Orbital Space Debris

Policy Recommendations in the Pursuit of Near and Long Term Space Sustainability

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August 2022

Youngstown State University - Mechanical Engineering

Washington Internships for Students of Engineering

Sponsored by ASTM International

“We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win.”

President John F. Kennedy

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EXECUTIVE SUMMARY

When thinking about how people go about their day, little thought or attention is used to understand the systems around us that allow our society to function. The current space infrastructure and satellite technology allow everyday services like television transmission, telephone capabilities, GPS and navigation equipment, weather and climate instruments, national security satellites, and scientific advancements that continue to build the future. Over time, each of these services has been threatened by millions of pieces of space debris that orbit uncontrollably at speeds of 17,500 mph.

Over the 60 years of space utilization, there have been over 6,000 launches that have resulted in over 56,000 tracked objects in orbit. Of these objects, 28,000 continue to remain in space. As of April 2022, 2,700 active working satellites orbiting Earth maintain communication with ground stations, and 2,850 dead or old satellites are no longer being used. Other smaller debris number in the thousands to millions. The rise in the commercialization of space encourages business innovation and exploration but also increases the concern of congestion and traffic management. Collisions that occur from space debris can cause small damage to satellites or create thousands of pieces of additional debris.

Engineers and scientists have continued to explain that solving the orbital space debris issue is simple but also complicated. At its core, space operators must have a 90% adherence to the 25-year post-mission disposal rule, and five pieces of space debris must be removed per year to stabilize the orbital debris environment. While this may seem easy, challenges arise from the fact that no rules of the road exist through international agreements, domestic and commercial regulation is insufficient, mega constellations are not considered as a system, 25-year rule compliance is poor, debris tracking standardization is nonexistent, essentially no debris removal technologies exist, and countries continue to purposefully create more debris my conducting anti-satellite weapons tests in orbit.

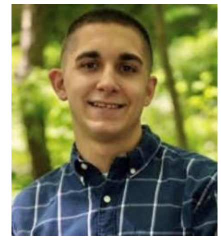
The solution to the space debris crisis is a multifaceted approach composed of the pillars of mitigation, tracking, and debris removal. Additionally, domestic regulation and international cooperation must be considered to stabilize the debris environment. The federal government should look to meet the following recommended policy objectives:

1. Investing in a flagship removal mission
2. Leveraging the commercial sector via a public-private partnership
3. Increasing 25-year rule compliance
4. Improving commercial space regulation.

These four policy objectives are of the utmost importance in stabilizing the orbital debris environment as thousands of more satellites continue to be launched yearly. By leading a domestic effort to reduce space debris, the federal government should also work with international partners to change from voluntary guidelines into binding agreements.

FORWARD

About the Author



Jason Hess is a junior at Youngstown State University in Youngstown, Ohio, and will complete his bachelor's degree in Mechanical Engineering with a minor in Mathematics in 2024. At Youngstown State, he is a member of the Sokolov Honors College, serves as the secretary of the American Society of Mechanical Engineers, works as an undergraduate research assistant where he leads a department-wide engineers week celebration, coordinates a development program for first-year engineers, and serves as an undergraduate teaching assistant for the first-year engineering program. Additionally, he serves as a volunteer varsity football coach at Wilmington Area High School in his free time. After college, he hopes to pursue a graduate degree in aerospace engineering and a master's degree in public administration, emphasizing national security and space policy with the goal of pursuing a career in public service.

About the WISE Program

The Washington Internships for Students of Engineering (WISE) Program was founded in 1980 through the collaborative efforts of several professional engineering societies to encourage engineering students to contribute to issues at the intersection of science, technology, and public policy. The nine-week Program allows fellows to spend the summer in Washington, DC, and gain exposure to the legislative and regulatory process through meetings with leaders in the Administration, federal agencies, and advocacy groups. For more information about the WISE Program, visit www.wise-intern.org.

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Acknowledgments

I would like to thank ASTM International for sponsoring me through this incredible internship opportunity. A special thank you to Matthew Pezzella and Travis Murdock for their guidance and support throughout the summer. To Dr. Gil Brown, who acted as the Faculty Member in Residence throughout the program. Thank you to YSU professor and ASTM board member Dr. Janet Gbur for recommending I apply to the program. And thank you to all of the WISE interns for their hard work, friendship, and determination as we navigated Capitol Hill together

ISSUE DEFINITION

This section defines and explains the orbital space environment, specifically focusing on the importance of space to our daily lives, the amount of debris in orbit, a characterization of size and collision effects, and the growing threat of orbital space debris due to the increased commercialization of space.

Why is Space Important to Modern Society?

When thinking about how people go about their day, little thought or attention is used to understand the systems around us that allow society to function. The importance of space can be related to the critical nature of safe and reliable infrastructure, whether it is the electric grid that powers our homes, the roads that connect us to the outside world, or the internet that transforms information sharing. Power, bridges, and the internet are necessary and critical parts of modern society; they are advancements that can be seen due to their terrestrial location on Earth. However, the advancements brought by civil, government, commercial space satellites, and infrastructure provide the backbone for all of modern society, although they are located hundreds of miles above the Earth.

The current space infrastructure and satellite technology allow everyday services like television, telephone, GPS and navigation equipment, weather and climate instruments, national security satellites, and scientific advancements that continue to build the future. Satellites in orbit are responsible for the vast array of television stations that allow people to be connected to local and international programming. This programming allows freedom and democracy to be spread worldwide by news stations while holding the government accountable. Additionally, television is critical in ensuring people have adequate updates on natural disasters. While telephones are connected on the ground by telephone towers, satellites are the only provider of telephone communication while traveling on planes. While telephone communication may seem grounded by the local region, all phones rely on highly specialized timing systems to ensure standardization and compatibility worldwide. GPS and navigation systems are essential services that allow people to travel efficiently and provide tracking mechanisms outside of the basic cell phone internet coverage. Along with national security and military satellites, GPS allows militaries to have up-to-date location information and ensure drones, helicopters, and planes can operate safely. Weather and climate satellites provide near instantaneous weather forecasts while also ensuring natural disasters like hurricanes can be seen days in advance, ultimately saving thousands of lives. Climate satellites measure the various aspects of the Earth's atmosphere, providing information to the scientists that help protect our planet. Communication satellites are also the backbone that allows business and the finance industry to communicate between locations, provide near instantaneous credit card authorization, pay at the pump gas stations, and enable the New York Stock Exchange to function seamlessly. [1]

While satellites enable essential functions of our daily lives, space is also a region that allows exploration. This exploration not only allows scientists to learn more about distant planets like the moon or mars, but it also allows them to peer back to seconds after the formation of the universe using satellites like the James Webb Space Telescope. Human exploration also benefits society by improving health care, making discoveries in microgravity, and inspiring the next generation to look at the stars and dream about studying science, technology, engineering, and mathematics. [2]

How Many Objects are in Space?

To allow the capabilities previously described, there is a need to have many satellites to ensure adequate reliability and function worldwide. In the past 60 years, satellites have been put into orbit constantly, but in the process of getting to orbit, debris is left along the way. Anytime a rocket is launched, it lets go of spent upper stages, which sometimes go back through the atmosphere and disintegrate. However, often the discarded rocket stages are simply left in space. As satellites do not last forever, defunct satellites cannot maneuver and continue to orbit the Earth. While it is clear that items in space are what we put up in orbit, various-sized fragments and debris are generated by various collisions. They can also be attributed to mission operations such as paint flecks from rockets or small bolts released when upper stages are disconnected.

