Incentivizing 'Active Debris Removal' Following the Failure of Mitigation Measures to Solve the Space Debris Problem: Current Challenges and Future Strategies

by

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ABSTRACT

Since the beginning of the Space Age in 1957, mankind has greatly benefited from the free exploration and use of outer space. Satellites placed in Earth orbit have enabled navigation, communication, weather prediction, disaster relief, and national security, among many other applications. Significant decreases in launch and satellite costs have spurred the introduction of many new space-faring nations, as well as a rapid increase in space activities by non-governmental entities, some of which are actively pursuing enormous constellations of thousands of satellites.

However, usable Earth orbits are not unlimited, and with this increase in space activity has come space congestion, in the form of operational and defunct satellites, expended rocket bodies, and leftover debris from fragmentation events. The number and mass of space objects in Earth orbit have increased at an alarming rate since the 1980s. Worryingly, international efforts to mitigate this trend since the 1990s have failed, stoking fears of a runaway ‘domino effect’ of space collisions. To preserve space for future generations, debris must be actively removed from space, but the international legal landscape poses serious challenges to such activities. This paper examines the problem of space debris, the failure of international efforts to mitigate additional debris, and the need for and legal challenges surrounding the active removal of debris from space.

The introduction to this thesis previews the major issues involved and its overall objectives, while explaining certain limitations and the methodology employed. Part I examines the causes, characteristics, and scope of the space debris problem. Part II reviews the national and international mitigation efforts taken to tackle the debris problem, arguing that they have ultimately failed, necessitating active debris removal. Part III describes several remediation technologies and then identifies and closely analyzes various legal and policy challenges complicating active debris removal. Finally, Part IV identifies and suggests potential national and international means to ameliorate some of these identified challenges.

RÉSUMÉ

Depuis le début de l'ère spatiale en 1957, l'humanité a considérablement bénéficié de l'exploration et de de l'usage libres de l'espace extra-atmosphérique. Parmi de très nombreuses applications, les satellites placés en orbite terrestre ont permis et assurés la navigation, la communication, la prévision météorologique, le secours aux sinistrés et la sécurité nationale des Etats. La baisse significative des coûts liés au lancement et aux satellites ont stimulé l'émergence de nombreuses nations dans le domaine spatial, ainsi qu'une augmentation rapide des activités spatiales menées par des entités non gouvernementales, dont certaines se consacrent à d'énormes constellations de milliers de satellites.

Cependant, les orbites terrestres utilisables ne sont pas illimitées et l'augmentation des activités spatiales s'est accompagnée d'une congestion de l'espace, sous la forme de satellites opérationnels et désaffectés, d'éléments de fusées usagés et de débris résultant d'évènements de fragmentation. Le nombre et la masse des objets spatiaux placés en orbite terrestre a augmenté à un rythme alarmant depuis les années 1980. Il est inquiétant de constater que les efforts internationaux déployés depuis les années 1990 pour atténuer cette tendance ont échoué, alimentant les craintes d'un foudroyant « effet domino » du nombre des collisions dans l'espace. Afin de préserver l'espace pour les générations futures, les débris doivent être activement retirés des orbites, mais le contexte juridique international pose de sérieux problèmes à la conduite de cette activité. Cette recherche examine la question des débris spatiaux, l'échec des efforts internationaux visant à en réduire l'accumulation, ainsi que les défis juridiques causés par leur retrait actif de l'espace.

Dans son introduction, cette thèse passe en revue les principales questions qui sont en jeu et ses objectifs généraux. La première partie examine les causes, les caractéristiques et la portée du problème des débris spatiaux. La deuxième partie passe en revue les efforts d'atténuation nationaux et internationaux déployés pour s'attaquer au problème des débris, faisant valoir qu'ils ont finalement échoué, nécessitant l'enlèvement actif des débris. La troisième partie décrit plusieurs technologies d'assainissement puis identifie et analyse en détails plusieurs défis juridiques et non juridiques qui compliquent l'enlèvement actif des débris. Enfin, la quatrième partie identifie et examine les potentiels moyens nationaux et internationaux de relever certains des défis identifiés.

ACRONYMS AND ABBREVIATIONS

ADR – Active Debris Removal

ASAT – anti-satellite

ASI – Italian Space Agency

CCL – Commerce Control List (US)

COPUOS – Committee on the Peaceful Uses of Outer Space

DoC – Department of Commerce (US)

DoS – Department of State (US)

EAR – Export Administration Regulations (US)

EDDE – Electro-Dynamic Debris Eliminator

ESA – European Space Agency

FAA – Federal Aviation Administration (US)

GEO – Geostationary Earth Orbit

GEODSS – Ground-Based Electro-Optical Deep Space Surveillance System (US)

GNSS – Global Navigation Satellite Systems

IADC – Inter-Agency Space Debris Coordination Committee

ISO – International Organization for Standardization

ISRO – Indian Space Research Organization

ISS – International Space Station

ITAR – International Traffic in Arms Regulations

ITU – International Telecommunication Union

JAXA – Japan Aerospace Exploration Agency

LEO – Low Earth Orbit

MEO – Medium Earth Orbit

NASA – National Aeronautics and Space Administration

ODMSP - Orbital Debris Mitigation Standard Practices (US)

OOS – On-Orbit Satellite Servicing

OST – Outer Space Treaty

SSA – Space Situational Awareness

SSN – Space Surveillance Network (US)

STM – Space Traffic Management

STSC – Scientific and Technical Subcommittee

SSN – Space Surveillance Network

UKSA – United Kingdom Space Agency

UN – United Nations

UNGA – United Nations General Assembly

UNOOSA – UN Office for Outer Space Affairs

USML – United States Munitions List

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INTRODUCTION

A. Issues and Objectives

At the dawn of the space age and for many years thereafter, outer space was accessible only to enormous governmental civil and defense infrastructures,[1] most notably those of the United States and the former Soviet Union. Over time that exclusivity evaporated, and today some 8,600 satellites have been launched into Earth orbit by governmental and commercial entities, of which only about 2,400 remain operational.[2]

In addition to these functioning satellites, uncontrolled and non-operational man-made matter also exists in space. In total, approximately 23,000 space objects greater than 10 centimeters in diameter are being tracked by the United States Air Force's Space Surveillance Network (SSN).[3] Many millions more pieces of smaller debris are estimated to be in orbit, but unobservable, and therefore untrackable, from Earth.[4] Some of this debris can be attributed to specific States, while much cannot.

En masse, these nonfunctional and uncontrolled pieces of space debris pose serious collision risks to operational satellites and manned spacecraft, as well as to the surface of the Earth, ultimately even threatening to contaminate the space environment itself. This risk, which has been acknowledged for many decades,[5] has continued to grow as the space environment has become more and more congested. In order to reduce this risk, individual States and the international

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[1] See Figure 1, "Payload Launch Traffic into $200 \leq h_p \leq 1750$km," *infra,* from ESA, "Space Environment Statistics" (2019), online: *ESA* <https://sdup.esoc.esa.int/discosweb/statistics/>.

[2] T.S. Kelso, "SATCAT Boxscore," (accessed 22 July 2019), online: *CelesTrak* <https://www.celestrak.com/satcat/boxscore.php>.

[3] J.C. Liou & H. Cowardin, "NASA Orbital Debris Program Office and the DebrisSat Project" (21 February 2018) at 5, online (pdf): *NASA* < https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180001502.pdf>.

[4] ESA, "Space Debris by the Numbers" (last updated January 2019), online: *ESA* <https://www.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Space_debris_by_the_numbers>.

[5] See, for example, Donald J. Kessler & Burton G. Cour-Palais, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," (1978) 83:A6 Journal of Geophysical Research 2637. NASA founded its "Orbital Debris Program Office" one year after this research, in 1979.

community have engaged in concerted debris mitigation efforts since the early 1990s, notably via the U.S. led, multi-national creation of the Inter-agency Space Debris Coordination Committee (IADC) in 1993 and the addition of space debris as a topic on the agenda of the Scientific and Technical Subcommittee (STSC) of the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) in 1992.[6] However, due to significant structural limitations within resulting mitigation guidelines and poor global compliance, these efforts have done little to stop year-on-year increases in the total number and mass of objects in Earth orbit.[7] Additionally, the emergence of new space-faring nations and commercial entities, accidental collisions, in-space fragmentations, and several intentional debris-creating events, specifically direct ascent anti-satellite (ASAT) missile tests, have compounded the problem of uncontrolled debris.

It is now the conclusion of many leading space organizations, such as the European Space Agency (ESA),[8] that space-faring nations must collectively move beyond simply pursuing mitigation efforts alone and to begin focusing on physically removing some of the debris from Earth orbit or properly stabilizing and storing it in special 'graveyard' orbits, a process known as remediation or, more commonly, active debris removal (ADR).[9] However, the legacy international space law regime, primarily inherited from the 1960s and 1970s in the form of five seminal UN

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[6] For a brief overview of these efforts, see NASA, "Orbital Debris Management & Risk Mitigation" (undated) at 24, online (pdf): *NASA* <https://www.nasa.gov/pdf/692076main_Orbital_Debris_Management_and_Risk_Mitigation.pdf>; For a thorough description of the creation of the IADC, see Nicholas Johnson, "Origin of the Inter-Agency Space Debris Coordination Committee" in NASA, "ARES Biennial Report 2011-2012," (2014) at 70-72, online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140011750.pdf>.

[7] See Figures 2 & 3, *infra,* from NASA, "Orbital Debris Quarterly News" 22:1 (February 2018) at 10-11, online (pdf): *NASA* <https://orbital debris.jsc.nasa.gov/quarterly-news/pdfs/odqnv22i1.pdf>.

[8] For ESA's justification for designating active debris removal as a "strategic goal," see ESA, "Active Debris Removal" (14 April 2017), online: *ESA* <http://www.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Active_debris_removal>.

[9] More specifically, ADR is used throughout this thesis to describe the process of "rendezvousing, capturing, stabilizing, towing, transferring to a disposal/graveyard orbit or relocating, and de-orbiting through orbital maneuvers for active or passive re-entry into the Earth's atmosphere." See Ram S. Jakhu, et al, "Regulatory Framework and Organization for Space Debris Removal and On-Orbit Servicing of Satellites," (2017) 4:3-4 Journal of Space Safety Engineering 129 at 130.

Space Treaties (the Outer Space Treaty,[10] the Liability Convention,[11] the Rescue and Return Agreement,[12] the Registration Convention,[13] and, to a lesser extent, the Moon Agreement[14]), creates special legal challenges inhibiting ADR. For example, the UN Space Treaties not only fail to provide a legally binding definition for what constitutes space debris, but they fail to mention debris at all. Further, there are no clearly recognized international obligations with respect to the creation nor the removal of space debris. Fundamental concepts from these treaties appear to have been drafted without envisioning a future world containing ADR space operations. For example, the "jurisdiction and control" provision in Article VIII of the OST establishes enduring, hegemonic control for States of registry over their space objects and fail to provide a mechanism for the transfer or abandonment of space objects. Further, the liability regime established by the Liability Convention disincentivizes ADR when it comes to both the owner of the piece of debris and the State wishing to carry out the ADR operation. It also fails to set out a standard of fault or to establish a mechanism for the transfer of liability. Each of these issues threatens to complicate necessary global ADR efforts. National defense concerns, economic concerns, and various national laws adopted by States since this time, notably export control laws, have further complicated the legal and policy landscapes for ADR operations.

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[10] *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*, 27 January 1967, 610 UNTS 205 (entered into force 10 October 1967) [*Outer Space Treaty or OST*].

[11] *Convention on International Liability for Damage Caused by Space Objects*, 29 March 1972, 961 UNTS 187 (entered into force on 1 September 1972) [*Liability Convention*].

[12] *Agreement on the Rescue of Astronauts, the Return of Astronauts and Return of Objects Launched into Outer Space*, 19 December 1967, 672 UNTS 119 (entered into force 3 December 1968) [*Rescue and Return Agreement*]

[13] *Convention on Registration of Objects Launched into Outer Space*, 12 November 1974, 1023 UNTS 15 (entered into force on 15 September 1976) [*Registration Convention*].

[14] *Agreement Governing the Activities of States on the Moon and other Celestial Bodies*, 5 December 1979, 1363 UNTS 3 (entered into force on 11 July 1984) [*Moon Agreement*]. Note that, while the other four UN Space Treaties have garnered wide-spread acceptance, the Moon Agreement has secured only 18 ratifications as of 1 January 2019. For a comprehensive list of adherents to each of the UN Space Treaties, as well as several other international space-related agreements, see COPUOS, Legal Subcommittee, *Status of International Agreements Relating to Activities in Outer Space as at 1 January 2019*, COPUOS, 2019, UN Doc A/AC.105/C.2/2019/CRP.3.

The failure of mitigation efforts and the global need for ADR, along with the aforementioned complex legal and policy challenges, will be the focus of this thesis. Part I defines the scope of the problem posed by space debris thorough an analysis of its causes, its observable characteristics, and its distribution throughout the primary Earth orbits. It further explains the dangers posed by uncontrolled debris, especially in light of its significant increase over time, and concludes by highlighting several discrete contributing factors and events that have dramatically exacerbated this increase in recent years.

Part II examines the historical failure of states to craft an international space *lex lata* to rein in or even moderate the increase in space debris. It details the drafting and widespread adoption of various soft law instruments at both the national and international levels. Ultimately, it argues that these measures have failed to adequately address the dangers posed by increasing space debris, thereby justifying the critical need for ADR.

After this need for ADR has been substantiated, Part III opens by briefly explaining some of the most promising technological methods of ADR. Then it analyzes the structural and systemic international and national legal challenges which currently frustrate the efforts of governmental, inter-governmental, and non-governmental entities wishing to carry out ADR, as briefly described above. Much of this analysis focuses on either lacunae or fundamental concepts embedded within the OST and the Liability Treaty. Part III also highlights certain national laws, specifically export control laws, as well as several policy issues, such as economic costs and national security considerations, which pose similar challenges to the successful implementation of ADR.

Finally, Part IV argues for a future strategy to address the challenges raised in Part III. Specifically, it advocates for the drafting and adoption of an entirely new multinational space treaty, describing the necessary changes to current international space law which must be made to facilitate the growth of ADR operations. Some of these changes include establishing new binding international definitions and obligations related to space debris, adjusting the jurisdiction and control rules for space debris, permitting the abandonment of space debris, modifying and modernizing the current liability regime, establishing a regulatory agency in charge of space debris, and empowering such an agency to raise funds for ADR. Short of the adoption of a new space treaty, Part IV alternatively discusses a role for more limited space protocols to existing UN treaties. Finally, Part IV concludes by addressing the ways in which individual States can also support ADR efforts through national legislation.

B. Context and Limitations

Before launching into the body of the thesis, a quick note on the context of the public international space law regime is in order. Little hard law has been generated to move the ball forward on a large scale since the Registration Convention in 1974. Soft law agreements, such as memoranda of understanding, voluntary guidelines, and a slew of UN General Assembly (UNGA) resolutions have instead helped filled that gap.[15] During this period of legal stagnation, the technology and practical means to safely and effectively accomplish several forms of ADR have become closer and closer to being fully realized. In fact, many commercial and governmental prototypes have been patented,[16] and some have already undergone operational testing in the outer space environment.[17] Without a modern legal landscape within which to operate, the implementation of this burgeoning ADR technology will be beholden to outdated legal concepts.

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[15] For a comprehensive review of these soft law mechanisms in international space law, see Francis Lyall & Paul B. Larson, *Space Law: A Treatise,* 2d ed (London: Routledge, Taylor & Francis Group, 2018), 33-48.

[16] See, for example, US, Patent No US 0,555,905 B2, The Aerospace Corporation & NASA, *System, Apparatus, and Method for Active Debris Removal* (31 January 2017).

[17] See, for example, Tereza Pultarova, "Watch a Satellite Fire a Harpoon in Space in Wild Debris-Catching Test (Video)" (18 February 2019), online: *Space* < https://www.space.com/space-junk-harpoon-removedebris-satellite-video.html>; Jonathan Amos, "RemoveDebris: UK Satellite Nets 'Space Junk'" (19 September 2018), online: *BBC* <https://www.bbc.com/ news/science-environment-45565815>.

This context, where the rollout of technological innovation is being stifled by legal stagnation, is the backdrop for this project and its lengthy description of the current seriousness of the space debris problem in Part I and its discussion of the challenges inhibiting ADR in Part III.

In part because of the above context, the door is open to many possible creative solutions to overcome the identified challenges and advance the efficacy of ADR within the space law landscape. However, it is worth noting here that, while Part IV suggests several desirable solutions, its intent is not to present exhaustive or fully developed legal proposals for new national and international law. Such an enterprise exceeds the scope of this project. Each of the ideas presented in Part IV is merely a starting point, worthy of future research and analysis if international progress is to be made on ADR.

Finally, while the descriptions of various ADR technologies in Part III(A) highlight an impressive variability, they are not intended to be extensive nor exhaustive. Instead, they are presented merely to provide context for understanding the current challenges and future strategies presented later in Parts III & IV.

C. Methodology and Terminology

While this project will primarily employ a doctrinal methodological approach throughout, it will occasionally resort to a comparative methodological approach, especially when analyzing various international mitigation efforts in Part II and national export control laws in Part III. After defining the physical characteristics and causes and dangers of space debris in Part I, Part II will primarily employ a doctrinal review of various international efforts aimed at debris mitigation but will also highlight similarities and differences between those efforts. Part III will see a continued doctrinal approach in the examination of international treaty law and national law to describe the challenges restricting ADR, referencing academic literature throughout. Finally, Part IV will again utilize a doctrinal approach to suggest various solutions to these challenges.

It will be worthwhile to make a brief comment on certain terms which will be used throughout this thesis. While the term "ADR" is a form of and generally synonymous with "remediation," ADR will be used as the preferred term, consistent with the prevailing usage in the literature. Also, ADR is used herein as a comprehensive term, without distinction to the many ways in which it might be conducted. For example, when discussing the jurisdiction and control of a piece of space debris during ADR, no distinction is made between conducting ADR by attaching an electrodynamic tether versus using a grappling arm. When such a distinction amongst the various methods of ADR may be relevant to the challenges discussed, such as with respect to international liability for damage if a ground-based laser is employed, it is made apparent. While the concept of on-orbit satellite servicing (OOS) can be closely related to ADR as a means of remediation, it will not be addressed in this project.[18]

The terms used to describe debris in space varies by organization. For example, NASA uses the term "orbital debris" or "micrometeoroid and orbital debris (MMOD)" while ESA employs the term "space debris." Depending on the user and the context, these terms may or may not include naturally occurring objects orbiting Earth, such as small fragments of rock or metal from meteoroids. This thesis will utilize the term "space debris," as this term is generally used in the literature to denote specifically the man-made debris orbiting Earth.[19]

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[18] OOS refers to the "capability of refueling, repairing, or upgrading satellites that have become non-functional while in space." By extending the functional life of the satellite, "OOS is a means of…space debris remediation." See Jakhu, et al, *supra* note 9 at 130.

[19] As such, this thesis does not specifically address the threats posed by naturally existing micrometeoroid debris nor any methods to address those threats.

Finally, in conducting ADR, it is most often the case that a space object will interact with one or more other space objects. In order to precisely identify these objects in relation to one another, the term "ADR object" or "ADR State" is used to denote the space object actively conducting the removal of a piece of space debris or the State possessing jurisdiction and control over that space object, respectively. Similarly, the term "space debris" is used to denote the targeted object of the removal action, while the term "debris State" is used to denote the State which possesses jurisdiction and control over that target.

Part I. Scope of the Space Debris Problem

While the term "space debris" is not defined in any of the UN Space Treaties, both the UNGA, through its adoption of the COPUOS Space Debris Mitigation Guidelines, and the IADC by virtue of its own Space Debris Mitigation Guidelines, subscribe to the following definition: "all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional."[20] Assuming this definition for purposes of discussion, grasping the scope of the space debris problem requires an understanding of where this type of debris comes from, where it is located, the dangers it poses, and how it has developed over time.

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[20] *Report of the Committee on the Peaceful Uses of Outer Space*, UNGAOR, 62nd Sess, Supp No 20, UN Doc A/62/20 (2007), Annex 1, para 1, adopted by the UNGA in *International Cooperation in the Peaceful Uses of Outer Space*, GA Res 62/217, UNGAOR, 62nd Sess, UN Doc A/RES/62/217 (2007); IADC, "Space Debris Mitigation Guidelines," IADC-02-01, Rev 1 (September 2007) at para 3.1. For a critical analysis of some of the legal challenges associated with this definition in relation to ADR, see COPUOS, STSC, *Active Debris Removal – An Essential Mechanism for Ensuring the Safety and Sustainability of Outer Space*, COPUOS, 2012, UN Doc A/AC.105/C.1/2012/CRP.16 at 30-32.

A. Causes of Space Debris

Man-made, non-functional objects in space are generated in several different ways. Most can be classified as either mission-related debris, discarded rocket bodies, fragmentation debris, microparticulate debris, or non-operational payloads.

1. Mission-Related Debris

Mission-related debris, sometimes described as operational debris, includes intentionally discarded objects due to the launch, deployment, activation, operation and de-orbit of the payload, which do not otherwise affect the integrity of the payload or launch vehicle.[21] It accounts for approximately 10-11% of all orbital space objects catalogued by the United States' Space Surveillance Network (SSN).[22] Mission-related debris most commonly includes smaller pieces of hardware intentionally released during payload deployment or operation, such as sensor or engine protective covers, straps, springs, temporary shields, or stabilization devices.[23] Advances in technology and design have resulted in a dramatic decrease in the creation of this type of space debris since 1990.[24]

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[21] NASA, Orbital Debris Program Office, "History of On-Orbit Satellite Fragmentations," 15th ed, NASA/TM-2018-220037 (4 July 2018) at 3, online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180008451.pdf>; Nicholas L. Johnson, "The Earth Satellite Population: Official Growth and Constituents," in John A. Simpson, ed., *Preservation of Near-Earth Space for Future Generations*, (Cambridge: Cambridge University Press, 1994) at 18.

[22] See Figure 4, *Relative Segments of the Catalogued In-Orbit Earth Satellite Population, infra*, from NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 3; COPUOS, *Active Debris Removal, supra* note 20 at 16-17.

[23] NASA, "Orbital Debris Management," *supra* note 6 at 6; Johnson, *supra* note 21 at 18.

[24] NASA, "Orbital Debris Management," *supra* note 6 at 3; ESA, "Annual Space Environment Report," GEN-DB-LOG-00271-OPS-SD (4 June 2019) at 47, online (pdf): *ESA* <https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf>.

2. Discarded Rocket Bodies

This category of space debris includes the discarded upper stages of the launch vehicle used to deliver the payload into its orbit. These stages can range in mass from less than 100 kilograms to as much as eight metric tons.[25] Similar to mission-related debris, discarded rocket bodies make up between 10-11% percent of all orbital space objects currently catalogued by the SSN.[26] While typical space missions leave a single rocket body behind in Earth orbit, others may leave as many as three strewn across separate orbits.[27] Incredibly, according to NASA, roughly 30% of all launch vehicle stages used since 1957 are still in orbit, [28] totaling nearly 1,950 rocket bodies in 2018.[29]

3. Fragmentation Debris

Fragmentation debris is debris created by the breakup of rocket bodies or payloads, whether caused by an internal explosion or anomalous physical separation or by some external collision event.[30] Fragmentation debris makes up the lion's share of space objects, or approximately 53% of all objects currently catalogued by the SSN.[31] Fragmentation events are categorized as either a satellite breakup or an anomalous event, the former generally being a high velocity, destructive event with fragments breaking off in different directions and at different velocities, while the latter is typically a lower velocity, unplanned and mostly-intact separation, often due to physical deterioration of the payload in the space environment.[32] Satellite breakups most commonly result

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[25] NASA, "Orbital Debris Management," *supra* note 6 at 3.

[26] *Ibid*; COPUOS, *Active Debris Removal, supra* note 20 at 16-17.

[27] Johnson, *supra* note 21 at 18.

[28] NASA, "Orbital Debris Management," *supra* note 6 at 6.

[29] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 8.

[30] Union of Concerned Scientists, "Historical Growth of Space Debris," (2009) at 3, online (PPT): U*CS* <https:// www.ucsusa.org/assets/documents/nwgs/Debris-growth-graph-5-18-09.ppt>.

[31] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 3.

[32] *Ibid*; Johnson, *supra* note 21 at 17-18.

from an accidental malfunction, especially by on-board propulsion systems, or may result intentionally, for example due to ASAT weapons testing,[33] whereby States test ground or air launched anti-satellite ballistic missiles by targeting and destroying their own satellites while still in Earth orbit.

Very few known fragmentation events to date have been caused by external collisions; instead, most are caused by internal explosions or anomalous physical separations.[34] While NASA figures show that more than 320 fragmentation events have occurred since 1957,[35] ESA estimates that fewer than ten of these have been due to accidental or intentional collision events.[36] Several of these ten will be discussed in more detail in Part I(D) of this thesis.

4. Microparticulate Debris

Microparticulate debris, as the names suggests, are the smallest form of space debris, ranging anywhere from micrometer dust particles to one-centimeter objects.[37] This type of debris is commonly released from solid rocket motors in the form of aluminum dioxide dust and particles.[38] It is also commonly found in the form of tiny flakes of material coatings or paint, degraded from either micro collisions or simple material deterioration from the harsh outer space environment.[39] Sodium potassium coolant liquid, once used to cool nuclear power sources, is

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[33] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 12; Johnson, *supra* note 21 at 17-18.

[34] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 12.

[35] *Ibid* at *i*. This includes a combination of 242 breakup events and 78 anomalous events. But see ESA, "Annual Space Environment Report," *supra* note 24 at 50 for ESA's differing sum of 532 such on-orbit satellite fragmentation events.

[36] ESA, "About Space Debris" (last updated 21 February 2018), online: *ESA* <https://www.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/About_space_debris>.

[37] *Ibid*.

[38] NASA, "Orbital Debris Management," *supra* note 6 at 12.

[39] ESA, "Position Paper on Space Debris Mitigation: Implementing Zero Debris Creation Zones," SP-1301 (February 2006) at 15, online (pdf): *ESA* < http://www.esa.int/esapub/sp/sp1301/sp1301.pdf>. This is not an insignificant source of microparticulate debris, as the ESA estimated in the same document that that there were over 63,000m^2 of painted surfaces orbiting the Earth in 2006.

another known cause of microparticulate debris.[40] In fact, NASA estimates that approximately 70,000-100,000 sodium potassium droplets of various sizes remain in low Earth orbit (LEO).[41] While small in size, the tremendously fast orbital velocities of microparticulate debris (up to ~10 km/s or 36,000 km/hr in the lowest orbits)[42] and the difficulty in tracking them can render them exceedingly dangerous. Because of this, NASA's Chief Scientist for Orbital Debris, Dr. Jer Chyi Liou, has categorized debris in the 1mm-1cm range as posing the highest mission-ending threat to current NASA space operations.[43]

5. Non-Operational Payloads

In addition to mission-related debris, ejected rocket bodies, fragments, and microparticulates, many defunct payloads remain in orbit, having either malfunctioned or reached the end of their useful lives. Functional and non-functional payloads together comprise just under 25% of the space objects catalogued by the SSN.[44] However, it is estimated that less than one-third of all orbiting payloads are still functional,[45] which means that more than 3,000 non-operational payloads continue to orbit the Earth as space debris.[46] Together, these defunct satellites comprise approximately 15% of the total space objects catalogued by the SSN.[47] Some non-operational payloads are small in size and mass, but others, especially older payloads in higher orbits, can weigh several tons.[48]

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[40] *Ibid* at 7.

[41] NASA, "Orbital Debris Management," *supra* note 6 at 11.

[42] Liou & Cowardin, *supra* note 3 at 5.

[43] J.-C. Liou, "Risk from Orbital Debris" (9 November 2018) at 6, online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180008560.pdf>.

[44] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 3.

[45] ESA, "About Space Debris," *supra* note 36. But see *ibid* at 1 for NASA's claim that this figure actually stands at more than 75%, which would translate to more than 4,000 non-functional orbiting payloads.

[46] ESA, "Space Debris by the Numbers," *supra* note 4.

[47] COPUOS, *Active Debris Removal, supra* note 20 at 17.

[48] NASA, "Orbital Debris Management," *supra* note 6 at 6.

B. Characteristics of Space Debris

1. Observability

Space objects are capable of being identified and tracked through the use of world-wide networks of ground-based and space-based optical telescopes and radars, the largest of which is the SSN maintained by the US Department of Defense.[49] The capability of the SSN to identify and track space objects differs based on the object's orbital altitude.

LEO, a portion of outer space ranging in altitude from the lowest boundary of space, however defined, up to 2,000 kilometers above the Earth's surface, is the area where most human activities in space take place, where the International Space Station (ISS) is positioned, and where many Earth observation satellites or telescopes are maintained.[50] Powerful phased array radars are most often used to detect space objects in this region.[51] Only identified space objects in excess of roughly 10 centimeters are routinely tracked by the SSN at this altitude.[52] However, advances in technology promise to reduce the size of trackable objects in LEO significantly. For example, a US DoD joint venture with Lockheed Martin called the "Space Fence" is expected to be operational on Kwajalein Atoll in the South Pacific in 2019, reportedly capable of tracking objects as small as a marble in LEO.[53]

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[49] Brian Weeden, "Tackling Space Debris Head On," (2013) 26:7 Phys. World 17 at 18.

[50] Rada Popova & Volker Schaus, "The Legal Framework for Space Debris Remediation as a Tool for Sustainability in Outer Space," (2018) 5:2 aerospace 55 at 2.

[51] COPUOS, STSC, *Towards Long-Term Sustainability of Space Activities: Overcoming the Challenges of Space Debris*, COPUOS, 2011, UN Doc A/AC.105/C.1/2011/CRP.14 at 12.

[52] J.-C. Liou, "USA Space Debris Environment, Operations, and Research Updates," (2018) at 9, online (pdf): *NASA* < https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180001749.pdf>; It is important to note that highly-sensitive individual sensors are capable of observing much smaller space objects. However, without multiple such sensors being positioned around the world to gather accurate orbital tracking data, these objects are only temporarily observed rather than continuously tracked by the SSN. See COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 13. For a graphical representation of this advanced capability in the US, see Figure 5*, infra*, from Liou & Cowardin, *supra* note 3 at 10.

