Policy tools for preventing, mitigating, and defending against orbital debris

Michael R. Migaud

Texas A&M University, 4350 TAMU, College Station, TX, 77843 USA

ABSTRACT

Earth's orbital environment is a common-pool resource which has been largely unregulated since the commencement of human space activity in the 20th century. Satellites – both operational and defunct – as well as expelled upper stage rocket bodies have congested orbital patterns and have increased the probability of asset conjunctures. Moreover, anti-satellite missile demonstrations from the United States, China, India, and Russia have added to the amount of debris circulating the planet. The need to minimize waste in space adds requirements to the governance of space and its uses that are evident in a range of types of policy tools, from laws and regulations and procurement requirements at the national level through international treaties and practices. This paper begins by providing a brief overview of the space waste issue and highlights events that have brought attention to the hazardous consequences of polluting the planet's orbital environment. Secondly, it examines existing literature and discourse on the state of orbital debris regulations and international practices, and provides the theoretical foundation explaining the role of regulation in protecting the orbital environment. Thirdly, this paper analyzes existing policy tools utilized by federal agencies and departments in the U.S. to address orbital waste. This paper is unique in that it divides such tools into three categories based on their ability to prevent the accumulation of debris in space, mitigate the effects of debris, and defend against waste in space, and then highlights how policies focused on prevention, mitigation, and defense perpetuate pillars of the U.S. Government Orbital Debris Mitigation Standard Practices. Additionally, this analysis examines international treaties, standards, and practices that promote sustainable activity in Earth's orbital environment to minimize the probability of asset collision. Finally, this paper discusses proposed policy changes in the U.S. outer space regulatory structure and evaluates contemporary discourse on proposed next steps for regulation of the planet's orbital environment and dialogue on the effectiveness of existing orbital debris-related laws, regulations, and international practices. This method of analysis provides a clear image of deficiencies in each policy realm. Much of the existing U.S. regulatory infrastructure focused on orbital debris can be categorized as preventing or mitigating debris issues through policy. Prevention policies exist as procurement requirements, technical standards for launch vehicle production and design, and requirements asset operators must comply with in order for their satellite to be cleared for launch. Policies that mitigate the ancillary effects of orbital debris focus on asset registration to improve U.S. space situational awareness, asset maneuver capabilities to minimize collisions in orbit, and on-orbit servicing. Existing orbital debris defense policies limit the amount of time an asset can remain in orbit and require asset operators to submit object retirement plans upon applying for launch licenses that explain what satellites are to do once their mission life has ended. This analysis exposes deficiencies in U.S. orbital debris policies focused on defending against space waste and highlights explanations for such weaknesses. Many strategies for defending against orbital debris through active debris removal and forced reentry have not yet proven to be economically or technologically feasible. International treaties and practices addressing orbital debris and human activity in the Earth's orbital environment discuss liability, asset registration, and offer non-binding recommendations to space faring nations on how to combat the issue of space waste. This paper contributes to existing research on policy tools used to address space debris by examining U.S. policies and international practices based on their ability to prevent, mitigate, and defend against orbital debris.

1 INTRODUCTION

Outer space plays an import role in everyone's lives, and economies around the world are reliant on human activity in space for agriculture, global health, education, security, research and development, and much more [1–3]. If left unchecked, the growing amount of orbital debris can have grave economic, social, and political consequences on humanity as debris can severely damage or destroy satellites in space. The need to minimize waste in outer space adds requirements to the governance of space and its uses that are evident in a range of types of policy tools, from laws and regulations and procurement requirements at the national level through international treaties and practices. This paper begins by providing a brief overview of the space waste issue and highlights events that have brought attention to the hazardous consequences of polluting the planet's orbital environment. Secondly, it examines existing literature on orbital debris regulations and international practices, and provides the theoretical foundation explaining the role of regulation in protecting the orbital environment. Thirdly, this paper analyzes existing policy tools utilized by federal agencies and departments in the United States to address orbital waste. This paper is unique in that it divides such tools into three categories based on their ability to prevent the accumulation of debris in space, mitigate the effects of debris, and defend against waste in space, and then highlights how policies focused on prevention, mitigation, and defense perpetuate pillars of the U.S. Government Orbital Debris Mitigation Standard Practices. Additionally, this analysis examines international treaties, standards, and practices that promote sustainable activity in space to minimize the probability of asset collision. Finally, this paper discusses changes in the U.S. outer space governance structure and evaluates discourse on proposed next steps for regulating Earth's orbital environment.

