Orbital Debris in Low Earth Orbit

Mitigation and Solutions through Policy and Technology

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Introduction

The significant increase in commercial and international space activity created an exponential climb in the amount of congestion and orbital debris, particularly in low earth orbit (LEO), which is forcing the U.S. to adjust how it operates in space while incorporating proliferated LEO-based missile warning capabilities into its space architecture. Space debris is commonly defined as man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional (UNGA, 2007). The problem of space debris is only increasing, as governments and commercial companies race to deploy communication and internet provider satellites in LEO. For example, SpaceX plans to launch more than 40,000 Starlink satellites to provide global internet, and China plans to launch almost 13,000 satellites in response (Chen & Chen, 2023). Amazon's Project Kuiper plans to launch a constellation of 3,236 satellites in LEO, and other companies from United Kingdom-backed OneWeb, Bharti Enterprises of India, and Eutelsat of France all plan to launch a proliferated LEO constellation (Project Kuiper, n.d.). Orbital debris, mostly caused by fragmentation events both accidental as well as intentional intercepts by surface-launched missiles (anti-satellite weapons), will only increase in LEO and will lead to a commensurate increase in collisions, causing even more debris (Kessler & Cour-Palais, 1978). This perspective underscores the importance of addressing the issue now, before it becomes impossible to contain and causes a catastrophic incident through further chain reactions.

This paper posits that risks associated with orbital debris can be mitigated, and it presents a multidisciplinary methodology to combat the growing challenge. The paper will first examine the current and ongoing international and U.S. domestic legal framework that is relevant to the space debris problem. Then, the paper will examine current and future space debris mitigation and removal technology solutions to identify potential approaches that can be leveraged to help address the challenge. Third, this paper will recommend a three-pronged approach to resolve the orbital debris issue by (1) investing in enabling technologies, (2) fostering a commercial market, and (3) encouraging "good steward" operational behavior with accountability measures.

Orbital Debris Explained

The significant increase in commercial and international space lift has led to an exponential climb in the amount of congestion and space debris, particularly in LEO. Existing international space law, treaties, and current U.S. policy regarding space norms and orbital debris all restrict America's ability to launch and operate in the space domain, while simultaneously advantaging competitors that do not adhere to these standards. The key question to address is how technology and policy can enable the U.S. to achieve national objectives while serving as an example of responsible space behavior, particularly as the Department of Defense pivots to a more resilient space architecture as evidenced by the Space Development Agency's (SDA) proliferated missile warning constellation that is designed to be fielded in LEO (Space Daily [SD], 2021).

The concept of space debris is based on the Space Debris Mitigation Guidelines established in 2007 by the United Nation's Committee on the Peaceful Uses of Outer Space (UN COPUOS). These guidelines define orbital debris as all man-made objects, including fragments and elements thereof, both in Earth orbit and re-entering the atmosphere, that are non-functional (UNGA, 2007). The European Space Agency (ESA) has noted that "in more than 60 years of space activities, more than 6,050 launches have resulted in some 56,450 tracked objects in orbit, of which about 28,160 remain in space and are regularly tracked by the U.S. Space Surveillance

Network and maintained in their catalogue…only a small fraction – about 4,000, are intact, operational satellites today" (ESA, n.d.-a, para. 3).

Most debris emanated from fragmentation events, both accidental and intentional intercepts by surface-launched missiles, such as anti-satellite weapons. Non-fragmentation debris is mostly micro-dust and particles released during solid rocket-motor firings or ejection of reaction cores. Also, ultraviolet radiation erodes paint and thermal covering on satellites, further contributing to the amount of debris on-orbit. The Kessler Syndrome posits that as the debris in LEO increases, it will lead to a commensurate increase in collisions, creating even more debris (Kessler & Cour-Palais, 1978). This view underscores the importance of addressing this issue now, before it becomes impossible to contain and causes a catastrophic incident with further chain reactions.

Two qualifiers must be addressed to limit the scope of the discussion. While space debris is present in all orbital regimes, the maximum debris concentration is found at altitudes of 800-1,000 kilometers and again near 1,400 kilometers, which from the DOD perspective places the planned SDA constellations square in the center of the challenge. That said, the key to addressing the most pressing issues with orbital debris is to develop procedures that can be applied to sweep areas in LEO, or altitudes below 2,000 kilometers. The other important distinction centers on the stakeholders involved in space debris. Although all nations depend in some way on space-based assets, there are but a few nations that are considered 'spacefaring' and possess the capability to launch objects into space, which includes the European Space Agency as well as commercial companies that are all focused on lowering the barrier to entry for space access.

International Agreements

International agreements have expanded into a necessary part of 21st century international relations. In particular, the multilateral approach has come to the fore over the past 70-80 years, as relationships between nations grew more complex and integrated. According to Thorp, the end of World War II, “brought universal agreement that hereafter international issues should be solved on a multilateral basis wherever appropriate” (1947, p. 318). One of the key challenges associated with these agreements is how to hold the parties accountable. Often, international agreements are “entered into by states but are not intended to be legally binding on the parties,”, which drives uncertainty whenever a nation fails to live up to its end of the bargain (Schachter, 1977, p. 296).