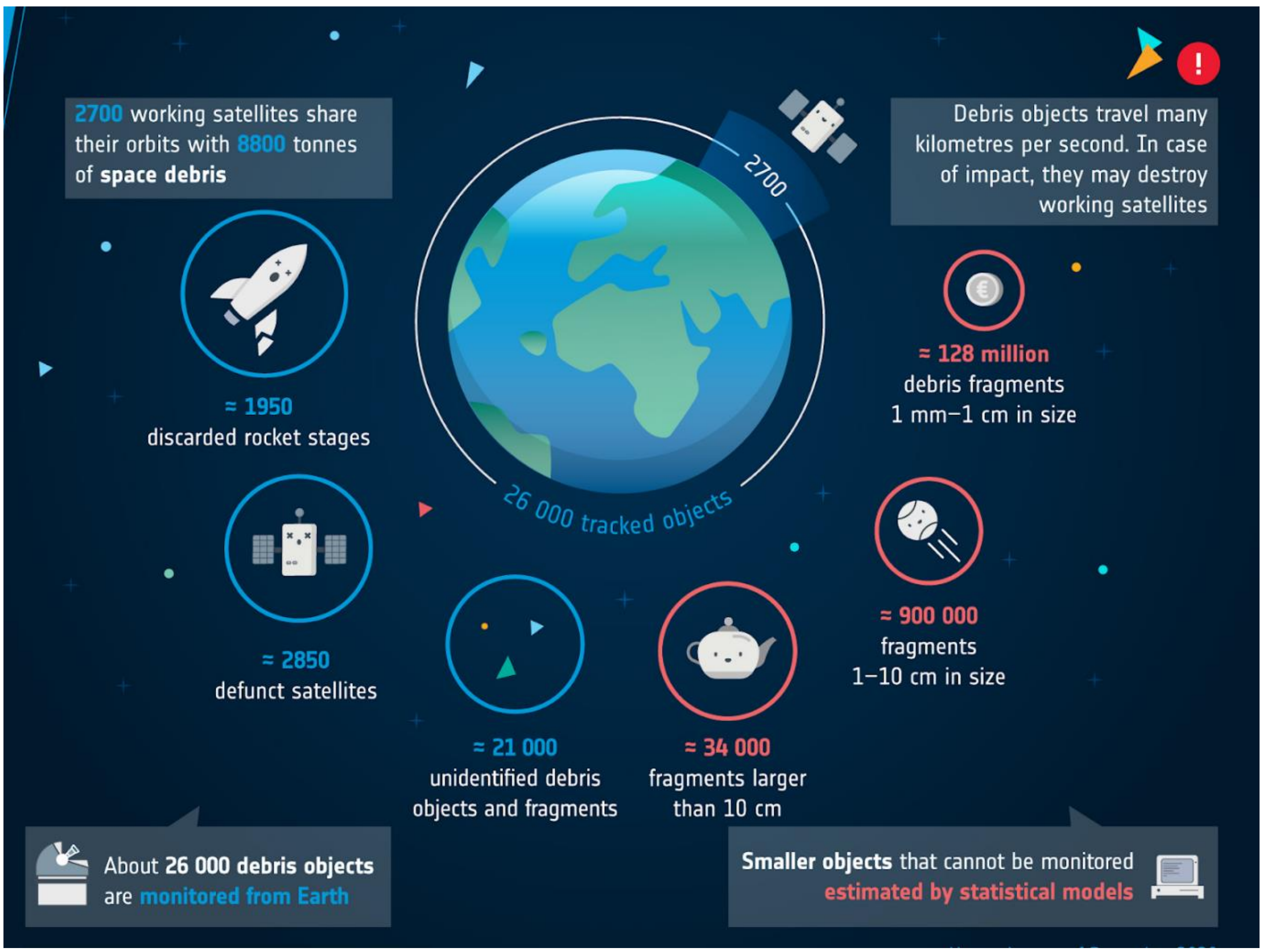

Figure 1: Number of satellites and debris in orbit as of December 2020 [3]

The number of active satellites, dead satellites, and thousands to millions of small debris fragments is of widespread study and attention. The amount of debris around Earth is put into better perspective by Figure 1; over the 60 years of space utilization, there have been over 6,000 launches that have resulted in over 56,000 tracked objects in orbit. Of these objects, 28,000 continue to remain in space [3]. As of April 2022, 2,700 active working satellites orbiting maintain communication with ground stations, 2,850 dead or old satellites longer being used, and 21,000 unidentified debris fragments [4]. While the previously mentioned items can be tracked with ground-based radar, other smaller debris number in the thousands to millions. NASA's Orbital Debris Program Office (ODPO) established over 500,000 pieces of debris ranging from 1 to 10 centimeters and over 100 million pieces of debris smaller than 1 centimeter [5].

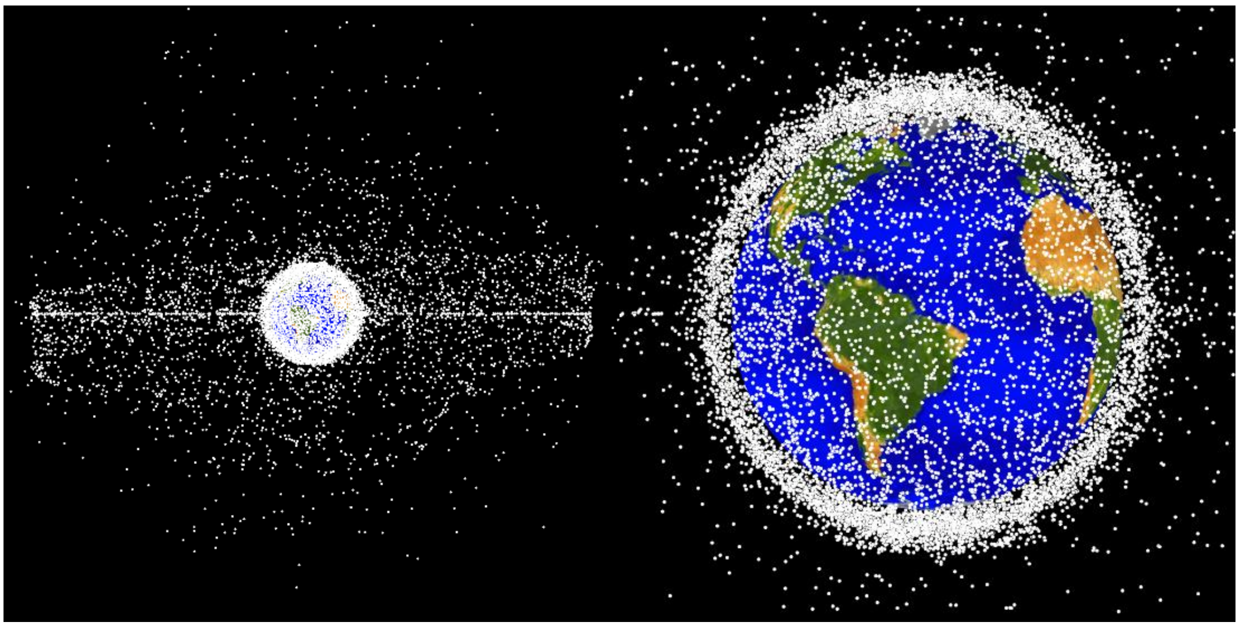

Figure 2: General overview of objects in orbit [6]

As it looks from Figure 2, the number of orbiting satellites in space debris seems enormous; however, these objects can be hundreds of miles apart, thereby making space a relatively empty domain. Additionally, both images show a region around Earth with satellites, while there is also a region further away that can be seen as a white disk or line of satellites. Scientists and engineers define these domains by Low-Earth Orbit (LEO) or Geosynchronous Equatorial Orbit (GEO) to better characterize the environment. Some everyday items in LEO are the ISS and fast internet providers such as SpaceX's Starlink system. LEO satellites fly at altitudes of 99 to 1,200 miles and orbit at 17,000 mph. This allows them to complete an orbit around the Earth every 100 minutes. GEO satellites commonly involve communication, weather, satellite radio, television, and Earth-imaging satellites. GEO satellites are much further away, at 22,000 miles in altitude. At this altitude, they fly at the same speed the Earth rotates and stays stationary over one location [7].

