earth's surface, 2251 can expect years of operation followed by decades more in retirement. Kosmos-3M's first stage immediately falls back to Earth, and the second stage, a 1.4-ton solitary rocket body that travels nearly to 2251's final orbit, is left drifting [1]. Only a couple years later, the satellite shuts down early. From then on, 2251 whips around the Earth day in and day out, ignorant to the steady launch of new satellites. Until in 2009, when 2251 smashed into another satellite. Had 2251 been working, operators on the ground may have seen the impending disaster and ordered a quick maneuver. As it happened, Iridium 33 did not see 2251 either, and the two satellites were obliterated. At 22 000 mph, the collision flung thousands of pieces of debris throughout Low Earth Orbit (LEO). These pieces silently circle the Earth and will for decades to come, until some other satellite like Iridium 33 crosses their path or until someone becomes willing to pay a hefty price and use cutting-edge technology to try to remove them. The International Space Station maneuvered away from a piece of Iridium 33 debris in 2012 and was struck by a piece of debris of unknown origin in June 2021 [2, 3].

The Kosmos-Iridium collision was a wake-up call for the space industry. If Iridium's loss of an operating spacecraft was not enough, that single event increased the cataloged objects in LEO by roughly 12%, as shown in Fig. 1 [4]. Today, the number of catalogued pieces of debris is more than double the number of spacecraft in orbit [5]. This figure includes rocket bodies and large fragments of destroyed spacecraft, but excludes objects like tools dropped by astronauts and paint chips, because they are too small to be tracked. At orbital speeds, even the smallest of these wandering missiles can cause crippling damage.

Collisions create huge quantities of debris in an instant, but there are other mechanisms for debris creating too. The more ordinary debris is a byproduct of operating in space;

¹Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA.

²Leaders for Global Operations Program, Massachusetts Institute of Technology, Cambridge, MA.

³Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA.

*Email: cbullock@mit.edu

The authors declare no conflict of interest.

© 2021 The Author(s)

Figure 1: Number of objects >10 cm in LEO. Credit: NASA ODPO. Red annotation added by authors.

much of it accumulates slowly like litter. In LEO, the orbit of an object naturally decays over time. Eventually, it will burn up in the atmosphere, but this can take decades to even hundreds of years [6]. Planning for spacecraft disposal is required by U.S. regulation, but not all actors and situations are covered, so it will require policy changes to cover some of these gaps (1). Unlike pieces of trash that float around in the ocean, however, pieces of space debris were typically once a part of some extremely high-value asset, whose owner was proud to claim it as their own. When that asset was intact, liability issues were fairly clear. When that asset breaks apart, perhaps unexpectedly or through no fault of the owner or manufacturer, things get murky. As a result, satellites, rockets, and smaller miscellany have outpaced natural decay with no one to clean them up. A study by the National Aeronautics and Space Administration's (NASA) Orbital Debris Program Office as far back as 2005 predicted that orbital debris populations will continue to grow just from collisions, even if no more objects were placed in orbit [7]. The bottom line is: without active measures, this problem will get worse. The cost of inaction could be the "Kessler Syndrome," a runaway chain reaction of collisions which renders huge swaths of LEO unusable as collisions become ever more frequent. In this scenario, enough debris accumulates to make collision likely, which increases the density of debris and the likelihood of collision further.

Satellites today are more integral to modern life than ever, and against the landscape of emerging opportunities like space tourism and emerging hazards like mega constellations with thousands of satellites, space debris sits at the heart of a growing set of technical and political challenges. Because debris proliferation poses a global threat, all of the world's spacefaring nations have long-term incentives to prevent it. The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) adopted a set of voluntary long-term sustainability guidelines in 2019, which include guidelines on registering objects, performing analyses to predict collisions, and fostering international cooperation. Because the implementation of these guidelines is on a voluntary basis, some states have argued in favor of updating the existing body of more binding space laws. In particular,

both the Chinese and Russian delegations to COPUOS have argued that the core space treaties, all of which were written several decades ago, have gaps to be filled, and no longer sufficiently meet the needs generated by new challenges in space [8]. These proposals have been contentious, but the need for new space laws may be clarified by assessing the risks posed by the status quo.