[53] Stew Magnuson, "News From Space Symposium: Tracking Objects in Space Both Easier, More Complicated," (11 April 2019), online: *National Defense Magazine* < http://www.nationaldefensemagazine.org/articles/2019/4/11/tracking-objects-in-space-both-easier-more-complicated>.

The areas in Medium Earth Orbit (MEO), or between 2,000 and approximately 35,000 kilometers above the Earth's surface, are used primarily for navigation and communication satellites.[54] All major Global Navigation Satellite Systems (GNSS) are located here, such as the U.S.'s Global Positioning System, Russia's GLONASS, Europe's Galileo, and China's BeiDou constellations.[55] Objects above approximately 5,000 kilometers are best detected through the use of optical telescopes, such as the U.S. Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS).[56] Generally, the ability to accurately track space objects in this region decreases from about 10 centimeters at the lowest regions of MEO to about one meter at the highest regions of MEO.[57]

Finally, Geostationary Orbit (GEO), or the orbits at and immediately adjacent to roughly 35,786 kilometers above the Earth's equator, are used primarily for communications and broadcasting.[58] Ideally, a graveyard orbit at least 235 kilometers above GEO is also used to dispose of satellites in this region at the end of their useful life.[59] Similar to upper MEO, objects located in GEO are best detected and tracked through the use of advanced electro-optical telescopes, although sometimes very powerful mechanical radars can be used.[60] Generally speaking, only space objects in excess of approximately one meter are trackable by the SSN in this region.[61]

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[54] Popova & Schaus, *supra* note 50 at 2.

[55] Lesley Jane Smith, "Legal Aspects of Satellite Navigation" in Frans von der Dunk & Fabio Tronchetti, eds, *Handbook of Space Law*, (Cheltenham, UK: Edward Elgar Publishing, 2015) at 556-566.

[56] Brian Weeden, et al, "Global Space Situational Awareness Sensors," (2015) at 9, online: *ResearchGate* <https://www.researchgate.net/publication/228787139_Global_Space_Situational_ Awareness_Sensors>; US, Air Force Space Command, "Fact Sheet: Ground-Based Electro-Optical Deep Space Surveillance," (22 March 2017), online: *Air Force Space Command* < https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/249016/ground-based-electro-optical-deep-space-surveillance/>.

[57] COPUOS, *Towards Long-Term Sustainability*, *supra* note 51 at 12.

[58] Johnson, *supra* note 21 at 18.

[59] IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 5.3.1.

[60] Weeden, et al, *supra* note 56 at 9; COPUOS, *Towards Long-Term Sustainability*, *supra* note 51 at 12.

[61] COPUOS, *Towards Long-Term Sustainability*, *supra* note 51 at 13. Note that ESA's Optical Ground Station (OGS) in Tenerife, Spain operates a telescope which can reportedly detect, but not track, objects as small as 30 centimeters near GEO, but it is not operated exclusively for this function. See T. Schildknecht, et al, "Optical Observations of Space Debris in High-Altitude Orbits," Proceedings of the Fourth European Conference on Space

2. Quantity, Mass, and Distribution Throughout Space

In total, the U.S. SSN currently tracks approximately 23,000 objects in space larger than 10 centimeters.[62] However, just because the SSN *tracks* an object does not mean that the genesis of that object is known for liability, jurisdictional, or any other purposes, nor does it mean that the object is necessarily functional. In fact, the identity is only known for approximately 19,500 of these objects (such that they have been *catalogued* by the SSN[63]) and only about 2,400 of all tracked objects are actually functional satellites.[64] This means that well over 90% of the tracked objects in the SSN are non-functional space debris. As for operational satellites, according to the Union of Concerned Scientists in November 2018 (when there were only 1,957 in orbit), 1,232 were operated in LEO, 558 were operated in GEO, 126 were operated in MEO, and a further 41 were operated in non-standard elliptical orbits.[65] In other words, 63% of all functional satellites in November 2018 were in LEO, 28.5% were in GEO, 6.5% were in MEO, and 2% were in elliptical orbits.[66]

While the SSN may only be actively tracking 23,000 space objects, advanced space debris modeling, such as NASA's LEGEND or ESA's MASTER,[67] as well as additional experiments conducted *in situ* and detailed analyses of recovered hardware provide insight into the volume of additional space debris *not* being tracked by the SSN, either because it is too small to track or

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Debris, SP-587 (2005) at 113 & 118, online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc4/paper/113/SDC4-paper113.pdf>.

[62] Liou, "Risk from Orbital Debris," *supra* note 43 at 7.

[63] Johnson, *supra* note 21 at 10.

[64] Kelso, "SATCAT Boxscore," *supra* note 2; For a graphical representation of all SSN-catalogued objects, both currently on-orbit and previously decayed, see Figure 6, *infra*, from T.S. Kelso, "SATCAT Growth," (accessed 30 April 2019), online: *CelesTrak* <https://www.celestrak.com/satcat/growth.png>.

[65] Union of Concerned Scientists, "UCS Satellite Database," (last updated 9 January 2019), online: *UCS* <https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.WhyVnVNrw2x>.

[66] *Ibid.*

[67] For a description of these models, as well as the statistical models used by JAXA, ISRO, ASI, and UKSA, see IADC, "Stability of the Future LEO Environment," IADC-12-08, Rev 1 (January 2013) at 5-7.

because it has simply not yet been identified.[68] Using these models and methods, ESA estimates that, as of January 2019, more than 34,000 pieces of space debris greater than 10 centimeters in size are orbiting Earth, while a further 900,000 exist between 1 and 10 centimeters.[69] Most astonishingly, ESA estimates that more than 128 million pieces of space debris exist between a millimeter and a centimeter.[70]

The distribution of these tracked objects, as well as the distribution of their overall mass, is critical for full understanding the context of the space debris problem. This is true because, just like operational satellites, the rest of the SSN's tracked space objects are not distributed equally throughout space. Most of this debris is found in incredibly important orbits, particularly in LEO between 600 and 1,500 kilometers and in GEO.[71] As Figure 7 depicts, *infra*, more than 60% of these objects are concentrated in LEO, with GEO making up the second most populous orbit.[72] The same can be said for the overall mass of these tracked space objects, but slightly less concentrated in LEO. The total mass of tracked objects in space is in excess of 8,000 metric tons,[73] of which well over 95% is made up by payloads and discarded rocket bodies.[74] Fragments and mission related debris only make up about 2% each.[75] The highest overall mass is concentrated in LEO, but GEO is not far behind, since payloads there are much older, some weighing as much as six tons.[76]

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[68] COPUOS, *Towards Long-Term Sustainability*, *supra* note 51 at 14; Popova & Schaus, *supra* note 50 at 2.

[69] ESA, "Space Debris by the Numbers," *supra* note 4.

[70] *Ibid.*

[71] COPUOS, *Towards Long-Term Sustainability*, *supra* note 51 at 17.

[72] See Figure 7, "Count Evolution by Object Orbit," *infra,* from ESA, "Space Environment Statistics," *supra* note 1.

[73] See Figure 8, "Mass Evolution by Object Orbit," *infra,* from *ibid.*

[74] See Figure 3, *infra,* from NASA, "Orbital Debris Quarterly News" *supra* note 7.

[75] *Ibid.*

[76] See Figure 8, "Mass Evolution by Object Orbit," *infra,* from ESA, "Space Environment Statistics," *supra* note 1; NASA, "Orbital Debris Management," *supra* note 6 at 6.

In short, while there are vast numbers of objects orbiting Earth, over 90% of what can be tracked is space debris. Further, this debris is most concentrated in the important LEO and GEO regions, whether measured in quantity or mass.

C. Dangers of Space Debris

The statistics presented above would be unremarkable but for the fact that space debris poses significant dangers to both global space operations and the environment itself. For example, space debris can threaten the viability of both manned and unmanned space operations. Excess debris can also over-pollute valuable Earth orbits or even threaten the surface of the Earth with falling debris that can contain chemical or nuclear hazards.

1. Manned and Unmanned Space Operations

It is clear that space debris, especially small, untrackable pieces, can be dangerous to both manned and unmanned space operations. Debris smaller than one centimeter can be shielded against and, therefore, generally only poses the risk of degradation or partial functional damage.[77] However, space debris over one centimeter cannot be effectively shielded against, and therefore poses a risk of severe or even catastrophic damage.[78]

Satellites routinely face unexplained anomalies, often only attributable to collisions with very small pieces of space debris. However, the first explainable collision between catalogued objects occurred in July 1996, when a legacy fragment from an exploded ESA Arianne rocket body collided with a 50-kg French microsatellite called ‘Cerise’ while orbiting at approximately 670 kilometers in altitude.[79] This collision destroyed the six meter gravity boom which stabilized the

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[77] COPUOS, *Active Debris Removal*, supra note 20 at 15.

[78] *Ibid.*

[79] See, generally, F. Alby, et al, “Collision of CERISE with Space Debris,” Proceedings of the Second European Conference on Space Debris, SP-393 (1996) 589-596, online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc2/paper/30/SDC2-paper30.pdf>.

satellite.[80] Fortuitously, it cleanly severed the boom and created only a single piece of trackable debris, the broken portion of the boom itself.[81] While the SSN warns satellite operators when its modeling software predicts such close encounters, known as "conjunction events," satellite operators may be unwilling or unable to navigate their satellites away from the space debris.

When it comes to manned space operations, the risks posed by space debris rapidly become more serious. For example, with regard to the crewed U.S. Space Shuttle, these risks prompted NASA to commission a "Space Shuttle Meteoroid and Debris Damage Team."[82] Post-mission analysis of the windows of the space shuttle revealed that pits were caused by debris impacts in orbit on every single mission,[83] leading to the replacement of 70 Shuttle windows between 1981 and 1998.[84] After considering the impact of debris on the Space Shuttle and using statistical modeling, NASA concluded that a 10-day Shuttle mission at 400 kilometers would, on average, result in more than 800 collisions with debris between .04 and .1 millimeter in size.[85] Notably, collision with a piece of debris of only 5 millimeters was likely to penetrate the crew cabin.[86] Of course, the most permanent, and therefore risky, human presence in outer space is that of the International Space Station (ISS), which continuously houses astronauts from various contributing nations and maintains an orbital altitude of roughly 400 kilometers.[87] Conjunction with a piece of space debris, especially one in excess of 10 centimeters, could easily result in the loss of human

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[80] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 400.

[81] NASA, "Orbital Debris Quarterly News" 1:2 (September 1996), online (pdf): *NASA*<https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv1i2.pdf>.

[82] NASA, Committee on Space Shuttle Meteoroid/Debris Risk Management, *Protecting the Space Shuttle from Meteoroids and Orbital Debris* (Washington, D.C.: The National Academies Press, 1997) at *V*.

[83] *Ibid* at 16.

[84] Loretta Hall, "The History of Space Debris," Space Traffic Management Conference (6 November 2014) at 3, online (pdf): *Embry-Riddle* <https://commons.erau.edu/cgi/viewcontent.cgi?article=1000&context=stm>.

[85] NASA, *Protecting the Space Shuttle*, *supra* note 82 at 9.

[86] *Ibid* at 15.

[87] Elizabeth Howell, "International Space Station: Facts, History & Tracking," (8 February 2018), online: *Space.com* <https://www.space.com/16748-international-space-station.html>.

life aboard the ISS. To manage this risk, the ISS has been forced to conduct 25 relocations, or "debris avoidance maneuvers," since 1999.[88]

2. Environmental Contamination

In addition to endangering manned and unmanned space operations, one of the most discussed risks of space debris is what has become known as the Kessler Syndrome, or the possibility for several major conjunction events to create a continuing knock-on effect that renders certain orbits contaminated and unfit for future space operations. This effect is based on Donald Kessler's original description of the risk of a rapidly forming "debris belt."[89] The problem with such a runaway cascade is that the resulting slew of space debris fragments may stay in orbit for incredibly long periods of time, depending on their altitude, surface area, mass, density, and a number of other atmospheric characteristics and influences.[90] For reference, a one kilogram CubeSat in a circular orbit at 600 kilometers will likely remain in space for approximately 32 years.[91] However, the orbital duration exponentially increases as orbital altitude increases, so much so that the IADC describes the average atmospheric drag-induced orbital lifetime for a typical spacecraft above 1,000 kilometers as "quasi-eternal."[92]

In addition to long-term environmental contamination in space, space debris can also impact the surface of the Earth, since debris in LEO will eventually re-enter the Earth's atmosphere. If the space object is large enough to survive reentry, it can pose a falling risk to

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[88] Liou, *supra* note 52 at 6. For a comprehensive review of such ISS debris avoidance maneuvers, see James S. Cooney, "International Space Station (ISS) Orbital Debris Collision Avoidance Process," (October 2016), online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160012726.pdf>.

[89] See, generally, Kessler & Cour-Palais, *supra* note 5.

[90] *Ibid* at 2643. See also, generally, Antonio Lira, "How Long Does it Take for a Satellite to Fall to Earth?," (2015) 50:1 Physics Education 71.

[91] Lira, *supra* note 90 at 73-74.

[92] IADC, "IADC Statement on Large Constellations in Low Earth Orbit," IADC-15-03 (September 2017) at 6. For a comparison of the timelines for orbital decay at 400, 600, 800, and 1000 kilometers, see COPUOS, *Active Debris Removal*, supra note 20 at 18.

humans on the ground.[93] Further, any chemical or nuclear material which survives re-entry can pose serious environmental dangers. One notable example of such danger occurred in 1978, when the Soviet satellite 'Cosmos 954,' powered by 50 kilograms of enriched uranium, crashed into northwestern Canada, sprinkling radioactive material across more than 100,000 square kilometers.[94]

D. Increase in Space Debris Over Time

As even a cursory glance at NASA's data set from Figures 2 and 3, *infra*, reveals, the total quantity and mass of catalogued space objects has been steadily increasing since the dawn of the space age. Between 1970 and 2018, the overall quantity of catalogued objects in space increased from approximately 2,800 to roughly 18,700, a growth of 567%.[95] Staggeringly, the overall mass of these objects during this same time increased from nearly 375 metric tons to approximately 7,700 metric tons, an increase of 1,953%.[96] The explanations for these dramatic and continued increases are broad, but can be partially explained by the intentional and accidental fragmentation of satellites, as well as the increase in space-faring nations and commercial space operations.

1. Fengyun-1C ASAT Test (2007)

One of the most dramatic contributions to the quantity of catalogued objects, and to fragmentation debris generally, is the intentional destruction of satellites from the testing of

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[93] COPUOS, *Towards Long-Term Sustainability*, *supra* note 51 at 21.

[94] Alexander F. Cohen, "Cosmos 954 and the International Law of Satellite Accidents," (1984) 10:1 Yale Journal of International Law 78 at 79; W.K. Gummer, et al, "COSMOS 954: The Occurrence and Nature of Recovered Debris," (May 1980) at 27, online (pdf): *IAEA* <https://inis.iaea.org/collection/NCLCollectionStore/_Public/12/595/12595268.pdf?r=1&r=1>.

[95] See Figure 2, *infra*, from NASA, "Orbital Debris Quarterly News," *supra* note 7 at 10. It is important to note that the overall quantity of space objects increased relatively little, only 4%, between 2010 and 2018. However, because of the enormous NewSpace constellations planned for LEO in the near future (discussed in Part I(D)(4), *infra*), this recent pause in catalogued space object growth is unlikely to continue.

[96] See Figure 3, *infra*, from NASA, "Orbital Debris Quarterly News," *supra* note 7 at 11.

military ASAT capabilities. Four different countries have conducted ASAT ballistic missile tests across a timespan of over 50 years, even as recently as March 2019.[97]

By far the most prolific debris-creating ASAT test was China's destruction of its defunct Fengyun-1C weather satellite in 2007. This polar-orbiting satellite was destroyed by a direct ascent ASAT at an altitude of approximately 865 kilometers,[98] creating more than 3,312 pieces of tracked debris.[99] It is estimated that an additional 32,000 pieces of untracked debris were also created.[100] A few years after the test, the debris field was scattered between 175 and 3,600 kilometers in altitude, in total representing 22% of all catalogued objects in LEO in 2010.[101] Debris from this test has caused the defensive movement of other satellites and even the ISS.[102] It is predicted that only approximately 21% of the debris from this ASAT test will decay and fall out of orbit by the year 2107.[103] In other words, roughly 79% of the entire debris field may still be orbiting the Earth a full century after the ASAT test was conducted.[104]

2. Cosmos 2251/Iridium 33 Collision (2009)

While intentional fragmentation events like ASATs can cause large debris fields, so can accidental collisions. The largest such accidental collision was the result of a defunct Russian

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[97] Ajey Lele, "The Implications of India's ASAT Test," (1 April 2019), online: *The Space Review* <http://www.thespacereview.com/article/3686/1>. The four countries are the US, the Soviet Union/Russia, China, and India.

[98] Joseph N. Pelton, *New Solutions for the Space Debris Problem* (Cham: Springer, 2015) at 3.

[99] T.S. Kelso, "Chinese ASAT Test," (last updated 22 June 2012), online: *CelesTrak* <https://celestrak.com/events/asat.php>.

[100] Brian Weeden, "2007 Chinese Anti-Satellite Test Fact Sheet," (last updated 23 November 2010) at 2, online (pdf): *Secure World Foundation* <https://swfound.org/media/9550/chinese_asat_fact_sheet_updated_2012.pdf>.

[101] NASA, "Orbital Debris Quarterly News" 14:4 (October 2010) at 3, online (pdf): *NASA* <https://www.orbitaldebris .jsc.nasa.gov/quarterly-news/pdfs/odqnv14i4.pdf>.

[102] Brian Berger, "NASA's Tera Satellite Moved to Avoid Chinese ASAT Debris," (6 July 2007), online: *Space.com* <https://www.space.com/4038-nasa-terra-satellite-moved-avoid-chinese-asat-debris.html>; NASA, "Orbital Debris Quarterly News," 19:4 (October 2015) at 1, online (pdf): *NASA* <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv19i4.pdf>.

[103] Weeden, "2007 Chinese Anti-Satellite Test," *supra* note 100 at 3. It is important to note that these predictions were made in 2012 and can be influenced by a number of factors, especially solar radiation. See COPUOS, *Active Debris Removal, supra* note 20 at 18.

[104] *Ibid*.

military communications satellite, Cosmos 2251, and an operational U.S. commercial communications satellite, Iridium 33, colliding over Siberia in 2009 at approximately 790 kilometers in altitude.[105] This event was the first recorded instance of two satellites accidentally colliding with one another in space.[106] Cosmos 2251 had an impressive mass of 900 kilograms, while Iridium 33 was smaller, but still a sizeable satellite, at 556 kilograms.[107] The collision caused Cosmos 2251 to fragment into 1,668 catalogued pieces of debris over 10 centimeters, while Iridium 33 broke up into 628 such pieces.[108] Thousands of additional pieces of debris less than 10 centimeters were also created.[109] The collision scattered debris across varying altitudes between 200 and 1,700 kilometers,[110] but was concentrated in the critically important LEO altitudes around 800 kilometers.[111] Some of this debris has even impacted the ISS, requiring it to perform a debris avoidance maneuver in 2015.[112] Scientific modeling predicts that a significant proportion of Iridium 33's fragments will remain in orbit for more than 100 years, while a significant amount of Cosmos 2251's debris will be in orbit for at least 25-50 years.[113] Behind the Chinese Fengyun-1C ASAT test, Cosmos 2251 and Iridium 33 are individually the number two and number four largest debris-creating fragmentation events in history, respectively.[114]

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[105] Brian Weeden, "2009 Iridium-Cosmos Collision Fact Sheet," (last updated 10 November 2010) at 1, online (pdf): *Secure World Foundation* <https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf>.

[106] *Ibid*.

[107] T.S. Kelso, "Analysis of the Iridium 33-Cosmos 2251 Collision," 10th Advanced Maui Optical and Space Surveillance Technologies Conference, (2009) at 8, online (pdf): *Amos Tech* <https://amostech.com/TechnicalPapers/2009/Iridium_Cosmos_Collision/Kelso.pdf>.

[108] NASA, "Orbital Debris Quarterly News" 20:1 & 2 (April 2016) at 6, online (pdf): *NASA* <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv20i1-2.pdf>.

[109] Weeden, "2009 Iridium-Cosmos Collision," *supra* note 105 at 1.

[110] Ram S. Jahku, "Iridium-Cosmos Collision and Its Implications for Space Operations," in Kai-Uwe Schrogl, et al, eds, *Yearbook on Space Policy 2008/2009: Starting New Trends*, 3d ed (Vienna, Austria: Springer, 2010) at 263.

[111] NASA, "Orbital Debris Quarterly News," 13:3 (July 2009) at 2, online (pdf): *NASA* <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv13i3.pdf>.

[112] NASA, "Orbital Debris Quarterly News," *supra* note 101 at 1.

[113] Kelso, *supra* note 107 at 7-8; NASA, "Orbital Debris Quarterly News," *supra* note 111 at 2.

[114] NASA, "Orbital Debris Quarterly News," *supra* note 108 at 6.

3. Indian ASAT Test (2019)

Another important debris-creating ASAT test occurred in March 2019, when India intentionally destroyed its own 740-kilogram Microsat-r satellite at an altitude of approximately 285 kilometers.[115] This satellite had been launched by India just two months prior to carrying out the ASAT test.[116] The resulting fragmentation created, as of May 2019, at least 84 pieces of trackable debris larger than 10 centimeters, in various orbits ranging from 200 all the way up to 2,250 kilometers in altitude, plus many more smaller, untrackable fragments.[117] Importantly, this debris field threatens the ISS, as approximately 79% of the created debris orbits in altitudes above it.[118]

While this debris-creating episode is nowhere near the magnitude of previous ASAT tests, most notably the Chinese Fengyun-1C test in 2007, it is worth highlighting here simply because it demonstrates that, even in 2019, States are still willing to knowingly and intentionally create space debris in vital Earth orbits. It is also worth noting the fact that, while many States expressed concern over this test and those before it, few, if any, declared such intentional debris-creating events to violate international space law,[119] whether under Article IX of the OST, which contains "due regard," "harmful contamination," and "harmful interference" provisions, or any other provisions of international space law. Some States even seemed to justify these events. For example, after the Chinese ASAT test, a spokesman for the UK Prime Minister went so far as to

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[115] Marco Langbroek, "Why India's ASAT Test Was Reckless," (30 April 2019), online: *The Diplomat* <https://thediplomat.com/2019/05/why-indias-asat-test-was-reckless/>.

[116] Kerry Hebden, "Debris from India's ASAT Test Worse Than Predicated," (3 May 2019), online: *Room* <https://room.eu.com/news/debris-from-indias-asat-test-worse-than-predicted>.

[117] Langbroek, *supra* note 115.

[118] *Ibid.*

[119] Matteo Frigoli, "Between Active Debris Removal and Space-Based Weapons: A Comprehensive Legal Approach," in Annette Froehlich, ed, *Space Security and the Legal Aspects of Active Debris Removal* (Cham, Switzerland: Springer, 2019) at 64; Jessica West, "It's Time to Speak Out About India's Reckless Anti-Satellite Test," (15 April 2019), online: *The Space Review* <http://www.thespacereview.com/article/3695/1>.

say that the UK did not believe the test "contravene[d] international law."[120] Other major space-faring States have appeared to draw similar conclusions about the legality of such tests. For example, in relation to India's test, while the U.S.'s NASA decried the intentional creation of debris as a "terrible, terrible thing,"[121] U.S. Strategic Command Commander General John Hyten made statements before Congress sympathetic to India's right to conduct such an ASAT test.[122]

4. Space-Faring Nations and Commercial Space Activities

In addition to the increase in space debris from dramatic fragmentation events, the total volume and mass of debris in the space environment is also increasing simply because there are more space participants than ever before, whether calculated in terms of space-faring nations or commercial activities. In the 1950s, as noted at the outset of this thesis, only the United States and the Soviet Union were active in space. Through the 1960s, another six countries joined them.[123] By 2011, that number had grown to more than 50.[124] Now, in 2019, there are at least 77 countries which have satellites in orbit, in addition to dozens more intergovernmental entities,[125] and more are joining these ranks all the time.

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[120] Pavle Kilibarda, "The Militarization of Outer Space and the Liability Convention," (2015) 40:3 Air and Space Law 271 at 273.

[121] Helen Regan, "India Anti-Satellite Test a 'Terrible Thing,' NASA Chief Says," (2 April 2019), online: *CNN* <https://www.cnn.com/2019/04/02/india/nasa-india-anti-missile-test-intl/index.html>.

[122] Chidanand Rajghatta, "In Unprecedented Support, US Defends India's Space Weapons Test Saying It Understands New Delhi's Concerns," (12 April 2019), online: *Times of India* <https://timesofindia.indiatimes.com/india/in-unprecedented-support-us-defends-indias-space-weapons-test-saying-it-understands-new-delhis-concerns/articleshow/68852883.cms>.

[123] These countries include the UK, Canada, Italy, France, Australia, and West Germany, in that order. See "First Time in History," (3 March 2019), online: *The Satellite Encyclopedia* <https://www.tbs-satellite.com/tse/online/thema_first.html>.

[124] Organization for Economic Cooperation and Development (OECD), "The Space Economy at a Glance 2011," (2011) at 20, online (pdf): *OECD* <http://dx.doi.org/10.1787/9789264111790-en>.

[125] T.S. Kelso, "SATCAT Sources," (accessed 7 May 2019), online: *CelesTrak* <https://www.celestrak.com/satcat/sources.php>.

Further, the global space economy has undergone incredible growth in the last several decades. In 2009, it was a U.S. $150-165 billion industry.[126] By the end of 2016, it was estimated to be worth roughly U.S. $345 billion[127] The commercial space industry is a large factor in this growth, since, as Figure 1, *infra*, indicates, commercial satellite launches have become far more numerous in recent years than government launches, even dominating certain subsectors. For example, SpaceX, a private U.S. company, has dramatically increased its role in launch services, conducting 17 of the 22 FAA-approved orbital launches in the U.S. in 2017.[128] New commercial companies are also revolutionizing the way space is accessed and exploited, using lean, agile startups to develop smaller (in both surface area and mass), cheaper, and more numerous satellite constellations, a shift in the space industry known as "NewSpace."[129] No longer simply supporting government operations, commercial entities are themselves becoming "key protagonists" in space.[130]

This exciting and ambitious new commercial approach to space is not likely to slow down anytime soon. In fact, it is only expected to increase. The market has recently enjoyed annual average growth of 6-8% and is projected to be worth between U.S. $1-2.7 trillion by the 2040s.[131] Companies are also going public with ambitious plans for massive new satellite constellations, designed to deliver commercial services to every corner of the globe. For example, OneWeb, a

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[126] OECD, *supra* note 124 at 10.

[127] US, Federal Aviation Administration (FAA), "The Annual Compendium of Commercial Space Transportation: 2018," (January 2018) at 1, online (pdf): *FAA* <https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf>. For a detailed breakdown of the space economy from the same source, see Figure 9, *infra*.

[128] *Ibid* at 41.

[129] Geoff Nunn, "Thinking Historically About NewSpace," (4 May 2018), online: *SpaceNews* <https://spacenews.com/op-ed-thinking-historically-about-newspace/>; Bohumil Dobos & Jakub Prazak, "To Clear or to Eliminate? Active Debris Removal Systems as Antisatellite Weapons," (2019) 47 Space Policy 217 at 218.

[130] Jean-Marie Bockel, "The Future of the Space Industry: General Report," North Atlantic Treaty Organization (NATO), Economic and Security Committee, 173 ESC 18 E fin (17 November 2018) at 2, online (pdf): *NATO* <https://www.nato-pa.int/document/2018-future-space-industry-bockel-report-173-esc-18-e-fin>.

[131] Jeff Joust, "A Trillion Dollar Space Industry Will Require New Markets," (5 July 2018), online: *SpaceNews* <https://spacenews.com/a-trillion-dollar-space-industry-will-require-new-markets/>.

communications company, recently launched the first six satellites in its anticipated 648-satellite constellation in LEO to provide global broadband internet coverage, with plans to eventually scale up to either 900 or 1,980 total satellites.[132] Similarly, Amazon has announced "Project Kuiper," its plan to develop a 3,236-satellite broadband internet constellation across three LEO altitudes.[133] Not to be outdone, SpaceX's global broadband internet plan, called "Starlink," has already received FCC approval for 4,425 satellites to be arranged in multiple LEO orbits, with an eventual goal of scaling upwards to as many as 12,000 satellites.[134] These commercial plans represent a marked paradigm shift in outer space, given the fact that there were only 994 total active satellites in Earth orbit in 2012.[135]

Facilitating this increase in new State and commercial activity in space is the fact that the costs associated with gaining access to space have been rapidly decreasing.[136] These decreases are partially due to the development of new space launch technology, like SpaceX's Falcon and Falcon Heavy rockets, but also because record numbers of smaller payloads are being combined into single launches, sharing the costs among many operators. For example, in 2017 India launched 104 satellites on a single mission, nearly tripling the previous world record of 37 set by Russia in 2014.[137]

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[132] Caleb Henry, "OneWeb's First Six Satellites in Orbit Following Soyuz Launch," (27 February 2019), online: *SpaceNews* < https://spacenews.com/first-six-oneweb-satellites-launch-on-soyuz-rocket/>.

[133] Alan Boyle, "Amazon to Offer Broadband Access Form Orbit With 3,236-Satellite 'Project Kuiper' Constellation," (4 April 2019), online: *GeekWire* <https://www.geekwire.com/2019/amazon-project-kuiper-broadband-satellite/>.

[134] Loren Grush, "FCC Approves SpaceX's Plans to Fly Internet-Beaming Satellites in a Lower Orbit," 27 April 2019), online: *The Verge* <https://www.theverge.com/2019/4/27/18519778/spacex-starlink-fcc-approval-satellite-internet-constellation-lower-orbit>.

[135] Bockel, *supra* note 130 at 5.