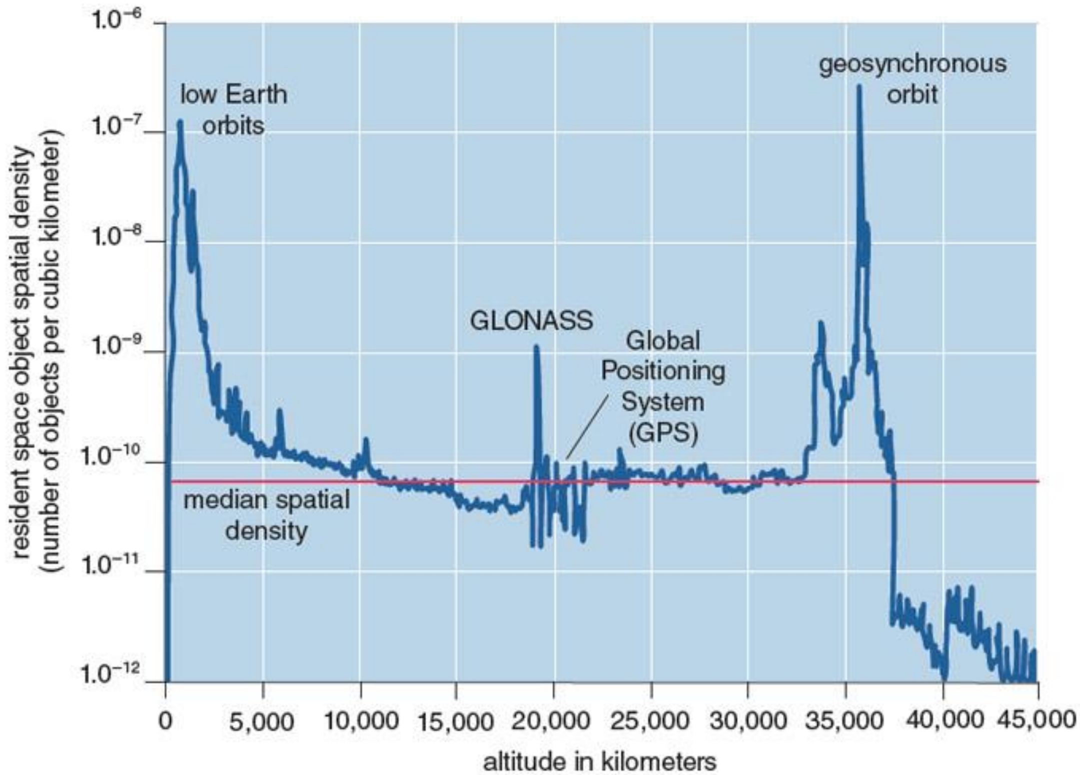

Figure 3: Density of space object by altitude graph [5]

To better characterize the environment of space from LEO to GEO, it helps to look at the number of objects per cubic kilometer as altitude increases. As shown in Figure 3, LEO and GEO orbits maintain the densest locations of objects, while in between, the density of objects goes down. It is also worth noting that the spike in the middle is the GPS location, about 20,000 kilometers away [5].

Since 1960, the total number of objects in orbit has steadily increased over time, as seen in Figure 4. Compared to the number of spacecraft in yellow, it is clear that it does not correlate to the total number of objects in blue. As a rocket launches, debris from the rocket body, paint chips, and small bolts are created and left up in space. Even though limiting debris generation from missions is an issue that needs to be addressed, the spikes in the total number of debris are all caused by different collision events that resulted when two satellites hit each other and produced thousands of small pieces of debris. The trajectory and almost exponential increase are of great concern as humanity continues to use space to its benefit [8].

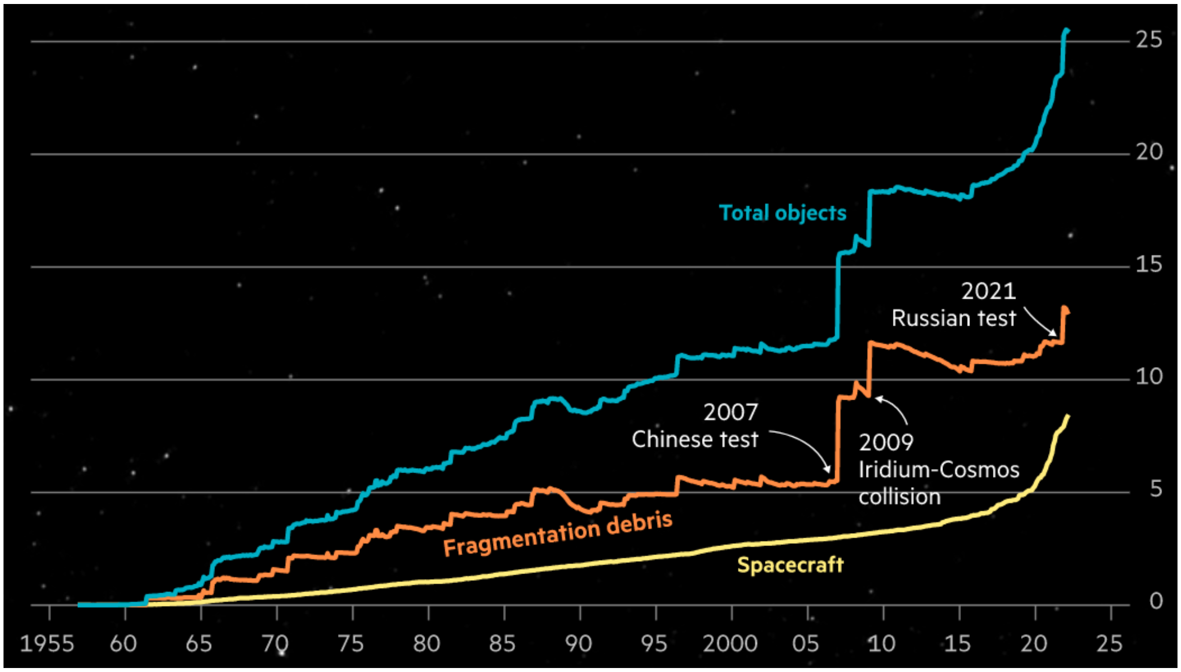

Figure 4: Total objects in orbit over time in the thousands [8]

Risks to Other Satellites and Overall Concerns

With thousands of dead satellites, thousands of school bus-size rocket body parts, and hundreds of thousands of small pieces of fragmentation debris, all of these items continue to orbit the Earth day after day and sometimes over decades. The Earth's atmosphere acts as a natural space broom that causes objects to eventually fall back to Earth. Imagine running on a track while the wind rushes directly into you. It is naturally a force that acts opposite to the direction of movement and slows us down. Airplanes also experience this as drag; however, as they fly higher in the sky, the drag is lessened because there are fewer air molecules as altitude increases. Going even higher in space, some air molecules exist. Still, it is very few and far between, which allows objects to orbit without constantly using propulsion mechanisms to stay in orbit [4].

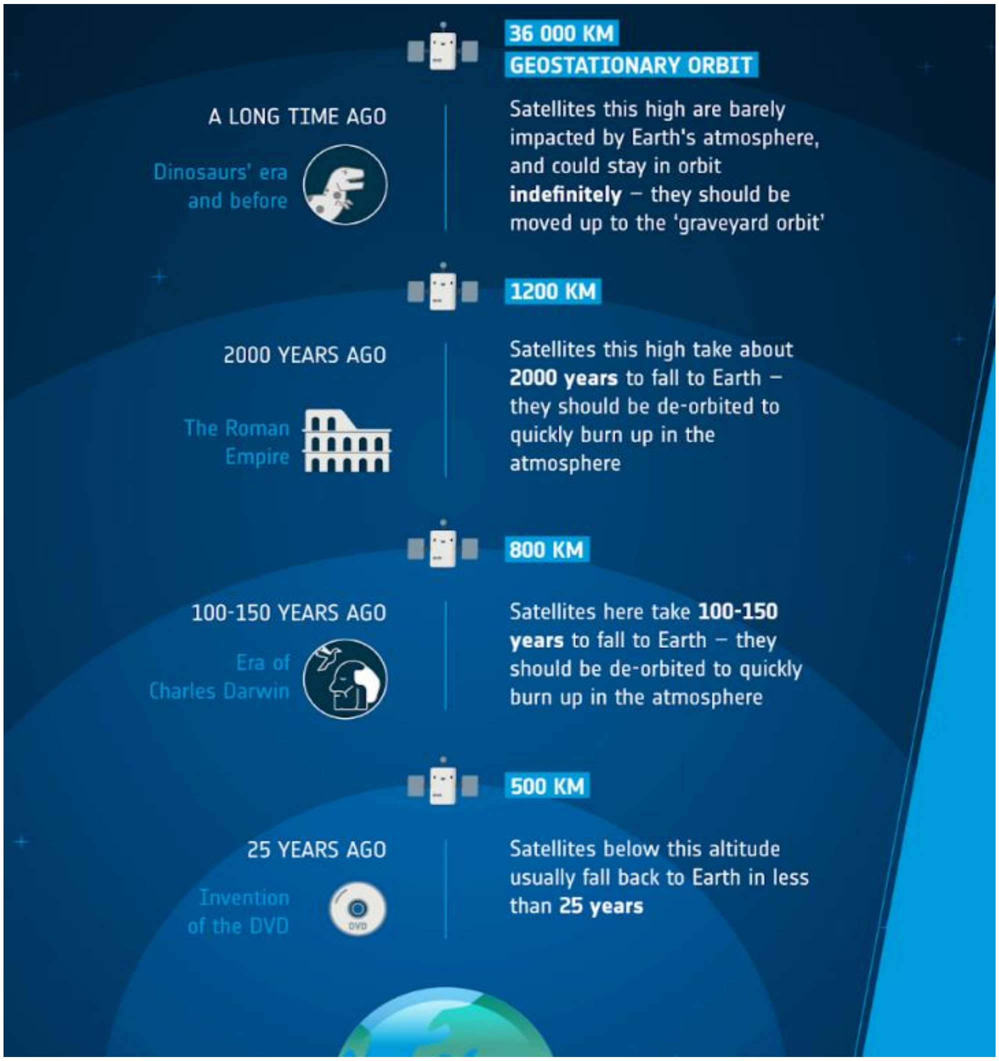

Figure 5: Time to fall to Earth by altitude [4]