Orbital debris can consist of a variety of different objects, but the Inter-Agency Space Debris Coordination Committee defines orbital debris as "all man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional" [4]. Synonymous terms for orbital debris used throughout this paper are space debris and space waste. The operational definition of space used in this paper is 100 kilometers (km) above sea-level [5]. The orbital environment surrounding Earth is commonly divided into three regions: low Earth orbit, medium Earth orbit, and geosynchronous Earth orbit. Low Earth orbit (LEO) is 200 km to 2,000 km above the planet's surface. Geosynchronous Earth orbit (GEO) is a region of orbital patterns greater than 35,800 km above the Earth's surface. Medium Earth orbit (MEO) is between LEO and GEO. The main focus of this paper will be on LEO and GEO because LEO is home to roughly 75 percent of all trackable objects orbiting Earth while GEO houses most communication satellites and five percent of trackable objects in orbit [6]. Debris can be caused by natural decay, collisions with man-made and natural objects in orbit, damage sustained by exposure to radiation and space weather, and intentional destruction [7].

There are numerous federal agencies and departments in the U.S. responsible for preventing, mitigating, and defending against space debris. In 2017, the Office of Science and Technology Policy (OSTP) submitted a report to Congress delineating the extent of the U.S. space waste regulatory infrastructure. The federal entities involved with space waste are the Federal Aviation Administration (FAA), the Federal Communications Commission (FCC), the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration, the U.S. Department of Defense (DOD), and the U.S. Department of State (DOS) [8].

The National Space Policy (NSP) of the U.S. is set by the President through executive actions. The President sets the space policy agenda, so the NSP can change from president to president. The NSP does not discuss specific policy actions but is a broad map of objectives related to space research and exploration. The most important piece of policy in the U.S. government for orbital debris is the U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP). NASA, the DOD, and representatives from the private sector developed the first version of the ODMSP in 1997, but the most current version was published in 2001 [6,8]. The ODMSP seeks to achieve four primary pillars: (1) control of debris released during normal operations; (2) minimize debris discharged due to accidental explosions; (3) select safe flight missions and vehicles; and (4) enforce asset post-mission retirement [9]. Subsequent policies related to orbital debris originate from objectives declared by the President through alterations to NSP, executive actions, and the ODMSP. The NSP has evolved over several decades and has become increasingly aware of the severity of polluting Earth's orbital environment. The first mention of orbital debris in a NSP came from President Ronald Reagan in 1988 after almost 30 years of human activity in space. The NSP published by President Barack Obama in 2010 built on the NSP of President George W. Bush by promoting peaceful space operations for all nations and supporting sustainable space operations to protect access to outer space for all nations [10]. President Donald Trump has published multiple executive actions that have tailored U.S. space operations and edited portions of President Obama's 2010 NSP, but he has not provided a new NSP as of the writing of this paper.

2 THE ORBITAL ENVIRONMENT

Earth's orbital environment is a common-pool resource which has been largely unregulated since the commencement of human space activity in the 20th century. Satellites – both operational and defunct – as well as expelled upper stage rocket bodies have congested orbital patterns and have increased the probability of asset conjunctures. Moreover, anti-satellite demonstrations from the United States, China, India, and Russia have added to the amount of debris circulating the planet. There have been almost 6,000 launches since 1957, and much of the human experience in space took place during the Cold War with a steady decline in the number of launches from the fall of the Berlin Wall in 1991 until 2006 when the number of launches per year begins to increase [11]. NASA began studying space debris in the 1970s through the Johnson Space Center and the Marshall Space Flight Center when the North American Aerospace Defense Command only tracked roughly 2,000 objects orbiting Earth [12].

Since the end of the Cold War in 1991, there have been several focusing events that have drawn attention to the issue of space debris. One of the most significant events occurred in 2007 when China used an ASAT missile to destroy its Fengyun-1C weather satellite. This ASAT demonstration created over 3,300 pieces of trackable orbital debris and an estimated more than 150,000 pieces too small to track [7,13,14]. Another significant orbital debris-related event was the first known satellite collision in 2009. This collision involved a defunct Russian satellite and an operational telecommunications satellite owned and operated by an American communications company at 22,300 miles per hour. This collision created more than 2,000 pieces of trackable debris and estimates suggest the debris will remain in orbit for at least a century unless forcibly removed [15]. A recent focusing event was in March 2019 when India used an ASAT missile to destroy a satellite operating in LEO.