[136] Between the 1950s and 2018, the estimated cost of launching one kilogram of mass into LEO has decreased from nearly $1M USD to an incredible $1,400 USD. See Harry W. Jones, "The Recent Large Reduction in Space Launch Cost," 48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico, online (pdf): <https://ttu-ir.tdl.org/bitstream/handle/2346/74082/ICES_2018_81. pdf?sequence=1&isAllowed=y>.

[137] Ellen Barry, "India Launches 104 Satellites From a Single Rocket, Ramping Up a Space Race," (15 February 2017), online: *New York Times* <https://www.nytimes.com/2017/02/15/world/asia/india-satellites-rocket.html>.

E. Conclusion

Space debris can be classified as either mission-related debris, fragmentation particles, microparticulates, jettisoned rocket bodies, and derelict payloads. While the SSN and other networks take great efforts to track and catalogue this debris, there are limits to what can be monitored, depending on the object's orbital altitude and size. Overall, space debris has been on a steady upward trend, both in mass and quantity, ever since the first days of human activities in space and shows no sign of slowing down. Worryingly, the most dramatic increases in space debris have occurred due to intentional fragmentation events, specifically ASAT tests. Other major fragmentation events have resulted from collisions or simply the on-orbit fragmentation of derelict payloads and rocket bodies. Apart from fragmentation events, space is simply becoming more congested as more and more States and commercial entities exploit the cheap access which advances in technology have provided. The overall quantity and mass of the debris from all of these sources are not uniformly distributed across space; rather, they are concentrated in the most heavily used orbits, primarily in LEO and GEO, and therefore pose a danger to both manned and unmanned space operations as well as to the space environment.

Part II. Space Debris Mitigation Efforts and Failure

The space debris problem described in Part I of this thesis began to catch the eye of scientists, governments and intergovernmental entities in the 1980s and early 1990s.[138] Eventually, the UN added it as a recurring item on COPUOS' STSC agenda, beginning in 1994.[139] However, no hard

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[138] Henry T. Scott, "Improving the Shield: Mitigating the Danger of Space Debris by Enforcing and Developing Already Existing Space Law," (2009) 34 Annals Air & Space L. 713 at 723.

[139] M.Y.S. Prasad, "Technical and Legal Issues Surrounding Space Debris – India's Position in the UN," (2005), 21 Space Policy 243 at 244.

law has been adopted at the international level to address this problem. Instead, various States and intergovernmental organizations began devising and applying their own strategies to mitigate the creation of additional space debris from future space activities and to apply these strategies to space operators through national laws and space licensing requirements. Eventually, in the 2000s, two major international mitigation guidelines were developed on a voluntary, non-binding basis and gained broad support, namely those of the IADC and the COPUOS STSC. While an encouraging first step, these voluntary, "soft law" guidelines appear to be the preferred method of regulating debris on the international stage, as opposed to any binding legal obligations.[140] It is the contention of this thesis that these mitigation efforts have failed to adequately address the escalating problem of space debris.

A. Early National and International Space Debris Mitigation Efforts

The earliest national efforts towards a comprehensive space debris mitigation guideline began in the United States in the mid-1990s with NASA, specifically NASA's "Guidelines and Assessment Procedures for Limiting Orbital Debris" in 1995.[141] This guideline implemented NASA's earlier 1993 announcement of Management Instruction (NMI) 1700.8, which had simply ordered each program to conduct a formal assessment of their potential to create debris.[142] The new, more specific guidelines further required all new NASA programs to conduct orbital debris

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[140] Lyall & Larson, *supra* note 15 at 276.

[141] NASA, Safety Standard 1740.17, "Guidelines and Assessment Procedures for Limiting Orbital Debris," (August 1995), online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19960020946.pdf>. It is worth noting that ESA had previously developed safety standard PSS-01-40 much earlier, in 1988, which, while not specifically devoted to space debris mitigation, contained basic requirements found in most future mitigation guidelines, e.g. passivation. See, generally, Christophe Bonnal, "A Brief Historical Overview of Space Debris Mitigation Rules," CNES (May 2016) at 7, online (pdf): *ESA* <https://indico.esa.int/event/128/attachments/729/798/01_Debris_Mitigation_-_Clean_Space_-_230516.pdf>.

[142] *Ibid* at 2.

assessments within the program's development phases and to generate debris assessment reports for review and concurrence.[143]

While NASA was undertaking these efforts, two influential U.S. studies were also analyzing the space debris problem, namely, those conducted by both the US National Research Council and the National Science and Technology Council. Both reports were released in 1995[144] and were influential in leading to the first iteration of a coherent national U.S. debris mitigation strategy[145] in 1997, the US Orbital Debris Mitigation Standard Practices (ODMSP).[146] The ODMSP contained four basic, but now standard, mitigation strategies: control debris released during normal operations, minimize accidental explosions, minimize opportunities for collisions, and dispose of payloads and launch vehicle components post-mission.[147]

Very soon after NASA developed its mitigation guidelines in 1995, the space agencies of other countries began to follow suit. In 1996, the National Space Agency of Japan (NASDA) promulgated its own mitigation standards,[148] which contained many of the same objectives as the NASA standard.[149] In 1999, France's Centre National d'Études Spatiales (CNES) published its own debris mitigation standards,[150] which later served as a model for a European-wide standard.[151]

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[143] *Ibid.* For a detailed overview of this original debris mitigation standard, see generally Robert Reynolds, et al, "An Overview of Revised NASA Safety Standard 1740.14," Proceedings of the Second European Conference on Space Debris, SP-393 (1996) at 721-726, online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc2/paper/6/SDC2-paper6.pdf>.

[144] National Research Council, "Orbital Debris: A Technical Assessment," (1995), online (pdf): *NASA* <https://www.orbitaldebris.jsc.nasa.gov/library/a-technical-assessment.pdf>; US, National Science and Technology Council, "Interagency Report on Orbital Debris," (1995), online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20000011871.pdf>.

[145] Scott, *supra* note 138 at 724.

[146] US, "Orbital Debris Mitigation Standard Practices," (1997), online ((pdf): *NASA* <https://orbitaldebris.jsc.nasa.gov/library/usg_od_standard_practices.pdf>.

[147] *Ibid.*

[148] Japan, National Space Development Agency of Japan, "Space Debris Mitigation Standard," NASDA-STD-18 (28 March 1996).

[149] A. Kato, "Comparison of National Space Debris Mitigation Standards," (2001) 28:9 Advances in Space Research 1447 at 1448-1449.

[150] France, Centre National d'Études Spatiales, "CNES Standards Collection, Method, and Procedure Space Debris – Safety Requirements," RNC-CNES-Q40-512 (1999).

[151] Jinyuan Su, "Control Over Activities Harmful to the Environment," in Ram S. Jakhu & Paul Stephen Dempsey,

Only one year after that, Russia's Roscosmos also developed its own standards.[152] Similar criteria were later adopted in China, Canada, and a host of other countries.[153] To ensure compliance, most States incorporated these standards into national law or enforced their national guidelines through their licensing procedures.[154]

While each State was determining the appropriate level of debris mitigation standards to impose upon its nationals, international and intergovernmental bodies were hoping to standardize debris mitigation efforts across space-faring nations. As far back as 1994, the International Law Association (ILA) developed its Draft Convention on Space Debris,[155] with a major focus of addressing the debris problem in tandem with liability and responsibility concerns.[156] Despite substantive contributions to the development of mitigation standards, the ILA Convention failed to develop into a legally binding international instrument.[157]

The ESA, a major intergovernmental space body now comprised of 22 countries, was also looking to standardize mitigation efforts. It promulgated a draft European Space Debris Safety and Mitigation Standard as well as a Space Debris Handbook in 2000. Together, these two documents regulated the implementation concepts and technical recommendations for debris mitigation and collision risk reduction for all space projects developed or controlled by ESA.[158]

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eds, *Routledge Handbook of Space Law*, (Abingdon: Oxon: Routledge, 2017) at 78.

[152] Russia, Russian Aviation and Space Agency, "Space Technology Items. General Requirements. Mitigation of Space Debris," Standard OCT 134-1023 (2000).

[153] For a current list, see, generally, UNOOSA, "Compendium of Space Debris Mitigation Standards Adopted by States and International Organizations," (accessed 9 May 2019), online: *UNOOSA* <http://www.unoosa.org/oosa/en/ourwork/topics/space-debris/compendium.html>.

[154] Su, *supra* note 151 at 77.

[155] Karl-Heinz Böckstiegel, "ILA Draft Convention on Space Debris," (1994) 43 Zeitschrift für Luft- und Weltraumrecht 395.

[156] Lotta Viikari, "Environmental Aspects of Space Activities" in Frans von der Dunk & Fabio Tronchetti, eds, *Handbook of Space Law* (Cheltenham, UK: Edward Elgar Publishing, 2015) at 754.

[157] *Ibid.*

[158] Jan Wouters, et al, "Space Debris Remediation, Its Regulation and the Role of Europe," Working Paper No. 153 (March 2015) at 10, online (pdf): *Ku Leuven* <https://ghum.kuleuven.be/ggs/publications/working_papers/2015/153woutersdemanhansen>.

Thereafter, ESA and the major national space agencies of Europe concluded the European Code of Conduct for Space Debris Mitigation in 2004.[159] While widely subscribed to by European space-faring nations, the Code of Conduct has been criticized as imprecise and difficult to enforce, mainly due to its voluntary nature.[160] More recent European attempts to coordinate the responsible and sustainable use of space have been conducted through the EU's diplomatic effort since 2012 to develop a wide-ranging, but non-binding and voluntary, Draft International Code of Conduct for Space Activities.[161] Notably for space debris mitigation, any potential adherent to this draft code would "resolve" to "refrain" from the intentional destruction of space objects, presumably a notional agreement not to conduct ASAT tests.[162] However, the draft code's future is uncertain since many States have raised various objections during its negotiation, while some others have simply refused to participate.[163]

Another international forum for debris mitigation standards emerged through the International Organization for Standardization (ISO), which is an independent, non-governmental membership organization aimed at the voluntary streamlining of international standards for its more than 160 member states.[164] In 2010, the ISO's body of international industry experts developed Standard 24113, "Space Systems – Space Debris Mitigation Requirements." This effort differed from some of the loftier guidelines which proved difficult to implement; instead Standard

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[159] "*European Code of Conduct for Space Debris Mitigation,*" Issue 1.0 (28 June 2004), online (pdf): *UNOOSA* <http://www.unoosa.org/documents/pdf/spacelaw/sd/2004-B5-10.pdf>. The other major national space agencies were from Italy, Germany, France, and the UK.

[160] Wouters, et al, *supra* note 157 at 11; Viikari, *supra* note 156 at 751, footnote 171.

[161] "International Code of Conduct for Outer Space Activities," draft version (31 March 2014), online (pdf): *European External Action Service* <https://eeas.europa.eu/sites/eeas/files/space_code_conduct_draft_vers_31-march-2014_en.pdf>; Viikari, *supra* note 156 at 759-760.

[162] International Code of Conduct, *supra* note 161 at art 4(2).

[163] Viikari, *supra* note 156 at 760. See also, Jinyuan Su & Zhu Lixin, "The European Union Draft Code of Conduct for Outer Space Activities: An Appraisal," (2014) 30:1 Space Policy 34 at 35.

[164] Cordula Steinkogler, "Small Satellites and Space Debris Mitigation," in Irmgard Marboe, ed, *Small Satellites: Regulatory Challenge and Chances* (Leiden: Brill Nijhoff, 2016) at 225.

24113 helped to normalize the more technical aspects of debris mitigation in outer space, enabling the application of somewhat streamlined design principles.[165] Standard 24113 was updated in 2011 and has been adopted by both the ESA and the European Cooperation for Space Standardization (ECSS).[166]

The International Telecommunication Union (ITU) also provides some guidance when it comes to space debris mitigation, specifically in GEO. The ITU is a specialized UN agency responsible for the allocation of global radio spectrum and satellite orbits.[167] In 2010, it promulgated Recommendation ITU-R S.1003-2, "Environmental Protection of the Geostationary-Satellite Orbit," which provides operational guidance for satellites in GEO, with an eye towards protecting the GEO region and reducing space debris.[168] Specifically, it encourages space operators to minimize debris creation in GEO and GEO transfer orbits, as well as to boost their satellites into a graveyard orbit of not less than 200 kilometers above GEO at their end of life.[169] Like the other international efforts towards debris mitigation noted above, ITU-R S.1003-2 is only a recommendation and is not legally binding on member States.[170]

B. IADC Space Debris Mitigation Efforts

The focus on debris mitigation by the various nations, their national space agencies, and international and intergovernmental organizations discussed above eventually coalesced around the IADC in the early 2000s. The IADC itself was founded by NASA, ESA, Roscosmos, and

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[165] *Ibid* at 225; Viikari, *supra* note 156 at 756.

[166] ESA, "Space Debris Mitigation Policy for Agency Projects," ESA/ADMIN/IPOL(2014)2 (28 March 2014) at 1, online (pdf): *IADC* <https://www.iadc-online.org/References/Docu/admin-ipol-2014-002e.pdf>.

[167] Steinkogler, *supra* note 164 at 223.

[168] ITU, "Environmental Protection of the Geostationary-Satellite Orbit," Recommendation ITU-R S.1003-2 (12/2010) (2010), online (pdf): *UNOOSA* <http://www.unoosa.org/documents/pdf/spacelaw/sd/R-REC-S1003-2-201012-IPDF-E.pdf>.

[169] *Ibid* at 1.

[170] Steinkogler, *supra* note 164 at 224.

Japan in 1993[171] as an "international forum of governmental bodies for the coordination of activities related to the issues of man-made and natural debris in space."[172] Its primary purpose is to provide opportunities for cooperation and the exchange of information related to space debris research activities amongst its members, as well as to identify debris mitigation strategies.[173] It has since grown to include 13 member agencies, including most of the world's major national space agencies.[174] In 2002, the four founding members plus seven newer members, notably including China's National Space Administration (CNSA) as well as the national space agencies of India, France, Italy, Germany, and the UK, developed a comprehensive set of guidelines called the IADC Space Debris Mitigation Guidelines (hereinafter "IADC Guidelines"), which were agreed to by consensus.[175] These guidelines were updated in 2007 and have become remarkably successful, despite only being voluntary.[176] In fact, they have been described as the "basis against which the world community is measuring success" and a "standard for the responsible space operator."[177] As such, most States and intergovernmental space organizations, including the U.S., the UK, and ESA, maintain domestic standards which are compliant with the IADC Guidelines.[178]

The updated 2007 IADC Guidelines describe the existing practices which have been identified and evaluated by various States to aid in limiting the generation of debris in space.[179] They particularly focus on 1) limiting debris released during normal operations, 2) minimizing the

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[171] IADC, "Terms of Reference for the IADC," IADC-93-01, rev.11.4 (28 September 2016) at 3, online (pdf): *IADC* <https://www.iadc-online.org/index.cgi?item=torp_pdf>.

[172] IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at 3.

[173] *Ibid.*

[174] IADC Website, (accessed 11 May 2019), online: *IADC* <https://www.iadc-online.org/>.

[175] IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at 3; IADC, "Terms of Reference," *supra* note 171 at 3.

[176] Lyall & Larson, *supra* note 15 at 276.

[177] Steven A. Mirmina, "Reducing the Proliferation of Orbital Debris: Alternatives to a Legally Binding Instrument," (2005) 99:3 The American Journal of International Law 649 at 661.

[178] Viikari, *supra* note 156 at 751. For a more thorough description of compliance with the IADC and other guidelines by state, see COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 30-34.

[179] IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 1.

potential for on-orbit breakups, 3) post-mission disposal, and 4) preventing on-orbit collisions.[180] They are designed to apply to mission planning and the design and operation, including the launch, mission, and disposal, of all spacecraft and stages intended to be operated in Earth orbit.[181] Importantly, the IADC Guidelines were the first to define space debris as "all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional."[182] It establishes LEO and GEO ± 200 kilometers and ± 15 degrees inclination as "protected regions" of space, worthy of unique attention for debris mitigation efforts.[183] The IADC Guidelines also encourage the creation of a Space Debris Mitigation Plan for every project or program in order to manage the implementation of its mitigation measures.[184]

Regarding limiting debris during normal operations, the IADC Guidelines recommend designing spacecraft and orbital stages such that no debris is intentionally released during normal operations, or if necessary, that it is limited as much as possible.[185] Further, the Guidelines recommend conducting an assessment to ensure that the risk from any released debris to other spacecraft and the environment itself is "acceptably low."[186]

In order to minimize on-orbit breakups, the IADC Guidelines recommend depleting any stored, on-board energy sources, such as batteries, propellants, or flywheels.[187] It also states that "intentional destructions, which will generate long-lived orbital debris, should not be planned or conducted."[188]

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[180] *Ibid* at paras 1 & 5.
[181] *Ibid* at paras 2 & 3.5.
[182] *Ibid* at para 3.1.
[183] *Ibid* at 3.3.2.
[184] *Ibid* at para 4.
[185] *Ibid* at para 5.1.
[186] *Ibid.* The term "acceptably low" is left undefined.
[187] *Ibid* at para 5.2.1.
[188] *Ibid* at para 5.2(3). The term "long-lived" is left undefined.

The IADC Guidelines also recommend post-mission disposal of GEO spacecraft well above the highest edge of the protected region, at an altitude of not less than 235 additional kilometers.[189] For spacecraft or orbital stages terminating in orbits which pass through LEO, the IADC Guidelines recommend that, presuming they are not being directly de-orbited, the post-mission orbital lifetime should be kept under 25 years.[190] In other words, at their end-of-life, spacecraft should be physically lowered to at least an altitude which will allow for natural decay due to atmospheric drag and other space forces within a 25-year window.

Finally, the IADC Guidelines recommend designing spacecraft to limit the consequences of collision with small debris, usually accomplished via shielding, and to maneuver spacecraft or coordinate launch windows as necessary to avoid other collisions.[191]

Despite their wide acceptance as a common baseline for debris mitigation efforts, the IADC Guidelines have been criticized for failing to give technical or functional advice regarding their practical implementation.[192] However, this complaint is somewhat lessened by the IADC's issuance of a supplementary support document to the Guidelines which provides the purpose behind and specific practices for each recommendation.[193]

C. United Nations Space Debris Mitigation Efforts

At the same time that the IADC was working on its Guidelines, the UN was also studying the space debris problem, with an eye towards standardizing debris mitigation efforts globally. In 1999, the STSC of COPUOS released a comprehensive report which concluded that debris

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[189] *Ibid* at para 5.3.1.

[190] *Ibid* at para 5.3.2.

[191] *Ibid* at para 5.4.

[192] Viikari, *supra* note 156 at 751; Su, *supra* note 151 at 77.

[193] See, generally, IADC, "Support to the IADC Space Debris Mitigation Guidelines," IADC-04-06, Rev 5.5 (May 2014), online (pdf): *IADC* <https://www.iadc-online.org/Documents/IADC-04-06%20Support%20to%20IADC%20Guidelines%20rev5.5.pdf>.

mitigation efforts were "a prudent step towards preserving space for future generations."[194] Putting this conclusion into action, the STSC then sought to build upon the success of the IADC Guidelines by pushing for broader, global consensus for debris mitigation within the UN. This goal was eventually achieved in early 2007 in the form of the COPUOS Space Debris Mitigation Guidelines (hereinafter "COPUOS Guidelines).[195] The entire United Nations General Assembly (UNGA) later endorsed these voluntary guidelines and further invited U.N. member-States to implement them through their own national mechanisms.[196]

The COPUOS guidelines are greatly influenced by and are nearly identical to the IADC Guidelines, which preceded them by almost five years.[197] As such, the COPUOS Guidelines adopt the IADC definition of "space debris" and similarly discuss limiting debris from normal operations, the passivation of on-board potential energy or power sources, collision avoidance, preferred end-of-life orbits, and avoiding intentional destruction.[198]

While the two sets of Guidelines are very similar, there are several important discrepancies, primarily because the IADC Guidelines are more detailed in nature.[199] For example, the IADC Guidelines discuss a specific altitude and formula for GEO end-of-life "graveyard" movements, while the COPUOS Guidelines merely recommend non-interference with GEO after the termination of operations.[200] Similarly, in relation to post-mission orbits affecting LEO, the IADC

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[194] COPUOS, STSC, *Technical Report on Space Debris*, UN Doc A/AC.105/720 (1999) at 42.

[195] The COPUOS Guidelines were adopted by the STSC in 2007. See COPUOS, *Report of the Scientific and Technical Subcommittee on its forty-fourth session, held in Vienna from 12 to 23 February 2007*, UN Doc A/AC.105/890 (2007) at para 99 & Annex IV. They were thereafter endorsed by COPUOS. See UN Doc A/62/20, *supra* note 19 at para 118 & Annex. A stand-alone version of the COPUOS Guidelines is conveniently maintained by UNOOSA. See UNOOSA, "Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space," (2007), online (pdf): *UNOOSA* <http://www.unoosa.org/documents/pdf/spacelaw/sd/COPUOS-GuidelinesE.pdf>.

[196] See UNGA Res 62/217, *supra* note 20 at paras 26 & 27.

[197] Wouters, et al, *supra* note 158 at 7.

[198] See, generally, UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195.

[199] Viikari, *supra* note 156 at 750.

[200] UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195 at para 4(7).

Guidelines expressly endorse a 25-year maximum orbital lifetime, while the COPUOS Guidelines refrain from suggesting any specific maximum orbital lifetime.[201] Unlike the IADC Guidelines, the COPUOS Guidelines affirmatively declare that exceptions to them may be justified.[202] In that sense, they appear more technically than legally oriented, especially since COPUOS' Legal Subcommittee played no part in their development.[203] Such differences between the IADC and COPUOS Guidelines may be explained by the concessions necessary to gather consensus in the larger and more political UN setting.[204] However, despite any required concessions, endorsement by the UNGA means that the COPUOS Guidelines enjoy appreciably broad international support.

In the 12 years since the promulgation of the COPUOS Guidelines, no further updates have been made, despite the dramatic increases observed in space debris. Instead, the "Long-Term Sustainability of Space Activities" was added as a COPUOS agenda item in 2010, resulting in the creation of a working group in the STSC focusing, in part, on space debris as an aspect of space sustainability.[205] In 2018, this agenda item eventually resulted in COPUOS agreeing by consensus to a set of "Guidelines for the Long-Term Sustainability of Outer Space Activities."[206] However, these guidelines contain little in the way of debris mitigation, other than to suggest wider compliance with the 2007 COPUOS Guidelines.

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[201] *Ibid* at para 4(6).

[202] *Ibid* at para 3.

[203] Stephan Hobe & Jan Helge Mey, "UN Space Debris Mitigation Guidelines," in Frans G. von der Dunk, ed, *International Space Law* (Cheltenham, UK: Edward Elgar Publishing, 2018) at 631; COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 28.

[204] See, generally, Ram Jakhu, "The Effect of Globalisation on Space Law," in Stephan Hobe, *Globalisation – The State and International Law*, (Stuttgart: Franz Steiner Verlag, 2009) at 74; COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 29-30.

[205] Viikari, *supra* note 156 at 762.

[206] COPUOS, *Guidelines for the Long-Term Sustainability of Outer Space Activities*, UN Doc A/AC.105/208/ CRP.20 (2018).

D. Failure of Space Debris Mitigation Efforts/Need for Active Debris Removal

The drafting and widespread acceptance of the IADC and COPUOS Guidelines, as well as other national guidelines and technical standards, are significant first steps towards slowing the growth of space debris. They have especially aided in reducing debris creation in certain contexts, such as the release of mission-related debris.[207] However, these two primary international mitigation efforts have significant, inherent limitations, some of which lead to a lack of compliance by space operators. Ultimately, both have failed to halt the continued increase in debris, whether measured by mass or quantity. Leading experts and space agencies now agree that mitigation efforts alone are insufficient to tackle the debris problem going forward; active debris removal must be implemented in conjunction with mitigation efforts.

1. Limitations of the Guidelines

While the IADC and COPUOS guidelines are, no doubt, an integral part of the solution for tackling the current debris problem, it is also important to note several structural limitations contained within them which have severely hampered their efficacy.

The most obvious and notable limitation of these two leading international guidelines is that they are entirely voluntary and non-binding.[208] The IADC Guidelines simply "encourage" compliance, while the COPUOS Guidelines state outright that they are "not legally binding under international law."[209] Because of this, even States which adhere to the guidelines retain the freedom to abide by them or disregard them.[210] Further, the guidelines offer no direct incentives

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[207] ESA, "Annual Space Environment Report," *supra* note 24 at 47.

[208] UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195 at para 3; IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 2.

[209] *Ibid*.

[210] Estoppel complaints for State violations would be unlikely to succeed since the COPOUS Guidelines expressly recognize at paragraph 3 that "exceptions to the implementation of individual guidelines or the elements thereof may be justified…".

for compliance[211] and are only applicable to private or commercial entities to the extent that national legislation requires compliance and thereafter actually enforces the guidelines.[212] Many compare this soft law regime to a "tragedy of the commons," or a situation in which actors continue to detrimentally exploit the pool of resources out of fear that complying with restrictive regulations will put them at a disadvantage as compared to others.[213] One commentator summed up this shortcoming succinctly by stating that:

> "because guidelines are unenforceable by nature, orbital debris mitigation rests predominantly on the amount of goodwill that states are willing to extend in voluntarily restricting themselves and their national operators from creating debris. Here the major space powers in this debate will likely continue to privilege their freedom of action in their activities over submitting to binding restrictions from international organisations, to ensure the security of their assets in orbit."[214]

Another significant structural limitation of the IADC and COPUOS Guidelines is that they are, by the very nature of the space environment, prospective standards as opposed to retrospective fixes. They are designed to be forward-looking and are meant to be applied to future mission-planning and "newly designed" spacecraft and orbital stages.[215] In contrast, they are only designed to be applied to already existing spacecraft "if possible" or "to the greatest extent feasible," which

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[211] Scott, *supra* note 138 at 726.

[212] Su, *supra* note 151 at 77.

[213] COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 37. See also, Scott J. Shackelford, "Governing the Final Frontier: A Polycentric Approach to Managing Space Weaponization and Debris," (2014) 51 Am. Bus. L.J. 429 at 443.

[214] Cenan Al-Ekabi, "Reigniting Europe's Leadership in Debris Mitigation Efforts," (24 May 2018), online: *Open Access Government* <https://www.openaccessgovernment.org/reigniting-europes-leadership-in-debris-mitigation-efforts/46074/>.

[215] Hobe & Mey, *supra* note 203 at 629; UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195 at para 3; IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 2.

is often not at all.[216] Further, legacy orbiting satellites and rocket bodies designed, planned, and launched in the 1950s or 1960s are almost certainly unable to be redesigned, modified, passivated, or moved into a graveyard orbit today.[217] Instead, they are largely defunct and uncontrolled. As the ultimate example, neither the IADC nor COPUOS Guidelines can offer any feasible mitigation action to take with regard to the oldest currently orbiting satellite, the U.S. Vanguard 1, which was launched in 1958 but ceased transmitting in 1964.[218] Further, these guidelines do nothing to address the enormous amount of other forms of existing space debris, such as uncontrolled rocket bodies or small pieces of debris from fragmentation events. This is a very significant shortcoming of the guidelines since, as noted before, all forms of space debris together constitute roughly 90-95% of the catalogued objects in space.[219] The best these mitigation guidelines can offer are strategies to minimize the risks of creating more debris in the future, while essentially ignoring the debris problem as it currently exists.

Additionally, neither the IADC nor COPUOS Guidelines effectively deter the intentional destruction of on-orbit space objects through ASAT tests. Instead, they merely encourage States to avoid the intentional destruction of spacecraft and orbital stages if it will "generate long-lived orbital debris."[220] However, despite both guidelines using terms like "long-lived," "long-term presence," "over the longer term," "long term interference," etc, neither set of guidelines defines what duration is envisioned by use of the word "long." Presumably, since the IADC Guidelines set 25 years as an acceptable post-mission orbital lifetime for payloads in LEO (described therein

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[216] *Ibid*.

[217] Viikari, *supra* note 156 at 757.

[218] NASA, "Vanguard 1," (last updated 20 March 2019), online: *NASA* <https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1958-002B>.

[219] COPUOS, *Active Debris Removal, supra* note 20 at 17; See also Fig 4, *infra*, from NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 3.

[220] UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195 at para 4(4); IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 5.2(3).

as “reasonable and appropriate”),[221] it is reasonable to argue that anything less than a 25-year orbital lifetime should not be considered “long-term.” If that is the case, then ASAT tests which generate, for example, 20-year debris fields could arguably be justified as entirely consistent with the IADC Guidelines. Further, rather than any sort of blanket restriction on ASAT tests, both guidelines seem to normalize the international acceptance of such tests by stating that, “when necessary,” they “should be conducted at sufficiently low altitudes such that orbital fragments are short-lived.”[222] Similar to their treatment of the phrase “long-term,” neither guideline elaborates on exactly what “necessary,” “sufficiently low,” or “short-lived” means. Given the ASAT tests discussed in Part I(D)(1) and (3), *supra*, the IADC and COPUOS Guidelines have clearly not deterred States from conducting ASAT tests which create “long-term” debris by any standard.

Additionally, the IADC and COPUOS Guidelines fail to consider or provide any sort of tailored guidance for wartime or national security related activities.[223] While peacetime military activities in space are beginning to comprise a smaller percentage of all space operations, they are still significant,[224] especially since conventional, direct-ascent ASAT weaponry does not exist in the commercial sector. Wartime military operations, without the restraint imposed by focused guidelines, could be devastating to the orbital environment. Further, national security-related activities in space are largely carried out by government actors, which are subject to internal policy guidelines rather than the traditional licensing mechanisms most often used to implement the IADC and COPUOS Guidelines.[225] As such, these government activities in space are likely to favor national security and freedom of operation over strict adherence to mitigation guidelines.[226]

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[221] IADC, “Space Debris Mitigation Guidelines,” *supra* note 20 at para 5.3.2.
[222] *Ibid* at para 5.2.3; UNOOSA, “Space Debris Mitigation Guidelines,” *supra* note 195 at para 4(4).
[223] Su, *supra* note 151 at 77.
[224] See Figure 1, *infra*, from ESA, “Space Environment Statistics,” *supra* note 1.
[225] COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 30.
[226] Al-Ekabi, *supra* note 214.