Risk Assessment

Given this background on the dangers of debris proliferation, the question naturally arises: just how dangerous is orbital debris, and which pieces pose the greatest threat to satellite operations? Aside from on-orbit collisions, which do provide some information about the near-Earth environment, albeit destructively, the primary sources for space debris data are space situational awareness (SSA) capabilities. Governments, and more recently commercial entities, need SSA to track active satellites as well as defunct satellites and other pieces of debris. Without SSA, these actors would be unable to react preemptively to collision risks. During a satellite's lifetime, its location may be highly relevant for its mission or the provision of its service, like imaging or telecommunications, but the potential for collisions means that SSA remains relevant long after a satellite becomes inactive or obsolete, or its operator refuses to share its location data.

SSA systems consist of both ground- and space-based telescope and radar systems, with several examples contrasted in Fig. 2, but the best predictive information on future collisions comes from SSA working in tandem with statistical models to fill in knowledge gaps [9]. Exact location of orbiting bodies can be difficult to predict due to nonlinear perturbations of the orbit—effects like drag from the outer atmosphere, solar radiation pressure, and gravitational effects of Earth's oblateness, among others—which make long-term models of how motion will evolve from a given set of starting conditions nearly impossible. These perturbations require tracking institutions to maintain active catalogs of space objects and their most recently known orbital parameters. Critically, some objects are not trackable, and while over 28 000 objects are regularly tracked and catalogued, as of January 2021 there are an estimated 900 000 objects between 1 and 10 centimeters in diameter [10].

Moreover, the emergence of new SSA sources has clashed with the U.S. Department of Defense (DoD), the preeminent source for space risk assessment. In October 2020, private SSA source LeoLabs predicted a 10% chance of collision between a defunct Soviet satellite and a Chinese rocket body—over 100 times the probability LeoLabs gave to another near miss in January 2020 that drew international attention [11, 12]. While no collision occurred, it was unusual for this prediction to remain unverified by the space traffic control team at the U.S. Space Command, particularly when LeoLabs' even less likely January prediction was quickly verified. Instead, CNN reported that the 18th Space Control Squadron outright rejected LeoLabs' October claim, stating a near-zero percent risk of collision [13]. These disagreements, rather

Figure 2: Debris detectability ranges for several sources of space data. The most comprehensive catalogue of space objects is maintained by the United States Air Force (USAF) Space Surveillance Network, which can detect objects at high altitudes, but generally not those which are smaller than 10 cm. For smaller particles, debris may be detected by the Haystack Ultrawideband Satellite Imaging Radar (HUSIR) and Haystack Auxiliary Radar, owned by the Massachusetts Institute of Technology, but only for altitudes below 2000 km. Credit: NASA ODPO.

than building consensus, guiding operators' maneuvers, and augmenting SSA as a whole with additional data as might be expected, may instead prove to create confusion as diversified SSA sources come online. Although the DoD already contracts with LeoLabs, granting LeoLabs credibility despite the October 2020 discrepancy, new policy measures may be needed to standardize collision warning procedures and accredit these new SSA sources, particularly when their predictions are of uncertain quality, guiding operators to minimize risk to both their investments and the orbital environments.

Parallel to the process of estimating the location of debris objects and their near-term trajectories is the estimation of long-term risk, which additionally incorporates information about objects' mass, cross-sectional area, velocity, and orbital lifetime. While models exist to estimate many critical factors separately, there is not a unified and widely-accepted metric for risk posed by space debris. Most scholars understand risk as the product of the probability of breakup or collision and the potential damage such an event would cause. However, in the past ten years, many indices have been proposed, centering on issues including: criticality, which assesses the probability that an object's breakup would pose a long-term threat to its orbital environment; severity, which places particular weight on the danger posed to other nearby objects by a breakup; and, most recently, remediation priority, which selects targets for removal from orbit [14]–[16]. The last of these should be noted for its highly international nature, as a collaboration between experts with diverse approaches to risk assessment. They collectively found that the highest risk objects in LEO were almost exclusively rocket bodies, with all of the top 20 resulting from launches by the Soviet Union and Russia between 1985 and 2004 [16]. In short, different priorities and assumptions

lead modelers to similar, but not identical, conclusions about objects' risk.