In 1959, the United Nations General Assembly established the COPUOS, which was “tasked with reviewing international cooperation in peaceful uses of outer space, studying space-related activities that could be undertaken by the United Nations, encouraging space research programmes, and studying legal problems arising from the exploration of outer space” (United Nations Office for Outer Space Affairs [UNOOSA], 2022, para. 1). The United Nations Office for Outer Space Affairs (UNOOSA) is the entity charged with conducting activities to build States’ capacity in space law and policy, ensuring an equal access to the benefit of space for all. One way UNOOSA provides this transparency and understanding is through the maintenance of space law publications, to include treaties and principles, as well as the Registry of Objects Launched in Outer Space.

By its very nature, international agreements must be written broadly to obtain consensus amongst all interested parties. As previously noted, this makes them open to interpretation that tends to dilute implementation and efficacy. More recently, as the exploration of space has increased, there has been a commensurate uptick in the difficulty in achieving consensus on new policies or agreements. The Treaty on Prevention of the Placement of Weapons in Outer Space and the Threat or Use of Force Against Outer Space Objects (PPWT) was first introduced by Russia and China in 2008 and revised in 2014, but it has been rejected by the United States (McClintock, et al., 2021). In a similar vein, U.S. efforts to push the Artemis Accords encountered resistance from Russia. Therefore, international consensus regarding the use of space revolves around the so-called 'five treaties,' which were enacted in the 1960s and 1970s. As a result, there are three international agreements this paper will examine that are most closely related to orbital debris management and mitigation.

Foundational Agreements

The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, commonly known as the Outer Space Treaty (OST), was adopted in October 1967 under the U.N. General Assembly and "is considered the basis of modern international space law" (McClintock, et al., 2021, p. 6). The OST emphasizes the responsibility of States for activities in outer space, and Article VI clarifies that any activities conducted by a non-government entity still falls under the purview of the appropriate State. Furthermore, Article VIII specifies that the launched object remains the property of that State. Regarding orbital debris, the OST also underscores the responsibility of all parties to avoid contamination and interference with other activities (UNOOSA, 2017).

Article VII of the OST further delineates the liability of States for damage caused by launching objects into space, but this was addressed further in the 1972 Convention on International Liability for Damage Caused by Space Objects (the Liability Convention). An important aspect of the Liability Convention is its definition of a launching State, which includes additional States that participate in a joint launch activity (UNOOSA, 2017). The December 25, 2021, launch of the Ariane 5 rocket provides a good example of viewing a launch activity through the combined lenses of the OST and the Liability Convention. On behalf of the ESA, the French company Arianespace conducted the launch carrying a U.S. payload (the James Webb Space Telescope) from the ELA-3 launch complex in the spaceport near Kourou, French Guiana. This activity resulted in multiple States absorbing some form of liability.

Furthermore, the Liability Convention specifies that launching States' liability extends to damage caused in space or on the surface of the Earth. The latter category can lay claim to the only case brought under the Liability Convention, the orbital decay and subsequent crash of the Soviet satellite Cosmos 954 into the Canadian countryside on January 24, 1978. This case provides examples of how difficult it could be to prove liability and receive recompense under the Liability Convention. For example, many observers expressed shock that the Soviet Union provided any compensation to Canada due to the potentially loose interpretation of 'damage' under the 1972 agreement and considering the remote area in which Cosmos 954 eventually crashed (Cohen, 1988).

The 1975 Convention on Registration of Objects Launched into Outer Space (Registration Convention) provides guidance that signatories will maintain a registry of all objects launched into space and furnish that information to the United Nations (UNOOSA, 2017). The Registration Convention details what information should be included in this registry, and United Nations General Assembly (UNGA) Resolution 62/101 provides a series of recommendations to standardize details provided in the registration of space objects (UNGA, 2008). This resolution, enacted on December 17, 2007, also acknowledged the potential for a space object to change ownership (UNGA, 2008). As previously mentioned, the UNOOSA is the agency charged with maintaining the Registry of Space Objects.

The Liability Convention outlines the shared responsibility in joint space activities, and UNGA Resolution 62/101 acknowledges the complexity of the responsibility structure due to the different types of organizations now involved in conducting space activities. The foremost example, the ESA, was established in 1975 and is currently comprised of 22 member states that work together to share financial and scientific resources to further space research and exploration. Despite the complexity involved in negotiation and decision making between 22 member states, the ESA continues to maintain its focus on safety and developed a Clean Space initiative to pioneer new techniques to remove space debris and deorbit defunct satellites (ESA, n.d.-b).