As shown in Figure 5, depending on the height of a satellite, the Earth's atmosphere can affect the length of a satellite's life over great extremes from years to millions of years. Simply put, the higher the altitude, the longer orbital debris will remain in orbit. Debris and objects orbiting at the height of the ISS at 400 km to 600 km typically take 25 years to fall back to Earth, where they often burn up in the atmosphere or land on the surface. Around 800 km, debris can remain in orbit over centuries and will far outlive the people who put the object up there and could outlive entire civilizations. Debris issues in GEO are some of the most concerning as there is essentially no natural atmospheric drag mechanism to deorbit these objects. While Earth's atmosphere is the primary way debris can be removed from orbit, propulsion mechanisms and other satellites can deorbit themselves by simply firing their rocket thrusters in the opposite direction they are traveling. This force induces a change in velocity that is not sustainable to continue to orbit around the Earth, and the object will fall [9].

As space debris continues to increase from launching more satellites into orbit and more objects colliding paired with understanding the length of time debris can remain in orbit, there is great concern about what happens when two pieces of space objects collide and what damage happens as a result. An on-orbit collision looks more like an explosion than any collision on the Earth’s surface. While hitting a piece of debris on the highway traveling at 60 mph may be very dangerous, things are moving much faster at 17,500 mph in space. This speed gives smaller items more kinetic energy than bigger items traveling at lower speeds. At these speeds, small bolts can destroy entire satellites, and paint flecks can damage satellites to the point where they cannot function [10].

Size of Debris		Amount in LEO	Potential Risk
10 cm and larger		At least 26,000	Catastrophic
1 cm and larger		Over 500,000	Mission-ending threat due to penetration of thermal protective systems, critical infrastructure (e.g., fuel tanks), and spacecraft cabins
1 mm and larger		Over 100 million	Significant impact or loss of mission due to penetration of fuel tank and other critical infrastructure; erosion of surfaces; potential to crack windows and in the case of human space flight, penetrate spacesuits

Figure 6: Size, amount, and potential risk of orbital debris [9]

In simple terms, objects in space travel at speeds ten times faster than a bullet and have 100 times more kinetic energy than a bullet. As shown in Figure 6, these extreme speeds and energy make millimeter-sized debris a significant threat to spacecraft by eroding surfaces, cracking windows, and penetrating human spacesuits. Centimeter-sized debris can cause mission-ending fuel tank and spacecraft penetration [9]. This explanation is not just hypothetical; orbital debris has produced accurate dangerous results and increased concern. In 1996 debris from a French rocket impacted a satellite, resulting in total destruction. Most recently, the astronauts on the ISS found a piece of debris that impacted the ISS’s Canada robotic arm.

Additionally, after the James Webb Space Telescope was launched, NASA astronomers found a millimeter-sized piece of debris had impacted the telescope’s mirror, causing scientists to have to compensate for distortions. While these debris collision events may seem alarming, they are nothing compared to what can happen when big things like satellites or school bus-sized rocket bodies hit each other. In 2009 a defunct Russian satellite destroyed a US Iridium commercial satellite in which 2,000 pieces of large, trackable debris were created. Also, in 2007

China deliberately tested anti-satellite capabilities and destroyed an old weather satellite that added more than 3,500 pieces of trackable debris and thousands of smaller fragments [11].

While collisions on Earth may be localized to highway or intersection, collisions in space affect all actors and threaten damaging spacecraft worldwide. If an object is low enough in orbit, it may fall back to Earth and break apart; however, if it is high enough, the debris cloud continues to go in uncontrolled circles all around the Earth, threatening to destroy any debris in its path with even the slightest impact. This global threat can cascade into a domino scenario where more debris is created in which the debris cloud continues colliding with other space objects, creating even more debris clouds. The movie *Gravity* from 2013 best makes sense of this scenario where one satellite on satellite collision caused the ISS to be destroyed along with all LEO satellites. While this is unrealistic due to how fast the cascade of events happened, it is a real possibility described as the Kesseler Syndrome. In 1978 NASA's Donald J. Kessler predicted, using mathematical models, that this domino scenario where debris creates more space debris is of mathematical possibility. He also described that the domino effect would not happen overnight and could be a slow-motion disaster over decades [12].

To best protect the critical infrastructure in space, the goal is to prevent the Kesseler Syndrome and mitigate the potential for a worldwide destruction event. While the previously described situation is unlikely, the current rate of launches is increasing exponentially, and the debris generation rate is growing in parallel. This debris growth will eventually make tracking objects more complicated and costly as information needs to be quickly disseminated across the globe to prevent any future collisions. Additionally, as space debris increases, satellites will be forced to carry extra fuel for maneuvers needed to dodge orbital bullets [10].

The current climate and public attention to orbital debris continue to increase yearly. News agencies regularly report on the threats aboard the ISS when debris passes by the station, causing astronauts to prepare to depart immediately in case of impact. Not only is the ISS becoming increasingly threatened, but the rise of new space actors and mega constellations also adds fuel to the fire. LEO satellite internet companies like Starlink and OneWeb currently place hundreds of satellites in congested LEO with the approval for tens of thousands more. There are also plans for Amazon and Telesat to pursue similar mega constellations [13].

For a better perspective, there are currently only 5,000 satellites operating in orbit. Starlink alone they have plans for two phases of growth. The first is a constellation of 4,000 satellites that are 250 miles apart, and the second is another constellation that uses 20,000 satellites that are only 50 miles apart [14]. This number of satellites is unprecedented, but the numbers only increase from there. Including the 24,000 Starlink satellites, space experts estimate an additional 58,000 new satellites to be launched by 2030. This rise in the commercialization of space encourages business innovation and exploration but also increases the concern of congestion and traffic management. As previously mentioned, accidents in space are not localized; they travel faster than ten times a bullet in circles around the Earth for as short as one year to as long as a million years [15]. Space is international in nature but operates by domestic law and regulations; the time to ensure that space remains safe and sustainable for the near future and beyond is of utmost importance to not only ensure that they daily service our phones, governments, and banks rely on remain operable but it also necessary to ensure that the crucible of curiosity of space exploration remains to inspire the next generation of scientists and engineers that will build our future.

BACKGROUND

This section provides background information to explain debris creation, tracking infrastructure, collision probability, and the three pillars of sustainability – mitigation, tracking, and removal. Additionally, an international and domestic legal and regulatory framework is provided to understand how current laws and regulations affect the orbital debris issue. Lastly, an overview of current events and stakeholders is investigated to understand better how policy can be implemented to help ensure a sustainable space environment for the next generations.

How is Orbital Debris Created?

As space debris becomes an increasingly dangerous problem, it is essential to understand the sources of space debris to best limit the generation of additional debris. At its most basic level, space debris is all generated by humans using rockets to put satellites and spacecraft into orbit.