While most of these indices and rankings intentionally focus their attention on derelict objects, which are non-responsive and may be difficult to characterize, one forward-looking project seeks to assess new satellite proposals before they are licensed. The Space Sustainability Rating (SSR), derived in collaboration between the World Economic Forum, the Massachusetts Institute of Technology Space Enabled Research Group, the University of Texas at Austin, the European Space Agency (ESA), and Bryce Space and Technology, relies on voluntary data sharing from satellite operators to prevent future high-risk satellite missions. The SSR is comprised of six modules, including an index-based measure of environmental footprint, similar to the indices above and as recommended in a public comment to the Federal Communications Commission (FCC), but also with considerations toward collision avoidance capabilities, increased trackability, and the degree to which satellites can be made interoperable with future on-orbit servicing [17, 18]. Its model shifts focus from pre-existing damages toward concrete design choices that manufacturers and operators can make, regardless of whether they are commercial or governmental, to center sustainability among their mission objectives. In this way, a consistent, standardized and public definition of what it means to be sustainable may prompt norm change and norm cascade, as highly rated companies receiving positive attention may use their sustainability rating to promote their space activities, encouraging others to follow suit. In June 2021, it was announced that eSpace, the space center of the École Polytechnique Fédérale de Lausanne (EPFL), a public research university in Switzerland, had been selected to operate the SSR [19]. It is slated to begin issuing sustainability certifications in early 2022.

Mitigation Options

The SSR exists as part of a much wider conversation on incentivizing responsible space behaviors, and debate remains on how governments might most effectively contribute. But before addressing the governmental role, different methods for reducing risk must be evaluated, enabling consensus on exactly which sustainable behaviors are to be incentivized. Sustainability, here, principally refers to long-term equitable access to the benefits of space shared across present and future generations, but might also be conceived to include responsible consumption of both Earth- and space-based natural resources in the pursuit of spaceflight [20].

The simplest and least expensive method of risk reduction is prevention. As such, planning for a satellite's post-mission disposal (PMD) was included in the orbital debris guidelines developed by NASA in the 1990s [21]. PMD typically requires reserving some onboard fuel to reenter the atmosphere or move to a graveyard orbit, an orbital plane that lies far away from common orbits used for satellite missions, such as one that is at a much higher altitude. Alternatively, a LEO operator

can intentionally choose a low orbit with a correspondingly short lifespan, letting atmospheric drag do the work of deorbiting. Making these plans in advance eliminates much of the risk that future satellites will become a floating obstacle like Kosmos-2251, which is why U.S. standard practices and international guidelines currently require programs to plan for disposal within 25 years of the end of the mission [22]. NASA maintains the stance that mitigating debris risks with measures like PMD is more cost-effective than debris removal [23].

However, these methods do nothing to address the population of derelict debris already in orbit, and there exists scholarly consensus, including support by NASA, that at the current juncture, active debris removal (ADR) will likely be required to reign in debris proliferation, despite its expense and outstanding technical challenges [24]–[26]. ADR exists within the wider domain of on-orbit servicing, a highly-anticipated set of tools for relocating, refueling and repairing satellites after launch.

While no ADR mission has removed debris from orbit yet, prototypes are now being tested. Last year, Northrop Grumman’s Mission Extension Vehicle-1 (MEV-1) spacecraft docked to Intelsat-901 by grabbing the satellite’s engine bell. MEV-1 now acts as the propulsion and control system, extending the communication satellite’s life and enabling its final disposal into a graveyard orbit in 2025 [27]. Docking with active and cooperative satellites such as these was already an engineering feat; doing so with uncooperative, damaged, or defunct objects would present even greater challenges. This method appears viable to reclaim large, high-value assets, but is unlikely to have a significant impact beyond these without strong policy incentives. The Japanese company Astroscale’s ELSA-d project takes it a step further. By adding a docking plate to a satellite’s design before launch, Astroscale hopes to enable capture of “semi-cooperative” satellites [28]. The demonstration will attempt to capture a small “client” object in a slow tumble, simulating capture of a defunct object. The natural tendency of an uncontrolled object in space is to start tumbling, caused by slight imbalances of outside forces. Tumbling objects are particularly challenging targets because a capturing vehicle must navigate a complex trajectory to safely dock [29]. Similar to grabbing the hand of a spinning ice-skater, this maneuver requires precise timing, and when successful, both feel a sudden impulse that could throw either off-balance. Moreover, if the client’s motion is not well understood, an imperfect docking might result in fragmentation and even more debris. Nonetheless, this method could be applied to future vehicles, eliminating the need to maintain a fuel reserve for deorbiting and guarding against some failures.