	United Nations Treaties		
	1967	**1972**	**1975**
	OST	**LIAB**	**REG**
China	Ratified	Ratified	Ratified
India	Ratified	Ratified	Ratified
Iran	Signed	Ratified	Signed
Israel	Ratified	Ratified	
Japan	Ratified	Ratified	Ratified
Korea, North	Ratified	Ratified	Ratified
Korea, South	Ratified	Ratified	Ratified
Russia	Ratified	Ratified	Ratified
United States	Ratified	Ratified	Ratified
European Space Agency*	22	21	19

Table 1. Status of UN treaties for space launch nations

**NOTE: Of the 22 member states of the ESA, all have ratified the 1967 Outer Space Treaty; all but Estonia ratified the 1972 Liability Convention; and all but Estonia, Ireland, and Romania ratified the 1975 Registration Convention (UNOOSA, 2022).*

The other relevant international government forum is the Inter-Agency Debris Coordination Committee (IADC), which emphasizes coordinating activities when responding to issues related to synthetic and natural debris in space. The IADC includes 13 member agencies representing Italy, Spain, China, Canada, Germany, India, Japan, South Korea, Russia, Ukraine, the United Kingdom, the United States, and the ESA. The IADC focuses on the exchange of information and cooperation on space debris research activities, as well as the identification of debris mitigation options (Inter-Agency Debris Coordination Committee [IADC], n.d.).

United States Space Policy

The United States has long been at the forefront of developing policy guidelines for the use and exploration of space. For example, the IADC website lists many references for space debris mitigation policies, guidelines, and standards, and the majority of these publications are from the United States. Of the 11 references listed, 6 are U.S. documents, 2 are U.N., 2 are ESA, and 1 is French (IADC, n.d.). Several of these policies will be contrasted to determine the balance between enabling the U.S. to serve as a responsible leader in the use of space, while acknowledging that many other actors are not fulfilling their commitments. It is also in the interest of the United States to ensure that it balances self-limiting policies with requirements as technology continues to develop to ensure its national space defense architecture remains operational. Unlike the previously mentioned international agreements, which are generally older due to a lack of multilateral consensus in recent years, the Trump and Biden administrations developed more recent policies that provide a more contemporary perspective.

Leib argues that America's desire to be a leader in space – not allowing other nations to dominate the discourse – is rooted in the concept of manifest destiny, tying this influence to the sense that the U.S. is a leader here on Earth (1999). Despite these types of criticisms, U.S. policy centers on serving as a global leader in the responsible use of space as well as ensuring a secure, stable, and accessible space domain for the world. During Vice President Kamala Harris' visit to Vandenberg Space Force Base in California on April 18, 2022, she announced that the United States would not conduct direct-ascent anti-satellite (ASAT) missile testing, as these types of tests create long-lived debris that threaten satellites and jeopardize the long-term sustainability of space (White House, 2022a). This message underscored the importance the U.S. places on managing and mitigating the growing congestion.

One of the key documents the IADC cites as a space debris mitigation standard is the United States Orbital Debris Mitigation Standard Practices (ODMSP). The ODMSP was originally published in 2001 with the goal of minimizing debris through safer operations, including launches and flight profiles. As the space environment evolved, the U.S. government determined the document required an update and subsequently published revised guidelines in November 2019. The ODMSP provides debris mitigation guidance for accidental explosions, operational configuration, flight profiles, space object disposal, and the normal release of debris during operations (National Aeronautics and Space Administration [NASA], 2019).

National-level strategic documents may not provide specifics for conducting activities in space, however they highlight the importance of space as a domain. In 2018, President Trump issued the United States Space Strategy that emphasized the importance of space to America's economic prosperity. This document called for strengthening the safety, stability, and sustainability of United States space activities (White House, 2018). Soon after, in June 2020, the

Department of Defense unveiled the Defense Space Strategy (DSS), which reiterated the national interests tied to space and establishing it as a warfighting domain. These two foundational events also coincided with the standup of the SDA, which signaled a significant pivot from U.S. space-based missile defense operating in GEO to the incorporation of proliferated LEO constellations to provide this critical national capability. As the U.S. shifted to a heavier reliance on LEO-based capabilities, the need to manage and mitigate the growing orbital debris issue became more apparent. Additionally, the U.S. also established a new branch of the Department of Defense, the U.S. Space Force to focus its space acquisition and warfighting into a single service. One of the key defense objectives assigned to the Space Force by the DSS is to ensure space stability, including the task to "uphold internationally accepted standards of responsible behavior as a good steward of space; and support U.S. leadership in space traffic management and the long-term sustainability of outer space activities" (Department of Defense [DOD], 2020, p. 2). The DSS also described the issue facing multilateral consensus as, "international understanding and agreement of what constitutes unsafe, irresponsible, or threatening behavior in space is nascent" (DOD, 2020, p. 4).

It is also worth noting that the Biden administration reiterated the importance of space by publishing a United States Space Priorities Framework in December 2021 stating, "U.S. national security space operations will continue to comply with applicable international law and demonstrate leadership in both the responsible use of space and stewardship of the space environment" (White House, 2021, p. 6). A key priority outlined in the Space Priorities Framework is to preserve space for current and future generations, which includes the U.S. serving as the lead in strengthening global governance of space activities by demonstrating "how space activities can be conducted in a responsible, peaceful, and sustainable manner," while also bolstering space situational awareness and prioritizing space sustainability through the mitigation, tracking, and remediation of space debris (White House, 2021, p. 7). President Biden also emphasized the importance of space within his 2022 National Security Strategy (NSS), by identifying space as an area that must be protected and accessible for all. This current NSS states that America will "work alongside the international community to ensure the domain's sustainability, safety, stability, and security" and expresses a desire to "responsibly steward the space environment" (White House, 2022b, p. 45).