The generation of space waste is something more countries are becoming aware of as more nations are involved in space activity than ever before. There are over 60 nations involved in varying levels of space activity, and that number is expected to steadily increase as the private space transportation sector provides launch services to more countries [7]. While more countries are involved in space activities, roughly 50 percent of orbiting operational satellites were under U.S. jurisdiction as of 2018. Additionally, the U.S., the Commonwealth of Independent States (CIS) (former Soviet Union countries), and China are responsible for 93 percent of all orbital debris that has been produced thus far [16]. In total, there are an estimated more than 500,000 pieces of debris smaller than 10 centimeters in diameter orbiting Earth and millions more that are too small to be tracked [7,14].

The production of space waste is a serious concern because of the grave consequences debris can have on ambitions of future space exploration beyond LEO. The Kessler Syndrome is a popular theory cited in defense of stronger regulation to prevent orbital debris because the theory suggests that if humans continue to recklessly operate in Earth's orbital environment, then there is a potential for the formation of a 'debris belt' in Earth's atmosphere. Debris will continue to decay and collide with each other, thus creating an unnavigable debris field surrounding Earth, rendering all space activity near impossible [17]. Other prominent research on the severity of space debris suggests minimizing collision probability while incentivizing debris removal is important because the orbital environment will be unnavigable within the next 200 years even if humans ceased all launches [18].

3 PROTECTING THE ORBITAL ENVIRONMENT

Many researchers writing on orbiting space waste frame this issue as a common-pool resource problem and analyze it using seminal work from Elinor Ostrom and Garrett Hardin. Hardin created the theory commonly known as 'the tragedy of the commons' that suggests people will used a shared resource system for their personal interests until it is spoiled. He claimed strong government regulation is necessary to prevent the destruction of the shared resource [19]. Ostrom wrote extensively on theories applicable to common-pool resource problems and was staunchly opposed to Hardin's suggestions. Ostrom argued that institutions would form organically to remedy common-pool resource problems, such as the accumulation of space debris in Earth's orbital environment, if certain conditions are met. Some of these conditions are that the problem is confined to a geographical area, people can learn about the status of the problem at a low cost, people understand the cycle of the issue and care about the future, and people believe there will be severe consequences for losing the resource [20]. Weeden and Chow [5,21] as well as Johnson-Freese and Weeden [22] apply Ostrom's theory to the Earth's orbital environment and provide potential policies on how to improve existing protection methods in relation to the international stage. In accordance with Schot and Steinmueller's transformative frame of science and technology policy, humans are now thinking of the externalities brought on by early human space exploration and the damage human pollution of LEO has caused [23]. Space plays an important role on everyday life, and science and technology policy used to address the issue of orbital debris must recognize the importance of space in the human experience. The accumulation of debris in LEO and beyond is not just a space security and national security issue; it is also a social, environmental, and economic issue. Tools used to combat orbital debris have taken the form of laws and regulations as well as international treaties, standards, and practices.

Much of the existing U.S. regulatory infrastructure focused on orbital debris can be categorized as preventing, mitigating, or defending against debris issues through policy. Existing literature claims fundamental elements of the issue of orbital debris can be separated into three parts, but there is disagreement on how these sectors should be described. Extant research analyzing debris mediation have split policies based on their ability to reduce the probability of debris generation, minimize collision probability, and support debris capture techniques, but broadly compare NASA's policies to that of other prominent space faring organizations on the international stage [16,24,25]. Debris prevention policies exist as procurement requirements, technical standards for launch vehicle production and design, and requirements asset operators must comply with for their satellite to be cleared for launch. Policies that mitigate ancillary effects of orbital debris focus on asset registration to improve U.S. space situational awareness, asset maneuver capabilities to minimize collisions in orbit, and reviving defunct satellites with on-orbit servicing. Existing orbital debris defense policies limit the amount of time an asset can remain in orbit and require asset operators submit object reentry plans upon applying for launch licenses that explain what satellites are to do once their mission life has ended. Distinguishing between preventing debris generation, mitigating problems potentially brought on by the existence of debris, and defending against debris through removal or limiting asset orbital lifetimes is important for analyzing the public policies used to combat space waste. This three-part distinction allows decision makers to individually analyze orbital debris policies aimed at pre-launch, mid-orbit, and post-mission phases of an asset's lifetime. Moreover, it creates an opportunity to see where more laws and regulations need to be enacted to counter potential deficiencies in current policies. For the purpose of this paper, preventative policies are laws and regulations intended to address the generation of orbital debris prior to launch through asset design and payload specifications. Mitigation policies focus on what is to be done to protect assets when they are already in orbit. Defensive policies and practices aim to minimize the total amount of debris in orbit for the security of future missions. Sections 3.1, 3.2, and 3.3 of this paper discuss how relevant federal entities engage in preventing, mitigating and defending against orbital debris in relation to the ODMSP.