Finally, while the IADC and COPUOS Guidelines discuss de-orbiting and re-orbiting measures for protecting the LEO and GEO regions, there is no discussion of end-of-life mitigation measures related to MEO at all. In order to preserve all Earth orbits, end-of-life issues related to the numerous GNSS constellations should also be included in these guidelines.[227]

2. Problems with Compliance

In addition to the structural limitations discussed above, there are also notable problems with IADC and COPUOS Guideline compliance. This is true despite the fact that these documents were derived through consensus in both the IADC and the UN, encompassing all of the leading space-faring States,[228] and that they have been widely implemented into national licensing mechanisms. Nevertheless, while certain aspects of the Guidelines enjoy broad uniformity, such as spacecraft design or passivation measures, compliance remains an acute problem when it comes to end-of-life operations or the intentional creation of debris.

In the protected LEO region, for example, compliance with the IADC's 25-year de-orbit guideline is mediocre at best. In 2017, the most recent year for ESA-compiled payload compliance data for LEO, only approximately 55% of payloads in LEO at their end of life were compliant with the 25-year rule.[229] Over 40% of all payloads in this region made no attempt whatsoever to clear LEO at their end of life,[230] comprising almost 60% of total end-of-life payload mass.[231] In one

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[227] *Ibid* at 35. For a discussion of MEO end-of-life strategies, see, generally, Raul Dominguez-Gonzalez, et al, "Long-Term Implications of GNSS Disposal Strategies for the Space Debris Environment," Proceedings of the Seventh European Conference on Space Debris, SDC-7 (2017), online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/758/SDC7-paper758.pdf>.

[228] The IADC Guidelines alone were drafted and agreed to by ESA and the space agencies of China, Japan, Russia, France, Germany, Italy, India, the US, and the UK. These countries, along with those represented by ESA, together account for an overwhelming majority of today's space activity. See Kelso, "SATCAT Boxscore," *supra* note 2.

[229] ESA, "Annual Space Environment Report," *supra* note 24 at 60. Note, however, that in compiling this data, ESA considers LEO re-orbits to altitudes above the protected region to be compliant with the IADC Guidelines, despite expressly stating at 56-57 that it is "against the spirit of those measures to leave space debris in orbit."

[230] *Ibid* at 63.

[231] *Ibid* at 64.

study, observing LEO end-of-life de-orbiting of payloads between 2000 and 2013, it was observed that only approximately half of all spacecraft even possessed orbit control capability.[232] Of those, just 27% performed end-of-life maneuvers, representing a mere 12% of the total spacecraft population in LEO.[233] Between 2000 and 2013, compliance with the 25-year de-orbit rule in LEO for payloads averaged 59%,[234] but has dipped as low as 20% in a single year, as it did as recently as 2008.[235] If naturally decaying payloads are excluded from this equation, fewer than 20% were successfully cleared from LEO at their end-of-life in 2017, while almost 80% never even made an attempt to clear it.[236] When it comes to the mass of these same satellites, the true scope of non-compliance is revealed. In 2016, one of the worst years on record since 1990, less than 30% of the total mass of all end-of-life LEO payloads complied with the 25-year rule.[237] Rocket bodies, as opposed to payloads, fare slightly better in LEO recently, with nearly 80% complying with the 25-year IADC rule in 2018.[238] However, compliance rates for rocket bodies in LEO between 2000 and 2013 are estimated at 60% overall, virtually the same as payloads.[239] This figure should increase in the future as the controlled re-entry of rocket bodies after launch is beginning to increase.[240] To painfully sum up LEO compliance with the guidelines, the IADC's Chairperson briefed the STSC of COPUOS in 2018 to the effect that "the current implementation level is considered insufficient and no apparent trend towards a better implementation is observed."[241]

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[232] Vincent Morand, et al, "Mitigation Rules Compliance in Low Earth Orbit," (2014) 1:2 Journal of Space Safety Engineering 84 at 89.

[233] *Ibid*.

[234] *Ibid* at 91.

[235] ESA, "Annual Space Environment Report," *supra* note 24 at 63.

[236] *Ibid* at 65.

[237] *Ibid* at 64.

[238] *Ibid* at 63.

[239] Morand, *supra* note 232 at 91.

[240] ESA, "Annual Space Environment Report," *supra* note 24 at 77.

[241] Mitsuru Ohnishi, "Review of IADC's Annual Activities," (2018) at 13, online (pdf): *IADC* <https://www.iadc-online.org/Documents/IADC-18-2%20IADC%20Presentation%20to%20the%2055th%20UN%20COPUOS%20STSC%20(2018).pdf>.

In GEO, the situation is slightly better. In 2018, more than 85% of the 16 disposed GEO satellites cleared the protected region.[242] This accounted for nearly 90% of the combined mass of the disposed satellites for 2018.[243] While this sounds promising, the compliance data can vary significantly depending on the year. In 2008, only seven of the 12 retired satellites were re-orbited properly,[244] and in 2015, a full 13 years after the IADC Guidelines were originally drafted, only five of 12 satellites in GEO were properly disposed of at their end-of-life.[245] Despite these low-performing periods, the IADC stated in 2018 that it has observed "a trend towards satisfactory levels" of GEO re-orbiting compliance in recent years.[246]

When it comes to the intentional creation of debris, States have occasionally radically departed from the two major guidelines, resulting in disastrous consequences. The most flagrant example of noncompliance, which resulted in the worst fragmentation event in history, was that of China's intentional destruction of Fengyun-1C in 2007, discussed *supra*. Interestingly, prior to this event China had been seemingly engaged in debris mitigation efforts on both the domestic and international fronts: it was a founding member of the IADC; actively participated in the drafting of the 2002 IADC Guidelines; released its own domestic Working Plan for Space Debris in 2003 and Requirements for Space Debris Mitigation in 2005; and signed the updated 2007 IADC Guidelines.[247] Yet, China still broke with the IADC Guidelines to intentionally destroy its satellite at an altitude that was certain to create a significant and long-lasting debris field, violating the spirit of the mitigation guidelines. China is not alone in this regard. The United States destroyed a satellite with a direct-ascent ASAT as recently as 2008, as did India in 2019. While these tests

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[242] ESA, "Annual Space Environment Report," *supra* note 24 at 74.

[243] *Ibid*.

[244] COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 35.

[245] ESA, "Annual Space Environment Report," *supra* note 24 at 74.

[246] Ohnishi, *supra* note 241 at 13.

[247] Rong Du, "China's Approach to Space Sustainability: Legal and Policy Analysis," (2017) 42 Space Policy 8 at 9-10.

varied from China's 2007 test in both altitude and the resultant debris field,[248] all have arguably softened both the IADC and COPUOS Guidelines' provisions that such intentional fragmentations "should be avoided" unless "necessary," and even then, only at "sufficiently low altitudes."[249] It is clear that national security concerns can lead to noncompliance with the IADC and COPUOS Guidelines. However, even if only an infrequent event, just a single act of noncompliance with the intentional destruction provisions has the capacity to cause significant, long-term implications for the space debris problem.

3. Failure to Reduce Debris

More telling than the structural limitations or compliance problems with the Guidelines is the clear failure of focused mitigation efforts since 2002 to halt the growth of debris. In essence, the more than 15-year trend in space debris growth after the implementation of these Guidelines speaks for itself.

From 2002 through 2018, the total catalogued mass of space objects has increased from roughly 4,750 to about 7,700 metric tons.[250] The quantity has experienced similar growth, from approximately 11,500 catalogued objects to almost 19,000.[251] Importantly, only about 2,250 of these catalogued objects are actually functioning satellites; the rest are considered space debris.[252] Mitigation efforts have not only failed to reduce the total amount and mass of space debris, they have failed to appreciably slow its growth rate. While there had been a slight trend of reduction in specifically fragmentation debris between 2011 and 2016, any derived benefit was erased many

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[248] See Part I, Section D(1) and D(3), *supra*; See, also, Scott, *supra* note 138 at 730-734.
[249] UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195 at para 4(4); IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 5.2.3.
[250] See Figure 3*, infra*, from NASA, "Orbital Debris Quarterly News," *supra* note 7 at 11.
[251] See Figure 2*, infra*, from *ibid* at 10.
[252] Kelso, "SATCAT Boxscore," *supra* note 2.

times over by both intentional and accidental fragmentation events.[253] As has been stated, "years of successful mitigation can be negated by a single large event."[254]

This growth trend in debris is expected to continue into the future in LEO even if mitigation guidelines related to end-of life disposal are complied with at a rate of 90%.[255] It will similarly continue to grow even assuming no future explosive fragmentation events occurred at all[256] or even if all new space launches were ceased entirely.[257] These are arguably unrealistic expectations given recent data. It is clear that mitigation alone does not offer a viable solution to the space debris problem.[258] Instead, research has shown that mitigation efforts must be combined with active debris removal in order to stabilize the growth of debris in LEO.[259]

4. Consensus of Space Experts and Agencies

While the data above is clear, it is also worth briefly noting the voices of major space experts and agencies on this issue. The majority of these experts and agencies are in clear agreement that mitigation efforts alone have proven themselves insufficient and that ADR must be actively pursued.

As far back as 2006, Jer Chyi Liou, NASA's current Chief Scientist for Orbital Debris, argued using statistical modelling that LEO's debris population was unstable and that growth

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[253] See Figure 2*, infra*, from NASA, "Orbital Debris Quarterly News," *supra* note 7 at 10.

[254] COPUOS, *Towards Long-Term Sustainability, supra* note 51 at 29.

[255] B. Bastida Virgili & H. Krag, "Analyzing the Criteria for a Stable Environment," Conference Paper, AAS/AIAA Astrodynamics Specialist Conference, AAS 11-411 (2011) at 1, online (pdf): *ResearchGate* <https://www.researchgate.net/publication/266556917_Analyzing_the_criteria_for_a_stable_environment>.

[256] J.-C. Liou, et al, "Controlling the Growth of Future LEO Debris Populations with Active Debris Removal," (2010) 66:5-6 Acta Astronautica 648 at 650.

[257] J.-C. Liou & N.L. Johnson, "Risks in Space From Orbiting Debris," (2006) 311 Science 340.

[258] Virgili & Krag, *supra* note 255 at 12.

[259] Joseph N. Pelton, "Possible Institutional and Financial Arrangements for Active Removal of Orbital Debris," in Joseph N. Pelton & Firooz Allahdadi, eds, *Handbook of Cosmic Hazards and Planetary Defense* (Cham: Springer, 2015) at 854-855. For a comparison of the growth of objects greater than 10 centimeters in LEO at current launch rates with 90% post-mission disposal alone vs. combined with ADR of either 2 or 5 objects per year, beginning in 2020, see Figure 10, *infra*, from J.-C. Liou, "NASA Orbital Debris Program Office Overview," (March 2019) at 21, online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190001584.pdf>.

would continue even with widespread implementation of mitigation measures.[260] He and his co-author concluded that ADR is the *only* solution.[261] Thereafter, the IADC pegged this issue as an official action item and similarly concluded in 2013 that, even assuming 90% compliance with commonly adopted mitigation measures, the LEO debris population will continue to grow.[262] Notably, the statistical modeling programs of the national space agencies of Italy, India, Japan, the U.S. and the UK, as well as ESA, all unanimously supported this conclusion.[263] Such research ultimately led the U.S. to formally declare that its ODMSP has been rendered "inadequate to control the growth of orbital debris."[264]

By 2017, the ESA-sponsored 7th European Conference on Space Debris, comprising hundreds of space industry, academic, and policy experts, also concluded that the existing space debris mitigation rules are insufficient.[265] Unsurprisingly, Holger Krag, the current head of ESA's Space Debris Office at the European Space Operations Center, which represents the interests of 22 member countries, also shares that opinion. He has long concluded that even strict implementation of the current mitigation measures will not stop future debris growth and that "the only possible way to achieve stability while continuing space activities is to perform ADR."[266]

E. Conclusion

After taking note of the growing threat of space debris in the 1980s, NASA and other national space agencies began to consider ways of mitigating the creation of new debris. Eventually major international efforts took place to develop comprehensive voluntary guidelines to rein in new

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[260] *Ibid*; Liou & Johnson, *supra* note 257 at 340.
[261] *Ibid*.
[262] IADC, "Stability of the Future LEO Environment," *supra* note 67 at 17.
[263] *Ibid*. These space agencies included ASI, ESA, ISRO, JAXA, NASA, and UKSA.
[264] US, Space Policy Directive-3, "National Space Traffic Management Policy," (18 June 2018) at para 5(a)(3).
[265] Lyall & Larson, *supra* note 15 at 280.
[266] Virgili & Krag, *supra* note 255 at 12.

debris creation. The first of these was promulgated by the IADC in 2002 and was later modified and adopted by COPUOS and the UNGA in 2007, eventually gaining widespread international support. Other agencies, like the ITU and the ISO, also contributed to the standardization of debris mitigation efforts. However, these mitigation efforts have failed to control the space debris problem, both due to various structural limitations within the guidelines themselves and due to a failure of space-faring nations and their citizens to faithfully implement them. Even the IADC itself bemoans the collective rate of compliance. Ultimately, the space debris population has continued to see significant increases, most notably in LEO. Space agencies and experts around the world are now in virtual unanimous agreement that mitigation efforts alone are insufficient and that ADR is absolutely necessary to stabilize vital Earth orbits.

Part III. Active Debris Removal and Its Current Challenges

In the face of the previously described debris problem and the failure of the various mitigation efforts made by the majority of space-faring nations to bring it under effective control, active debris removal has now become a necessity. However, there are significant challenges complicating the successful implementation of ADR. Part III briefly overviews several of the most promising ADR technologies, whether based in space or conducted from the surface of the Earth. Thereafter, it analyzes the most pressing legal and policy challenges complicating the successful implementation of ADR.

A. Description of Active Debris Removal Technologies

Currently, while there are not yet fully operational ADR technologies,[267] there are a plethora of proposed methods to remove space debris from Earth orbit.[268] Only a few have even been physically tested *in situ*, so much ADR technology remains conceptual and none is sufficiently advanced to currently begin widespread operations.[269] Even so, the wide spectrum of possible ADR methods reveals great promise, and many ADR projects are currently under way or are being planned for the near future.[270]

1. Contactless Active Debris Removal

Practical methods exist for actively removing pieces of space debris without the need for ever physically contacting the object. These methods seek to lower the orbital altitude of the debris by reducing its velocity,[271] thus exposing the debris to the cleansing effects of the lower LEO atmosphere. Such methods are desirable because they remove the risk of a collision between an ADR object and its space debris target.[272] However, they are slow to adjust their target's altitude[273] and are therefore generally best suited for small LEO debris.[274] Examples include focusing lasers beams on the debris, or dispersing gas plumes, mists, or aerogels in space to artificially influence

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[267] Peter Stubbe, *State Accountability for Space Debris: A Legal Study of Responsibility for Polluting the Space Environment and Liability for Damage Caused by Space Debris* (Leiden: Brill Nijhoff, 2018) at 58-59.

[268] See, generally, C. Priyant Mark & Surekha Kamath, "Review of Active Debris Removal Methods," (2019) 47 Space Policy 194.

[269] *Ibid* at 204.

[270] See, for example, Pelton, *supra* note 98 at 11-26.

[271] Minghe Shan, et al, "Review and Comparison of Active Space Debris Capturing and Removal Methods," (2016) 80 Progress in Aerospace Sciences 18 at 28.

[272] Akihiro Sasoh, et al, "Characteristics of Ablation Impulse Induced by Repetitive Laser Impulse Radiations," Proceedings of the Seventh European Conference on Space Debris, SP-672 (2017) at 2, online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/298/SDC7-paper298.pdf>.

[273] Shan, et al, *supra* note 271 at 28.

[274] Brian Weeden, "Overview of the Legal and Policy Challenges of Orbital Debris Removal," (2011) 27:1 Space Policy 38 at 39.

the atmosphere immediately surrounding the debris and therefore alter its velocity and altitude.[275] Additionally, ion-beam shepherds can be used to focus a plasma stream at a piece of debris to impart a propulsive force.[276]

The most promising contactless ADR method uses directed-energy beams, or lasers, to affect the orbital altitude of primarily smaller pieces of debris in LEO.[277] This can be accomplished in several ways and via ground or space-based lasers.[278] Low-intensity lasers can be used to affect the debris' velocity in the form of focused light pressure, much like the solar radiation already affecting space debris.[279] Higher intensity lasers, whether continuous or pulsating, can be focused on overhead debris to ablate the material, creating tiny, high-velocity ejections of plasma roughly perpendicular to the surface of the object, the thrust of which can be used to affect the debris' velocity and altitude.[280] However, significant technological hurdles remain. For example, calculating the exact orbital parameters of small debris fragments and then intersecting that debris with sustained and effective laser intensity requires highly precise tracking information and is, even then, complex and inexact.[281] Ultimately, incredibly difficult problems of laser intensity,

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[275] Claude R. Phipps, et al, "Removing Orbital Debris With Lasers," (2011) at 3, online (pdf): *arXiv.org* <https://arxiv.org/ftp/arxiv/papers/1110/1110.3835.pdf>; Shan, et al, *supra* note 271 at 28.

[276] Mark & Kamath, *supra* note 268 at 197.

[277] Quan Wen, "Removing Small Scale Space Debris by Using a Hybrid Ground and Space Based Laser System," (2017) 141 Optik 105 at 105.

[278] Pelton, *supra* note 98 at 55.

[279] Claude R. Phipps, "A Laser-Optical System to Re-Enter or Lower Low Earth Orbit Space Debris," (2014) 93 Acta Astronautica 418 at 419.

[280] *Ibid*; Claude R. Phipps & Christophe Bonnal, "A Spaceborne, Pulsed UV Laser System for Re-Entering or Nudging LEO Debris, and re-orbiting GEO Debris," (2016) 118 Acta Astronautica 224 at 227; Sasoh, et al, *supra* note 272 at 2.

[281] See, generally, Michael Mercurio, et al, "Debris-Laser Beam Probability of Intersection in the Presence of Uncertainty," Proceedings of the Seventh European Conference on Space Debris, SDC-7 (2017), online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/174/SDC7-paper174.pdf>; J.-C. Liou, "Active Debris Removal and the Challenges for Environment Remediation," (17 June 2012) at 4, online (pdf): *NASA* <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120013266.pdf>.

pulse duration, tracking, and space situational awareness (SSA) must be overcome before widespread implementation is feasible.[282]

2. Capture and De-orbit/Re-orbit

While contactless ADR methods hold potential promise, the primary approach currently under development is the physical capturing and de-orbiting or re-orbiting of the target piece of space debris.[283] Once the ADR object makes physical contact with the space debris, the two objects become linked, for example via a tether or grappler, and the ADR object can then use its internal propulsion system to 'tug' the composite system to a new higher or lower orbit or even de-orbit it entirely.[284] Many different methods have been proposed to accomplish such a capture: nets, grappler tentacles, robotic arms, or even harpoons.[285] Some of these methods have already undergone space-based, proof-of-concept testing. For example, RemoveDEBRIS, a UK-led and EU funded project, successfully harpooned a sample of a typical satellite panel affixed to an extended boom in 2019.[286]

In comparison to the contactless methods described previously, the physical capture of space debris comes with additional challenges. Since it necessarily requires the launching of an ADR object into space to make contact with the debris, there is significant expense involved.[287] This expense is compounded by the fact that most capture ADR methods are only designed to

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[282] Pelton, *supra* note 98 at 41-42; See, generally, *ibid*.
[283] Pelton, *supra* note 98 at 57-58.
[284] R. Benvenuto, et al, "Tethered-Tugs for Active Debris Removal: Microgravity Experimental Validation of Dynamics and Control," Proceedings of the Seventh European Conference on Space Debris, SDC-7 (2017) at 1, online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/725/SDC7-paper725.pdf>.
[285] See, generally, Shan, et al, *supra* note 271 at 19-25; Pelton, *supra* note 98 at 20; Umberto Battista, et al, "Design of Net Ejector for Space Debris Capturing," Proceedings of the Seventh European Conference on Space Debris, SDC-7 (2017), online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/279/SDC7-paper279.pdf>.
[286] *Ibid*.
[287] Pelton, *supra* note 98 at 58.

remove a single piece of debris.[288] In addition, physical capture ADR methods must overcome the difficult reality that it is common for space debris, especially large pieces, to be tumbling on an axis rather than orbiting smoothly.[289] Further, the debris object may have an unknown mass or center of mass or lack any fixture for easy grappling.[290] Physically linking up with tumbling or otherwise unstable debris with unknown orbital characteristics can be dangerous since it may result in unknown rotational forces after capture, ultimately increasing the risks of fragmentation and the creation of even more debris.[291] Ultimately, "rendezvous and interaction with an uncooperative and unprepared object has never been performed before."[292]

However, such methods also have some advantages. Unlike some contactless ADR methods, they are theoretically feasible for both large and small objects in all orbits, from LEO to GEO, assuming enough fuel is available.[293] Further, to alleviate the financial costs involved, some ADR capture and de-orbit devices have been proposed as a group of vehicles to clean up multiple pieces of space debris at the same time. For example, NASA has patented designs for capture-method ADR devices which can be augmented to contain up to eight individual de-orbiters within a single payload.[294]

3. Attachment of Active or Passive De-Orbit Aids

Distinct from physically capturing debris and re-orbiting or de-orbiting it through moving a composite system, others have proposed methods of ADR designed to approach into close

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[288] *Ibid*.

[289] Shin-Ichiro Nishida, et al, "Space Debris Removal System Using a Small Satellite," (2009) 65 Acta Astronautica 95 at 95-96.

[290] Shan, et al, *supra* note 271 at 29; Nishida, et al, *supra* note 289 at 101.

[291] Aleksander A. Lidtke, et al, "Considering the Collision Probability of Active Debris Removal Missions," (2017) 131 Acta Astronautica 10 at 10; Nishida, et al, *supra* note 289 at 95-96, 101.

[292] Lidtke, et al, *supra* note 291 at 10.

[293] Pelton, *supra* note 98 at 65.

[294] Patent No US 0,555,905 B2, *supra* note 17 at 8-10 & 31.

proximity with or make physical contact with the target debris, but thereafter attach either an active or passive aid to hasten reentry. Most often, this attached de-orbit aid aims to interact with the limited atmosphere in LEO, thereby increasing its drag effect, or to make use of solar radiation or the Earth's geomagnetic field to affect the orbit of the targeted debris.[295] For example, some have proposed affixing long tethers to increase drag, whether by physical momentum exchange or through electro-dynamic forces.[296] Others have suggested using propelled nets to ensnare satellites and thereby increase atmospheric drag, as was done by the RemoveDEBRIS mission in 2018, utilizing a mock satellite it released itself.[297] Still others have proposed solar or drag sails to slow and de-orbit debris.[298] In fact, the final on-orbit test for the RemoveDEBRIS project before reentry will be to employ such a drag sail to observe its effects on a reentering spacecraft.[299] Similar tests have already been successfully conducted in LEO, such as was done by the InflateSail project in 2017 with a much smaller CubeSat.[300] Other ideas include attaching inflatable balloons or even spraying the target debris with expanding aerogels, foams, sticky balls, or even freezing mists to increase surface area,[301] since the effect of atmospheric drag on debris is compounded if its area-to-mass ratio increases.[302]

One of the most unique and ambitious ADR methods involving a de-orbit aid is designed to employ nets to remove multiple pieces of LEO debris by increasing atmospheric drag or towing

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[295] Nishida, et al, *supra* note 289 at 96; Shan, et al, *supra* note 271 at 26-27.

[296] NASA, "Orbital Debris Management," *supra* note 6 at 29; Shan, et al, *supra* note 271 at 26-27; See, generally, Nishida, et al, *supra* note 289.

[297] For a full overview of this project and its progress, see G.S. Aglietti, et al, "RemoveDEBRIS Mission: 2nd Briefing to UN COPUOS," Scientific and Technical Subcommittee (February 2019), online (pdf): *UNOOSA* <http://www.unoosa.org/documents/pdf/copuos/stsc/2019/tech-32E.pdf>.

[298] Shan, et al, *supra* note 271 at 27; Aglietti, *supra* note 297 at 10.

[299] Aglietti, *supra* note 297 at 10.

[300] See, generally, Craig Underwood, et al, "The InflateSail CubeSat Mission – The First European Demonstration of Drag-Sail De-Orbiting," 4th IAA Conference on University Satellite Missions and CubeSat Workshop, IAA-AAS-CU-17-04-05 (December 2017), online (pdf): *University of Surrey* <http://epubs.surrey.ac.uk/849323/1/The%20 inflatesail%20cubesat%20mission.pdf>.

[301] Pelton, *supra* note 98 at 59; Shan, et al, *supra* note 271 at 26;

[302] Shan, et al, *supra* note 271 at 26.

the objects to a lower orbit.[303] Designed by Star-Tech Inc., the device is called an Electro-Dynamic Debris Eliminator (EDDE) and would use a low mass (~20-80 kilograms) but very long (multiple kilometers) electro-dynamic aluminum tape that contains net stations at either end.[304] Each net station could contain up to 100 house-sized nets, with each individual net weighing roughly 50 grams.[305] This system would be able to generate its own electricity for operation by using the Earth's magnetic field, as well as from solar arrays spaced throughout the tape.[306] It would then be steered around LEO, netting and deorbiting debris until it ran out of nets. It is estimated by its developers that a single EDDE could remove approximately 135 pieces of debris in a three-year period and that 12 EDDEs could be deployed to remove up to 2,500 pieces of debris in about seven years' time.[307]

These various methods still face challenges similar to the more standard 'capture' ADR methods. Specifically, they can still be quite complex and dangerous operations if the target piece of space debris is tumbling, has an unknown center mass, or lacks a stable fixture point.[308] Some fare better than others in this regard, since shooting foam or a drag net at debris from a stand-off distance is obviously less risky than capturing and physically affixing a momentum exchange tether to it. Further, these methods are mostly appropriate and effective only for smaller debris in LEO.[309] Regardless, since the ADR object will not be using its on-board propulsion to move the composite system, this method faces another serious challenge in that the re-orbiting piece of

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[303] Pelton, *supra* note 98 at 59; See, generally, Jerome Pearson, et al, "EDDE Spacecraft Development for Active LEO Debris Removal," 65th International Astronautical Congress, IAC-14, A6, 6.4x23806 (2014), online (pdf): *Star-Tech, Inc.* <http://www.star-tech-inc.com/papers/EDDE_Debris_Paper_IAC14A664x23806_2014Sept28.pdf>.
[304] Pearson, et al, *supra* note 303 at 2-3.
[305] *Ibid* at 7.
[306] *Ibid* at 2.
[307] Pelton, *supra* note 98 at 24.
[308] Weeden, *supra* note 274 at 39-40.
[309] Pelton, *supra* note 98 at 55.

debris will reenter the atmosphere in an uncontrolled fashion, possibly posing a danger to people or objects in flight or on the surface of the Earth.[310]

B. Legal Challenges Complicating Active Debris Removal

While many of the ADR technologies described above are theoretical, some are at or very nearly deployment-ready. However, the legal landscape in space is far from clear when it comes to ADR. In fact, several significant legal challenges complicate ADR and must be addressed by the international community prior to large scale ADR efforts being undertaken.

1. Definition of Space Debris

The first significant legal challenge inhibiting ADR is a threshold one: the lack of an international, legally binding definition of space debris.[311] As some have noted, "it may be easier to identify what is not space debris than to obtain agreement as to what it is."[312] In order to discuss the concept of space debris thus far, this thesis has employed the general IADC/COPUOS Guideline definition for simplicity, namely, all "man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional."[313] This definition was, notably, endorsed by the UNGA in 2007.[314] As such, it has been described as the first broadly international definition for space debris.[315] However, this definition is limited to the context of the IADC and COPUOS Guidelines themselves, meaning that it has no binding legal applicability in relation to any international space law treaties or declarations.[316] This is

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[310] COPUOS, *Active Debris Removal, supra* note 20 at 26.

[311] Joshua Tallis, "Remediating Space Debris," (2015) 9:1 Strategic Studies Quarterly 86 at 89.

[312] C. Q. Christol, "Suggestions for Legal Measures and Instruments for Dealing with Debris," in Karl-Heinz Böckstiegel, ed, *Environmental Aspects of Activities in Outer Space* (Köln: Carl Heymanns Verlag, 1990) at 257.

[313] UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195 at para 1; IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 3.1.

[314] UNGA Res 62/217, *supra* note 20 at paras 26 & 27.

[315] Hobe & Mey, *supra* note 203 at 628.

[316] *Ibid*.

problematic because none of the major UN space treaties or Declarations ever even mentions the terms 'space debris' at all,[317] despite the clear OST requirements in Article IX to explore and use space, including the Moon and other celestial bodies, with "due regard" while avoiding its "harmful contamination."[318] Neither is there any coordinating body or regulatory agency to aid in their interpretation, as they were adopted across many years and by different sets of state parties.[319] The Liability and Registration Conventions speak only of "space objects," without ever distinguishing between functional and nonfunctional or useful and non-useful space objects.[320] They merely note that the term 'space object' "includes component parts of a space object as well as its launch vehicle and parts thereof.[321] Importantly, they are also silent when it comes to fragments of space objects.[322] Some consider this definition to be poorly crafted and vague, in that it is so broad as to extend to any "tangible human or even robotic-crafted matter or instrumentality in outer space."[323] If such an all-encompassing definition somehow excluded space debris, it would result in the perplexing conclusion that space debris is not governed by the current international space law regime at all, to include rules relating to international responsibility and liability for space objects.[324] Therefore, space debris should rightly be considered a subset of space objects under current international space law.[325]

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[317] Joyeeta Chatterjee, et al, "Active Orbital Debris Removal and the Sustainability of Space," in Joseph N. Pelton & Firooz Allahdadi, eds, *Handbook of Cosmic Hazards and Planetary Defense* (Cham: Springer, 2015) at 935.

[318] OST, *supra* note 10 at art IX.