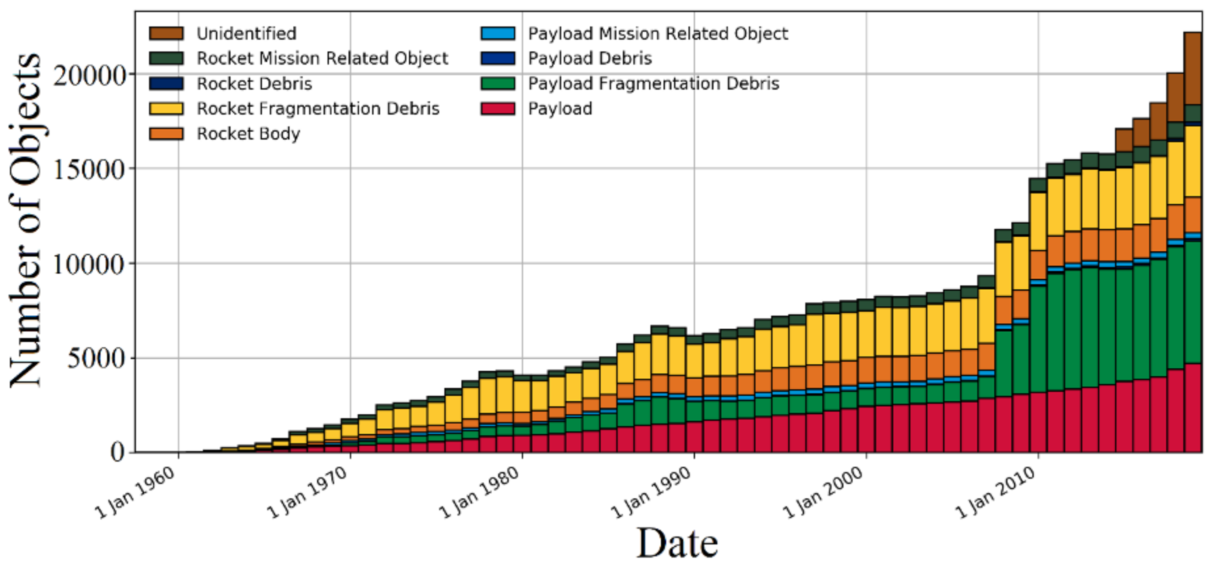

Figure 7: Number and types of trackable pieces of space debris in Earth Orbit [16]

As shown in Figure 7, the sources of space debris vary among several categories and have changed over time. Among these items, it is best to distinguish debris from intact non-fragmented items and fragmentation debris created by collisions. In the non-fragmented debris category is mission-related objects. When a rocket launches, it is necessary to reduce its weight to optimize fuel use. This fact of physics causes engineers to drop rocket boosters, fairings at the top of a rocket containing the payload, and the interstage that connect the first and second stages [16].

The small objects dropped as a rocket travels into space are mission-related debris. Small bolts and metal fragments are deposited from the disconnection of rocket body parts, and millimeter-sized pieces of paint also fall off the rocket and are inserted into orbit [17]. During human space flight, astronauts have lost items while on spacewalks. Among dropped items are tools used to repair satellites, screws connecting the ISS, cables used to connect components, cameras used to take pictures of their work, and surprisingly an astronaut's glove. Other less-known sources of mission-related debris are the byproduct of technology and the materials that engineers use. Rocket motor firings have released dust-sized to cm-sized aluminum oxide deposits, and Russian satellites have released droplets of reactor coolant from a sodium-potassium alloy into space. Additionally, the extreme ultraviolet environment of space, along with atomic oxygen and small particles, erodes satellite surface coatings and generates more debris [3]. Lastly, as satellites cannot last forever due to lack of fuel, battery power generation, and solar panel damage, old defunct satellites are the primary source of non-fragmented debris [16].

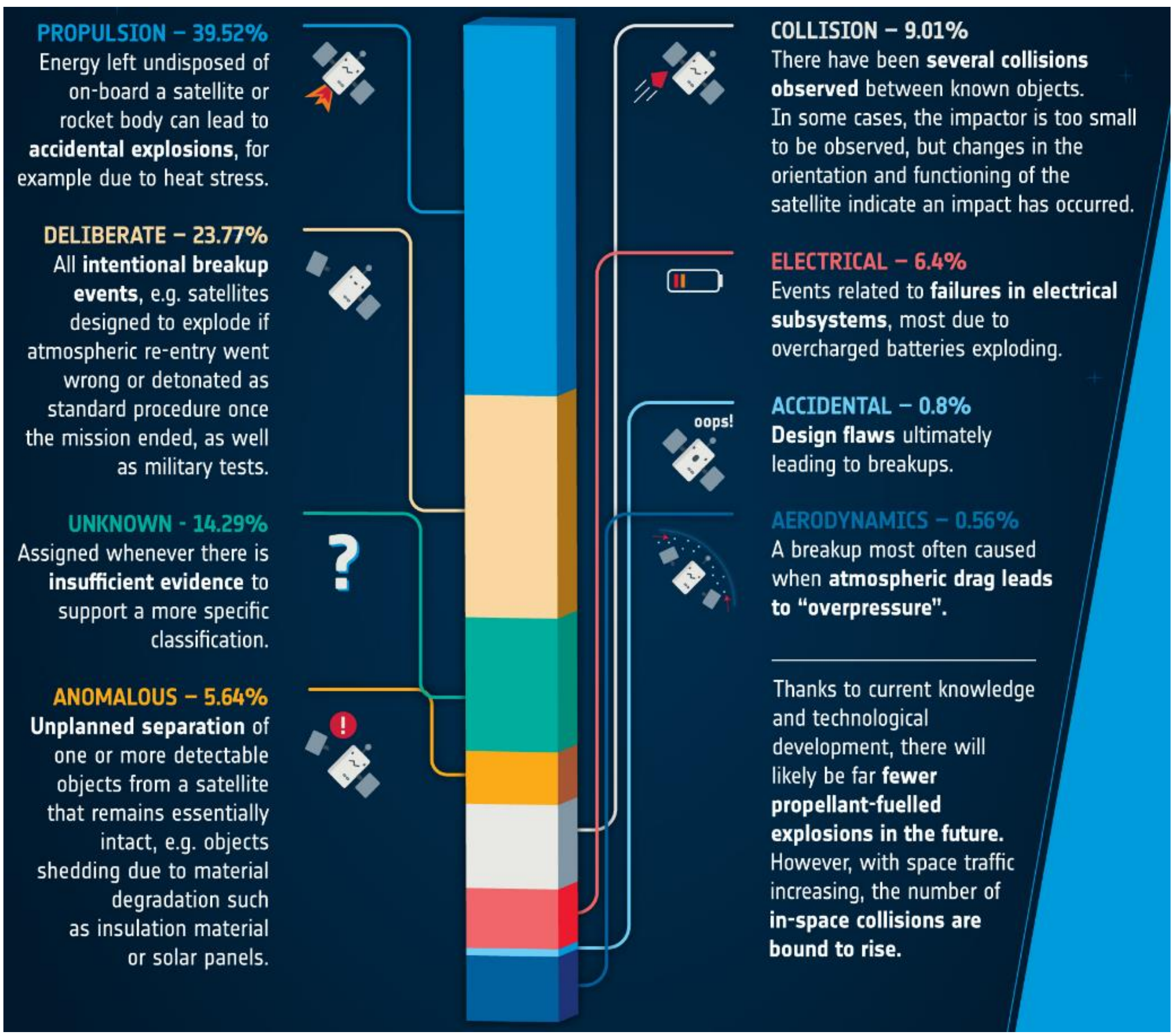

Figure 8: percentage causes orbit fragmentation debris [4]

Although non-fragmented debris is a significant threat to space sustainability, the sources of fragmented debris are among some of the most dangerous as they generate thousands of smaller pieces of debris resulting from large objects colliding. Figure 8 shows fragmented debris is caused by propulsion explosions, deliberate destruction, accidental collisions, and electrical failure. The leading cause of on-orbit fragmentation is the result of small amounts of fuel that remain in tanks and explode when satellites are not properly disposed of after their mission ends. There have also been situations where accidents have happened, such as the 2009 US Iridium-33 and defunct Russian military satellite collision event. Lastly, the greatest threat of on-orbit fragmentation events is the deliberate destruction of a satellite by a kill vehicle [3].

Almost all major countries have successfully maintained military dominance in space by launching kill vehicles purposely intended to destroy other satellites. The United States, China, Russian, and India have all conducted anti-satellite (ASAT) tests. Russia and India have generated over 6,000 pieces of trackable debris that will continue to orbit the Earth for the next half century [8]. In 2007 China used a ballistic missile interceptor to destroy a defunct Fengyn-1C weather satellite [18]. This event alone still accounts for 10 percent of all trackable debris, and where 79 percent of the original debris will not re-enter the atmosphere in the next century. In 2008 the United States conducted Operation Burnt Frost, which destroyed a defunct reconnaissance satellite in which 99 percent of the debris burned up in the atmosphere months after the test [8]. On March 27, 2019, India took a different approach by launching a small satellite into orbit two months before, followed by a kill vehicle interceptor that destroyed the orbiting satellite 30 seconds after authorization. This event was limited to about one-third the altitude of the Chinese test, and all the debris created fell back to Earth after a few weeks [19]. In November of 2021, a Russian ASAT destruction of Cosmos 1408 satellite caused the United States and Russian astronauts' lives to be threatened on the ISS, resulting in a lockdown rescue readiness state to be initiated [13]. While the purposeful destruction of satellites may eventually end, the current situation will vary from pieces of non-fragmented mission-related debris and fragmented debris from explosions. ASAT testing has exacerbated the potential for more collisions from fragmented debris that continue to threaten the space infrastructure the modern world relies on daily.