3.1 Preventing Orbital Debris

Policy tools utilized to prevent the accumulation or generation of space debris primarily fall under the purview of the first and second pillars of the ODMSP. Each of these pillars focus on controlling the amount of debris released during normal asset operations and minimizing the amount of waste generated from unintended explosions. The ODMSP further states spacecraft and rocket bodies should be designed to limit the amount of risk they generate for other objects in orbit. Additionally, every situation where a piece of debris greater than five millimeters in diameter is released from an asset and is expected to remain in orbit longer than 25 years should be considered and approved on the basis of cost effectiveness and importance to mission operations [9]. The FAA, FCC, NASA, and NOAA all have policies or regulations in place that aim at preventing the generation or accumulation of orbital debris and align with the first two pillars of the ODMSP.

The FAA plays an important role in preventing the generation of orbital debris because they must approve all launches and attempts at object reentry in the U.S. In order to be approved for launch or reentry, asset operators must submit specific plans to the FAA detailing the content and structure of the launch vehicle. This process is in place to track the amount of combustible material aboard launch vessels and to identify particular facets of an asset or launch process that have potential for generating debris. Moreover, license applicants must submit and maintain risk assessments throughout an asset's launch, operational lifetime, and retirement missions. Many satellites – especially in GEO – are important for land and space-based communications systems so the FCC has a significant responsibility to minimize debris generation. The FCC places restrictions on radio frequencies (RF) that can be utilized during mission operations. Minimizing RF disturbances protects satellites from interferences that might cause malfunctions and operational errors. Additionally, there are limits on the size of antennas that can be attached to telecommunications satellites. FCC regulations mandate asset operators must expel all unused sources of energy aboard their satellite prior to any retirement missions to minimize the probability of unexpected explosions. Like the FCC, NOAA is important in regulating the orbital environment because it is responsible for all space-based remote sensing data collection devices. All remote sensing device operators have to obtain a license of approval from NOAA before their device can be launched into orbit. License applicants must submit operation plans detailing projected orbital patterns, all technology aboard the device, orbital capabilities and limitations, and more. NOAA licenses are only granted to applications with goals aligned with missions of NOAA or other government agencies.

NASA is a unique legal authority in the realm of orbital debris because it conducts research through the Orbital Debris Program Office of the John Space Center to develop technology that strengthens asset integrity upon collisions. Additionally, rules prompted by NASA are only compulsory for entities utilizing the U.S. government's space launch system. NASA has produced a document called the Procedural Requirements for Limiting Orbital Debris (NPR 8715.6A) and it states all missions that NASA is involved with have to comply with the NASASTD Process for Limiting Orbital Debris and NASA-HDBK 8719.14 Handbook for Limiting Orbital Debris [6,26]. These documents are important in regulating the generation and accumulation of debris because they promote what is commonly known as the '25-year rule'. This rule states objects launched into space should not remain in orbit beyond 25 years. Additionally, these documents require each project operator must produce official assessments of the potential for generating orbital debris during an object's launch, orbit lifetime, and reentry. Asset operators must submit assessments describing spacecraft dimensions, potential for debris released during normal operations, potential for unexpected breakups or explosions, any hazardous materials aboard launch vessels, and potential launch vehicle disposal plans. Assessments are regularly updated to note changes in design and capabilities [6,27].

3.2 Mitigating the Effects of Orbital Debris

Policies intended on mitigating the effects of orbital debris align with the third pillar of the ODMSP. The overall goal of this pillar is the selection of operations and launch assets with maximum security against debris. This objective is comprised of two sub goals that focus on minimizing collisions with objects throughout orbital lifetime general mission operations [9]. Avoiding collisions with large objects during an asset's orbital lifetime can be achieved through designing a mission profile for an asset that limits the probability of colliding with known objects. Additionally, the pillar stresses the importance of conducting research aimed at strengthening launch vessel and satellite structural integrity in the event of collision with pieces of debris [9].