Further expanding the capability envelope are some capture tests demonstrated by the RemoveDebris spacecraft. RemoveDebris snagged a tumbling target with a net, grabbed a stationary solar panel with a harpoon, and attempted but failed to deorbit with a drag sail. The net in particular adds a substantial new capability, since the object was quickly

spinning and kept at a safe distance [30]. The drag sail was subsequently demonstrated on Spaceflight’s SHERPA mission as an alternative to propulsive deorbiting in some LEO orbits. Future versions of these capture methods may be able to address some of the highest-priority existing debris, like the rocket body left behind by the Kosmos-2251 launch. However, they will not be able to capture the many small pieces of debris. For these, researchers have proposed various new, untested methods [31].

Incentivizing Sustainability Through Policy

National governments and international governmental organizations have been involved in regulating spaceflight since its inception, well before the contemporary role of non-governmental actors in space and a global space economy with annual revenues of over USD 300 billion could even be imagined [32]. With past actors unable to predict the present importance of space, it is only reasonable that past policy interventions might fail to meet present needs. Critically, unsustainability is far easier and cheaper than responsible action, so without intervention, private actors may find themselves particularly unmotivated to expend extra resources on plans for managing environmental risk.

There is a longstanding precedent to employ regulation to combat problems of common pool resource management, such as the management of fisheries and forests where overuse can diminish future access, and the global commons of the Earth orbital environment may benefit from many of these traditional regulatory strategies [33]. At the most foundational level, subsidies and taxes form the basis of a carrot-and-stick approach. One analysis finds that tax at launch, with rates ranging from 0.2 to 2% of production cost, with rebates for good behavior, including maneuvering away from a potential collision and adhering to post-mission disposal regulations, could significantly improve compliance [34]. Another finds that orbital use fees which begin at nearly 1% of average annual profits generated by a satellite and rise over time with rising congestion would remove costly losses caused by present risk and could strongly benefit the long-term value of the satellite industry as a whole [35]. Similar to the rebate method, governments might then tackle non-controllable and defunct debris with tax credits for orbit cleaning, or following the example of deposit-refunds as seen in the management of terrestrial plastic waste. Somewhat more aggressively, the U.S. government might adapt the “polluter pays” principle from the Clean Water and Clean Air Act. In this scenario, the orbital environment might act akin to a Superfund site, establishing a trust that risky and unsustainable actors in the space industry are compelled to pay into [36]. All of these approaches might be considered Pigouvian taxes—attempts by a government to control negative externalities [37]. Among the primary disadvantages of Pigouvian taxes is the difficulty of optimally pricing them, which may require knowledge unavailable to public institutions.

An approach outside of the realm of taxes might come

in the form of significantly tightening the licensing process for space missions, a process currently within the jurisdiction of the FCC. The government, whether through the FCC or another agency, may consider using a licensing process in conjunction with a standardized rating system for risk to preclude any space mission designs with moderate to high levels of risk from launch. Presently, the FCC's licensing system is designed to allocate electromagnetic spectrum usage, which satellites use to transmit data, not to assess debris risk, and it is known to be incredibly permissive in the licenses it grants [38]. In contrast to the above approach, this regulatory approach suggests that there are some actions too harmful to price, that no tax would be high enough to justify some space behaviors, for instance, mega constellations above a certain size. This caution might be appropriate given the remaining uncertainties in quantifying risk; it avoids the issue of undertaxing if some kinds of space missions turn out to be riskier than anticipated.