Methods and Approaches to Promote Space Sustainability

The challenges within the space debris crisis resemble the difficulties of tackling the challenge of climate change. As the Earth is not home to one country, there is an obvious need to gain international support in this endeavor. To ensure the planet remains at a reasonable temperature, the United Nations and countries worldwide signed the Paris Agreement in 2015. This commitment produced long-term goals for all nations, including mitigation of carbon emissions, tracking all countries' progress every five years, and research to remove carbon and enhance resilience [20]. The solution to ensuring space sustainability and preventing an orbital debris disaster incorporates a multifaced approach just like the Paris Agreement. Debris mitigation techniques should be used to stop creating more debris, tracking technologies are needed to ensure satellite operators have eyes in orbit, and debris needs to be removed to reduce the probability of cascading collision events. Each country must address these three areas while also collaborating internationally to write the rules of the road for the space highways of the future [21].

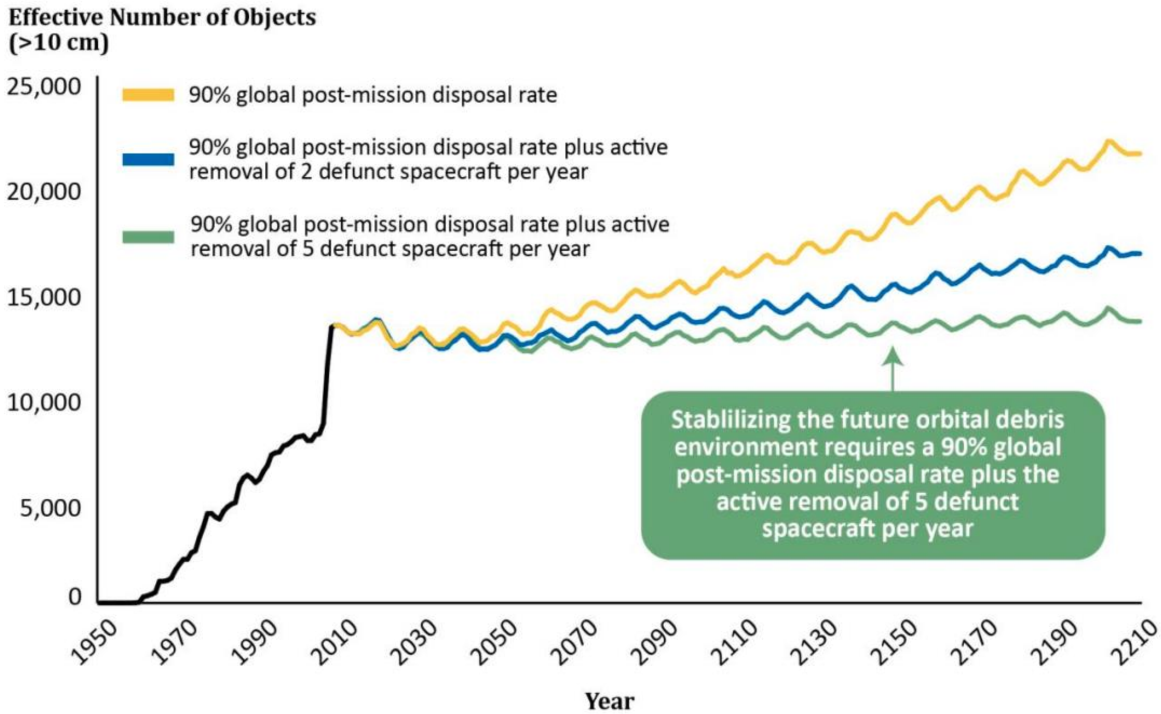

Figure 9: Estimated Impacts of Successful Post-Mission Disposal and Active Debris Removal Activities on LEO's Orbital Debris Environment [9]

Engineers and scientists worldwide, from NASA to ESA, have all concluded that the best way to ensure space sustainability is relatively simple. As Figure 9 shows, the approach involves ensuring that countries comply with the globally recognized 25-year post-mission disposal guidelines and that a total of 5 satellite to rocket body-sized objects are removed from orbit per year [22]. Although this goal is simple, the solution still involves international compliance, debris mitigation, tracking objects, and active debris removal and servicing.

Debris Mitigation

Debris mitigation incorporates both prevention and limiting the generation of additional space debris. This can include hardware and software systems that limit debris generation as a satellite gets put into orbit, reducing paint chips and hardware debris. Mitigation also involves the simple idea that satellites should not explode due to fuel mismanagement. Lastly, post-mission disposal guidelines must be adhered to at a 90 percent level worldwide to mitigate the generation of additional space debris. Through international and domestic guidelines and regulations, it is widely understood that objects must be disposed of 25 years after their mission ends. The guidelines have described that objects in LEO should be deorbited into the atmosphere, and objects and GEO should be boosted into a higher graveyard orbit.

Tracking Satellites and Space Debris

Tracking and sharing satellite and debris location information is one of the most critical parts of ensuring space sustainability. While individual nations are responsible for their orbiting objects, there is not one internationally recognized entity that tracks satellites and space debris. To fill this void, a mix of global powers use their systems to track space objects. China and Russia have their own tracking infrastructure but do not share it with the international community. To fill this void, the United States offers its services and shares space object tracking data worldwide with anyone who needs it. The US Air Force's Joint Space Operations Center (JSOC) takes this job in the United States. It monitors the ISS and other NASA satellites for potential collisions while making data available to any other country that needs it.

The US uses the Space Surveillance Network (SSN) to monitor objects and spacecraft that are 10 cm or bigger. This system operates using over 30 ground-based telescopes and radar along with six orbiting satellites that monitor objects in orbit. Due to the increased size of this debris and satellites, the SSN can update space objects' location and predict where they will be over 72 hours in advance [9]. For debris smaller than 10 cm, the SSN cannot accurately determine the debris' location, so radar installations determine the approximate number of debris using algorithms to generate a probability model of the object's location [12].

As the space industry becomes more commercialized, companies, and other governments have sought out private space tracking data sources to supplement basic tracking data from DOD. This advancement has been the impetuous in transferring space tracking and awareness from DOD to the Department of Commerce NOAA Office of Space Commerce (OSC). Further progressed by President Trump, Space Policy Directive-3 (SPD-3) requires an Open Architecture Data Repository (OADR) system to be created by NOAA OSC that increases transparency, gives access to better data, and improves close encounter tracking probabilities [15]. Although the transfer of space object tracking and awareness from DOD to NOAA has been slow, NOAA hopes that the OADR will be operational in 2024 [23].

Active Debris Removal and Remediation

A logical solution to ensure the space debris crisis does not worsen is to remove old spacecraft or increase their life by giving them more fuel. Methods for deorbiting space debris include using lasers to slow satellites down, nudging objects into disposal orbits with propulsion mechanisms, and deorbiting objects down using satellite tugboats. While lasers are the most efficient way to deorbit satellites, they are plagued with research difficulties and are not much of an option today. However, space tugboats that either nudge objects into higher graveyard orbits or bring objects through the atmosphere have progressed beyond lab testing and are being created by a few governments and even some ambitious companies [24].

Start-up companies like ClearSpace and Astroscale have developed technologies to deorbit space debris and have been relatively successful. In August 2021, Astroscale's ELSA-d mission demonstrated the ability to attach to a client's spacecraft and move the object into the atmosphere or a graveyard orbit. Additionally, in May of 2022, the ELSA-d spacecraft demonstrated the ability to approach and rendezvous with a satellite, further progressing the active removal technologies that will be needed [25]. In 2018 Surrey Satellite Technology Ltd. Successfully conducted a mission called RemoveDEBRIS that fired a net onto a small floating object in space. Building on that success in 2019, they also successfully fired a harpoon onto a target, pulling the object down into the atmosphere [26]. Lastly, ClearSpace is building its ClearSpace-1 mission that aims to remove an ESA-owned object from orbit by 2025 [27].