On July 7, 2021, Secretary of Defense Lloyd Austin issued a memorandum outlining the Tenets of Responsible Behavior in Space, with one of the five tenets specifically aimed to "limit the generation of long-lived debris" (Austin, 2021, para. 2). The memo also directed the Commander of U.S. Space Command to develop additional guidance regarding the tenets. On February 9, 2023, Secretary Austin approved the associated behaviors that were submitted by General James Dickinson. Specifically, Behavior 2.1 declares: "Design, operate, and maintain space objects through end-of-life disposal in ways that limit the generation of long-lived debris" (Austin, 2023, TAB A, para. 2.1).

The final piece of recent U.S. policy addressing space debris is the National Orbital Debris Implementation Plan (July 2022), which provides U.S. government interagency guidance to address orbital debris challenges. This plan lays out the specific activities related to space debris that is required to be coordinated across all U.S. government departments and agencies. The activities described include monitoring the orbital debris environment, understanding the effects of space weather on satellite predictions, regulating space activities, remediating debris, and collaborating with the international community (National Science and Technology Council [NTSC], 2022).

These policies exemplify the desire of the United States to set the standard of responsible space behavior. Strategy and policy can provide prescriptive rule sets for government agencies, but in the end, legislation is needed to ensure that corporations also adhere to the desired behavior. This view is even more critical when examined through the lens of appropriations, which can include directive language on the use of federal funds to meet specific requirements such as orbital debris mitigation plans. To further codify these U.S. space policies into law, the previous Congress took up two pieces of legislation, but at the time of this writing, neither had received the requisite support for passage to the President. They are worth examining, however, as both proposals provide a strong foundation to counter the orbital debris issue.

The Orbital Sustainability (ORBITS) Act was introduced in the Senate in September 2022, and it passed unanimously in December of the same year. The ORBITS Act focused on the remediation of orbital debris and the development of standard practices to support a safe and sustainable environment in space. The nation's increased reliance on space and the growing threat of orbital debris are the key factors that led to the introduction of this legislation. In addition, the text of the ORBITS Act specifically notes the importance of United States leadership in mitigation and remediation efforts for orbital debris. The ORBITS Act emphasizes that best practices for space safety throughout the continuum of operations, including transparent data sharing, is also critical to these efforts (ORBITS Act of 2022, 2022). Although the Senate passed this legislation, it was not taken up by the House before the conclusion of the 117th Congress.

In December of 2022, Congressmen Don Beyer and Donald Norcross introduced the Space Safety and Situational Awareness Transition Act. This bill is intended to promote space safety by providing the foundation to understand where objects are located in space to help predict debris patterns. In addition, it emphasizes the global leadership role for the United States as "essential for the safety and sustainability of the space environment" (Space SSA Transition Act of 2022, 2022, sec. 201(5)). The bill targeted appropriations for the Department of Commerce as well as NASA to enable coordinated space situational awareness efforts across commercial entities and the U.S. government and to make that information available to the public and international community. In his official press release, Congressman Norcross emphasized that as "space becomes more crowded every day, we must manage the risk of collisions, ensure the safety of spacecraft, and support the sustainability of space for the future" (Beyer, 2022, para. 3). Although introduced in the House on December 14, 2022, upon the conclusion of the 117th Congress, this bill had not been discharged from the Subcommittee on Space and Aeronautics to the House of Representatives for a vote.

Department of Defense Impacts

Secretary Austin's aforementioned Tenets of Responsible Behavior in Space are a necessary standard for the U.S. to protect its space assets and to ensure the long-term viability of space operations. While there are impacts from the self-imposed restrictions, there is a clear need to establish norms and standards as on-orbit congestion continues to increase. The specific challenge of orbital debris mitigation affects every space user, and its impacts range from launch cancellations due to debris fields and probability of collision to the loss of life for astronauts (Georgescu, et al., 2019, p. 146). Therefore, it is critical for the Department of Defense to operate as a responsible user of space to protect America's launch and space operations.

On October 31, 2022, the Assistant Secretary of the Air Force for Space Acquisition, Mr. Frank Calvelli, released his Space Acquisition Tenets to drive three priorities for National Security Space (NSS) acquisition: speed, resilience, and integration (2022). These priorities are wholly dependent upon the DOD's ability to introduce orbital diversity and leverage the commercial marketplace, which will only be achieved through an increased focus on mitigating orbital debris for all users and operators. At the nexus of both tenets, the Space Force's SDA is leading the drive to meet Secretary Calvelli's objectives while also complying with Secretary Austin's direction. The SDA will be required to incorporate the responsible use of space into its program strategy while actively pivoting from the Space Force's traditional missile warning architecture using low quantity, bespoke Geostationary Orbit (GEO) based missile warning and tracking satellites to a smaller statured, proliferated Low Earth Orbit (LEO) based constellation set to field between 2023 and 2030 (Space Daily [SD], 2021).