Minimizing collisions is a priority for those observing the orbital environment or operating an asset orbiting Earth. The DOD and NASA utilize a robust space situational awareness (SSA) infrastructure comprised of earth and space-based lasers and satellites to track man-made and natural objects orbiting Earth through the 18th Space Control Squadron of U.S. Strategic Command (STRATCOM) [28]. SSA is the "ability to monitor and understand the state of the space environment, including the ability to track, understand and predict the location of human-generated and natural objects in orbit" [7]. STRATCOM manages both an internal and public database (space-track.org) of objects in orbit. In 2004, the U.S. Air Force began an initiative called the Commercial and Foreign Entities Pilot Program through which they share classified satellite positioning data with select countries around the world. As of April 2018, the DOD was sharing SSA data with 14 nations, 2 regional organizations, and more than 65 private corporations [7]. Sharing SSA data with entities beyond the U.S. government allows STRATCOM to observe more objects in orbit and prevent collisions with objects they might not otherwise have seen. STRATCOM provides 72 hour advanced notice of potential collisions to registered asset operators [15].The FCC regulates alterations in telecommunication satellite maneuvers and requires operators conducting orbit inclinations in GEO to provide notice within 30 days of any maneuvers to ensure changes in inclination do not disturb RFs or orbital paths of other satellites. NASA has been utilizing collision avoidance technology aboard the International Space Station (ISS) since 1988 to change orbiting patterns to avoid conjunctures. Engineers model a 30-mile-wide by 30-mile-long and 1-mile-deep box around the ISS and track all objects that pass through or orbit near this box. If the threat of a collision is perceived to be significant, NASA collaborates with the Russian space agency to determine the safest course of action for avoiding collision [14]. As of 2018, the ISS has conducted 25 maneuvers to prevent collisions across its lifetime and receives around 50 collision warnings a year with at least one warranting movement [7,29].

3.3 Defending Against Orbital Debris

Policy tools intended to strengthen defense capabilities against orbital debris correlate with the fourth pillar of ODSMP. This pillar discusses disposal methods for orbiting assets in three manners: atmospheric reentry, maneuvering assets into storage orbits, or through active debris removal. There are a limited number of policies that has been adopted in the U.S. focused on defending against orbital debris as it is described in the ODMSP. The FCC has regulations mandating telecommunications satellites operating in GEO must exit orbit or move into a storage orbit once the satellite's operations have been completed. NASA's 25-year rule also says assets must maneuver into a storage or graveyard orbit if reentry is not feasible. As discussed later in Section 5 of this paper this paper, there are political, economic, and technological issues related to orbital debris defense policies that must be solved on the international stage before advances in such policies can begin.

4 INTERNATIONAL AGREEMENTS AND PRACTICES

Outer space does not belong to any particular country and international law stresses the importance of preserving outer space for future generations. International space law focuses on cooperation in space between all countries, nongovernmental organizations, and the private sector, and forbids the storage of weapons of mass destruction (WMD) in outer space. International practices for outer space activity come from treaties, conventions, and special coalitions dedicated to researching specific space-related issues. In 2018, the UN General Assembly (UNGA) passed a resolution supporting the peaceful and responsible use of outer space to preserve it as a resource for future generations [30]. This resolution expands several provisions within previously enacted international treaties and agreements related to human activity in space. Existing space treaties and conventions are primarily focused on the peaceful uses of outer space, liability, and registering launches.

4.1 International Treaties

The seminal international agreement governing human activity in space is the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies. This agreement is commonly referred to as the “Outer Space Treaty”. The Outer Space Treaty states nations are responsible for the space security of all national space activities under their legal jurisdiction and claims states shall be liable for damage caused by their state space system. It also states nations active in space shall avoid the harmful contamination of space and outlaws the ability of states to harbor WMDs aboard space faring assets [31]. Several other treaties and conventions were created to expand provisions within the Outer Space Treaty.