[319] Ram S. Jakhu & Yaw O. M. Nyampong, "Some Legal and Regulatory Constraints on the Conduct of Removal and On-Orbit Satellite Servicing," 63rd International Astronautical Congress, IAC-12, A6, 6, 6, x13110 (2012) at 8; Pelton, *supra* note 98 at 6.

[320] Steinkogler, *supra* note 164 at 213; Bin Cheng, *Studies in International Space Law*, (Oxford: Clarendon Press, 1997) at 506.

[321] Liability Convention, *supra* note 11 at art I(d); Registration Convention, *supra* note 13 at art I(b).

[322] Christol, *supra* note 312 at 259.

[323] Chatterjee, et al, *supra* note 317 at 935.

[324] Stephen Gorove, *Developments in Space Law: Issues and Policies* (Dordrecht: M. Nijhoff, 1991) at 165; Frigoli, *supra* note 119 at 54-55.

[325] Cheng, *supra* note 320 at 506; Jakhu & Nyampong, *supra* note 319 at 7; Steinkogler, *supra* note 164 at 213-214. But see Zhuang Tian, "Proposal for an International Agreement on Active Debris Removal," in Annette Froehlich,

The reason that a commonly agreed to and legally binding definition is so important is because it is not altogether clear what the term 'non-functional' necessarily means, or how being non-functional appreciably alters the legal characterization of a 'space object.' Specifically, core international space law concepts, like those concerning liability or jurisdiction and control, do not turn on a space object's functionality.[326] Since 'space objects' include components parts thereof, even if a space object is fragmented into pieces, those fragments are likely still space objects.[327] If these fundamental and well-settled principles of international space law are unaffected by a space object losing its functionality, it is hard to grasp what legal effect, if any, the COPUOS space debris definition intends to impart. In other words, if a non-functional payload remains a space object and therefore subject to the core legal principles of the international space law regime, what useful distinction is gained by declaring it to be 'space debris?'

Further, because of the lack of a *de jure* space debris definition, it is unclear what criteria should be applied when determining whether a given space object is functional or not. For example, is a non-maneuverable payload non-functional? Maneuverability is seen by many to be a critical component of what is understood by the term 'functional,'[328] yet few would consider an otherwise functioning LEO CubeSat to constitute space debris simply because it lacked an on-board propulsion system. What if the space object retained its maneuverability but its sole probe was non-operational? Without an accepted, binding definition, these questions are difficult to answer. Even if the criteria were clear, it is not obvious who gets to make the functionality determination, which would likely, at least in part, turn on the space object's subjective value to

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ed, *Space Security and the Legal Aspects of Active Debris Removal* (Cham: Springer, 2019) at 118-120 for why some commentators disagree with this interpretation of the scope of "space objects."

[326] Pelton, *supra* note 98 at 74.

[327] Cheng, *supra* note 320 at 506.

[328] Chatterjee, et al, *supra* note 317 at 935.

its owner.[329] An otherwise non-functional satellite (whatever that means) may still be quite useful for discrete scientific purposes, for cannibalization, or even for space manufacturing.[330] For example, it could be scavenged for parts or utilized as a test satellite to hone on-orbit satellite servicing capabilities or ADR technologies. Therefore, being non-functional is not necessarily synonymous with being non-valuable, or, as some have put it, space debris does not necessarily mean "space waste."[331]

Additionally, if functionality is to define space debris, it is difficult for States to make this assessment properly, if at all, for objects not under their own jurisdiction and control. While States "shall…as soon as practicable" furnish basic information about their space objects to the UN under Article IV of the Registration Convention, many do not.[332] Others, like Russia, register payloads, but not discarded rocket bodies.[333] Further, while States "may" update the registration,[334] there is at present no legal requirement under international law to share the day-to-day functional status of satellites with other nations and certainly no state practice of such transparency.[335] In the national security context, it is understandable that States may be reluctant to volunteer up-to-date information about the functionality of their critical remote-sensing, communication, positioning,

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[329] Philip de Man, "Disused Unitary Satellites and The Non-Appropriation Principle: A Functional Comparison," in Ram Jakhu, et al, eds, *Global Space Governance* (Montreal, PQ: McGill Centre for Research in Air and Space Law, 2015) at 453.

[330] Tian, *supra* note 325 at 117; Alexander William Salter, "Space Debris: A Law and Economics Analysis of the Orbital Commons," (2016) 19 Stanford Technology Law Review 221 at 233-234.

[331] Jakhu & Nyampong, *supra* note 319 at 7.

[332] Ram S. Jakhu, et al, "Critical Issues Related to Registration of Space Objects and Transparency of Space Activities," (2018) 143 Acta Astronautica 406 at 410.

[333] *Ibid* at 407.

[334] Registration Convention, *supra* note 13 at art IV(2).

[335] Darren McKnight & Kris Walbert, "Proposed Series of Orbital Debris Remediation Activities," Proceedings of the Seventh European Conference on Space Debris, SDC-7 (2017) at 2, online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/1/SDC7-paper1.pdf>; Weeden, *supra* note 274 at 40; See, generally, Jakhu, et al, *supra* note 332.

and early warning capabilities.[336] Therefore, without insider information, States may disagree on whether a given space object is truly non-functional, and therefore debris.[337]

Further, the IADC/COPUOS definition fails to include some arguably non-functional items in space that others tend to include. For example, non-man-made, or naturally occurring, objects in Earth orbit are exempted from the IADC/COPUOS definition of space debris. Despite this, some countries, for example the United States, prefer the term 'orbital debris,' which it defines to include non-man-made objects.[338] Additionally, objects not in orbit around the Earth or reentering the atmosphere are excluded from the category of space debris.[339] Therefore, a non-functional, man-made payload in orbit around the moon is, for whatever reason, not considered space debris under the IADC/COPUOS definition.

In short, the lack of an international, legally binding definition of space debris creates uncertainty about how to objectively identify space debris and how space debris is treated in relation to the laws surrounding space objects within the current international space law regime, specifically in terms of liability and jurisdiction and control. Instead, the only definition which has gained traction is not legally binding, is limited to the specific context of the IADC/COPOUOS Guidelines, and fails to clearly define its critical terms.

2. <u>No Legal Duty To Prevent or Remove Space Debris</u>

Another challenge inhibiting ADR is the failure of international space law to impose a clear legal obligation on States to avoid the creation of space debris or a duty to remove its own space debris. The first four UN space law treaties from the 1960s and 1970s laid the foundation of

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[336] Jakhu, et al, *supra* note 332 at 411, 413-414.
[337] Weeden, *supra* note 274 at 40.
[338] Hobe & Mey, *supra* note 203 at 628.
[339] *Ibid*.

today's hard international space law, and little has changed since then.[340] Because none of these UN treaties discusses space debris *per se*, it has been questioned whether they directly apply to its creation or removal at all.[341] Many of the fundamental principles laid down in these treaties, especially the OST, are now considered customary international law.[342] Regardless, application of these specific principles to the problem of space debris is difficult, as they are likely too vague to support any international obligation to avoid the creation of space debris.[343] For example, it is not clear how the "due regard" principle or the "harmful contamination" principle from Article IX of the OST could or should be applied to the creation of space debris, since virtually all space missions release *some* debris. How much 'regard' should be given to other countries in relation to the creation of space debris? How much contamination via space debris is harmful? The OST fails to provide clear answers both because it fails to define what these terms mean and because it is not at all clear that these specific provisions were ever intended to directly address the problem of space debris.[344]

It can be useful when struggling to apply international space law to the creation of space debris to consider not just the minimal or expected level of debris creation inherent in virtually all space missions, but to consider the most egregious or wanton acts of debris creation, such as ASAT tests.[345] If such a dramatic, intentional example does not violate international space law, it can hardly be said there is an affirmative duty to refrain from creating space debris. However, as already noted in Part II(D)(1), *supra,* the IADC/COPUOS Mitigation Guidelines afford States the

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[340] Pelton, *supra* note 98 at 70.
[341] Wouters, et al, *supra* 158 at 6.
[342] Popova & Schaus, *supra* note 50 at 4.
[343] Wouters, et al, *supra* 158 at 6.
[344] N. Jasentuliyana, "Space Debris and International Law, (1998) 26 J. Space L. 139 at 141.
[345] See Wouters, et al, *supra* 158 at 7 for such a comparison.

discretion to conduct these intentional fragmentation events "when necessary."[346] While non-binding, these Guidelines are widely adopted and are therefore indicative of the *opinion juris* of nearly all space-faring States. Similarly, States have been reluctant to step forward to themselves condemn these intentional debris-creating events as illegal under any substantive provision of customary international law or treaty law.[347] Therefore, even in the historically worst examples of intentional debris creation, ASAT tests, there is no clear consensus that a violation of an international obligation has taken place, severely undercutting any argument that public international space law forbids the creation of debris itself.

Some have suggested that the fundamental, underlying goals of the UN space treaties could arguably create some sort of an "implied" obligation to limit debris.[348] However, while perhaps in keeping with the collective spirit of the treaties, State practice belies this through repeated ASAT tests and the millions of pieces of space debris currently in Earth orbit. It is clear that the creation of space debris is not, in and of itself, illegal under international law.[349] Without a legal duty to refrain from creating space debris, there is, by extension, certainly no obligation to affirmatively remove space debris via ADR.[350]

Because no legal duty exists to refrain from creating space debris nor to remove one's space debris, there is little legal incentive for states to develop and field ADR technology. Indeed, a "tragedy of the commons" scenario arises wherein preventing or removing space debris is in the

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[346] UNOOSA, "Space Debris Mitigation Guidelines," *supra* note 195 at para 4(4); IADC, "Space Debris Mitigation Guidelines," *supra* note 20 at para 5.2.3.

[347] Wouters, et al, *supra* note 158 at 7; Frigoli, *supra* note 119 at 64.

[348] Wouters, et al, *supra* note 158 at 6.

[349] Du, *supra* note 247 at 11; Popova & Schaus, *supra* note 50 at 6; COPUOS, *Towards Long-Term Sustainability*, *supra* note 51 at 22-23; Ram S. Jakhu, "Regulatory Aspects Associated with Response to Man-Made Cosmic Hazards," in Joseph N. Pelton & Firooz Allahdadi, eds, *Handbook of Cosmic Hazards and Planetary Defense* (Cham: Springer, 2015) at 1072; M. Emanuelli, et al, "Conceptualizing an Economically, Legally, and Politically Viable Active Debris Removal Option," (2014) 104 Acta Astronautica 197 at 200.

[350] Peter Malanczuk, "Review of the Regulatory Regime Governing the Space Environment – The Problem of Space Debris," (1996) 45 Zeitschrift für Luft- und Weltraumrecht 37 at 58; Popova & Schaus, *supra* note 50 at 6.

interest of all States, but few are willing to bear the costs because the legal regime does not require them to do so.[351] Therefore, despite the IADC and COPUOS Guidelines' recognition of the debris problem, without clear international legal obligations to avoid creating and to remove space debris, it is a challenge to motivate States to play their part in solving the debris problem.

3. Jurisdiction and Control of Space Debris

One of the most foundational concepts of early international space law is that the State of registry retains continuing "jurisdiction and control" over its space objects.[352] However, the application of this bedrock principle serves to frustrate the advancement of ADR.

a) Jurisdiction and Control Under Current Space Law

The UNGA outlined the concept of "jurisdiction and control" – even before the adoption of the first UN space treaty – in its 1963 "Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space."[353] This document declared that the State "on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and any personnel thereon, while in outer space. Ownership of objects launched into outer space, and of their component parts, is not affected by their passage through outer space or by their return to the Earth."[354] Several years later, in 1967, virtually identical language was reiterated in the OST.[355] However, the OST failed to clarify how such a registration was to be carried out. The Registration Convention remedied this in 1973 by explaining that the

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[351] Pelton, *supra* note 98 at 33.
[352] OST, *supra* note 10 at art VIII.
[353] *Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space*, GA Res 1962 (XVIII), UNGAOR, 18th Sess, Supp No 15, UN Doc A/RES/1962 (XVIII) (1963).
[354] *Ibid* at para 7.
[355] OST, *supra* note 10 at art VIII. While the language in Art VIII is nearly identical to the 1963 UNGA Declaration, it expands the concept by also applying ownership to objects landed on or constructed on celestial bodies.

launching State of a space object launched into Earth orbit or beyond shall register it "by means of an entry in an appropriate registry which it shall maintain."[356] If there is more than one launching State, they "shall jointly determine" which single State will register the space object.[357] Determination of "the contents of each registry" and "the conditions under which it is maintained" was left to the individual States,[358] but certain information shall be passed onto the Secretary General for compilation in a UN Register.[359] Further, it defined the term "State of registry" as "a launching State on whose registry a space object is carried…."[360]

"Jurisdiction," in this context, entails the right of the State of registry to exert legal enforcement over and liability and responsibility for the space object, while "control" reserves to the State of registry the right to technically oversee and maneuver the space object.[361] Combined, the concept of "jurisdiction and control" provides States with a level of certainty over their space objects within an international legal regime that does not otherwise permit States to assert sovereignty in outer space, since Article II of the OST prohibits national appropriation through claims of sovereignty or any other means.[362] Critically, a State of registry's right to jurisdiction and control continues even if technical control over the space object is lost.[363]

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[356] Registration Convention, *supra* note 13 at art II(1).
[357] *Ibid* at art II(2).
[358] *Ibid* at art II(3).
[359] *Ibid* at arts III & IV.
[360] *Ibid* at art I(c).
[361] Popova & Schaus, *supra* note 50 at 9; Pelton, *supra* 98 at 74; Gordon Chung, "Jurisdiction and Control Aspects of Space Debris Removal," in Annette Froehlich, ed, *Space Security and the Legal Aspects of Active Debris Removal* (Cham: Springer, 2019) at 33-34.
[362] COPUOS, *Active Debris Removal, supra* note 20 at 32; OST, *supra* note 10 at art II; Chung, *supra* note 361 at 33; Frigoli, *supra* note 119 at 55.
[363] de Man, *supra* note 329 at 451.

b) Challenges for Active Debris Removal

The first and most obvious challenge posed to ADR by the legal concept of jurisdiction and control is that it establishes an exclusive hegemony over the space object for the registering State. In other words, no other State may interact with, rendezvous with, capture, or otherwise molest a space object without first obtaining the registering State's express permission.[364] Historically, this concept has proven itself quite useful, since any unilateral right to remove space objects, even seemingly abandoned or unimportant debris, would likely cause significant international conflict because of national security concerns, perhaps even leading to war.[365] However, obtaining the permission of a State to perform ADR on its space object would be a complicated endeavor, and may be denied or even ignored for any or no reason at all. Such permission is likely to become even more complicated if the relevant space object is owned by a private entity instead of the State itself. Further, there is currently no standardized mechanism or accepted international protocol for requesting and receiving permission for ADR activities.[366] The natural result of this exclusivity is that, barring express permission, it limits the ADR efforts of countries to only those space objects under their own jurisdiction and control, or more specifically, those objects on its national registry. Limiting countries to ADR of only their own space objects restricts them from freely targeting the pieces of debris which will most help ameliorate the global debris problem, namely those with high collision probabilities which have the largest masses and

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[364] *Ibid* at 452; Weeden, *supra* note 274 at 41; Frigoli, *supra* note 119 at 56; Popova & Schaus, *supra* note 50 at 9.

[365] Malanczuk, *supra* note 350 at 59; F. K. Schwetje, "Liability and Space Debris," in Karl-Heinz Böckstiegel, ed, *Environmental Aspects of Activities in Outer Space* (Köln: Carl Heymanns Verlag, 1990) at 36-37.

[366] Weeden, *supra* note 274 at 41; Pelton, *supra* note 98 at 74.

surface areas and are located in the most congested orbits.[367] Without such freedom, global ADR efforts will be seriously stunted.

If express permission is denied, the legal concept of jurisdiction and control can also limit the number of potential nations conducting ADR. By number, approximately one-third of the space debris in orbit in 2011 was owned by the United States, one-third by Russia, and one-third by China.[368] Therefore, unless these three countries grant others permission to conduct ADR on their space objects, there are only a few major players who will even be legally permitted to tackle the debris problem through ADR, and none of them will be capable of doing it single-handedly.[369] With regard to mass, 70% of the total mass of space objects in LEO in 2014 belonged to Russia, primarily consisting of disused rocket bodies.[370] If Russia does not itself conduct ADR, which, as already discussed it has no obligation to do, and also refuses to give its permission for other countries to remove its space objects, the majority of the mass in LEO is legally untouchable because of the jurisdiction and control provision in Article VIII of the OST. Some have described this exclusivity as one of the most significant legal obstacles inhibiting ADR efforts.[371]

Not only is jurisdiction and control definitively established for the State of registry of a space object, the challenges for ADR are compounded by the fact that this exclusivity is ongoing. In other words, the right to jurisdiction and control does not end as long as the object is in space, so there is never temporal cessation of jurisdiction and control,[372] irrespective of the object's

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[367] For a thorough description of how such a target should be selected, including several identified targets, see Christophe Bonnal, et al, "Space Debris Removal: Recent Progress and Current Trends," 85 Acta Astronautica 51 at 54-55.

[368] Weeden, *supra* note 274 at 41.

[369] *Ibid*.

[370] Pearson, et al, *supra* note 303 at 10, 14.

[371] Popova & Schaus, *supra* note 50 at 9.

[372] COPUOS, *Active Debris Removal, supra* note 20 at 32; OST, *supra* note 10 at art VIII; Chung, *supra* note 361 at 38-41.

functionality.[373] This continuity raises questions regarding the transferability or abandonment of objects under a State's exclusive jurisdiction and control. Currently, there is no international space law mechanism for transferring jurisdiction and control of on-orbit space objects, so it is not surprising that there is scant State practice.[374] Even still, transfers have occurred before, albeit in limited numbers. For example, in 1997, the United Kingdom transferred ownership of three satellites to China concurrent with Hong Kong's return, thereafter notifying the UN that it had removed these satellites from its national registry.[375] China, conveniently also a launching State of these satellites, subsequently re-registered them on its own national registry and then informed the UN.[376] However, the fact that there is no obligation for States which acquire on-orbit satellites to confirm the status of their registration with the original launching States complicates matters, as does the lack of an obligation to report this change of ownership to the UN in order to amend the UN Register.[377] Without clear international obligations and consistent State practice in re-registering transfers, it may become difficult to determine which State possesses jurisdiction and control of a given space object, further complicating ADR. For this reason, the UNGA encouraged states to submit information on their practices regarding on-orbit transfer of ownership of space objects, with an eye towards harmonizing such practices.[378] Several years later, the Assembly expressly recommended that, upon any change in "supervision" of an on-orbit space object, the State of registry should notify the UN of the new operator and the date of the change.[379] It further

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[373] Chatterjee, et al, *supra* note 317 at 935.

[374] *Ibid* at 936; Pelton, *supra* 98 at 74.

[375] See Jakhu, et al, *supra* note 332 at 412 for a description of this on-orbit transfer and three others, each resulting in varying levels of registration.

[376] *Ibid*.

[377] *Ibid* at 413.

[378] *Application of the Concept of the "Launching State*," GA Res 59/115, UNGAOR, 59th Sess, UN Doc A/RES/59/115 (2004) at paras 3-4.

[379] *Recommendations on Enhancing the Practice of States and International Intergovernmental Organizations in Registering Space Objects*, GA Res 62/101, UNGAOR, 66nd Sess, UN Doc A/RES/62/101 (2007) at para 4(a).

recommended that, if there is no State of registry at the time of the change, the new operator should itself furnish that information.[380] Despite this, the possibility remains for difficulties and disputes regarding the registration, and thus, jurisdiction and control, of transferred space objects.[381]

Perhaps more important than transferability, the UN space treaties and declarations are silent about the possibility of legally renouncing or abandoning jurisdiction and control of one's space objects.[382] Further, there is no clearly recognized concept of abandonment of jurisdiction and control of a space object in practice in public international space law,[383] despite some notable authors arguing for the reasonableness of such an approach.[384] This is because Article VIII of the OST states that jurisdiction and control are continuous while in space and that ownership extends even after the object returns to the Earth. Therefore, legacy pieces of debris that are clearly unguided and non-functional, such as defunct payloads or rocket bodies left over from the 1960s, are still legally tied to their States of registry.[385] Without a recognized concept of abandonment of jurisdiction and control for uncontrolled debris that the State of registry has expressed a permanent intent not to recover or utilize, akin to derelict property in maritime law,[386] the fact that the State of registry retains exclusive sovereignty seriously inhibits the ADR efforts of other nations.

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[380] *Ibid* at para 4(b).

[381] Jakhu, et al, *supra* note 332 at 412.

[382] Chatterjee, et al, *supra* note 317 at 936.

[383] Lyall & Larson, *supra* note 15 at 78; Malanczuk, *supra* note 350 at 59.

[384] See de Man, *supra* note 329 at 452-453 for several of these authors, including Bin Cheng and CW Jenks; See also, Chung, *supra note* 361 at 41; Chelsea Munoz-Patchen, "Regulating the Space Commons: Treating Space Debris as Abandoned Property in Violation of the Outer Space Treaty," (2018) 19:1 Chicago Journal of International Law 233 at 246-250.

[385] Frigoli, *supra* note 119 at 57.

[386] Hamilton DeSaussure, "An International Right to Reorbit Earth Threatening Satellites," (1978) 3 Annals of Air and Space Law 383 at 391. "Derelict property in maritime law is property on the high seas (or other navigable waters) which has been abandoned by those in charge of it without hope of recovering it or returning to it." *Ibid*. Since such derelict property is legally salvageable by all States, it creates an interesting analogy with uncontrolled, abandoned space debris. For an extensive discussion of this analogy, see Christol, *supra* note 312 at 268-276.

Further complicating ADR, the concept of jurisdiction and control arguably extends even to debris fragments,[387] meaning that States likely still possess sovereign control over the fragments of their formerly intact space objects. This is because pieces of space debris, as discussed in Part III(B)(1), *supra*, are still generally considered "space objects" under the UN space treaties. Further, while left undefined, Article VIII of the OST also expressly references its applicability to the "component parts" of space objects. However, despite the concept of jurisdiction and control likely applying to fragments, there is no express requirement to register fragments resultant from an on-orbit breakup.[388] Neither do States accomplish this registration in practice. It would be surprising if, for example, China individually registered the thousands of trackable fragments from its 2007 ASAT test. In fact, registration practices are much less onerous; some States, such as Russia, interpret "space objects" to only mean payloads and therefore fail to even register their spent rocket bodies at all,[389] much less the many fragments of their exploded rocket bodies.

This general lack of registration of fragments, rocket bodies, and sometimes even functional payloads, leads to the final major problem regarding the concept of jurisdiction and control, namely that of attribution. Since in practice registration is far from consistent,[390] it can be difficult, if not impossible, to determine which State possesses jurisdiction and control of a given space object, especially in relation to debris fragments.[391] If jurisdiction and control applies to space objects in perpetuity, even arguably to fragments, and it is unclear which country has created or registered a specific piece of debris, then no State will *ever* be able to acquire the legal permission needed to remove it via ADR. It is worth noting that some have suggested the concept

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[387] Pelton, *supra* 98 at 74; Tallis, *supra* note 311 at 91; Munoz-Patchen, *supra* note 384 at 245.

[388] Jasentuliyana, *supra* note 344 at 144; R. Ghadawala, et al, "Commercial Aspects of Active Debris Removal: Technical and Legal Challenges," (2016) 5:1 Journal of Aeronautics and Aerospace Engineering 1 at 4.

[389] Jakhu, et al, *supra* note 332 at 407.

[390] *Ibid*; Lyall & Larson, *supra* note 15 at 79; Agatha Akers, "To Infinity and Beyond: Orbital Space Debris and How to Clean It Up," (2012) 33:2 U. La Verne L. Rev. 285 at 306-207.

[391] Lyall & Larson, *supra* note 15 at 78; Frigoli, *supra* note 119 at 58.

of jurisdiction and control should not apply to small pieces of debris, especially if it is no longer possible to determine its corresponding state of registry.[392] Regardless of these arguments, there is simply no State practice of removing unregistered space objects, further hindering ADR efforts.[393]

4. Liability for Space Debris

Another foundational concept of early international space law, liability for damage caused by space objects, is laid out in the Liability Convention of 1972. Unlike the concept of jurisdiction and control, liability for damage caused by a space object rests with the launching states or states.[394] Unfortunately, the application of such a liability regime in the ADR context creates legal uncertainty and discourages efforts to remove debris.[395]

a) Liability Under Current Space Law

Just like jurisdiction and control, the UNGA outlined the concept of liability for space activities in its 1963 "Declaration of Legal Principles" by providing that each State which "launches or procures the launching of a space object" and each State "from whose territory or facility an object is launched" is "internationally liable for damage to a foreign State or its natural or juridical persons by such object or its component parts on the Earth, in air space, or in outer space."[396] This State or group of States are now known as the "launching State" or "launching States."[397] Several years later, in 1967, virtually identical language was reiterated in the OST.[398] However, both the UNGA and the OST failed to elaborate on the application of international

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[392] Christol, *supra* note 312 at 268; Munoz-Patchen, *supra* note 384 at 245-246; de Man, *supra* note 329 at 453.
[393] COPUOS, *Active Debris Removal, supra* note 20 at 32.
[394] Liability Convention, *supra* note 11 at arts II & III.
[395] Pelton, *supra* 98 at 71.
[396] UNGA Res 1962 (XVIII), *supra* note 353 at para 8.
[397] Liability Convention, *supra* note 11 at art I(c).
[398] OST, *supra* note 10 at art VII.

liability for space activities with any specificity. The Liability Convention remedied this in 1972 by clarifying via *lex specialis* that a launching State is "absolutely liable" for any damage caused by its space object or component parts on the "surface of the Earth or to an aircraft in flight," but only liable for damage caused elsewhere, *i.e.* in space, if the damage is due to "its fault or the fault of persons for whom it is responsible."[399] The Convention limits damage to injuries to people and property,[400] thereby excluding generalized damage to the outer space environment itself.[401] Thus, a dual liability regime is created, either absolute or fault-based, depending on where the damage occurs. However, no definition or standards for fault are provided, nor is any standard of care prescribed.[402] The Liability Convention also maintains the four-pronged OST definition of a launching State, namely the State which launches or procures the launch, or the State from whose facility or territory the launch occurs.[403]

It is important to note that modern space objects often have more than a single launching State and can sometimes have as many as four or more,[404] the identities of which may or may not be entirely transparent to the international community.[405] Three launching States would result under the Liability Convention, for example, in the case of a French company procuring the launch of its satellite through a Russian spaceport located in Kazakhstan. In cases of damage caused by a space object with more than one launching State, all are jointly and severally liable.[406] Relevant for the ADR context, if space object A, launched by State A, is damaged through a collision with

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[399] Liability Convention, *supra* note 11 at arts II & III.
[400] *Ibid* at art I(a). Note that this seriously limits the Liability Convention's application to environmental damage. See Lawrence D. Roberts, "Addressing the Problem of Orbital Space Debris: Combining International Regulatory and Liability Regimes," (1992) 15 B.C. Int'l & Comp. L. Rev. 51 at 64.
[401] Frigoli, *supra* note 119 at 57.
[402] Schwetje, *supra* note 365 at 40; Jasentuliyana, *supra* note 344 at 143.
[403] Liability Convention, *supra* note 11 at art I(c).
[404] Pelton, *supra* note 98 at 31.
[405] Stubbe, *supra* note 267 at 397-399.
[406] Liability Convention, *supra* note 11 at art V(1).

space object B, launched by State B, thereafter causing damage to a third party, whether on Earth or in space, then State A and State B are jointly and severally liable according to the general liability rules from Article II and III, with the burden of compensation apportioned based on comparative fault.[407] If the relative degree of fault is unknown or cannot be apportioned between States A and B, then liability will be apportioned equally.[408]

Finally, it is also important to note that the term "space objects" as defined by Article I(d) of the Liability Convention arguably includes the fragments of space objects resulting from on-orbit breakups.[409] This is because any other interpretation would create a significant, virtually fatal, lacuna in the international space liability regime, since no State would then be responsible for damage caused by the debris fragments which total nearly 53% of all space objects.[410] Therefore, damage resulting from, for example, any of the thousands of small fragments resulting from a space collision or an ASAT test, may also subject the original launching State or States to liability.

b) Unique Risks of Active Debris Removal Related to Liability

Before discussing the challenges posed by this liability regime as it relates to ADR, it is important to consider that ADR is an inherently risky undertaking, since all ADR technologies require some form of interaction with space debris.[411] More often than not, this interaction takes the form of a direct physical connection between objects co-located in space. In LEO, that means linking up objects which may be traveling with velocities in excess of 30,000 kilometers per hour,

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[407] *Ibid* at art IV.

[408] *Ibid* at art IV(2).

[409] Scott, *supra* note 138 at 746; Gorove, *supra* 324 at 165. Note that some commentators maintain that a plain reading of the Liability Convention excludes fragments from the definition of "space objects." See, for example, Roberts, *supra* note 400 at 64 & Tian, *supra* note 325 at 118-120.

[410] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 3.

[411] Weeden, *supra* note 274 at 41; Tian, *supra* note 325 at 125.

or over 8 kilometers per second.[412] Such on-orbit rendezvous or docking maneuvers are already complex for stable, controlled objects, much less for pieces of space debris which may be unguided, tumbling, lacking any obvious grapple point or docking mechanism, physically degraded, or even full of volatile residual fuel.[413] Further, the resultant movement of the joint, post-capture system can be quite unpredictable, especially as the center of mass of the debris is not necessarily known.[414] All of these challenges with direct-capture ADR methods increase the risk of an accidental on-orbit fragmentation event,[415] possibly resulting in the creation of more debris or even runaway liability.

Even in circumstances without physical capture, such as through the use of directed-energy lasers, ADR is not without additional risks. A longer-than necessary laser pulse (just near a millisecond) risks over-ablating the debris material, creating "splashing" and potentially even more debris.[416] Further, since the laser must necessarily cross through other space orbits, it has the potential to accidentally illuminate functional spacecraft, which can damage or degrade sensitive on-board optical sensors.[417] Also, laser-based ADR methods will, by design, result in the uncontrolled reentry of space debris. If any part of the debris survives reentry, it inherently poses a threat to aircraft in flight and to people and property on the surface of the Earth.