SDA's second constellation is designed to provide "global indications, warning, tracking, and targeting of advanced missile threats, including hypersonic missile systems" (Space Development Agency [SDA], n.d., para. 1). Dr. Derek Tournear, the Director of the SDA, outlined his vision for the National Defense Space Architecture, which he said, "will consist of a layered approach, eventually featuring hundreds of satellites that can track targets such as missiles, hypersonic vehicles and other objects; provide position, navigation and timing for warfighters in GPS-denied environments; and communicate with platforms and warfighters on Earth and between other satellites" (SD, 2021, para. 8). The shift to incorporate a more layered space architecture leveraging both legacy GEO-based systems as well as proliferated LEO constellations is particularly significant in light of the Secretary's tenets, since LEO is where most orbital debris is located due to its commercial viability and relative ease of access. Adding entire constellations of critical national security satellites to provide a layered missile defense capability increases resiliency through orbital diversity, but simultaneously exposes those satellite vehicles to the most congested orbit where satellites will interact countless times per day with commercial assets, foreign government assets, and orbital debris.

Many of the activities in space are codified in the ODMSP, as this document outlines the on-orbit regulations for U.S. space assets. "The guidelines originally had four fundamental objectives: control of debris released during normal operations, minimize debris generated by accidental explosions, limit the chance for satellite collisions during launch and orbital lifetime, and remove spacecraft and orbital stages at the end of their mission operations from the densely populated orbit regions no longer than 25 years after mission completion" (Cottom, 2021, p. 104). Additionally, in September 2022, the Federal Communications Commission (FCC) enacted a more restrictive and legally binding standard for FCC licensed satellites and for foreign satellites seeking access to U.S. markets. This change lowered the ODMSP twenty-five-year satellite removal standard to no more than five years, which will require planned active or passive disposal to comply with the law (Federal Communications Commission [FCC], 2022). While the change is needed to corral the growing orbital debris, many experts still insist a more active approach is required to manage the challenge.

Enabling On-Orbit Technologies

As far back as 2011, there have been model-based predictions highlighting the growing orbital debris concern and its impacts to the space domain if left unchecked. Mr. Benjamin Bastida Virgili, an orbital debris expert from ESA, led an analysis that showed the impact of the growing congestion even if the launch rate were to completely halt. His research concluded that passive mitigation standards such as the FCC's new five-year law and Secretary Austin's Tenets are necessary but insufficient by themselves to control the cycle of debris that has been going since the first satellite launch. Virgili goes on to state, "predictions show that the population has already reached a point, where the number of objects would increase even without further human interaction. This also means that current mitigation measures are insufficient to stop this growth" (Virgili & Krag, 2011, p. 1). Virgili's conclusion underscores the importance of both passive and active mitigation processes to ensure the U.S. maintains its ability to leverage commercial and DOD space capabilities.

The technology to enable active orbital debris mitigation divides into four sub-groups: sensors to locate and track debris, attitude control systems/propulsion to maneuver for ingress and egress, the ability to identify the inertial parameters of the object, and the mechanism to grapple or collect the orbital debris. Of those four sub-groups, the most technically challenging is the sensor package to assess movement in both non-cooperative and cooperative operations.

Some of the sensor solutions address both location and tracking, as well as measuring the six degrees of freedom state of a target (Bezouska & Barnhart, 2019); these technologies are fundamentally tied to active debris mitigation. Professor David Barnhart is currently a University of Southern California researcher who previously co-founded Millennium Space Systems. His team is working to develop space technologies and architectures, notably the satellite swarm capability to, "cooperatively determine position and orientation (known as pose) of their constituent satellites by collecting and sharing relative pose measurements" (Bezouska & Barnhart, 2019, p. 1). This technology would help resolve the most challenging aspect of active debris mitigation: identifying, tracking, and determining orbital parameters to a high enough fidelity to safely maneuver and grapple the object.

Another viable solution is the commercially developed Kall Morris Incorporated (KMI) design for locating and grappling space debris. During an interview with Mr. Troy Morris, KMI co-founder and Director of Operations, he provided an overview of the main technical challenge for active debris removal and KMI's solution when he stated, "Retrieving orbital debris is difficult in a non-cooperative capture. This presents a challenge when the debris transfers rotational energy, which can in turn create more debris, making it vital to determine the rotation of object before attempting to retrieve it" (T. Morris, Personal Communication, March 16, 2023). KMI uses its proprietary solution TumblEye, that observes the target on approach and determines rotation in each axis, enabling safe and secure interaction (T. Morris, Personal Communication, March 16, 2023).

Academic researchers proposed a novel solution that provides a workaround to circumvent the complexity and uncertainty of the on-orbit swarm technology and the sole reliance of only using visual reference to determine orbital parameters. This approach is based on the utilization of a "flexible rod to change a target's movement, which is a prerequisite to identify the true values of the target's dynamic properties." Their research concludes that, "for identification of the physical properties of an unknown floating target in orbit, visual observation is safe but, when used alone, it cannot fully identify all the inertial parameters of the target object" which makes their solution unique while still allowing the use of complementary on-orbit maneuver technologies such as commercial attitude control systems (Meng, et. al., 2019, p. 573).

If successful, either of these technologies would resolve the most complex technological challenges that will enable the ability to locate and remove orbital debris. Fortunately, there are dozens of commercial companies attempting to resolve these challenges in their pursuit of overarching on-orbit objectives, such as logistics and refueling, which provides multiple complementary technologies required for active orbital debris mitigation.