Finally, for a market-based approach, one may consider a cap-and-trade system for risk. Oft-compared against a carbon tax in debates surrounding the management of another global commons, the atmosphere, a cap-and-trade system for debris risk would set a maximum on space assets, measured by mass, size, quantity, SSR rating, or other relevant factors. Actors could then trade allowances on an open market or earn back credits by funding debris removal, thereby allowing them to resume new launches. Although it is governmental organizations which authorize these allowances in the first place and set the market in motion, risk assessment and debris removal could be a largely private endeavor if the cap and measurement of risk remain fixed. Just like the uncertainty present in deciding optimal tax rates, cap-and-trade poses challenges in determining how many allowances should be present in the system. We should expect taxing use of space to be associated with capping abatement cost and uncertain levels of orbital pollution. Conversely, cap-and-trade results in capping allowable orbital pollution level and an uncertain abatement cost; they are mirror images of the same optimization problem [39]. It should be noted, however, that cap-and-trade has been subject to many critiques in the climate regime, for example, that it might legitimize inaction on the part of a few large buyers, which would analogously apply to the space debris case, potentially resulting in underfunding and underutilization of ADR [40].

Naturally, each of these routes comes with a number of challenges. Any policy avenue that relies on quantification of risk requires a well-accepted risk standard, which may be complicated by the many diverse perspectives on risk assessment detailed above. Economically, concern has been expressed regarding the potential overregulation of the budding space industry. Key officials, including former Secretary of Commerce Wilbur Ross, FCC Commissioner Michael O'Rielly, and Ranking Member of the House Subcommittee on Space Rep. Brian Babin (R-TX) have each expressed reservations that regulation may be overburdensome or that it may be too soon to enact regulation

[41]–[43] (2). For legislation to be at all feasible, space sustainability advocates may benefit from collaborating with economists and industry leaders to make clear the long-term financial benefits of early action to remaining skeptics. One compromise for ameliorating constraints on industry might include risk-sharing, wherein the U.S. government offers to indemnify operators whose satellites cause massive damages through collision or other fragmentation only if they had previously complied with sustainability requirements. This case may be analogous to the risk-sharing between the U.S. and commercial launch providers, where financial protection against catastrophic launch failures that exceed a certain maximum probable loss makes possible an otherwise impossibly risky industry [44].

Additionally, there remain unresolved international and dual-use issues. Any U.S. regulation would apply only to American businesses, and would be greatly reduced in effectiveness without international cooperation. A tax on unsustainable American operators does nothing to curb choices made in other spacefaring states. Even if the U.S. dramatically increases its ADR research spending with the intent to fund the rise of an American competitor to Japanese and European debris removal technologies, it may still be disallowed from deorbiting the Russian rocket bodies deemed most dangerous without the explicit consent of Russia, the nominal owner of those pieces of junk. The same technological advancements which might enable the close approaches necessitated by ADR have previously produced international controversy because they may also be used for spying, hacking or outright destruction of a satellite [45]. Both ADR technologies and the sharing of mission data required for ADR may even fall under export controls, further increasing the difficulty of full transparency and technological diffusion [46]. Relatedly, any operators of satellites with classified missions may not want to normalize a precedent of close approaches, and as such, early ADR applications may need to operate on an explicit invitation-only basis; a block grant to remove whatever debris they can would be extremely unlikely.

Mirroring these constraints are a host of enabling opportunities. Negotiation processes to avoid overregulation of space industry may result in public-private partnerships that achieve greater sustainability than either sector separately. The need for unified international norms for sustainability complement other ongoing concerns with the insufficiency of international space law, including drives for demilitarization and for inclusiveness toward new state entrants to space. Finally, while NASA is not a regulator, it has historically had tremendous norm-setting power through non-binding guidelines as one of the earliest and largest buyers of space services. Thus, it may have the greatest ability to set precedent of any organization by asking an ADR enterprise, once its technological readiness has been proven, to deorbit a NASA-owned satellite.