Finally, ADR, by its nature and purpose, alters the orbital altitude of targeted space debris. In doing so, the space debris will inevitably pass through the orbits of other space objects either on its own or in tandem with its controlling ADR object, thereby increasing the risk for conjunction events.[418] Some have suggested that this creates the need for an ADR traffic management system

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[412] Roberts, *supra* note 400 at 55.
[413] Nishida, et al, *supra* note 289 at 95-96; Shan, et al, *supra* note 271 at 29; Weeden, *supra* note 274 at 41.
[414] Shan, et al, *supra* note 271 at 25.
[415] Jakhu, et al, *supra* note 9 at 130.
[416] Phipps & Bonnal, *supra* note 280 at 227.
[417] Weeden, *supra* note 274 at 42.
[418] *Ibid* at 41-42; COPUOS, *Active Debris Removal, supra* note 20 at 32.

which can apprise other space operators of the up-to-date orbital characteristics for the ADR object's transitory path, especially for ADR objects which will conduct repeated or continual maneuvers, such as the proposed EDDE.[419]

c) *Challenges for Active Debris Removal*

Because ADR increases the risk for further fragmentation and damage to other objects in space and people and objects on the surface of the Earth, as discussed above, the current space liability regime creates several specific challenges for the development of ADR.

In order to explore these challenges, consider the following, completely plausible, ADR scenario. Assume that a single State, State A, launches and later registers a defunct rocket stage in upper LEO, orbiting at 1,200 kilometers in altitude. A second State, State B, requests and receives express permission from State A to conduct ADR on the rocket body. Thereafter, State B launches an ADR object, captures the rocket body, deorbits it to 400 kilometers, and then releases it to naturally decay and reenter the Earth's atmosphere. State B's ADR object then deorbits itself and burns up entirely upon reentry. Two weeks after the ADR mission concludes, the rocket body, still orbiting at roughly 400 kilometers, explodes for an unknown reason and a large piece of the resultant debris strikes the ISS, destroying the station and killing five astronauts from three different countries. Given the regime established under the Liability Convention, it is unclear which State would bear international liability for this damage. Since the damage occurred in outer space, the launching State of the space object causing the damage is liable if the damage is due to its fault or the fault or persons for whom it is responsible.[420] But whose fault is the damage? State A left an arguably dangerous piece of space debris behind in orbit where it could

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[419] Weeden, *supra* note 274 at 41-42.

[420] Liability Convention, *supra* note 11 at art III.

harm other space objects and astronauts, as it ultimately did. However, State B, with the permission of State A, captured this debris and moved it down to a lower, but crowded, orbit which enabled it to harm the ISS. What about the explosion? Without more information, which may be impossible to acquire, there is no way to know whether the explosion would have occurred it the debris was left alone or if State B's capture and de-orbiting was somehow deficient, itself causing the explosion to occur. It is impossible to determine on these facts whether State A or State B, or perhaps both, is at fault for this damage, especially without an explanation for the explosion and some legally enunciated standard of care. Yet other States and their astronauts have obviously suffered damage and should be entitled to compensation. Further, how are we to factor into the current liability rules that State B was, separate and apart from the fragmentation event and ultimate damage, doing the world a great service by attempting to shorten the orbital lifetime of the debris?

This hypothetical highlights the striking ambiguity that results when the current space law liability rules are applied to an ADR scenario. This legal ambiguity creates several significant disincentives in relation to ADR, both for the launching State(s) of the targeted debris object and the launching State(s) of the ADR object.

First, the current liability rules disincentivize States from conducting ADR on their own space objects. As argued above, ADR itself increases the chance of additional fragmentation and damage. Therefore, launching States face a lower likelihood of eventual liability if they simply ignore their space debris and leave it on-orbit. Even if the space debris breaks up on-orbit and its fragments cause damage to another State's space object, it is unlikely to result in liability. This is because the onus is on the claimant State to prove causation, and thus attribution of the fragment and the identification of its launching State(s), in addition to fault or negligence,[421] burdens which, due to the remoteness of outer space, may be practically impossible to carry.[422] Even if these burdens were able to be carried, in practice the Liability Convention has never been invoked in relation to damage caused by debris fragments in space, only on the face of the Earth.[423] Therefore, the liability regime disincentivizes States from conducting ADR on their own debris.

Second, the liability rules, and specifically their ambiguity, create a disincentive on the part of the State of registry of the debris (which will be, in virtually all cases, also a launching State[424]) to authorize other States to conduct ADR on their debris. Specifically, if an accident were to occur during direct capture ADR, thereby causing damage to the space object of a third party, it is not immediately clear whether, under Article IV of the Liability Convention, the launching State(s) of the ADR object or the launching State(s) of the targeted space debris would be most at fault. This is, in part, because it is not clear what fault looks like under the Liability Convention. Does simply launching a satellite which later becomes debris itself amounts to negligence under the Liability Convention's fault-based regime for space damage?[425] On the one hand, since all space missions release at least *some* amount of debris, it seems unreasonable that the leaving behind of debris is, in and of itself, negligent in relation to any damage it may cause at a later time during an ADR accident.[426] On the other hand, leaving a multi-ton, pressurized, unguided rocket body to float around a congested orbit for 50 years does not seem like something a prudent actor would do, especially if the technology exists to avoid doing so. This ambiguity under the liability rules is

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[421] Liability Convention, *supra* note 11 at art III.

[422] Malanczuk, *supra* note 350 at 53-54; Shackelford, *supra* note 213 at 497; Stubbe, *supra* note 267 at 405-406.

[423] Scott Kerr, "Liability for Space Debris Collisions and the Kessler Syndrome (Part 1)," (11 December 2017), online: *The Space Review* < http://www.thespacereview.com/article/3387/1>. The only time the Liability Convention has been invoked since its inception almost 50 years ago was for damage caused in Canada from the reentry and crashing of the Soviet nuclear satellite Cosmos-954 in 1978. See, generally, Cohen, *supra* note 94.

[424] Registration Convention, *supra* note 13 at art II.

[425] Schwetje, *supra* note 365 at 40-41; Tallis, *supra* 311 at 90.

[426] *Ibid* at 40.

created because the Liability Convention fails to set out any standard of care or method for determining fault.[427] Further, since the Liability Convention has only been invoked once in the nearly 50 years since its inception, and even then only for damage to the Earth,[428] there is no indication from any sitting tribunal of what standard of negligence is appropriate to apply in relation to damage in space from ADR activities. In circumstances of uncontrolled reentry of space debris, for example from contactless ADR methods like ground-based lasers, the question of who bears the fault may not even be relevant. Instead, since there is technically only one space object involved, the launching State(s) of the debris would be absolutely liable under the Liability Convention if the reentering debris caused damage on the surface of the Earth.[429] Therefore, in such cases, the launching State(s) of the piece of debris, not the State controlling the ADR laser, will bear 100% of the risk of liability resulting from the ADR mission. For these two reasons, even if a well-meaning State offered to conduct ADR on the space debris of another State, the debris-creating State may not be inclined to accept an increased risk of damage under circumstances of unclear or one-sided liability.

Third, not only does the current liability regime deter ADR from the perspective of the launching State(s) of the debris in multiple ways, it also disincentivizes other well-meaning States from ever even offering to conduct ADR on their behalf. This is because the ADR object is, generally speaking, the active participant in the interaction with and re-orbiting/de-orbiting of an otherwise uncontrolled, but trackable and largely predictable, debris object. Therefore, even though it may be argued that leaving behind debris is itself negligent, it is just as reasonable to argue that the launching State(s) of the ADR object has considerably more control and influence

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[427] Jasentuliyana, *supra* note 344 at 143; Tian, *supra* note 325 at 126.
[428] Kerr, *supra* note 423.
[429] Liability Convention, *supra* note 11 at art II.

over what occurs during the ADR attempt. In that sense, the launching State(s) of the ADR object could reasonably be found to be more at fault for any mishap during the ADR process which causes damage and apportioned the majority of the liability, especially if damage results after the orbit of the space debris has already been adjusted by the ADR object, as in the hypothetical described above. If the launching State(s) of ADR objects arguably stand to bear a larger share of the liability for any damages occurring while conducting ADR on the space debris of other States, there is an obvious legal disincentive to undertake such activities.

These three significant disincentives are further exacerbated by the fact that there is no recognized international mechanism for launching States to transfer their liability for a space object to another State.[430] In the ADR context, this means that States are unable to transfer liability for their own space debris even to a willing ADR State. As has been observed, "once a launching State is always a launching State."[431] In practice this means that if a State's territory is used to launch a space object, even if that State played no part in procuring or conducting the launch whatsoever and no part in operating or controlling the space object thereafter, it is jointly and severally responsible along with any other launching States for any damage caused by that space object in perpetuity under the terms of the Liability Convention. This illogical apportionment of liability is a commonly criticized aspect of the current space law regime.[432] It appears that the drafters of the Liability Convention did not foresee private space operators or on-orbit satellite sales[433] and premised their liability rules on the erroneous assumption that the launching State would be singular and would always have undisputed physical control of the relevant space

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[430] Popova & Schaus, *supra* note 50 at 10; Pelton, *supra* note 98 at 73-74.

[431] Jakhu, et al, *supra* note 332 at 408.

[432] Pelton, *supra* note 98 at 71 & 73.

[433] *Ibid* at 71 & 74-75.

object.[434] In order to cope with this regime, States and private space operators must circumvent the Liability Convention by utilizing complex systems of private, bilateral indemnification agreements, as expressly permitted in Article V.[435] These agreements are only binding between the individual parties, so the States remain liable under the Liability Convention in public international space law.[436] Despite these agreements, the structural defect in the Liability Convention and its impediment to ADR efforts remains.

Overall, the ambiguity surrounding liability for ADR missions and the resulting disincentives are significant legal challenges which complicate and inhibit ADR efforts. Not surprisingly, Joseph Pelton has called the rules surrounding the Liability Convention the "largest legal barrier to efficient orbital debris removal."[437] Unless and until these are adjusted or clarified, ADR efforts are likely to be stifled into the future.

5. Export Control Laws

Another significant legal obstruction inhibiting ADR is the proliferation of nationally and internationally imposed export control laws, primarily in the way such laws operate to inhibit the transfer of space technology and stifle international cooperation to accomplish ADR. In short, export controls are designed to restrict the shipment or transmission, styled an "export," of controlled military or dual-use materials, goods, services, or technologies outside of the country or to foreign operators in any location.[438] Importantly, they can also apply to the "reexport" of such items, even by foreign actors, such as is the case in the United States if such items contain

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[434] Babak Shakouri Hassanabadi, "Complications of the Legal Definition of 'Launching State'," (2 September 2014), online: *The Space Review* <http://www.thespacereview.com/article/2588/1>.
[435] *Ibid*; Popova & Schaus, *supra* note 50 at 10.
[436] Popova & Schaus, *supra* note 50 at 10; Liability Convention, *supra* note 11 at art V.
[437] Pelton, *supra* note 98 at 73.
[438] Research Regulatory Affairs, "Export Control Definitions and Terms," (2019), online: *Rutgers* <https://orra.rutgers.edu/ecdefinitions>.

US-origin components or technology.[439] These export restrictions are often premised on strategic interests, especially during wartime, as well as concerns for foreign policy, nuclear non-proliferation, or combating terrorism.[440] Export controls commonly apply to various types of space-related technology, especially satellite and satellite components and launch systems. In combination with the continuing jurisdiction and control of registered space debris, as discussed in Part III(B)(3), *supra*, these export controls make it much more difficult for States to grant permission to other countries to perform ADR on their space debris, especially if it contains any U.S.-origin component or technology.[441] This is because granting a foreign entity the right to access, capture, and control a piece of space debris (and therefore any on-board items or technology) for ADR purposes, even if only momentary, would fall within the scope of an "export" within most export control laws because, in order to be effective, this term is often defined in strikingly broad terms.[442] Even the simple sharing of technical data to enable such a mission could violate export control laws.[443] Therefore, even if State A is willing to absorb the liability risks and financial costs required to deorbit State B's space debris, State B may have adopted national laws or agreed to international arrangements which ban it from granting permission for or aiding such a mission, either outright or without first obtaining special authorizations. Most modern space-

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[439] Fabio Tronchetti, "Legal Aspects of the Military Uses of Outer Space," in Frans von der Dunk & Fabio Tronchetti, eds, *Handbook of Space Law* (Cheltenham, UK: Edward Elgar Publishing, 2015) at 367; 15 CFR § 734.14.

[440] Stanley J. Marcuss & Michael B. Zara, "A Better Way Through the Export Control Thicket," (2016) 14 Santa Clara J. Int'l L. 47 at 48; 15 CFR § 730.6.

[441] COPUOS, *Active Debris Removal, supra* note 20 at 34.

[442] *Ibid*; 15 CFR 730.5; Tian, *supra* note 325 at 121-122. The US generally defines the "export" of controlled objects as: 1) an actual shipment or transmission out of the US, 2) releasing or otherwise transferring technical data to a foreign person in the US, 3) transferring registration, control, or ownership of any aircraft, vessel, or satellite by a US person to a foreign person, 4) releasing or otherwise transferring a defense article to an embassy in the US, or 5) performing a defense service on behalf of, or for the benefit of, a foreign person, whether in the US or abroad. See 22 CFR § 120.17; 15 CFR § 734.13; US, Department of Commerce's Office of Space Commerce & Federal Aviation Administration's Office of Commercial Space Transportation, "Introduction to U.S. Export Controls for the Commercial Space Industry," 2d ed (November 2017), online (pdf): *Office of Space Commerce* <https://www.space.commerce.gov/wp-content/uploads/2017-export-controls-guidebook.pdf>.

[443] Jakhu, et al, *supra* note 9 at 131.

faring nations, including Canada,[444] France,[445] India,[446] Russia,[447] China,[448] and many others maintain some form of export controls.[449] Without question, the most restrictive country in the world in terms of export controls, whether in general or specifically as it relates to space technology, is the United States through its sprawling International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR).[450] These overlapping, comprehensive export control rules are so pervasive that they have led to a demand in the global space market for

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[444] Ram S. Jakhu, "Regulation of Space Activities in Canada," in Ram S. Jakhu, ed, *National Regulation of Space Activities* (Dordrecht: Springer, 2010) at 87-91; Global Affairs Canada, "A Guide to Canada's Export Controls," (last updated 13 May 2016), online: *Government of Canada* <https://www.international.gc.ca/controls-controles/about-a_propos/expor/guide.aspx?lang=eng>.

[445] Philippe Achilleas, "Regulation of Space Activities in France," in Ram S. Jakhu, ed, *National Regulation of Space Activities* (Dordrecht: Springer, 2010) at 121.

[446] Ranjana Kaul & Ram S. Jakhu, "Regulation of Space Activities in India," in Ram S. Jakhu, ed, *National Regulation of Space Activities* (Dordrecht: Springer, 2010) at 166-169 & 196-197.

[447] See, generally, Vladamir A. Orlov, "Export Controls in Russia: Policies and Practices," (1999) 6:4 The Nonproliferation Review 139.

[448] Yun Zhao, "Regulation of Space Activities in the People's Republic of China," in Ram S. Jakhu, ed, *National Regulation of Space Activities* (Dordrecht: Springer, 2010) at 263-264.

[449] Jakhu, et al, *supra* note 9 at 132.

[450] For an amusing explanation of the confusing and overlapping expanse of U.S. export control regulation, see, generally, Marcuss & Zara, *supra* note 440, where the authors describe the incomprehensible web of more than 1,500 pages of regulations spread across three federal agencies. Prior to 2014, the export-controlling U.S. Munitions List (UMSL), maintained by the Department of State (DoS), contained virtually all space-related technology. DoC & FAA, *supra* note 442 at 5-6 & 8; 22 CFR § 121.1. Items and covered technology on this list are considered "defense articles" without any civilian use and require a license prior to exporting or re-exporting them to any foreign person or State. Mark J. Sundahl, "Space Tourism and Export Controls: A Prayer for Relief," (2010) 75 J. Air L & Com. 581 at 590; 22 CFR § 120.6. In 2014, the DoS reorganized the USML to remove a significant amount of civil and commercial satellite technology. Bockel, *supra* note 130 at 4; DoC & FAA, *supra* note 442 at 8-9. Still, certain critical technologies remain on the UMSL, such as various rocket and space launch vehicle technology under Category IV and various classified spacecraft and ground control systems under Category XV, including the components, technical data, and services of each of these. DoC & FAA, *supra* note 442 at 21; 22 CFR § 121.1. Notably, China, a major global space power, is categorically barred from exports under current ITAR regulations. 22 CFR § 126.1(d)(1). Despite the loosening of these restrictions, most space technologies are still subject to export control through the Department of Commerce's Export Administration Regulations (EAR) and Commerce Control Lists (CCL), which operates to restrict the export of certain unclassified, dual-use goods and technologies, including but not limited to training simulators, production equipment, ISS equipment, and spacecraft buses. DoC & FAA, *supra* note 442 at 1, 5-6, 8-9 & 25-29; 15 CFR Part 774. Notably, the EAR carves out export license exceptions for certain U.S. allies, primarily NATO countries. 15 CFR § 740.20; DoC & FAA, *supra* note 442 at 9-10.

the development of "ITAR-free," and therefore freely tradeable, satellites,[451] and have even had the unintended effect of stimulating the Chinese rocket and satellite industries.[452]

Restrictive export control laws are not just limited to domestic legislation; they have even cropped up through international arrangements to limit the transfer of and access to sensitive weapons and dual-use technologies. For example, while less restrictive than the US system, the European Union maintains a collective set of export controls which specifically includes various types of space technology.[453] Additionally, more than 40 countries have banded together under the so-called Wassenaar Arrangement, a non-binding, multinational agreement which creates a comprehensive export control regime for many dual-use items.[454] The current list of Wassenaar-controlled dual-use goods, technologies, and munitions restricts the transfer of numerous types of space launch vehicles and spacecraft, including their components.[455]

In conclusion, these various export control restrictions, whether imposed by national law or adopted internationally, serve to inhibit ADR efforts when combined with the jurisdiction and control rules from Article VIII of the OST. The aggressive export rules of one country, for example the U.S., may even inhibit other countries from agreeing amongst themselves to remove

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[451] Bockel, *supra* note 130 at 4; Peter B. de Selding, "U.S. ITAR Satellite Export Regime's Effects Still Going Strong in Europe," (14 April 2016), online: *Space News* <https://spacenews.com/u-s-itar-satellite-export-regimes-effects-still-strong-in-europe/>.

[452] Caleb Henry, "Back-to-Back Commercial Satellite Wins Leave China Great Wall Hungry for More," (22 August 2017), online: *Space News* <https://spacenews.com/back-to-back-commercial-satellite-wins-leave-china-great-wall-hungry-for-more/>.

[453] Commission Delegated Regulation (EU) 2018/1922, amending Council Regulation (EC) No 428/2009 Setting up a Community Regime for the Control of Exports, Transfer, Brokering, and Transit of Dual-Use Items, (2018) OJ L 319. For a detailed discussion of EU export controls, see Tronchetti, *supra* note 439 at 369-377.

[454] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies, Final Declaration (done 19 December 1995) at 4, online (pdf): *Wassenaar.org* <https://www.wassenaar.org/app/uploads/2015/06/WA-DOC-17-PUB-001-Public-Docs-Vol-I-Founding-Documents.pdf>. The purpose of the Wassenaar Arrangement is to "promote transparency and greater responsibility in transfers of conventional and dual-use goods and technologies, thus preventing destabilizing accumulations." *Ibid;* See also, Tronchetti, *supra* note 439 at 363-366.

[455] See, generally, Wassenaar Arrangement, "List of Dual-Use Goods and Technologies and Munitions List," (December 2018), online (pdf): *Wassenaar.org* <https://www.wassenaar.org/app/uploads/2018/12/WA-DOC-18-PUB-001-Public-Docs-Vol-II-2018-List-of-DU-Goods-and-Technologies-and-Munitions-List-Dec-18.pdf>. For an example of Wassenaar-controlled space technology, see para 9.A.4..

space debris, due to the extraterritorial application of reexport rules within these export control laws. Of course, these are not absolutely fatal to ADR; exceptions to export control laws may generally be made at the agency or national level, on a case-by-case basis. Regardless, they all work together to create a complex web of global restrictions which constrain states from freely, or at least inexpensively and expeditiously, granting their permission for other states to conduct ADR on their space debris.

6. Regulatory Vacuum

Space debris and the necessary ADR response are significant global public policy matters that should be of universal concern. So far, the most visible efforts to tackle the problem have been conducted through the IADC and COPUOS, but only as it relates to mitigating new space debris. As already noted, this has proved insufficient. A regulatory agency with the mandate to address this problem through ADR has not yet emerged in the international sphere. Despite the creation of international space law treaties and the evolution of customary international space law, as yet there is no clear international agency in charge of space safety, space traffic management (STM), or other space debris-related concerns.[456] While there are international agencies which deal with regulating certain aspects of space, such as the ITU with respect to frequency allocation, harmful radio interference and GEO slot management,[457] no single agency coordinates the ADR operations discussed in this thesis. This regulatory void has caused the United States, a major global space-power to call for deeper global engagement through bilateral and multilateral discussions and through existing international organizations, specifically in relation to STM and standards on behavior surrounding the space debris environment.[458]

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[456] Pelton, *supra* note 98 at 6 & 75-76; McKnight & Walbert, *supra* note 335 at 4.
[457] Pelton, *supra* note 98 at 76.
[458] US, Space Policy Directive-3, *supra* note 264 at para 5(c).

Without some sort of centralized, global organization to coordinate international ADR efforts, or possibly even to conduct ADR itself,[459] it is difficult to imagine that States will be able to overcome the fundamental legal challenges to ADR already discussed, such as jurisdiction and control issues, liability issues, or export control restrictions. Further, even if these issues were worked out, there is no agency to ensure space safety and traffic management for ADR efforts. For example, in the case of the EDDE, discussed in Part III(A)(3), *supra*, there would be an extremely long ADR device continuously moving throughout space, capturing and moving around pieces of debris. It would be imperative that some centralized STM organization share its orbital details with space-faring nations at all times, in order to prevent collision events.[460] It would also be imperative that the EDDE be operationally managed in such a way that communication with it did not cause harmful radio frequency interference with other functioning satellites, no small challenge for multiple ADR objects constantly traversing various altitudes and inclinations all over outer space. Yet there is no global regulatory agency to manage these inescapably transnational issues.

Until some form of international regulatory framework is developed, ideally through a new comprehensive, multilateral space agreement, it is "unlikely that substantial progress can be made with regard to a coordinated approach to ADR."[461]

C. Policy Challenges to Active Debris Removal

In addition to the lacunae and foundational concepts embedded in the UN space treaties, as well as overlapping national and international export control regimes, there are two major policy

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[459] Pelton, *supra* note 259 at 866-867; Jakhu, et al, *supra* note 9 at 135-136.

[460] Weeden, *supra* note 274 at 41-42.

[461] Pelton, *supra* note 98 at 76; See also Popova & Schaus, *supra* note 50 at 12.

issues which also inhibit the development of ADR. Specifically, these include economic and strategic challenges.

1. Economic Challenges

Like many other uniquely global challenges, the question of economics plays a central role in the efficacy of ADR operations. As noted in Part III(B)(4)(b), *supra*, since most ADR concepts anticipate launching an ADR payload into space to make physical contact with the target debris, an ADR mission will generally be an expensive endeavor. It will contain all of the research and development costs, licensing costs, insurance costs, launch costs, ground-station costs, and operational costs that any traditional space venture would include.[462] However, the end result will obviously not include any commercial space application to sell or license, such as television broadcasting or Earth observation, to recover these costs. Further, while it may develop in the future, there is currently no global market for providing hireable ADR services. Additionally, since most proposed ADR concepts anticipate only deorbiting a single piece of debris across the life of the ADR object, many ADR operations would be unable to spread the costs across deorbiting several pieces of debris, making each mission incredibly expensive.[463] Given the lack of convertible income stream, at least at the current time, and the limited utility of individual, "single-debris" missions, some have argued that all current ADR systems now available "suffer from a 'business case' that lacks a clear and solid economic rationale for their use.[464] Regardless of such blanket statements, it is incredibly difficult to cost a "typical" ADR mission, since they

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[462] Carsten Weidemann, et al, "The Economics of the Control of the Space Debris Environment," Proceedings of the Sixth European Conference on Space Debris, SDC-6, Paper 86 (2013) at 2, online (pdf): *ESA* <https://conference. sdo.esoc.esa.int/ proceedings/sdc6/paper/86/SDC6-paper86.pdf>.

[463] Pelton, *supra* note 98 at 58.

[464] *Ibid* at 25.

can vary infinitely in the number of targets, size of targets, distance of orbital adjustment, and method of ADR,[465] yet ADR must still compete against other, obviously cheaper alternatives.

For example, the conceptual costs of intervening only at the last minute to alter debris orbits through micro, gas-induced orbital adjustments, so-called "just-in-time collision avoidance," would likely amount to only U.S. $1-3 million per launch, meaning it could theoretically be as much as 1,000 times cheaper than the cost of an average ADR operation.[466] This determination is made by calculating the average cost of reducing one on-orbit collision. Since ADR operations are premised on the concept of reducing collisions through the wholesale cleanup of space, it could take the removal of approximately 35-50 pieces of space debris to reduce a single collision, totaling anywhere from U.S. $300 million to U.S. $3 billion per collision reduction.[467] Separate and apart from the costs of ADR missions, studies have also been conducted to determine the relative value to be gained by removing a piece of debris and thereby reducing the chances of needing to replace an operational payload due to a destructive collision event. In one such study from 2013, it was estimated that removing a small satellite in sun-synchronous orbit would only return a "value" worth approximately U.S. $14,500 on average, compared with U.S. $306,000 for the removal of a large, 2,000 kilogram piece of debris.[468] If the relative costs for ADR operations remain too high and the monetary benefit derived from removing debris objects remains too low, it may result in the unfortunate conclusion that it is simply easier to just keep launching replacement satellites than

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[465] See, generally, Toru Yamamoto, et al, "Cost Analysis of Active Debris Removal Scenarios and System Architectures," Proceedings of the Seventh European Conference on Space Debris, SDC-7, Paper 660 (2017), online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/660/SDC7-paper660.pdf>.

[466] McKnight & Walbert, *supra* note 335 at 4.

[467] *Ibid* at 5.

[468] Leonard Vance & Allan Mense, "Value Analysis for Orbital Debris Removal," (2013) 52 Advances in Space Research 685 at 692 & 694.

to remove defunct ones,[469] making it hard for States to justify the economic costs of fielding ADR systems.

Given the global nature of the space debris problem, it is also unclear which States should pay for the high costs of ADR. Should all nations contribute equally for ADR operations since the space debris problem is a global one? Perhaps that is appropriate, but probably not, in light of the fact that the overwhelming majority of the space debris currently in Earth orbit was created by relatively few nations, most prolifically the USSR/Russia, China, and the United States.[470] It is arguably unfair to require States which have never created a single piece of debris to subsidize the historical environmental negligence of other, more industrialized, ones. This argument has repeatedly been made in the international climate change arena and has come to be known as "common but differentiated responsibilities."[471] Such a concept appears highly relevant to ADR and the space debris problem. Even if it were clear which States should be putting up the money to conduct ADR, other policy questions inevitably emerge. For example, should the cost of ADR be borne upfront at the time of launch or provided later, when it comes time to actually remove the piece of debris? Additionally, with commercial enterprises comprising a larger and larger percentage of modern space activity, how much of the costs for ADR could or should be shifted to the commercial space industry as opposed to being borne by States themselves? Should the space participant who created a particular piece of space debris be responsible for removing it, whether civilian or government? Individual responsibility seems to be the fairest solution but becomes problematic if the participant, whether civilian or government, is unable or unwilling to

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[469] Satomi Kawamoto, et al, "Current Status of Research and Development on Active Debris Removal at JAXA," Proceedings of the Seventh European Conference on Space Debris, SP-672 (2017) at 1, online (pdf): *ESA* <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/655/SDC7-paper655.pdf>.

[470] Kelso, "SATCAT Boxscore," *supra* note 2.

[471] *United Nations Framework Convention on Climate Change*, 9 May 1992, 1771 UNTS 107 (entered into force 21 March 1994) [UNFCCC] at arts 3(1) & 4(1).

pay for the debris to be removed. Overall, these economic policy challenges related to ADR do not have readily apparent solutions. Much more will need to be discussed and agreed to by global players, likely by and through regulatory organizations, global ADR funds, launch taxes, or through new or modified international instruments before the financial aspects of ADR can be settled.

2. Strategic Challenges

Another critical policy challenge facing ADR is the fact that most ADR technologies are also capable of being used nefariously.[472] In other words, any method of physically capturing, affixing objects to, or repositioning a piece of space debris could similarly be used to capture an enemy satellite, affix a weapon or intelligence device to it, alter its orbit, or simply disrupt or destroy it.[473] Because of this, virtually all ADR methods are considered "dual-use" technology,[474] since they could also be utilized as ASAT "space weapons."[475] Their development and use can be seen by some countries as the creation or refinement of on-orbit ASAT technology and, therefore, a threat to their freedom of use of space for important strategic, primarily national defense, purposes.[476] So, as ADR technology is perfected and proliferated to solve the debris problem, it simultaneously and problematically increases global strategic fears of its misuse, threatening to further militarize, or even weaponize, the space domain.

Very similar to the jurisdiction and control and liability issues discussed in Parts II(B)(3) and (4), *supra,* these strategic challenges make it less likely that States would be willing to permit

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[472] Weeden, *supra* note 274 at 42; Frigoli, *supra* note 119 at 62.

[473] Frigoli, *supra* note 119 at 60 & 62; Tallis, *supra* note 311 at 92-93.

[474] Frigoli, *supra* note 119 at 62; Dobos & Prazak, *supra* note 129 at 221.

[475] Jakhu, s*upra* note 349 at 1072.