International and Domestic Historical Recognition of the Issue

While the space debris issue may be getting more attention in modern times, the roots and solutions to the issue have been widely studied by the United Nations and space fairing countries. The United Nations General Assembly (UNGA) created the Committee on the Peaceful Uses of Outer Space (COPUOS) in 1959 "to govern the exploration and use of space for the benefit of all humanity: peace, security, and development. The Committee 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 programs, and studying legal problems arising from the exploration of outer space" [28].

From 1959 to late 1968, space became more of a household topic, and mission frequency increased. Some scientists at NASA were concerned that space debris would be a hazard to exploration; however, the North American Aerospace Defense Command (NORAD) determined that these small objects posed little to no risk. In 1978 Dr. Don Kessler of NASA published a paper that described the possibility of a systemic domino effect disaster was mathematically possible, and we should all be concerned about the issue. Through the 1980s, a series of US DOD ASAT tests were conducted that processed hundreds of pieces of debris, and a French Ariane rocket body exploded, which added hundreds of more pieces of debris. Both events raised the profile of the issue, and in 1988 President Regan issued the first official policy to minimize the creation of new debris [29].

Although the 1988 National Space Policy did not address policies to solve orbital debris, it raised the issue to a Presidential and national government level with the words "all space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments, and systems will strive to minimize or reduce the accumulation of space debris consistent with mission requirements and cost-effectiveness" [30]. Next, an international focus was added by President George H. W. Bush in the 1989 National Space Policy, stating, "The United States government will encourage other spacefaring nations to adopt policies and practices aimed at debris minimization" [31]. This policy eventually led to the creation of a multilateral Inter-Agency Space Debris Coordination Committee (IADC) in 1993 with members of Europe, Russia, Japan, and the United States [29].

Through the 1990s, the Clinton administration undertook background research to understand the space debris issue better. In 1995 the US National Research Council published the Orbital Debris Technical Assessment, which looked at the risks and hazards posed by space debris and recommended protection and mitigation methods to reduce future debris creation [32]. Separate from the Orbital Debris Technical Assessment of 1995, the White House issued an Interagency Report on Orbital Debris in November 1995. This report updates information on orbital debris measurement and mitigation techniques while also recommending better tracking abilities, future study of LEO systems, engineering design guidelines, international strategy, and updates on US policy on debris [33]

At the turn of the century, the United States released the United States Government Orbital Debris Mitigation Standard Practices (ODMSP) document in 2001, effectively informing regulation for US Government operators such as NASA, NOAA, USGS, DOD, and the Intelligence Community. The ODMSP provided information "limit the generation of new, long-lived debris by the control of debris released during normal operations, minimizing debris generated by accidental explosions, the selection of safe flight profile and operational configuration to minimize accidental collisions, and post-mission disposal of space structures" [34]. This work would eventually come to international recognition in 2002 when the 13 member countries of the IADC released the Space Debris Mitigation Guidelines. This was a crucial step in space sustainably as the fundamental principles of preventing orbit break up, removing the defunct end-of-life spacecraft from orbit after 25 years, and limiting a consensus process agreed to the objects released during regular operation by all of the IADC member agencies [35].

Current International and Domestic Regulatory and Legal Framework

Global Legal Landscape

International space law is generally divided into two categories: binding laws such as treaties, standards, and national regulations. The second is non-binding resolutions and agreements that describe voluntary goals and ideas. Both binding and non-binding laws and agreements form the current legal landscape that works alongside each other to promote space sustainability [36].

Binding Laws and Agreements

The backbone of global space law is widely recognized as the 1967 Outer Space Treaty. The treaty has been ratified by 111 countries and signed but not ratified by 23 other counties [37]. It comprises various articles that have continued to be the backbone of international space law for the past 50 years. Article 1 of the treaty says that the exploration and use of outer space shall be available to all humankind and free to use by all countries without discrimination following international law. Next, Article 6 on international responsibility for national activities described that all countries "shall bear international responsibility for national activities in outer space … by governmental agencies or non-governmental entities." Simply put, Article 6 describes that countries are responsible for monitoring government and commercial space missions and authorizing them [38].

Article 9 of the 1967 Outer Space Treaty describes how counties should conduct space operations. Sentence 1 states, "States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding" [38]. In this sentence the words "due regard" has been a topic of debate. As there is no definition for "due regard" the phrase has allowed poor compliance to the requirements of the treaty. Lastly Article 9 sentence 2 of the treaty describes those countries shall "conduct exploration of [the moon and other celestial bodies] to avoid their harmful contamination ... resulting from the introduction of extraterrestrial matter" [38]. This clause has wildly been known not to introduce Earth organisms to different planets and not necessarily to protect the Earth from orbital debris.

In 1972 the United Nations released the Liability Convention, which says "in the event of damage being caused elsewhere than on the surface of the earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be liable only if the damage is due to its fault or the fault of persons for whom it is responsible" [39]. As this convention is not explicitly related to space debris, the term "space object" also considers orbital debris to be applicable under the definition. Under this convention, the fault for damage goes back to the launching state for that space object, and commercial companies must use their national government to sue under the convention [40].

With the increased use of outer space and the need to identify and track space objects, the United Nations adopted the 1974 Convention on Registration of Objects Launched into Outer Space. This convention would require maintaining a registry of their space objects and allowing United Nations to access the information [41]. Most importantly, this convention gave the Liability Convention traction as it fixed the identification issue if any damage occurred to a space object [36].

Non-Binding Guidelines

In the form of non-binding agreements and guidelines, the international community has released documents that help shape space debris policy. International groups such as the IADC, COPUOS, and ISO have all developed several significant guidelines. In 2007 the UN COPUOS committee adopted a document that described specific guidelines countries should adhere to. Among these were limiting debris generation during normal operations, minimizing break-up potential during operational phases, limiting the probability of accidental collisions, avoiding intentional destruction, discharging fuel sources at the end of a satellite's life, disposing of old spacecraft from LEO, and disposing of old spacecraft in GEO [42].

Building on the IADC guidelines released in 2002, the committee updated the guidelines in 2007 and 2020. The 2007 updates were only clarifications related to fundamental principles of preventing orbit break up, removing the defunct end-of-life spacecraft from orbit after 25 years. The 2020 revision updated the objects passing through the LEO section. It reinforced the 25-year deorbit guidelines and said the probability of disposal success should be at least 90%. Additionally, a higher probability of success and shorter deorbit lifetime should be considered for prominent constellations of satellites. The update also clarified that countries should consider the environment and human population when deorbiting objects with various toxic and radioactive substances. Lastly, under controlled reentry, the operator should inform relevant air traffic and maritime traffic authorities during the event [35].

International consensus-based standards on space debris mitigation have gained recognition in the International Organization for Standardization (ISO). The ISO 24113 standard is the most important of the various ISO standards on space debris mitigation. This standard is a high-level document that looks at how measures can be implemented in the categories of mitigation, tracking, and removal in greater detail than the UN COPUOS and IADC guidelines. While ISO standards are essential to implement specific international guidelines further, the ISO standards are ultimately nonbinding and require countries to transfer the standards into actual regulations [22].

US Regulatory Regime

US Space Sectors

In the United States, space endeavors are grouped into civil, national security, and commercial sectors. While each of the three sectors utilizes similar manufacturing, engineering, and launch industrial bases, the government has distributed regulatory power and oversight to various agencies within the United States government. Civil operations are non-defense missions such as launching the Space Shuttle, Artemis missions, James Webb Space Telescope, and various space satellites that conduct research and exploration. NOAA, within the Department of Commerce, focuses on ocean and atmosphere monitoring and uses civil space to operate a fleet of satellites to monitor these areas. NASA operates everything else from the ISS to Mars and has broad authority to study many scientific-related missions.

National security missions are missions within the defense and intelligence sectors. Satellites in this area could be GPS and spy satellites that take pictures and allow increased military capabilities on the ground. The US DOD oversees these missions and other intelligence community members. Lastly, commercial space encompasses any private sector company that operates in space. From communication, television, internet, and imagining to space tourism, these sectors are regulated by NOAA, FAA, and FCC [43].