Translating Technological Advances into Strategy

The aforementioned technologies offer progress toward building solutions to mitigate the growing orbital debris problem. There are dozens of companies and as many approaches attempting to resolve the on-orbit issue. Therefore, examining a handful of key enabling technologies offers the best opportunity for the U.S. to respond to the congestion in space while maintaining its ability to operate. National security systems are at increased risk without widely adopted norms of behavior in space and are exacerbated by the uncontrolled orbital debris. Missile warning systems depend on a safe and reliable operating environment to perform their nationally critical mission across both GEO and LEO, therefore a mitigation plan that covers a comprehensive and multi-layered approach to stem and dispose of orbital debris will be required to address the issue in a meaningful way. A multidisciplinary approach incorporating policy and technology with intersecting lines of effort will maximize the likelihood of success.

One critical input to the multidisciplinary approach is the identification and incorporation of existing efforts both nationally and internationally. Universities have also teamed with government and industry to help address the issue through research and development of innovative technologies, as evidenced by Professor Barnhart’s project through his engineering course to create orbital debris remediation solutions. Within the Space Force, the Assured Access to Space program office is pursuing efforts to service and maneuver satellites, and these efforts will demonstrate and employ technology that is complementary for active orbital debris mitigation. Moreover, the Space Force’s SpaceWERX Orbital Prime team provided 124 companies with seed-funding for debris remediation (Holt, 2022).

Multiple other efforts within the U.S. government offer promise toward orbital debris mitigation efforts. During an interview with Professor Barnhart, he shared how the Defense

Advanced Research Projects Agency's (DARPA's) Tactical Technology Office started a program to leverage satellite's star trackers for change detection, which would help inform the visual identification of orbital debris (D. Barnhart, personal communication, March 24, 2023). Within the Office of the Director of National Intelligence, the Space debris Identification and Tracking (SINTRA) program intends to "drive the state of the art to detect, track, and characterize lethal non-trackable orbital space debris" (Intelligence Advanced Research Projects Activity, n.d., para. 1). NASA's Astromaterials Research & Exploration Science division features a program office focused on orbital debris, which oversees efforts to upgrade orbital models and promote orbital debris research (Astromaterials Research & Exploration Science, n.d.).

Translating those technologies into operational capabilities, however, will prove challenging. Many early-stage innovations fall victim to the "valley of death," as they attempt to graduate from lower Technology Readiness Levels (TRLs) into programs that deliver results. This valley is a well-known transition risk where promising technologies fail due to lack of resources or practical application. Given the disastrous consequences an orbital impact could create, the best way to address this possibility of technologies getting caught in the valley of death is by pursuing a multidisciplinary approach that pushes several key technologies instead of fixating on a single solution, regardless of how promising that single solution may be. An effective strategy can be designed by integrating policy initiatives and technological innovations, as well as by demonstrating good stewardship of the global commons. This paper will outline a trinary approach to mitigating the orbital debris problem by: (1) investing in enabling technologies, (2) fostering a commercial market, and (3) encouraging "good steward" operational behavior with accountability measures.

Initiative #1: Investing in Enabling Technologies

As discussed in the Enabling On-Orbit Technologies section of this paper, orbital debris mitigation technologies break down into four sub-groups. Two of those sub-groups are maturing rapidly with higher TRLs: attitude control systems for maneuvers and mechanisms to collect debris. More significant advancements could be achieved through efforts and funding focused onto the other two sub-groups: improved sensors to locate debris and the ability to identify inertial parameters. While technologies for those lagging sub-groups currently exist, they are inadequate to effectively manage the technical challenge of active debris removal. Therefore, to maximize the impact of constrained resources, increasing efforts and funding into these two areas would offer the greatest opportunity to accelerate technological progress toward the operationalization of debris mitigation technologies.

During a discussion with retired General John Hyten, former Vice Chairman of the Joint Chiefs of Staff, he explained, "we have a surveillance infrastructure that is ancient. Inherently because it is built on a sparse data set, the error on the algorithm is large," which drives overly conservative error margins. By developing and employing better algorithms enhanced by artificial intelligence, the problem of orbital debris could be minimized challenges (J. Hyten, personal communication, March 24, 2023). Refined conjunction probability assessments would enable space operators to understand when debris threatens a satellite or station, which would significantly decrease the quantity of debris-dodging maneuvers, thereby saving propellant for truly critical operations. Further, combining artificial intelligence-enhanced surveillance algorithms with change detection data collected from star trackers, potentially capitalizing on products from the aforementioned DARPA program, will improve the general awareness of the space domain. Since these efforts can leverage existing hardware, the algorithm and analysis techniques could be developed, tested, and implemented with relatively small financial investments. Moreover, partnerships with academic institutions and government labs (e.g., the Air Force Research Laboratory) could enable significant maturation in a relatively short timeframe.