Conclusions

The known risks of space debris are myriad. Improving SSA capabilities make it clearer each day that without

decisive action, future generations' access to the benefits of space may be limited. When the next major collision will occur is at once an open statistical question and an invitation to operators to make it as far away as possible. The work of the scientific community has painted clear benchmarks on what makes an individual piece of space debris pose the greatest risk, and also what concrete steps, like detectability and maneuverability, can be taken to ensure that new satellites pose fewer risks than ever. Using these benchmarks to standardize the quantification of risk could pave the way toward integrating long-term sustainability into the space industry, but the success of this effort would depend on the effective cooperation between public, private, and academic actors. Whether through taxation, subsidization, the use of hard bans, or a market-based approach, creative policy-making will be needed to overcome extant national and international challenges standing in the way of incentivizing sustainable use of space.

Acknowledgements

The authors would like to thank MIT for the opportunity to work on these complex, interesting problems and to the Review's editorial team for their support developing the ideas in this article.

Citation

Bullock, C. & Johanson, R. T. Policies for incentivizing orbital debris assessment and remediation. *MIT Science Policy Review* 2, 8-14 (2021). <https://doi.org/10.38105/spr.16gdw8z5d4>.

Open Access

This *MIT Science Policy Review* article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

Legislation Cited

- (1) 85 FR 52422.
- (2) 85 FR 30790.

References

- [1] Anselmo, L. & Pardini, C. Ranking upper stages in low earth orbit for active removal. *Acta Astronautica* 122, 19–27 (2016). <https://doi.org/10.1016/j.actaastro.2016.01.019>.
- [2] Weeden, B. 2009 Iridium-Cosmos Collision Fact Sheet. Tech. Rep. (2010). Online: https://swfound.org/media/205392/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf. Accessed: July, 2021.
- [3] Strickland, A. Space junk hit the International Space Station, damaging a robotic arm. *CNN* (2021). Online: <https://www.cnn.com/2021/06/01/world/iss-orbital-debris-robotic-arm-scn/index.html>. Accessed: July, 2021.
- [4] National Aeronautics and Space Administration. *Orbital Debris Quarterly News* 13 (2009). Online: <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv13i2.pdf>. Accessed: July, 2021.
- [5] National Aeronautics and Space Administration. *Orbital Debris Quarterly News* 24 (2020). Online: <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv24i4.pdf>. Accessed: July, 2021.
- [6] Schaus, V. *et al.* Results of reference long-term simulations focussing on passive means to reduce the impact of space debris. *7th European Conference on Space Debris* 7 (2017). Online: <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/342/SDC7-paper342.pdf>. Accessed: July, 2021.
- [7] Liou, J.-C. & Johnson, N. L. Risks in space from orbiting debris. *Science* 311, 340–341 (2006). <https://doi.org/10.1126/science.1121337>.
- [8] Committee on the Peaceful Uses of Outer Space. Legal Subcommittee 806th meeting – unedited transcript (2010). Online: https://www.unoosa.org/pdf/transcripts/legal/LEGAL_T806E.pdf. Accessed: July, 2021.
- [9] Lal, B., Balakrishnan, A., Caldwell, B. M., Buenconsejo, R. S. & Carioscia, S. A. Global trends in Space Situational Awareness (SSA) and Space Traffic Management (STM). Tech. Rep. (2018). Online: <https://www.ida.org/-/media/feature/publications/g/gl/global-trends-in-space-situational-awareness-ssa-and-space-traffic-management-stm/d-9074.ashx>. Accessed: July, 2021.
- [10] European Space Agency. Space debris by the numbers (2021). Online: https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers. Accessed: July, 2021.
- [11] Wall, M. 2 big pieces of space junk could collide thursday night (2020). Online: <https://www.space.com/possible-space-junk-collision-leolabs-oct-15-2020>. Accessed: July, 2021.
- [12] Wall, M. The odds of a NASA, US military satellite crash above Pittsburgh have gone up. (They're still low.) (2020). Online: <https://www.space.com/nasa-iras-ggse-4-satellites-collision-risk-update.html>. Accessed: July, 2021.
- [13] Wattles, J. Why we don't know exactly what happened during a near-collision in space. (2020). Online: <https://www.cnn.com/2020/10/16/tech/space-junk-tracking-scn/index.html>. Accessed: July, 2021.
- [14] Rossi, A., Valsecchi, G. B. & Alessi, E. The criticality of spacecraft index. *Advances in Space Research* 56, 449–460 (2015). <https://doi.org/10.1016/j.asr.2015.02.027>.
- [15] Letizia, F., Colombo, C., Lewis, H. G. & Krag, H. Assessment of breakup severity on operational satellites. *Advances in Space Research* 58, 1255–1274 (2016). <https://doi.org/10.1016/j.asr.2016.05.036>.
- [16] McKnight, D. *et al.* Identifying the 50 statistically-most-concerning derelict objects in LEO. *Acta Astronautica* 181, 282–291 (2021). <https://doi.org/10.1016/j.actaastro.2021.01.021>.
- [17] Lifson, M., Roberts, T. G., Arnas, D., Linares, R. & Wood, D. Comments of the Astrodynamics, Space Robotics, and Controls Laboratory (ARCLab) and Space Enabled Research Group. Tech. Rep. (2020). Online: <https://ecfsapi.fcc.gov/file/100968628105/FCC%20Orbital%20Debris%20FNPRM%20Comments%20ARCLabSpaceEnabled.pdf>. Accessed: July, 2021.