[476] Weeden, *supra* note 274 at 42. Such an outcry did, in fact, follow testing by China of on-orbit servicing and satellite capture technology in 2013. See Frigoli, *supra* note 119 at 67.

a foreign state, especially a perceived adversary, to remove pieces of its space debris.[477] Even worse, it may make states skeptical of ADR technology altogether. To ameliorate these strategic fears, States will likely need to engage in information exchanges and transparency and confidence-building measures, perhaps through an ADR-focused international regulatory organization.

D. Conclusion

Other than the fact that ADR is absolutely necessary to stabilize the space environment, much remains unclear about ADR technology and its eventual implementation in outer space. The current proposals for various methods of ADR are incredibly varied, from lasers to harpoons to nets to solar sails. While some are closer to implementation, virtually all require further development and testing.

As the technology matures, serious legal and policy challenges must be addressed before ADR can be implemented on any meaningful scale. Most of the legal challenges stem from the legacy UN space law treaties which make up the specialized field of international public space law. As a threshold matter, since there is no mention of space debris at all in this regime, it appears that debris concerns were not being considered at the time of drafting. Without a definition of and clear legal obligations in relation to debris, it is difficult to adequately deal with the space debris problem at the international level. Legal challenges also flow directly from the foundational legal concepts of these treaties, such as “jurisdiction and control” and the core liability principles. It remains to be seen how ADR will be conducted without relaxing the jurisdiction and control rules or further clarifying the principles of liability, especially as they may apply to fault-based damage in outer space during ADR operations. Further, the application of these concepts to non-State,

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[477] Popova & Schaus, *supra* note 50 at 10.

commercial actors must be clarified. Notwithstanding these legal challenges, ADR operations otherwise face considerable policy challenges regarding financial feasibility and strategic distrust over "dual-use" technologies.

Part IV. Future Strategies

Given the importance of ADR operations to the stability of outer space and the significant legal and policy challenges inhibiting them, it is critical that the global community rapidly develops strategies to facilitate ADR. No longer can the world community afford complacency in the face of the rapid growth of space debris, hoping that lukewarm compliance with mitigation guidelines will magically reverse the more than 60-year trend. It must make prompt and decisive changes to the international space law regime, developing a *lex ferenda* which both clarifies and encourages ADR. However, the nature of the debris problem is such that no one State or small group of States can adequately solve it alone. Therefore, while States should not be complacent in their domestic space initiatives, comprehensive and radical international solutions must be prioritized. It is the contention of this thesis that the swiftest and most comprehensive way to accomplish this goal is through the drafting and widespread adoption of a new multinational space treaty. Using the challenges to ADR discussed in Part III as a guide, Part IV will address how such a new treaty should be structured to facilitate ADR in the future.

A. New Space Treaty

The most direct method of overcoming the legal challenges related to ADR would be to draft an entirely new international space treaty focusing specifically on the issue of debris. The most obvious place to negotiate a new space treaty would be through COPUOS, where each of the previous space treaties has originated. Unfortunately, this process can be painfully slow and generally operates only via consensus.[478] Some have worried that the consensus needed to adopt a new treaty through COPUOS would render it too diluted to be effective.[479] Partly because of this, Christopher Williams has suggested the possibility of bypassing COPUOS as a forum altogether and instead negotiating a binding multinational instrument amongst only the active space-faring nations, thereby generating an instrument which might later be used as a template for a future COPUOS agreement.[480] Williams believes that such a course of action could have the benefit of speeding up negotiations since they could be limited to "only knowledgeable States," more easily avoiding "being sidetracked by tangential issues."[481] Regardless of how the treaty itself may come about, such a new, comprehensive space compact should be constructed incorporating the principles presented below.

1. *Mandate* Compliance With COPUOS Guidelines

As argued in Part II of this thesis, stabilizing the LEO space environment requires not only the implementation of effective ADR, but also continued, strict adherence to the COPUOS Mitigation Guidelines, especially regarding post-mission disposal.[482] Because of this, any new treaty addressing the space debris problem should extend beyond hortatory language simply reemphasizing the importance of member States adopting the guidelines, as COPUOS and the UNGA have repeatedly done throughout the years.[483] Instead, it must include language whereby States agree to be internationally bound by the COPUOS Guidelines. The elevation of the

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[478] Tian, *supra* note 325 at 114-115.
[479] *Ibid*; Mirmina, *supra* note 177 at 658.
[480] Christopher D. Williams, "Space: The Cluttered Frontier," (1995) 60:4 Journal of Air Law and Commerce 1139 at 1182-1183.
[481] *Ibid* at 1182.
[482] See Figure 10, *infra*, from Liou, *supra* note 259.
[483] See, e.g., COPUOS, *Guidelines for the Long-Term Sustainability of Outer Space Activities*, *supra* note 206; UNGA, *International Cooperation in the Peaceful Uses of Outer Space*, *supra* note 20.

Guidelines to a treaty obligation will transcend the inevitable precatoriness of a guideline regime and have a more likely prospect of generating higher levels of compliance by States in the future.

2. *Define* Space Debris

Any new treaty space treaty must develop a clear definition of space debris, specifically as it relates to controllability, communication, and functionality.[484] The relationship of these attributes to space objects can dramatically expand or contract the scope of what is internationally considered to be debris. For example, a control-based definition alone would arguably be overbroad, since it would include all unguided space objects, whether functional or not. While the current, non-binding IADC/COPUOS definition hinges on functionality and may therefore be more appropriate,[485] it still remains unworkable. The concept of "functionality" is, by itself, inadequate to legally delineate what is and is not space debris, especially in a world where the capability to service or refuel a nonfunctional satellite through OOS is rapidly maturing. Therefore, space debris must be further defined. If it is not, problems will arise in situations where States or commercial entities still have practical uses planned for currently non-functioning satellites.

Arguably, any new treaty definition of space debris should clarify that all fragments resulting from collisions, explosions, or unknown breakup events, which together total more than 53% of all tracked space objects,[486] should be categorically considered space debris. Post-fragmentation, they are of certainly quite limited use and are most likely entirely non-functional. The remaining bulk of the tracked space objects, notably intact but non-functional payloads and expended rocket bodies, arguably have some future potential use or "functionality," whether it be

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[484] Tian, *supra* note 325 at 116-117.
[485] *Ibid* at 117.
[486] NASA, "History of On-Orbit Satellite Fragmentations," *supra* note 21 at 3.

via the extension of usable life through OOS or simply salvage operations. Acknowledging this abstract, future functionality makes it difficult to declare such material to be space debris in such a way that any other State may capture and de-orbit/re-orbit it without authorization. Therefore, when defining space debris in a new multinational treaty, it will be necessary to define a time-period after the loss of functionality within which a State must somehow utilize the space object or forfeit exclusive jurisdiction and control over it. While admittedly an arbitrary time span, this thesis suggests adopting the IADC/COUPUS Guidelines' 25-year timeline for post-mission de-orbiting of LEO payloads. In that regard, any intact but non-functional object not utilized by its State of registry within 25 years of becoming non-functional should be considered space debris, regardless of any potential future uses for the object. However, it must be acknowledged that, even under this clarified definition of space debris, transparency surrounding the point at which a space object loses its functionality remains problematic due to the difficulty of obtaining accurate data for often secretive outer space systems.

More than simply defining what space debris is, however, a new treaty must also adequately situate the notion of debris in the context of the prior UN space law treaties. Imperatively, this means clarifying in binding fashion whether or not space debris, however defined, is a subset of space objects,[487] especially when it comes to the fragments resulting from on-orbit explosions, ASAT tests, or conjunction events. This is crucial because, if space debris is a subset of space objects, then the State of registry retains jurisdiction and control of that debris under the OST and the Registration Convention, even if the resultant debris is shattered into thousands of fragments. However, if space debris is not a subset of space objects, then the problematic jurisdiction and control and liability concepts found in previous UN space treaties

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[487] Tian, *supra* note 325 at 118-119.

would simply not apply to it.[488] In other words, once a space object becomes space debris, the right of the State of registry to exert jurisdiction and control over it ceases, such that any State may conduct ADR on it. The latter interpretation is much preferred, as it can provide the significant legal flexibility required to disregard the unhelpful traditional rules of liability and jurisdiction and control applicable to space objects and develop more appropriate long-term rules for space debris to facilitate ADR. At the same time, the decades-old system that States have come to rely upon for traditional space objects would be retained, preserving the necessary order amongst States with functioning satellites.[489] For this reason, any new space treaty negotiated to address space debris should declare that it does not fall within the confines of Article VIII of the OST, meaning that the State of registry no longer retains jurisdiction and control over a space object once it becomes debris. Similarly, any new treaty should clarify that space debris falls outside the definition of a space object for purposes of Article I(d) of the Liability Convention and thereafter enunciate the liability regime applicable to space debris independent of traditional space objects and in a manner which encourages ADR (discussed *infra*).

3. *Clarify* International Obligations Regarding Space Debris

A new space treaty should also clearly express binding obligations on States in relation to space debris creation or space debris removal. Currently, as discussed in Part III(B)(2), no such obligations exist. Ideally, a new space treaty would contain a binding obligation to refrain from the creation of debris altogether and an obligation to clean up any created debris. Unfortunately, an outright ban on any debris creation or an obligation to clean up all created debris is currently unrealistic, as it is too ambitious for the state of current technology, including both space launch

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[488] *Ibid*; Frigoli, *supra* note 119 at 55; Gorove, *supra* note 324 at 165.

[489] Williams, *supra* note 480 at 1184-1185.

technology and ADR technology. Neither would such a ban/obligation dyad comport with the prevailing political environment. However, a new space treaty should at least seek to extend the principles found in the IADC/COPUOS Guidelines in order to ban, rather than merely discourage, the *intentional* creation of space debris unassociated with space launch and payload emplacement operations, thus making illegal the kinetic destruction of satellites using direct ascent ASATs. This is critical because these ASAT tests can create vast amounts of extremely long-lasting space debris fragments. As noted previously, the 2007 Chinese ASAT test currently accounts for the single largest fragmentation event in space history.[490] Similar to the way that nuclear testing has been banned via international treaty in certain locations,[491] outer space is a unique environment that should be shielded from military testing which is seriously deleterious to its future operational use, as kinetic ASAT tests arguably are.

Even if States cannot agree on sweeping obligations banning space debris or kinetic ASAT tests, new treaty negotiations should consider other, less onerous, ways to facilitate ADR through binding obligations related to debris. For example, a new treaty should include an affirmative obligation to update the UN registry entry when a payload becomes nonfunctional debris. Doing so would force international transparency for ADR operations, since States would be responsible for publicly "declaring" their national space debris. It would also publicly start the 25-year period within which the State must utilize the space object's latent functionality or lose exclusive jurisdiction and control over it. Additionally, it would be helpful for attributional purposes to set a timeline for registering newly launched space objects with the UN, or even a requirement to register the observable fragments of one's national debris. Finally, States could consent to be

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[490] NASA, "Orbital Debris Quarterly News," *supra* note 108 at 6.

[491] For example, the Partial Nuclear Test Ban Treaty of 1963 banned nuclear tests in the atmosphere, outer space, and underwater. See, generally, *Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water*, 5 August 1963, 480 UNTS 43 (entered into force 10 October 1963) [PTBT].

bound under international law to remove a small portion, perhaps as low as 1% or even a single intact piece, of their own space debris each year,[492] similar to binding carbon emission reduction targets. This would go a long way towards stabilizing the LEO environment, as NASA's data shows that removing merely five pieces of debris could significantly alter the total debris population in the future by reducing the frequency of conjunction events.[493]

4. *Adjust* Liability Rules For Space Debris

If space debris is no longer considered a space object, the liability regime established by the Liability Convention no longer applies to space debris. As such, new liability rules must be established under the replacement regime. First and foremost, to properly incentivize ADR, any new space treaty must be clear that liability for damage caused by space debris is no longer permanently tethered to the "launching State" as defined in Article I(c) of the Liability Convention. As argued in Part III (B)(4), this outdated rule makes little sense in today's highly cosmopolitan, commercially-dominated space industry. Instead, liability should be clarified to flow to the State of registry at the time the space object becomes debris. If there is no State of registry at that time, liability should rest with the State which last maintained operational control over the object. In this way, the State liable for damage caused by the space debris is appropriately the State that registered it or actually controlled it, rather than a "launching State" which may have merely provided the territory or facility for its original launch.

Further, the standard of liability for damage caused by single debris objects and single ADR objects in space should be clarified and should incentivize ADR operations. For example, the liability standard applied to debris-creating States should be adjusted. Specifically, the

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[492] COPUOS, *Active Debris Removal*, supra note 20 at 40.

[493] See Figure 10, *infra*, from Liou, *supra* note 259.

standard of liability applied to the debris-creating State for damage caused in outer space by its debris should be heightened from fault-based to a rebuttable presumption of fault or even to absolute liability, as it already is for damage caused on the surface of the Earth. This would increase the potential liability of States for damage caused by its debris in space and therefore disincentivize the creation of new debris. In the opposite vein, the liability standard applied to States for damage caused by ADR objects should similarly be adjusted in a new space treaty. Specifically, rather than the current nebulous "fault" standard for liability, damage caused by a single ADR object should be held to a lessened standard, such as requiring an injured party to show wanton or gross negligence on the part of the ADR operator, or even have liability for potential damages suspended entirely.[494] This reduced liability standard for ADR objects is premised both on the general need to incentivize ADR operations, but also a recognition of the service that ADR ultimately provides to all space-faring nations.

Apart from adjusting the liability standards for damages caused by single pieces of space debris or single ADR objects, it would also be wise for any new space treaty to address the composite systems which are uniquely and inevitably created by predominant capture ADR methods. If an ADR object and a piece of captured space debris are operating as a conjoined system and jointly cause damage to a third party or in the process of conjoining collide into one another and thereafter cause damage to a third party, the traditional Liability Convention rules would consider the responsible states jointly and severally liable, but apportion the burden of compensation based on comparative fault.[495] However, as demonstrated by the hypothetical ADR damage scenario in Part III, a fundamental flaw in the current liability regime is that it is incredibly difficult, and often impossible, to determine precisely which party is at fault for

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[494] Tian, *supra* note 325 at 127; COPUOS, *Active Debris Removal*, supra note 20 at 32.
[495] Liability Convention, *supra* note 11 at art IV.

damages flowing from delicate ADR operations conducted in outer space. Therefore, any new treaty addressing space debris should simply avoid the confusion and impossible burden of proof involved in determining comparative fault for these situations. Instead, when it comes to damages arguably caused by both the ADR and its targeted space debris, it should simply automatically apportion liability equally between the State of registry or the operating States for both the ADR object and the piece of space debris rather than expecting States to demonstrate their share of the comparative fault. This clarity flowing from streamlining the liability rules will remove much of the unknown liability exposure for ADR operations inherent in the current regime.

Finally, to bring the liability regime in line with the modern era of private, commercial space ventures, any new space treaty should include provisions affording States the ability to formally transfer liability for their space debris to any other State which is willing to conduct ADR or else specifically authorize cross-waivers of liability for ADR operations,[496] similar to the private arrangements authorized under Article V of the Liability Convention.

Each of these adjustments to the liability regime surrounding space debris would operate to disincentivize the creation of space debris, while at the same time incentivizing its active removal.

5. *Authorize* the Abandonment of Space Objects

Any new space treaty should also include language to clearly permit States which no longer wish to limit ADR from third parties to effectively abandon their space objects in some way.[497] Permitting a state to, as Bin Cheng called it, "disown"[498] jurisdiction and control over its space

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[496] Jakhu, et al, *supra* note 9 at 132.
[497] *Ibid* at 132.
[498] Cheng, *supra* note 320 at 506-507.

objects would greatly increase the ability of other States willing to conduct ADR on those objects to do so. It would also erase the 25-year waiting period discussed above in circumstances where a State has no intention of ever utilizing a nonfunctional space object in the future. Ideally, in order to maximally facilitate ADR, the treaty should also establish a public, international registry, similar to that established by the Registration Convention, to consolidate information related to all such abandoned or disowned debris objects.[499]

6. *Establish* a Global ADR Organization

Any new space treaty addressing debris should also commission a global regulatory agency or organization to coordinate and regulate global ADR efforts. Options for the structure and mission of such a global ADR entity are endless: it could be an organization to exchange legal and technological information, conduct ADR research, establish best practices or guidelines for ADR (in much the same way the IADC has with space debris mitigation), manage and distribute ADR funds, assist with SSA or STM, coordinate global ADR efforts, settle ADR disputes, help select ADR candidate targets, or even to actually conduct ADR operations itself.

Ram Jakhu, Yaw Otu Nyampong, and Tommaso Sgobba have suggested an intergovernmental organization structure which also directly incorporates public and private space operators, akin to the models used for the International Telecommunications Satellite Organization (INTELSAT) or the International Maritime Satellite Organization (INMARSAT) in the 1960s and 70s.[500] This is the ideal structure for ADR efforts, because any organization solely comprised of

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[499] *Ibid* at 506.

[500] Pelton, *supra* note 98 at 44. Tommaso, Jakhu, and Nyampong have called for an organization mirroring INTELSAT, which they described as a "group of public and private joint venturers, combining their technical and financial resources to establish and operate facilities which each participant intended to use to provide services within its defined market area." They propose creating a multinational ADR organization via a state-driven treaty document outlining the scope and structure of the organization itself and an additional operating agreement which outlines the rights and obligations of its members, which they believe should include private and public space industry operators. See, generally, Jakhu, et al, *supra* note 9.

States or their space agencies would fail to include a significant and growing portion of the space industry, namely private operators. No ADR strategy or solution to the debris problem can be successful without integrating and coordinating with the private space industry.

However, other commentators have suggested alternative structures. For example, Agatha Akers has proposed a UN-designated research "center" to spearhead ADR efforts.[501] Alternatively, already existing organizations can be a potential avenue to fill this regulatory void for ADR. There has been recent discussion about expanding several currently-existing organizations to regulate many parts of future space activities, such as STM, safety, or environmental pollution, and from a variety of established international agencies, such as the International Civil Aviation Organization (ICAO), the ITU, or the World Meteorological Organization (WMO).[502] ICAO, a specialized agency of the UN which oversees the safety and security of international civil aviation, has received more attention than others, especially in the realm of STM,[503] largely due to the emergence of suborbital flights reigniting the age-old debate of the boundary between air space and outer space.[504] However, ICAO could theoretically be tasked to regulate space traffic as high as GEO.[505] If an organization like ICAO is assigned more space related functions in the future, such as in relation to suborbital STM, perhaps it can be empowered in a new UN space treaty to also take on the task of acting as a global forum for ADR operations and related safety issues.[506] Beyond the remit of the aforementioned organizations, the IADC, an intergovernmental organization made up of all of the major space-faring nations and

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[501] Akers, *supra* note 390 at 315.

[502] Pelton, *supra* note 98 at 45.

[503] *Ibid* at 76-77. For a comprehensive discussion regarding joint international regulation of airspace and outer space, see, generally, Studies in Space Policy, Vol 7, in Ram S. Jakhu, et al, eds, *The Need for An Integrated Regulatory Regime for Aviation and Space: ICAO for Space?* (Wien: Springer, 2011).

[504] Studies in Space Policy, *supra* note 503 at 42-43 & 53-64.

[505] *Ibid* at 43; Pelton, *supra* note 98 at 76.

[506] Pelton, *supra* note 259 at 866; See, generally, Studies in Space Policy, *supra* note 503.

dedicated to the issue of space debris, is another natural international forum within which to discuss ADR coordination and regulation efforts.

Regardless of the structure of the forum, any organization established by a new space treaty should be specifically empowered to raise funds for ADR (discussed *infra*), select ADR targets, and conduct ADR operations on space debris. The outsourcing of target selection and removal to an international, treaty-based ADR organization is critical to minimizing the strategic concerns of States over the potential weaponization of ADR technology.[507] If the multinational organization is in charge of selecting ADR targets and/or controlling the ADR operations, nations will have less cause for concern that a rogue State would abuse or exploit ADR operations. Further, if empowered to select targets, the organization would be in a position to focus ADR operations on the least strategic and least controversial pieces of debris, or even on completely unattributable debris, thereby building international confidence and transparency for centralized ADR operations.[508]

7. *Empower* the ADR Organization to Raise Funds

As noted in Part III(C)(1), *supra*, ADR operations are not currently economically viable and are subject to a "tragedy of the commons" problem. Therefore, authorizing a newly created ADR organization to raise money in order to diffuse the subsidization of removal efforts is paramount.

Perhaps the simplest way of collecting revenues for a global ADR fund would be to include provisions in the new space treaty which authorize the established ADR organization to promulgate a process for the imposition of a global tax to be levied against either States or

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[507] Frigoli, *supra* note 119 at 68.
[508] COPUOS, *Active Debris Removal, supra* note 20 at 38.

commercial entities for the launching of space objects,[509] sometimes styled a “space access fee.”[510] This type of fee would have the benefit of shifting the majority of the costs associated with ADR to those States and commercial entities which launch the most space objects. However, given all of the variables and unknowns when it comes to the creation of space debris and ADR operations, it is incredibly difficult to determine an appropriate or optimal tax amount per launch.[511] Agatha Akers has suggested a simple flat-rate fee of U.S. $5 million for each unmanned object launched into space and U.S. $1 million for each manned space launch.[512] Others, such as Molly Macauley or Joseph Pelton, have considered basing the tax off a percentage of the production or operational costs of the spacecraft and launch vehicle, suggesting figures anywhere from a fraction of a percent[513] to roughly 5%,[514] this range being multiple times lower than what is commonly paid in launch insurance costs.[515] Zhuang Tian has pointed out that the mass of the launched object and its eventual orbital altitude should be factored into the tax, since larger objects are more likely to fragment into many more pieces and will remain in orbit longer at higher altitudes.[516] It could also be useful to scale the tax based on the relative probability or risk of collision for specific intended orbits. In other words, the more congested or hazardous the orbit, the higher the tax should likely be.[517] Finally, it could also be beneficial to provide discounts on the front end or rebates on the back end for deorbiting, graveyarding, shielding, installing maneuvering capability, or any other

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[509] Joseph S. Imburgia, “Space Debris and Its Threat to National Security: A Proposal for a Binding International Agreement to Clean Up the Junk,” (2011) 44 Vanderbilt Journal of Transnational Law 589 at 630; Pelton, *supra* note 259 at 857; Tian, *supra* note 325 at 123.
[510] Akers, *supra* note 390 at 311.
[511] Molly K. Macauley, “The Economics of Space Debris: Estimating the Costs and Benefits of Debris Mitigation,” (2015) 115 Acta Astronautica 160 at 161.
[512] Akers, *supra* note 390 at 313.
[513] Macauley, *supra* note 511 at 163.
[514] Pelton, *supra* note 259 at 857.
[515] *Ibid* at 859 & 863.
[516] Tian, *supra* note 325 at 123.
[517] Emanuelli, et al, s*upra* note 349 at 201; Macauley, *supra* note 511 at 163.

desirous debris mitigation strategies.[518] Such a scheme would work to increase compliance with mitigation guidelines while simultaneously generating revenues to further global ADR efforts.

While a launch tax would be the simplest and preferred method to raise global funds for ADR efforts, a new space treaty could alternatively be negotiated to directly establish economic contributions to the ADR organization from various countries.[519] These contributions could be effectuated in multiple ways. Joseph Imburgia and Timothy Nelson have suggested basing a State's monetary contribution on its relative proportion of the space debris population, akin to a market-share or "polluter pays" principle.[520] However, this would quickly limit the pool of contributors to only space-faring nations, and would also require enormous, upfront contributions from just three or four countries which may be unwilling or unable to satisfy their share of the costs.[521] Alternatively, it has been suggested that all countries which are space-faring nations as well as all those which partake in the benefits of space use and exploration should contribute to the global fund.[522] These contributions could instead be apportioned equitably,[523] similar to the approach adopted by major climate change treaties in regards to carbon emissions,[524] whereby the more industrialized nations contribute the most capital.

Regardless of the method utilized, any new space treaty must seriously address the economics of space debris by empowering the global organization to generate funds to subsidize ADR.

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[518] Macauley, *supra* note 511 at 162; Pelton, *supra* note 259 at 858 & 867; Tian, *supra* note 325 at 125.

[519] Imburgia, *supra* note 509 at 629.

[520] *Ibid*; Timothy G. Nelson, "Regulating the Void: In-Orbit Collisions and Space Debris," (2015) 40 Journal of Space Law 105 at 113.

[521] Akers, *supra* note 390 at 313.

[522] Tian, *supra* note 325 at 123.

[523] Popova & Schaus, *supra* note 50 at 13.

[524] See, e.g., UNFCCC, *supra* note 471 at arts 3(1) & 4(1).

B. An Alternative Approach: Space Treaty Protocols

Any realistic discussion of a new space treaty must confront the fact that no widely adopted space treaty has been created in almost 45 years. Therefore, a comprehensive treaty addressing space debris faces stiff challenges.[525] There is arguably too little political will or desire to presently conclude such a multinational agreement.[526]

However, even if a completely new space treaty regarding space debris is unpalatable, many of the same or similar adjustments discussed above can be made to the existing treaty regime through limited protocols to the current UN treaties. Again, a precondition for such changes would be a viable, binding legal definition of space debris. However, after the definition and legal status of debris is clear, the liability or jurisdiction and control rules applicable to such debris could be modified in piecemeal fashion, separate and apart from those rules that apply to "space objects," so long as enough States would be willing to agree to the changes. While a comprehensive space debris treaty is optimal, even modest adjustments to these treaties could seriously aid future ADR efforts, for example by simply updating the Registration Convention to set a deadline for registering a space object or by a binding obligation to provide updates after orbital movements or fragmentation events,[527] thereby clarifying the status of space objects and their controlling State. While even a protocol to a UN space treaty may seem farfetched, some U.S. politicians have publicly stated that it may be time to revise some of the concepts contained in the OST, especially in relation to the widespread growth of commercial space operators.[528]

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[525] Mirmina, *supra* note 177 at 652-653; Pelton, *supra* note 98 at 77.

[526] COPUOS, *Active Debris Removal, supra* note 20 at 45; Mirmina, *supra* note 177 at 652-653.

[527] Akers, *supra* note 390 at 313-314.

[528] Jeff Foust, "Is it Time to Update the Outer Space Treaty?," (5 June 2017), online: *The Space Review* <http://www.thespacereview.com/article/3256/1>.

C. Concurrent National Efforts

During the negotiation and conclusion of a new space treaty or protocol, States should not sit idly by; they must themselves take aggressive domestic steps to further ADR efforts. These will most easily take the form of requirements embedded in the national licensing systems that most States have enacted pursuant to Article VI of the OST, which requires States to authorize and continually supervise the space activities of their non-governmental entities, but could also take the form of taxes or punitive measures.

1. Licensing Requirements for Active Debris Removal

States can quickly and easily amend their national licensing requirements to overcome some of the challenges inhibiting ADR operations, in much the same way that many have done for space debris mitigation efforts.[529] In essence, States may enact licensing laws and regulations which prescribe preconditions on space activities or require their national space operators to take certain measures or to conduct their space activities in certain ways.

As the simplest example, in order to overcome the lack of an international obligation to remove one's own space debris, a State may simply make debris removal a license condition. In other words, the domestic license required to launch an object into outer space can be conditioned on the license holder agreeing to remove any resulting space debris related to that object, a so-called "assured removal clause"[530] or "assured removal requirement."[531] However, such a licensing provision could only feasibly be applied to a payload and perhaps its rocket stages, since the mandated removal of microparticle exhaust particles or paint flecks or thousands of fragments

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[529] Popova & Schaus, *supra* note 50 at 12.
[530] COPUOS, *Active Debris Removal, supra* note 20 at 40.
[531] Viikari, *supra* note 156 at 759.

from an on-orbit explosion or collision is not economically realistic nor even currently possible. Alternatively, a State could require a potential licensee to either prove an adequate level of solvency or to carry an insurance policy in an appropriate amount to cover the costs of paying the State or a third-party company to conduct ADR to remove any resulting debris.[532] Similar insurance conditions on licenses are already commonplace when it comes to off-setting potential liability for causing damage to persons or property.[533] Finally, States could even reserve for themselves the right to order the license holder to conduct or pay for ADR in an appropriate situation, to be determined by the licensing state on a case by case basis.[534]

States should also make legislative changes within other domestic licensing regimes. For example, they could choose to make exceptions in the domestic legislation or regulations which govern their export controls to authorize the "export" of certain space-related products and technologies without a license for the express and limited purpose of destruction of the debris via ADR-assisted deorbiting. This would obviate the need to apply for and receive an approved license for the export, which as noted in Part III(B)(5), *supra*, can be confusing, costly, and time consuming.[535] Even carving out just a partial exception, such as for only the least sensitive information and technology, would support ADR operations, especially from the United States since most satellites have at least some U.S. export-controlled technology or subcomponents.[536]

The primary benefit of embedding these kinds of conditions into national licensing laws is that the State can thus mandate ADR for objects under its own jurisdiction and control. In this regard, so long as the operation is conducted by an ADR object from the same nation, huge

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[532] COPUOS, *Active Debris Removal, supra* note 20 at 40.

[533] See, e.g., Annette Froehlich & Vincent Seffinga, eds, *National Space Legislation: A Comparative and Evaluative Analysis* (Cham, Switzerland: Springer, 2018) at 162-165.

[534] COPUOS, *Active Debris Removal, supra* note 20 at 33.

[535] *Ibid* at 34.

[536] Jakhu, et al, *supra* note 9 at 131.

inhibitors of ADR can be avoided, namely the pernicious liability and jurisdiction and control mechanisms of the UN space treaties and export control laws.

While amending national space policy, lawmakers should take notice that many national licensing regimes do not apply to governmental space activities, especially military ones, and some even exempt certain government sponsored civilian space activities.[537] Because of this, merely amending a State's domestic space licensing provisions would fail to capture the entirety of its national space operations. In order to fill that gap, States should establish separate guidelines for those excepted government entities to require similar ADR operations, since most space agencies and intergovernmental organizations still comply with various other governmental measures or guidelines regulating their activities.[538] As an example, while the U.S. Department of Defense does not require a license to launch its space objects, it still must adhere to the U.S. Government Orbital Debris Mitigation Standard Practices.[539] Thus, while perhaps not subject to the traditional national licensing process, government activities can still be required to promote ADR operations.