One other technology, albeit at a far lower technical maturity than space domain awareness innovations, that could pay dividends is a satellite coating that minimizes fragmentation. Professor Barnhart offered that the materials science field could develop innovative coatings that reduce the likelihood of catastrophic chain reactions when orbital impacts occur, similar to shatterproof windshields and impact-resistant coatings sold on the commercial market today (D. Barnhart, personal communication, March 24, 2023). This space-grade coating would mitigate the devastative effects following a collision and reduce the amount of debris created and jettisoned into space. If the U.S. were to develop such a coating and make it available to all spacefaring entities free of charge, this would not only help mitigate the risk of an uncontrolled debris cloud growth, but it would also demonstrate the nation's commitment to being leaders in the responsible use and stewardship of the space environment documented in the United States Space Priorities Framework (White House, 2021, p. 6).

Initiative #2: Fostering a Commercial Market

Dr. John Plumb, the Assistant Secretary of Defense for Space Policy, advised against lowering the ODMSP standard solely to ease the DOD's space operation capability (J. Plumb, personal communication, January 27, 2023). He outlined the tremendous value that maintaining a higher standard provides the country because it helps solidify the nation's leadership role in the space domain. Instead, to address orbital debris concerns, Dr. Plumb recommended that the DOD should establish a commercial market of orbital debris mediation capabilities, while acknowledging that a single contract would be insufficient to demonstrate enough of a demand to commercial investors. Similarly, commercial space companies rely upon suppliers, and those smaller entities need stability to maintain operations. General Hyten remarked, "the only way you get a stable supply chain with the industrial base is to stabilize it with multi-year contracts" (J. Hyten, personal communication, March 24, 2023). Therefore, the U.S. government should structure an acquisition strategy for debris mediation that demonstrates a demand, supports the industrial base, and builds the foundation for a commercial market. The DOD can help fund this growing commercial marketplace and directly encourage business activity by leveraging multiple contracting tools at its disposal.

The Department of Defense has the authority to carry out certain prototypes, research, and production efforts through Other Transaction Authority (OT) (10 U.S. Code § 4021 – *Research Projects: Transactions Other Than Contracts and Grants*, n.d.). This unique authority gives the DOD the ability to enter into agreements with non-traditional defense contractors, such as small businesses, research institutions, and non-profit organizations. It allows the DOD and other agencies to bypass certain Federal Acquisition Regulation requirements, which can accelerate the acquisition process and provide faster and more flexible ways to develop and acquire new technologies and capabilities. OTs are valuable tools that can grow this marketplace because they encourage participation of non-traditional defense contractors, and they establish cost-sharing arrangements that encourage public-private partnerships. For example, the Space Force's Space Systems Command established the Space Enterprise Consortium in 2017, and this entity actively solicits bids from member companies over a range of mission areas to foster collaboration with companies that have not previously worked with the DOD. A quick market search through the Space Enterprise Consortium found over 50 companies independently developing space debris technology, ready to form partnerships with the U.S. government to tackle this issue.

The Small Business Administration (SBA) and its programs offer both funding and acquisition paths to develop space debris mitigation and removal marketplace. The Small Business Innovation Research (SBIR) program encourages domestic small businesses to engage in federal research and development with the potential for commercialization. It is a competitive awards-based program with the overarching goals of stimulating technological innovation and increasing private-sector commercialization of innovations derived from federal research and development funding. The government has employed SBIR programs to demonstrate a faster and smarter strategy in technology investments and to foster partnerships with small and non-traditional businesses.

Another SBA financial assistance program that can flow capital into this marketplace is through small business investment companies (SBIC). In essence, the SBIC program is a form of U.S. government-sponsored venture capital firm that provides startup capital. This strategy is attractive because the government does not need to award and manage contracts with startup companies. Instead, the program leverages commercial investment entities to identify promising startups and emerging companies, provide funding, assess risk, and manage investments. By utilizing a combination of OTs, SBIR, and SBIC efforts, the U.S. government can seed a commercial marketplace to accelerate orbital debris mitigation activities.

Lieutenant General Philip Garrant, the Space Force's Chief Strategy and Resourcing Officer, proposed a use case that would establish a commercial partnership and encourage a marketplace aimed at resolving the orbital debris mitigation challenges (P. Garrant, personal communication, March 25, 2023). General Garrant identified an opportunity for near-term debris remediation efforts. He shared that the UHF Follow-On (UFO) satellite communications constellation has multiple assets in GEO that are non-operational. The United States Navy transferred oversight of the UFO constellation to the Space Force, and now the Space Force is responsible for these defunct satellites that occupy key positions in the GEO belt and are incapable of maneuvering to disposal orbits. These satellites provide ideal opportunities for the Space Force to test and demonstrate the capability to maneuver non-cooperative targets, thereby cleaning up the GEO belt of multiple large pieces of orbital debris. Maneuvering these satellites out of GEO would create more GEO slots for other missions and would provide valuable lessons applicable to future cleanup activities in LEO. Additionally, by targeting defunct U.S. military satellites, the Space Force would demonstrate its commitment to good stewardship of the global commons to other spacefaring nations. This approach also has the added benefit of creating potential long-term efforts that can offer stability to the industrial base.