- [18] Rathnasabapathy, M. *et al.* Space sustainability rating: designing a composite indicator to incentivise satellite operators to pursue long-term sustainability of the space environment. *71st International Astronautical Congress* (2020). Online: <https://dam-prod.media.mit.edu/x/2020/10/14/IAC%202020%20Manuscript%20October.pdf>. Accessed: July, 2021.
- [19] EPFL Space Center. eSpace to operate the Sustainable Space Rating by 2022 (2021). Online: <https://espace.epfl.ch/2021/06/17/espace-to-operate-the-sustainable-space-rating-by-2022/>. Accessed: July, 2021.
- [20] Committee on the Peaceful Uses of Outer Space. Guidelines for the long-term sustainability of outer space activities (2018). Online: www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf. Accessed: July, 2021.
- [21] National Aeronautics and Space Administration. Technical report on space debris. Tech. Rep. (1999). Online: https://orbitaldebris.jsc.nasa.gov/library/un_report_on_space_debris99.pdf. Accessed: July, 2021.
- [22] National Aeronautics and Space Administration. U.S. government orbital debris mitigation standard practices, November 2019 Update. Tech. Rep. (2019). Online: https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf. Accessed: July, 2021.
- [23] NASA Office of Inspector General. NASA'S efforts to mitigate the risks posed by orbital debris. Tech. Rep. (2021). Online: <https://oig.nasa.gov/docs/IG-21-011.pdf>. Accessed: July, 2021.
- [24] Maclay, T. & McKnight, D. Space environment management: Framing the objective and setting priorities for controlling orbital debris risk. *Journal of Space Safety Engineering* **8**, 93–97 (2021). <https://doi.org/10.1016/j.jsse.2020.11.002>.
- [25] Shan, M., Guo, J. & Gill, E. Review and comparison of active space debris capturing and removal methods. *Progress in Aerospace Sciences* **80**, 18–32 (2016). <https://doi.org/10.1016/j.paerosci.2015.11.001>.
- [26] Liou, J.-C., Johnson, N. L. & Hill, N. Controlling the growth of future LEO debris populations with active debris removal. *Acta Astronautica* **66**, 648–653 (2010). <https://doi.org/10.1016/j.actaastro.2009.08.005>.
- [27] Redd, N. T. Bringing satellites back from the dead: mission extension vehicles give defunct spacecraft a new lease on life - [news]. *IEEE Spectrum* **57**, 6–7 (2020). <https://doi.org/10.1109/MSPEC.2020.9150540>.
- [28] CONFERS. Astroscale (2019). Online: <https://www.satelliteconfers.org/team/astroscale/>. Accessed: July, 2021.
- [29] Michael, J., Chudej, K., Gerdts, M. & Pannek, J. Optimal rendezvous path planning to an uncontrolled tumbling target. *IFAC Proceedings Volumes* **47**, 347–352 (2013). <https://doi.org/10.3182/20130902-5-DE-2040.00001>.
- [30] Aglietti, G. *et al.* The active space debris removal mission RemoveDebris. Part 2: in orbit operations. *Acta Astronautica* **168**, 310–322 (2020). <https://doi.org/10.1016/j.actaastro.2019.09.001>.
- [31] Mark, C. P. & Kamath, S. Review of active space debris removal methods. *Space Policy* **47**, 194–206 (2019). <https://doi.org/10.1016/j.spacepol.2018.12.005>.
- [32] Satellite Industry Association. 2020 state of the satellite industry report. Tech. Rep. (2020). Online: <https://sia.org/news-resources/state-of-the-satellite-industry-report/>. Accessed: July, 2021.