Much of existing international space law focuses on liability initially addressed in the Outer Space Treaty of 1967. The Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space of 1968 builds off of the Outer Space Treaty by stressing the importance of astronauts as voyagers of man-kind and cooperation in space by mandating nations must return assets belonging to other countries [32]. This relates to orbital debris because some objects reenter Earth’s atmosphere and crash down outside the jurisdiction of the country that initially launched the asset. Another important piece of international space law comes from the Convention on International Liability for Damage Caused by Space Objects in 1972. This convention states launching nations are liable for damage caused by its space assets on the surface of Earth or to aircraft. Additionally, these nations are also liable for damage due to faults in orbit and beyond [33]. This convention incentivizes countries to regulate the components, structure, and activity of objects launched into space to limit the probability of assets operating under their jurisdiction inflicting damage on another country’s asset. The Iridium-Cosmos collision in 2009 was a major challenge to this convention, but the first time this law was tested was in 1978 when a Russian satellite crashed in northern Canada. The asset’s nuclear reactor did not separate from the asset and entered the atmosphere with the satellite, thus spreading radioactive debris over a large portion of northern Canada [5,15].

In 1961, the UNGA passed a resolution calling on states to furnish information on all orbital launches to the Committee on the Peaceful Uses of Outer Space (COPUOS). The resolution also called on the Secretary General of the UN to create a launch tracking database that is now the Space Object Register (SOR) within the UN Office of Outer Space Affairs (UNOOSA) [34]. The 1976 Convention on Registration of Objects Launched into Outer Space was convened to increase the amount of information recorded within UNOOSA’s SOR for liability purposes. Governments and nongovernmental organizations wanted to expand the scope of the 1961 resolution to ensure the SOR would serve as an open access repository of launch data. The SOR only maintains records of when launches occur and the types of assets being launched. As of April 2019, 89 percent of all objects launched into space since 1965 have been registered with UNOOSA’s SOR [35].

4.2 International Organizations

There are numerous parties involved in space activity, but these groups can be largely categorized as governmental and non-governmental. The major international actors related to orbital debris are the UN through COPUOS and UNOOSA, the Inter-Agency Space Debris Coordination Committee, and the International Telecommunications Union. Each of these organizations have provided orbital debris mitigation standard practices to the space faring community with the intention of promoting sustainable practices in outer space.

As previously discussed in Section 4.2, the primary UN entities focused on outer space activity are UNCPUOS and UNOOSA. In 2010, UNCPUOS created the Working Group on Space Debris with the mission of developing debris mitigation standards. The standards produced contain seven main guidelines. These sections cover debris released during normal mission operations and through intentional break ups. It explicitly says assets should not have a ‘fail mode’ that could be a serious cause of the asset to break up. Additionally, the standards discuss the importance of minimizing the amount of fuel residing within the asset during launch, orbit, and reentry to minimize the probability of unintentional explosions. Many of the known explosions in LEO and GEO have come from stored energy aboard assets so the standards say, “all on-board sources of energy should be depleted or made safe when they are no longer required for mission operations or post-mission disposal” [36].

The Inter-Agency Space Debris Coordination Committee (IADC) is comprised of representatives from 13 space faring nations and conducts research on space debris issues in order to promote sustainable practices in Earth’s orbital environment. The IADC meets several times a year and has thousands of engineers and technical experts working on developing best practices for orbital devices. The IADC published space debris mitigation guidelines in 2007 that stress the importance of minimizing asset fuel combustion. An important piece of these guidelines is that the IADC says if governments are going to destroy their satellites, they need to do so at low orbits so the debris will be collected in orbital drag at a faster rate and pose less of a threat to other assets in orbit [37].

The International Telecommunications Union (ITU) is an independent, specialized commission within the UN that focuses on coordinating the international electromagnetic spectrum. The ITU also handles disputes between nations about electromagnetic interference and orbital paths [5]. The report published by the ITU on protecting the environment of GEO provides some recommendations for space faring parties on debris mitigation. The ITU claims it is paramount to shorten the amount of time satellites are in orbit and minimize the portability of debris expulsion during a satellite's placement. Secondly, it claims transferring satellites to 'graveyard' orbitals should be done cautiously to prevent interference or collision with other satellites in GEO. Thirdly, the ITU says that until it is technologically and economically feasible to retrieve objects from GEO or return them to Earth at the end of their operation, there should be protected regions below and above GEO to protect assets from interference when other satellites are adjusting inclination or are being relocated to graveyard orbital paths. Finally, the ITU states that much of the known debris in GEO is a result of propulsion fuel explosions so satellite operators need to carefully calculate the proper amount of fuel necessary for assets to achieve desired operational orbital patterns with only the exact amount of fuel in reserves to ensure the asset can be pushed out of orbit once retired [38].