2. Taxes/Sanctions

Similar to the idea of funding a global ADR operations via launch taxes, individual States should impose their own launch fee or launch tax in order to fund their national ADR efforts. In essence, every space launch by a national of that State or occurring from its territory or facilities could be required to pay a mandated surcharge, which can then be applied toward debris removal efforts. The collected resources could be utilized to support a national pledge of reducing a certain percentage of the State's existing space debris per annum. Alternatively, it could fund ADR

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[537] Viikari, *supra* note 156 at 759.

[538] Popova & Schaus, *supra* note 50 at 12.

[539] US, Department of Defense, *Space Policy*, DoDD 3100.10 (18 October 2012, Incorporating Change 1 Effective 4 November 2016) at para 4(d).

research or subsidize or offset the costs of national or private ADR efforts. As previously described, various rebates to this national tax could also be returned for the proper disposal of a space object at its end of life or for compliance with other desirable mitigation measures, like shielding or graveyarding.

Alternatively, instead of a flat tax or tax and rebate structure, punitive sanctions could be imposed for the intentional or negligent creation of space debris. For example, the failure to properly deorbit a payload at its end of life could be met with a fine, perhaps scalable to the size of the resulting debris or the relative dangerousness of its orbit. Finances raised from these punitive sanctions could be used to further supplement the national ADR operations described above.

One benefit of establishing taxes and sanctions at the national level is that these measures can be instituted relatively quickly and with minimal international coordination while treaty or protocol negotiations are still ongoing. At the same time, these measures could form a starting point for groups of States to coordinate and regionalize similar actions, with an eye towards the possibility of eventually forming a global launch fee for ADR, as discussed above.[540] For example, it is not inconceivable that a domestic launch tax unilaterally imposed by an ESA member State might inspire other ESA States to follow suit and eventually to be adopted by all ESA States, perhaps even setting a precedent for inclusion in the new space treaty or protocol.

One potential drawback of such a national launch tax or sanction structure is that early adopting States may inadvertently discourage space launches by their citizens or from their territory and facilities, since they will have created additional costs and punitive regulations that might otherwise be avoidable by simply relocating the space activities. Therefore, until a truly

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[540] Pelton, *supra* note 259 at 857 & 860.

global solution is instituted through a multilateral space treaty, it would be important to determine precisely what level of launch fees or debris sanctions would create a sustainable additional cost for a nation's space industry, while at the same time generating sufficient revenues to adequately subsidize national ADR efforts.

D. Conclusion

To comprehensively address the debris problem in a way that clarifies and incentivizes future ADR efforts, it is critical that States modernize the international space law regime surrounding debris through a new multilateral space debris treaty. Such a treaty must address the major challenges facing ADR efforts: it must compel compliance with COPUOS Mitigation Guidelines; adequately define space debris; clarify debris obligations; alter and alleviate the dual strangleholds of liability and jurisdiction and control; authorize the abandonment of space objects; establish an international regulatory agency for ADR; and create a funding mechanism for the agency's global ADR efforts. If global consensus cannot be reached on such a sweeping treaty, these individual issues must be tackled in piecemeal fashion through protocols to the existing UN space treaties. During what is likely to be a lengthy negotiation process for these changes, individual space-faring States still have a role to play. Until global solutions are realized, they should update their domestic space licensing and taxation laws in ways which incentivize and raise resources for national ADR operations.

CONCLUSION

The congestion of usable Earth orbits with space debris has been many decades in the making. While some are more responsible than others, all space-faring nations have contributed to this debris problem, only a modest portion of which is even observable to mankind. The rampancy of debris has only worsened over time, whether measured by mass or number of pieces of debris. Since widespread recognition of the problem in the early 1990s, the world has witnessed verified on-orbit collisions between space debris and functional satellites, collisions between actual payloads, and numerous intentional, sometimes catastrophic, kinetic ASAT tests. It has also observed a rapid increase in the number of space-faring nations and the maturation of a commercial space industry, both further exacerbating and complicating the space debris problem.

In the face of this unchecked debris growth, significant advances have been made towards practices aimed at mitigating the creation of new debris. Decades of work through multinational space organizations and the UN have ultimately resulted in widely adopted mitigation guidelines, as well as the standardization of spacecraft designs, operation, and disposal. However, these laudable efforts suffer greatly from serious conceptual failures internal to the guidelines, as well as from poor compliance rates. Ultimately, they have proven insufficient. Even assuming perfect compliance with these mitigation measures and the unrealistic hope of zero additional explosions or collisions in space, the debris population will continue to grow, especially in critical areas of LEO. Active debris removal, or the process of capturing debris and relocating it to either a disposal orbit or effectuating its reentry, is therefore necessary to stabilize the space environment and must be carried out as soon as possible.

However, the international space law regime failed to anticipate the problem of space debris and the rise of non-governmental space actors. It is therefore ill-suited to administer the operationalization of widespread ADR efforts. Long-standing, fundamental space law principles embedded in the seminal UN space law treaties stand in the way of effective global ADR. International space law needs to clearly define and situate space debris within its legal structure, or else risk paralysis by would-be ADR actors for fear of undertaking unknown or excessive liability or of violating the rights of other States. It must address and update, if necessary, the concept of "launching States" and their never-ending liability for damage, as well as modernize the currently unworkable liability regime. It must develop mechanisms which loosen the grip of jurisdiction and control of space objects by their States of registry. It must adopt and integrate new legal concepts which enable and facilitate the abandonment or transfer of space objects. Further, it must grapple with the lack of a coordinating agency for global ADR efforts and the nationally and internationally imposed export controls which pervade the space industry and stifle ADR. Overlapping these significant legal constraints are the enormous costs which must be shouldered to clean up the space environment and the distrustful national security apparatuses which must be convinced that ADR objects are not secret weapons.

Going forward, states, national space agencies, intergovernmental agencies, and multinational space organizations should begin considering adjustments to this stifling international space law regime, ideally through a new multinational space debris treaty or ADR-positive protocols to existing treaties. At the very least, they must begin to develop a regulatory regime which facilities ADR, hopefully via an ADR-coordinating global agency, whether created from scratch through international agreements or assigned to a currently existing entity, such as ICAO. This agency needs to be empowered to raise funds to stimulate ADR technology, subsidize ADR efforts, and perhaps even conduct ADR itself. At the same time, individual States should be taking local measures to adjust their own licensing requirements to facilitate and encourage ADR, while at the same time instituting new launch taxes or even sanctions for the creation of debris.

These legal and policy challenges are no small tasks, but they must be tackled in order facilitate ADR and preserve the long-term sustainability of our precious Earth orbits.

FIGURES

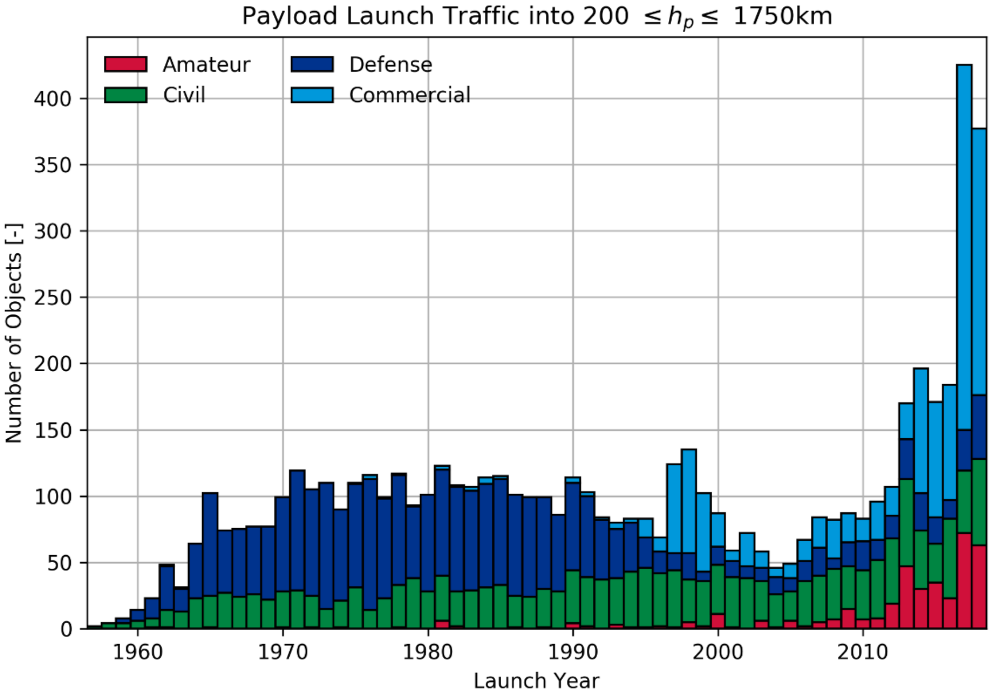

Figure 1. Credit: ESA

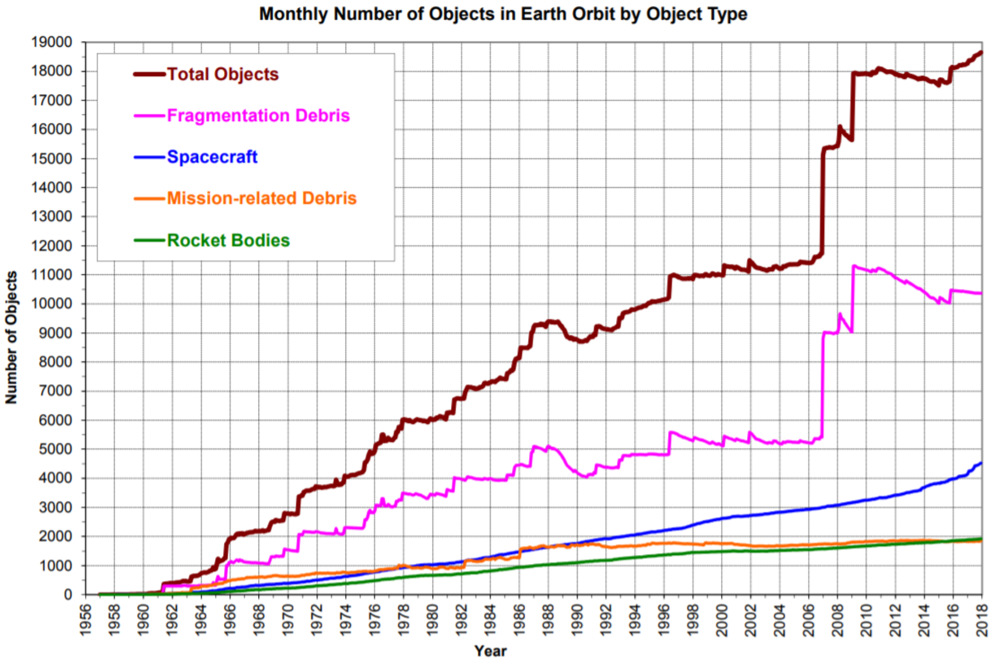

Figure 2. Credit: NASA

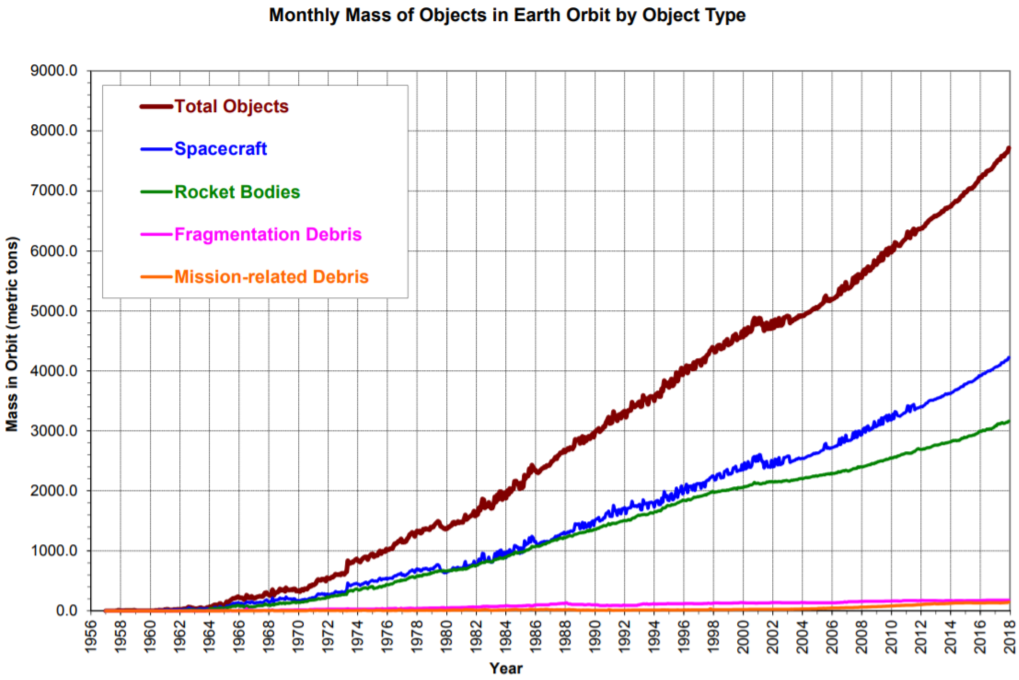

Figure 3. Credit: NASA

Relative Segments of the Catalogued In-Orbit Earth Satellite Population

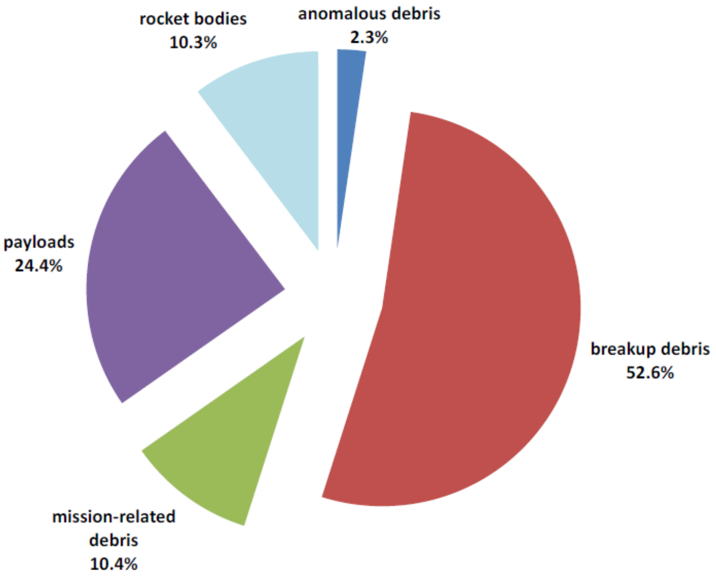

Figure 4. Credit: NASA

SSA Coverage in the US

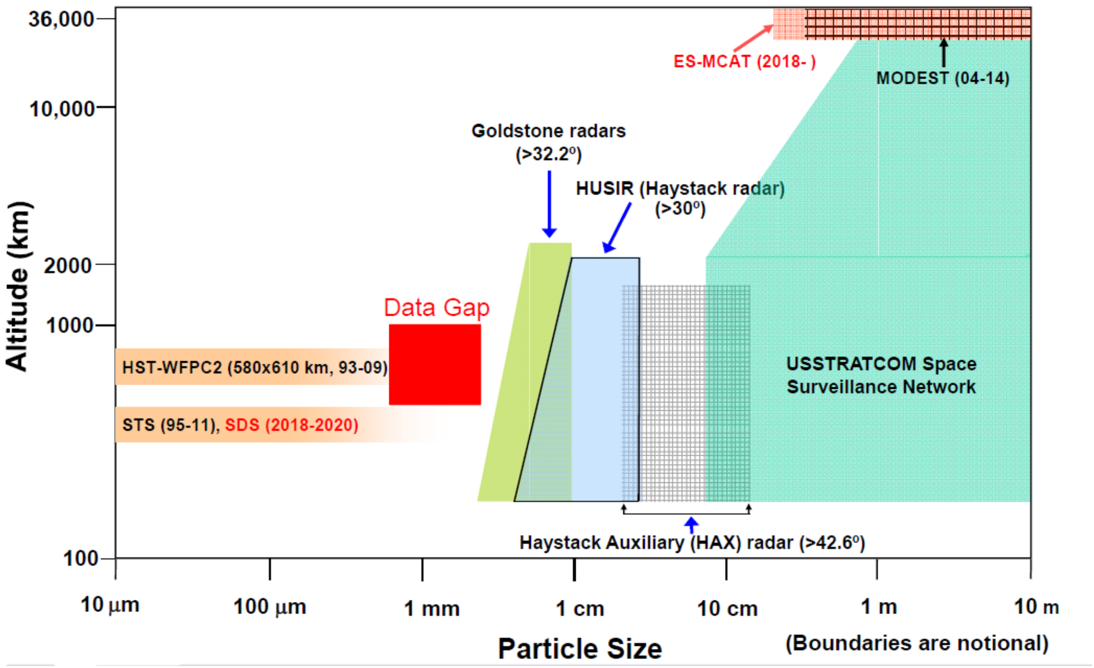

Figure 5. Credit: NASA

Number of Objects Catalogued by the SSN Over Time

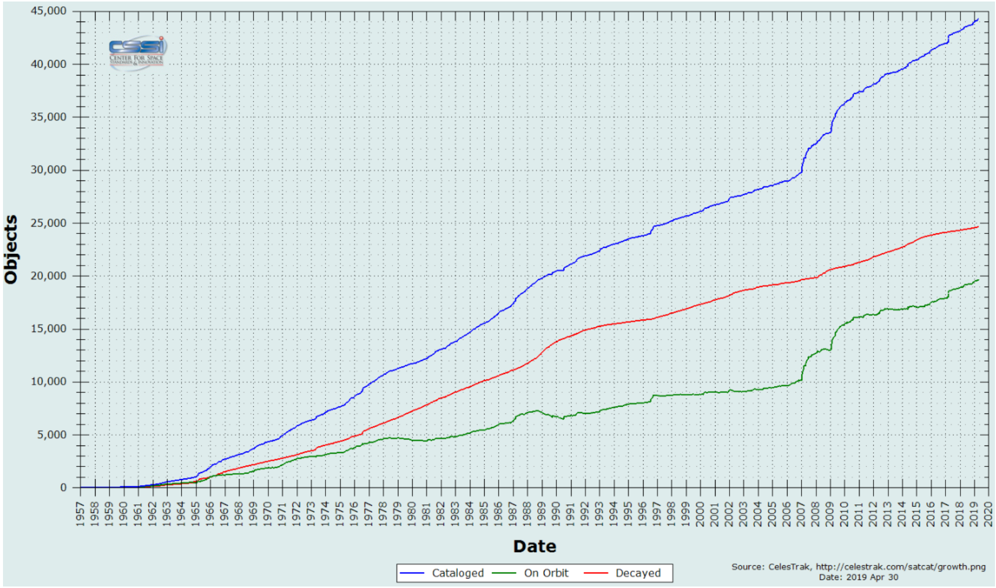

Figure 6. Credit: CelesTrak

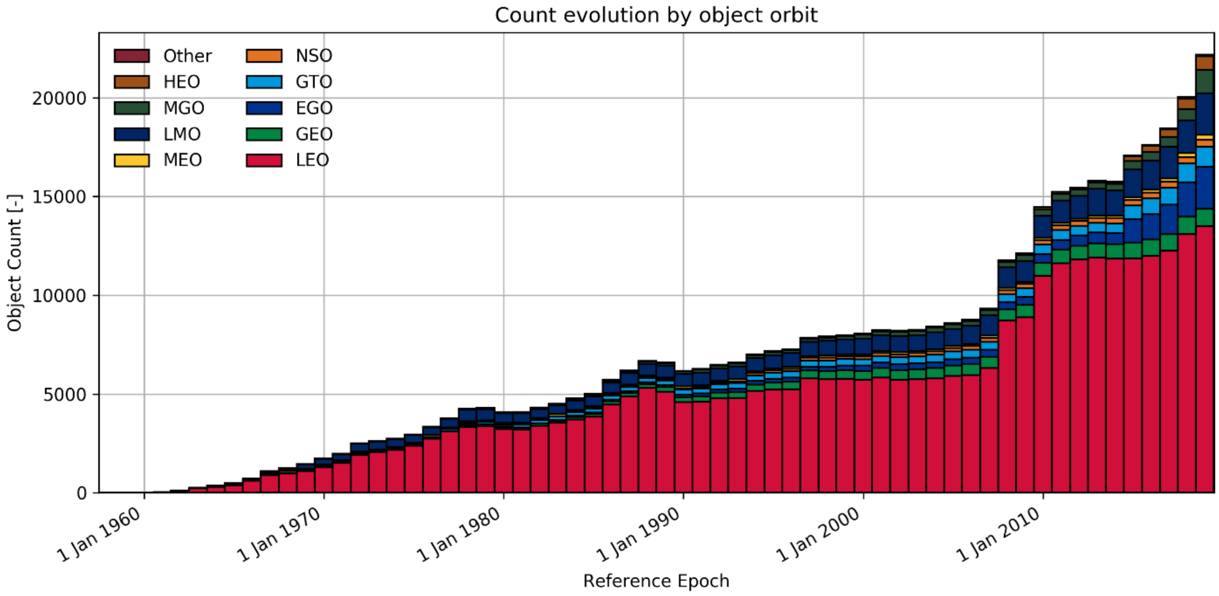

Figure 7. Credit: ESA

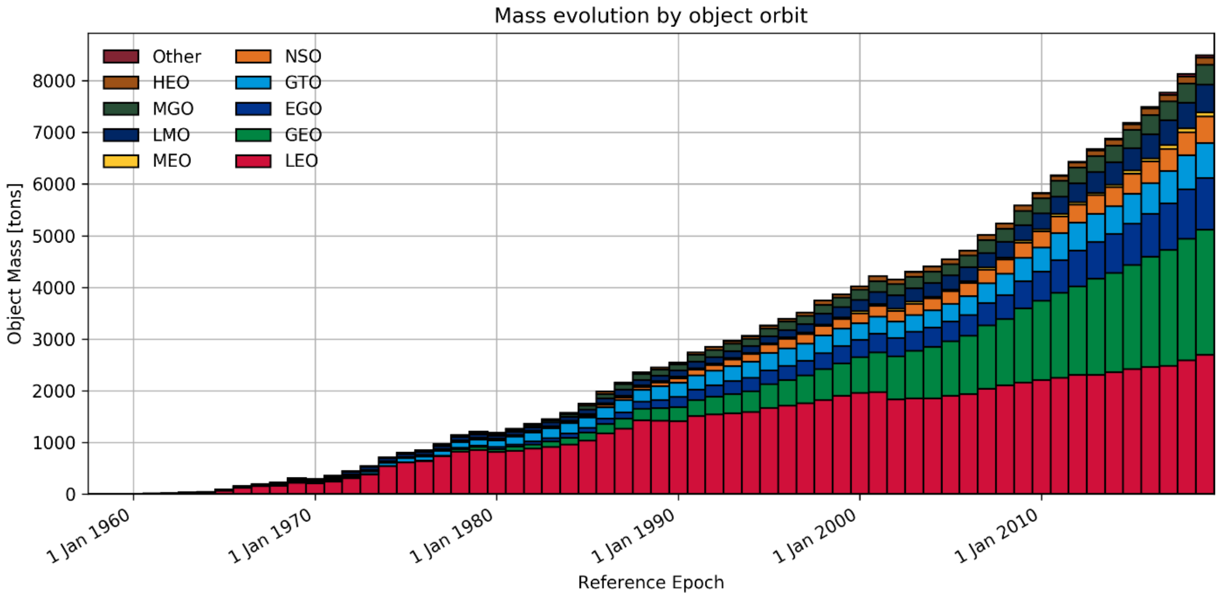

Figure 8. Credit: ESA

The Global Space Economy in Context

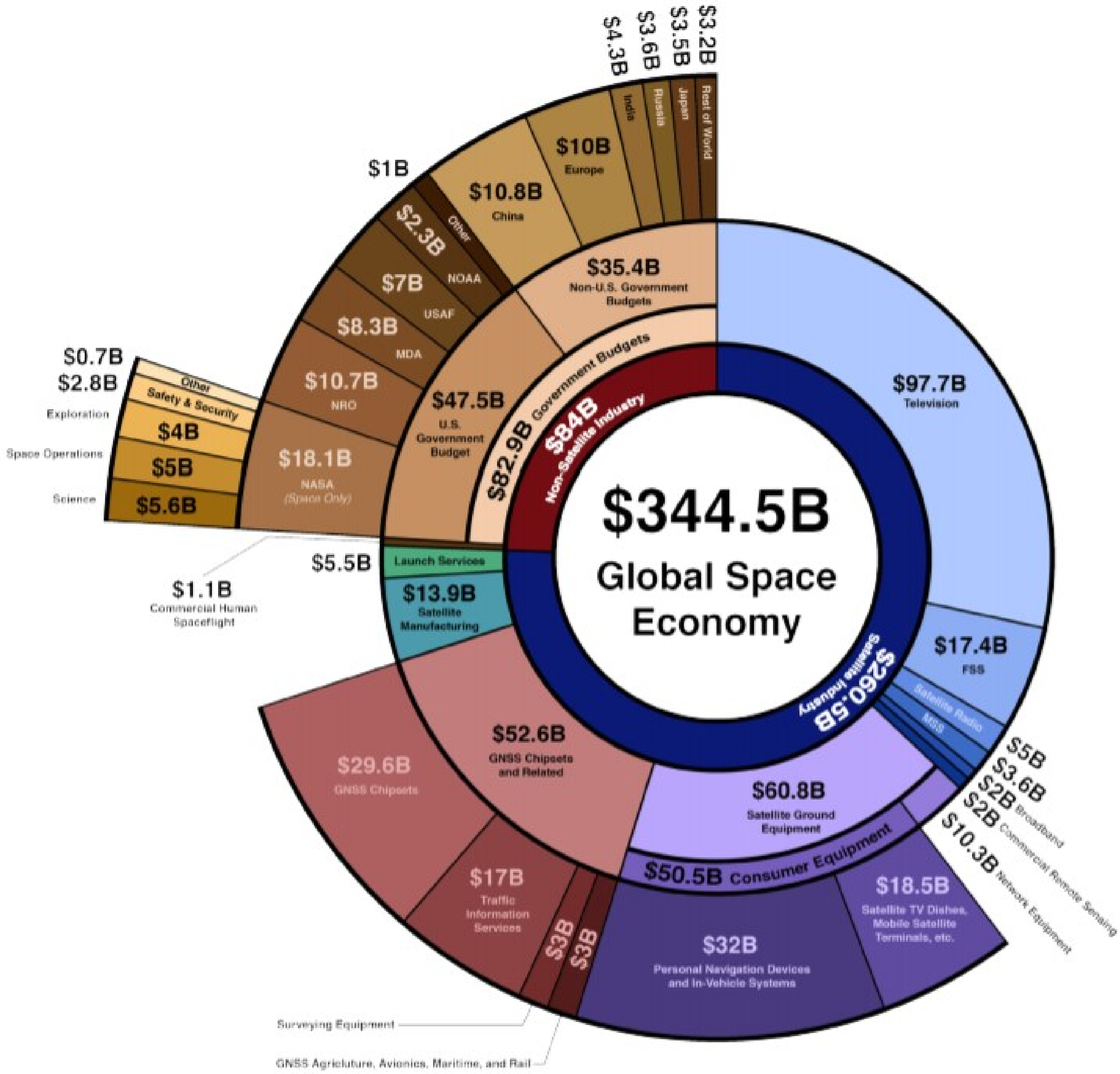

Figure 9. Credit: FAA

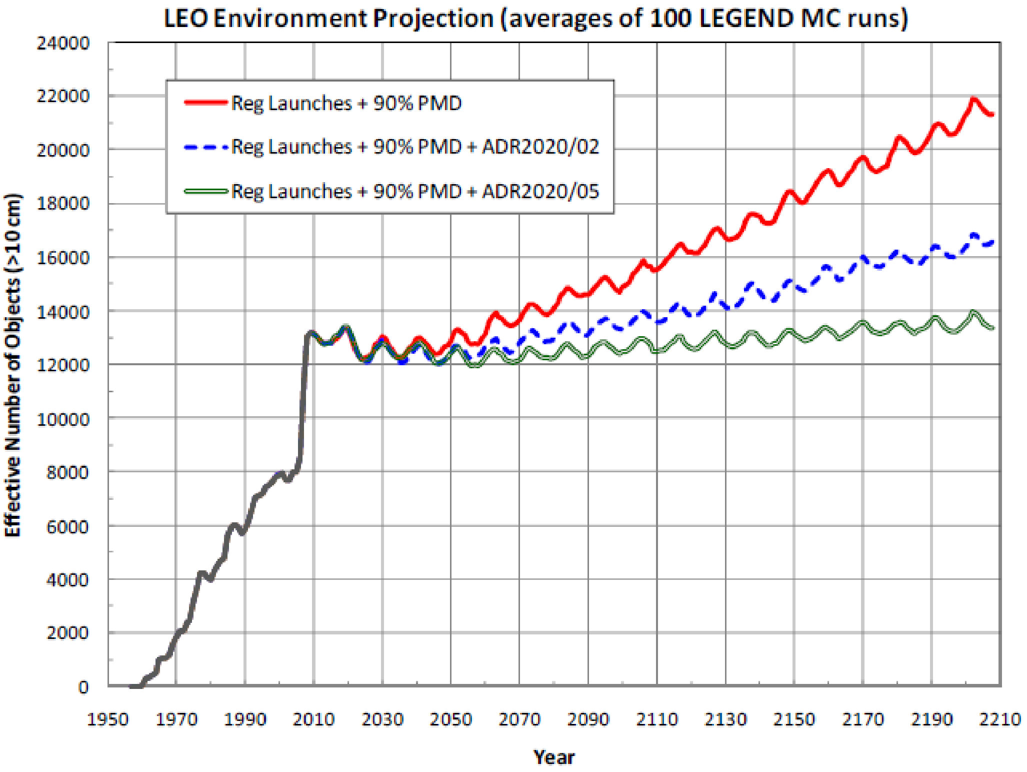

Figure 10. Credit: J.-C. Liou, NASA

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