- [33] Oz, B. S. Governing outer space as a global commons: examining tragedy in orbital medium. *University of Cape Town* (2020). Online: <https://open.uct.ac.za/handle/11427/29842>. Accessed: July, 2021.
- [34] Macauley, M. K. The economics of space debris: estimating the costs and benefits of debris mitigation. *Acta Astronautica* **115**, 160–164 (2015). <https://doi.org/10.1016/j.actaastro.2015.05.006>.
- [35] Rao, A., Burgess, M. G. & Kaffine, D. Orbital-use fees could more than quadruple the value of the space industry. *Proceedings of the National Academy of Sciences* **117**, 12756–12762 (2020). <https://doi.org/10.1073/pnas.1921260117>.
- [36] Baiocchi, D. & Welsch, W. *Confronting space debris: strategies and warnings from comparable examples including Deepwater Horizon* (RAND Corporation, Santa Monica, CA, 2010).
- [37] Salter, A. W. Space debris: a law and economics analysis of the orbital commons. *Stanford Technology Law Review* **19**, 221–238 (2016). Online: https://law.stanford.edu/wp-content/uploads/2017/11/19-2-2-salter-final_0.pdf. Accessed: July, 2021.
- [38] Berger, E. NASA objects to new mega-constellation, citing risk of “catastrophic collision” (2020). Online: <https://arstechnica.com/science/2020/11/nasa-objects-to-new-megaconstellation-citing-risk-of-catastrophic-collision/>. Accessed: July, 2021.
- [39] Taylor, J. B. Tragedy of the space commons: a market mechanism solution to the space debris problem. *Columbia Journal of Transnational Law* **50**, 253–279 (2011). Online: <https://heinonline.org/HOL/LandingPage?handle=hein.journals/cjtl50&div=9&id=&page=>. Accessed: July, 2021.
- [40] Hovi, J. & Holtzmark, B. Cap-and-trade or carbon taxes? The feasibility of enforcement and the effects of non-compliance. *International Environmental Agreements: Politics, Law and Economics* **6**, 137–155 (2006). <https://doi.org/10.1007/s10784-006-9002-6>.
- [41] Department of Commerce. Commerce Department releases new regulations to support U.S. leadership in commercial satellite remote sensing industry (2020). Online: <https://www.space.commerce.gov/commerce-department-releases-new-regulations-to-support-u-s-leadership-in-commercial-satellite-remote-sensing-industry/>. Accessed: July, 2021.
- [42] Henry, C. FCC punts controversial space debris rules for extra study (2020). Online: <https://spacenews.com/fcc-punts-controversial-space-debris-rules-for-extra-study/>. Accessed: July, 2021.
- [43] United States Congress Committee on Science, Space and Technology. Opening statement of Space & Aeronautics Subcommittee Ranking Member Brian Babin (2020). Online: www.congress.gov/116/meeting/house/110487/documents/HHRG-116-SY16-MState-B001291-20200211.pdf. Accessed: July, 2021.
- [44] Federal Aviation Administration. Liability risk-sharing regime for U.S. commercial space transportation: study and analysis. Tech. Rep. (2002). Online: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/faaliabilityrisksharing4-02.pdf. Accessed: July, 2021.
- [45] Roberts, T. G. & Bullock, C. A sustainable geostationary space environment requires new norms of behavior. *MIT Science Policy Review* **1**, 34–38 (2020). <https://doi.org/10.38105/spr.kug3iij320>.
- [46] Rivière, A. Potential export control challenges and constraints for emerging space debris detection and removal technologies: the case of on-orbit collision. *Advances in Astronautics Science and Technology* **3**, 105–114 (2020). <https://doi.org/10.1007/s42423-020-00066-x>.