5 DISCUSSION

Human activity in space will become increasingly risky as the amount of debris in Earth's orbital environment continues to grow. The commercial space exploration sector and the number of nations active in space are both growing at unprecedented rates. With these rapid changes taking place, it is important to evaluate the adequacy of contemporary policy tools for combating orbital debris in the U.S. and on the international stage [39]. As highlighted in Section 3, many U.S. policies focused on orbital debris are either preventing the accumulation of orbital debris or mitigating the effects of orbital debris. This analysis exposes deficiencies in U.S. policies defending against space waste. As more nations and private space corporations become active in Earth's orbital environment, it is important that regulators begin to tailor legislation and public policy toward removing debris from LEO and beyond. Debris will only continue to accumulate as more actors take part in space exploration and focusing solely on preventing debris generation from launch vehicle and payload design will not solve the problem posed by space debris. If unremoved, existing debris will collide over time and possibly bring the Kessler Syndrome to fruition.

The ODMSP highlights active debris removal (ADR) as a method of defending against space debris. ADR is the ability to retrieve objects in space and bring them out of orbit. The Defense Advanced Research Projects Agency's Catcher's Mitt Final Report researched the feasibility of using ADR technology to collect space waste and forcibly remove it from orbit. This report concluded that contemporary ADR ambitions are economically and technologically unfeasible [6,40]. Other research has suggested the adoption of on-orbit servicing (OOS) technology aboard satellites as a method of repairing defunct assets or forcibly removing stray objects from orbit [29,41]. A NASA study of OOS capabilities in 2010 suggests the technology for OOS exists but needs to be further developed to sustain autonomous servicing aboard legacy satellites at orbits far from LEO [42]. Enacting public policy favorable to ADR and OOS research would be beneficial to space regulators seeking to formulate space debris defense policies and clean up Earth's orbital environment.

There are also political and security issues with ADR and OOS that stem from a greater range of complications on the international stage. Many within the security and defense sector are concerned advancements in ADR and OOS capabilities would pose a threat to U.S. national security because adversarial nations that are active in space could steal dual-use technology from American satellites [6]. In addition to this security concern, many debate whether ADR and OOS are public goods to be provided through an international fund or space faring governments on a per case basis, or as private goods that should come from the commercial space sector [29,43]. This sentiment is also shared with respect to adopting a global SSA system that identifies all satellites in orbit to prevent collisions. If the goal is to minimize uncertainty in space operations, then there should be push for expanding shared satellite data services with more of the 60 space faring nations [7]. Addressing these political and security issues will be beneficial for all parties involved with space activity because if governments can successfully reduce the risk of travelling through the orbital environment, then there is the potential for a multi-billion-dollar industry solely focused on removing defunct or retired assets from orbit [44]. Resolving economic, political, and technological issues related to OOS, ADR, and SSA will improve the effectiveness of debris policies.

Policies at the national level for the U.S. and on the international stage suffer from compliance issues and a fragmented regulatory structure. In the U.S., NASA's rules for mitigating orbital debris mention entities launching objects into space using U.S. space infrastructure are not required to comply with NASA's regulations if compliance would be too financially cumbersome for the launching party. These technical guidelines serve more as a model for private space corporations to follow as they conduct their own missions. NASA's 25-year rule also suffers from a lack of compliance [6]. Compliance is also an issue on the international stage where countries are not reporting all launches under their jurisdiction to UNOOSA's SOR. International space law also continues to suffer from the lack of coordination across different respectable authorities, complications with ensuring countries comply with international space law, and the political relevancy of cleaning up the orbital environment [29]. Larsen [39] highlights that international debris mitigation guidelines have not been adopted universally and are often interpreted and enforced in different manners across all space faring nations. At the time of writing this paper, there are a variety of potential policy changes going on related to orbital debris in the U.S. In June 2018, President Donald Trump signed Space Policy Directive 3, a presidential proclamation in which he directed leaders from several federal agencies to develop a national SSA and space traffic management policy. Moreover, President Trump called on the Department of Commerce to serve as the regulatory institution responsible for managing space-related data [45]. The FCC also published a proposed new rule making entirely dedicated to strengthening its regulations on orbital debris related issues [46]. Additionally, both chambers of the 115th U.S. Congress held hearings on space security issues and SSA, and each unsuccessfully attempted to pass legislation related to activity in outer space.