Colonel Meredith Beg has been given the responsibility to develop the strategy for a complementary effort. In her role as the Space Force's Service Lead for Space Mobility and Logistics within the Assured Access to Space (AATS) program office, her focus to date has not been on tackling the orbital debris problem. Rather, her focus is looking at potential solutions that "would allow a satellite to expend its onboard fuel, and then use a commercial contracting vehicle to hire a provider to maneuver it to a disposal orbit" (M. Beg, personal communication, March 26, 2023). That goal would allow Space Force satellites to maximize capability while still being ODMSP-compliant, and it also lends itself to servicing and refueling opportunities. As an example, it is projected that future satellites may soon have requirements for refueling capabilities, so that they can enable sustained maneuver. Colonel Beg's efforts would pair with this potential requirement to extend operational life for these national security assets. That said, these efforts pursued by the AATS program office employ the same enabling technologies needed to maneuver defunct satellites to disposal orbits. By either expanding the program's scope, or by pivoting its first few missions toward orbital debris efforts, this strategy could jumpstart a commercial market through a multi-year orbital debris remediation program.

Initiative #3: Encouraging "Good Steward" Behaviors

As documented earlier in this paper, the United States aims to set the example for norms of behavior in space. The first two initiatives directly support this effort, by advancing technologies that will protect the global commons of the space domain, and by boosting a commercial marketplace to actively remove orbital debris, starting with inoperative U.S. government assets. Finally, this paper will provide additional background into the policy and legal realm, by pursuing measures that will encourage "good steward" behavior from other spacefaring entities.

First, the United States should act upon the Liability Convention, which establishes who is responsible for damage caused by the launch and orbiting assets both in space and on the surface of the planet and specifies that responsibility falls upon the launching State and additional States that participated (UNOOSA, 2017). However, the U.S. only mandates that U.S. government satellite operators must comply with ODMSP; commercial entities are not required to abide by the policy. This condition should be updated to extend the requirement such that all commercial satellites that do business in America must abide by ODMSP, regardless of whether they launch from the United States or from external spaceports.

Within the Federal Aviation Administration (FAA), the Office of Commercial Space Transportation (AST) "authorizes launch and reentry operations, the operation of launch and reentry sites, and issues safety element approvals" (FAA, n.d., para. 10). Effectively, AST licenses U.S. commercial entities to place objects into orbit. Additionally, 51 U.S. Code § 50905 directs that U.S. launch companies performing commercial launches are required to have a license from the FAA, even if the launch is conducted outside of the U.S. Therefore, to direct that commercial launches and satellites must abide by ODMSP, the AST licensing process is the appropriate methodology. This procedure may have the ancillary effect of motivating commercial industry to aid in the maturation of emerging technologies that better characterize orbital debris, as it would directly benefit them by making it easier to demonstrate ODMSP compliance. Additionally, to improve overall space domain awareness, the licensing process should institute a requirement to share change detection data from star sensors. Of note, it is expected the FAA will publish a notice of proposed rulemaking in the relatively near future to amend its orbital debris requirements to be more closely aligned with ODMSP.

In addition to extending the ODMSP compliance requirement to commercial entities, the FAA should consider taking steps to strongly encourage commercial entities to obtain additional insurance for orbital debris damage caused by their assets. With the aforementioned initiatives to improve space surveillance, the ability to attribute debris will grow more robust. By holding space entities accountable and legally liable for damage caused by debris emanating from their assets, as prescribed in the Liability Convention, a commercial insurance industry could rise to address the nascent market. Further research and collaboration would be needed to understand how much insurance would be needed, and whether the U.S. government would step in to cover catastrophic losses beyond a reasonable threshold of commercially procured insurance. Currently, the U.S. government provides indemnification, which holds commercial companies liable for the first $500 million of damages, and the government takes responsibility for the remainder of damages up to $2.7 billion. Reexamining these thresholds could prove useful to ensure that commercial providers are incentivized to act as good stewards.

These efforts by the United States to expand orbital debris mitigation into its domestic commercial sector would undoubtedly establish the nation as the global leader in protecting the space domain. Encouraging good behavior, and in some cases mandating good behavior, will further the country's goal to demonstrate leadership in the use of, and stewardship of, the space environment. By extension, this model will inspire other nations to abide by the same guidelines, which improves the long-term sustainability of the space domain for all users. Most spacefaring countries will follow the U.S. lead, though some global powers like China and Russia are less likely to exercise restraint in the space domain. Diplomacy and global standing, along with the potential embarrassment on the world's stage when space operations go awry, would be key to enticing these spacefaring nations to improve their behaviors. By holding the moral high ground, the U.S. would be better positioned to convince these holdout nations to change their ways.

Conclusion

The three-tiered approach described in this paper will not immediately resolve the risk of orbital debris. That said, it will better position the nation and the world for continued use of the space domain for the foreseeable future by taking proactive steps to address the risks and impacts of orbital debris. It aligns with the United States Space Priorities Framework, which directs the country to demonstrate leadership in space, and it does so by building upon the norms of space behavior. It also ensures the emerging LEO-based missile defense constellation will be offered an increased measure of protection thereby helping safeguard the nation's ability to execute in the space domain. With the rise of proliferated LEO constellations, and with limited orbital slots in the GEO belt, the time to act is now.

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