Based on this analysis of policy tools utilized by the U.S. and the international space community to combat orbital debris, I have developed recommendations for both the U.S. and international space faring community on how efforts to ease the issue of space debris can be improved. In terms of current space debris governance in the U.S., there needs to be less fragmentation in the regulatory process. Efforts to regulate outer space activity should be consolidated into a singular federal department, agency office or regulatory commission. As highlighted in earlier sections of this paper, there are numerous federal authorities in the U.S. with regulatory jurisdiction over commercial and civil space activity. If the horizontal integration of regulatory authority is done in a manner that minimizes market disruptions and costs firms must incur to change their existing operations, there is the potential for greater coordination in the public sector toward combating orbital debris. Increased coordination in regulation would allow each government institution with jurisdiction over American activity in space to leverage their respective technical field of expertise and better inform decisions made by other policy makers. Efforts like the one I am proposing have been successfully undertaken in other realms of science and technology policy. An example is the U.S. Environmental Protection Agency, the U.S. Department of Agriculture, and the U.S. Food and Drug Administration created a coordinated framework for regulating biotechnology [47]. This level of collaboration between these federal agencies facilitates communication between experts in each agency in regulating biotechnology while minimizing burden imposed on federal employees and private industry.

Horizontal integration of orbital debris governance from NASA, NOAA, FAA, FCC, and other relevant agencies in a manner similar to that of the coordinated framework on biotechnology or through the development of regulatory commission filled by employees of each agency would reduce transaction costs for firms seeking clearance for operating in space while minimizing communication barriers between employees of each agency. Each of these institutions play an important role in promoting sustainable activity in outer space through public policy so it is important they collaborate with one another and have appropriate methods for communicating about space related issues with one another. Reforming existing governance structures to maximize communication and coordination between bureaucracies would minimize regulatory burden imposed on commercial space transportation companies or parties seeking to launch assets into space because asset operators would only have to interface with a singular commission or body that consists of technical experts from each of the relevant regulatory authorities.

Much work is needed on the international stage to address political, economic, and security issues that are holding back the proliferation of ADR, OOS, and SSA capabilities. This problem can be addressed through holding an international convention on debris removal and asset repair operations like conventions aimed at creating international law for liability in space and to promote the registration of launches. Holding a convention addressing orbital debris can greatly benefit regulating human activity in Earth's orbital environment. The Liability Convention came about after nearly a decade of negotiations and debates related to the liability of nations for hazards caused by activity in outer space [48]. As mentioned earlier in Section 1, NASA scientists and engineers have been discussing the implications of space debris since the 1970s, so this is not an issue that has gone without study. Forming the Liability Convention also took place when there were few countries active in some capacity in outer space and when the private space transportation sector was nonexistent. One should expect that negotiating the details of an international convention dedicated to orbital debris and space sustainability would be more challenging than the conversations that took place in the 1960s and 1970s to set up the Liability Convention because of the democratization of space and the proliferation of the commercial space transportation sector. An international legal convention dedicated to orbital debris would allow representatives from space faring nations and commercial space transportation companies to develop strategies for addressing political and security concerns of ADR, OOS, and SSA without imposing significant economic burden on entities operating assets in space. With more actors involved in outer space, it is crucial the international community develop legal regulations for entities operating in LEO and beyond. Convening a convention will take a lot of time, money, and effort from nations and private companies to negotiate the terms of an orbital debris convention, but similar to the Liability Convention, it will provide a long-term remedy to a serious issue by developing regulations for protecting the longevity of Earth's orbital environment.

6 CONCLUSION

The accumulation of space debris in Earth's orbital environment is a common-pool resource problem that can have grave social, economic, and political consequences if ignored. There are a broad range of policy tools utilized by the U.S. and in the international community to regulate the generation and accumulation of orbital debris. Defense policies will be difficult to develop and implement until technology utilized for ADR missions becomes economically and technologically feasible for the private space faring sector to operationalize. Moreover, further work is needed on the international stage to address the economic, political, and security issues of ADR, OOS, and SSA. International treaties and practices addressing orbital debris and human activity in the Earth's orbital environment discuss liability, asset registration, and offer non-legal binding recommendations to space faring nations on how to combat the issue of space waste. Debris removal policies will be slow to make a positive impact on space waste orbiting Earth until issues mentioned throughout this paper are addressed.

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