Laws Granting Regulatory Power

Over time, Congress has given the regulatory authority of space activities to various agencies within the federal government; the various legislation is compiled within Title 51 of the United States Code [44]. The Communications Act of 1934 has been amended over time to regulate commercial satellites, licensing, and coordinating the use of radio spectrum. Apart of the act was the creation of the FCC, an independent regulatory agency in the US federal government. In 1958 President Eisenhower signed the National Aeronautics and Space Act that established NASA and gave it broad authority over space knowledge, space vehicles, missions, safety, and sharing knowledge with defense agencies. The Commercial Space Launch Act of 1984 and amendments since then granted the FAA under the US Department of Transportation regulatory authority for commercial spaceflight. Under the US Department of Commerce, the Land Remote-Sensing Policy Act granted NOAA the power to license and regulate the remote sensing industry in 1992. Lastly, the US Space Force was created by the National Defense Authorization Act of 2020 to take over the space activities of the US Air Force [45].

Implementation Across the Federal Government

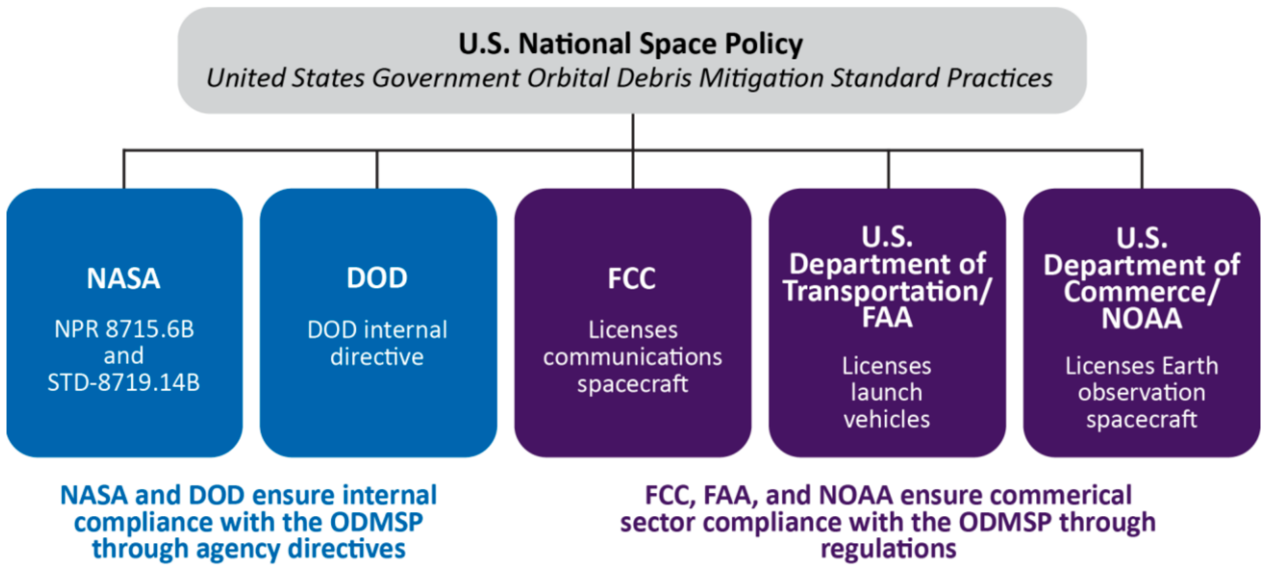

Figure 10: US Government Orbital Debris Mitigation Policy Implementation Framework [9]

The United States has developed a wide-ranging top-down approach to orbital debris space policy, implementing the broad authority given to the Executive branch by Congress. Implementation is derived from the Presidential US National Space Policy guided by the US ODMSP and then distributed under the direction of the White House National Space Council. OSTP to governmental agencies divided by government and civil space operations. From Figure 10, the blue section represents civil and national security space in which NASA and DOD ensure internal compliance with the ODMSP through internal agency directives. The purple section represents commercial space where the FCC, FAA, and NOAA ensure commercial compliance with the ODMSP through regulations. It is also important to note that NASA provides expertise to DOD, FAA, FCC, and NOAA on orbital debris migration, tracking, and updating mitigation policies, even though they cannot provide any regulation over the commercial sectors [9].

National Space Policy

US National Space Policy is the government's prime mover of space policy. While most presidents have released US National Space Policy executive documents, the Obama policy in 2010, Trump policies from 2017-2020, and the Biden policy in 2021 set the stage for solving the current orbital debris crisis. The 2010 Obama National Space Policy addressed the importance of preserving space in an orbital debris context, “The United States shall seek to minimize the creation of orbital debris by government and non-government operations in space to preserve the space environment for future generations” [46]. It also directed NASA and DOD to “Pursue research and development of technologies and techniques… to mitigate and remove on-orbit debris” [46]. While this was the first time a president mentioned removing debris from orbit, it did not assign NASA or DOD to remove an on-orbit object. Instead, it only directed them to pursue elementary research.

Recognizing the growing threat of space debris, President Trump issued a series of Space Policy Directives; among these was Space Policy Directive-3 National Space Traffic Management Policy (SPD-3) in June 2018. In the policy, President Trump directed, “Debris mitigation guidelines, standards, and policies should be revised periodically, enforced domestically, and adopted internationally to mitigate the operational effects of orbital debris” [47]. SPD-3 also directed the ODMSP to be updated, addressing “operating practices for large constellations, rendezvous and proximity operations, small satellites, and other classes of space operations” [47]. Lastly, SPD-3 transferred space object tracking responsibility from a military agency to a civilian organization. It further required the Office of Space Commerce under NOAA in the Department of Commerce to assume the responsibility of tracking space objects and debris that DOD US Space Command currently operates [47]. This policy would eventually lead to the update of the US ODMSP in 2019 [48]. The current transfer of space tracking and conjunction assessment services from the US Space Force to Commerce using the Open Architecture Data Repository (OADR), in which a prototype version was released in February 2022 [49]. Lastly, SPD-3 would be the impetus for FCC to review their space debris regulations released in 2020 [50].

The Trump Administration, in conjunction with NASA and the international community, released the Artemis Accords in October 2020 to further establish “Principles for a Safe, Peaceful, and Prosperous Future” [51]. This agreement established a set of principles for international countries and private sectors to follow in pursuing outer space. The Accords promoted transparency in describing public policies and plans. They used standards to promote interoperability, further reinforcing the importance of object registration, mitigation of orbital debris, and post-mission spacecraft disposal [51]. Countries have signed the accords; however, notable exceptions to the signatories include India, Russia, and China [52].

Most recently, the Biden Administration released the United States Space Priorities Framework in December 2021, which sought to guide the efforts of the US National Space Council. Among the wide-ranging policies, the Biden Administration stated, “The United States will engage the international community to uphold and strengthen a rules-based international order for space” [53]. Furthermore, it expressed the administration's support of NOAA’s OADR transfer from DOD [54]. The document said, “US regulations must provide clarity and certainty for the authorization and continuing supervision of non-governmental space activities, including for novel activities such as on-orbit servicing, orbital debris removal” [53]. However, the document highlighted the need for further regulation; it did not grant authority to any government agency to implement these needed regulations [54].

US Orbital Debris Mitigation Standard Practices

To better implement National Space Policy, NASA, DOD, FAA, FCC, and NOAA reference the US ODMSP, as each agency must follow the ODMSP by law. This approach ensures cohesiveness among definitions and specific standards to inform regulation and operations

[55]. As described in previous sections, the US ODMSP was initially drafted in 2000; however, SPD-3 required them to be updated after nearly two decades of amendments. This effort clarified and added additional standard practices needed due to the advancing nature of space exploration and commercialization [56]. NASA led an interagency working group to update the document, which was completed in 2019 [9].

Objective	Implementation
Limit the amount of debris released during normal operations	Design spacecraft to eliminate or minimize debris released during normal operations
Limit the risk to other spacecraft by minimizing accidental explosions while the spacecraft is in operation and after the end of its mission	• Design spacecraft subsystems to limit the probability of accidental explosions • Deplete all on-board sources of stored energy (e.g., batteries, propellant) at the end of mission
Prevent on-orbit collisions	• Shield against small debris to ensure successful post-mission disposal • Make spacecraft maneuverable by loading it with extra propellant to allow for the avoidance of large debris and other spacecraft
Post-mission disposal	At end of mission: • Follow the “25-year rule” to lower the altitude of the spacecraft at the end of mission so that atmospheric drag pulls it into Earth’s atmosphere to burn up or reenter within 25 years • Move the spacecraft into Earth’s atmosphere or further away from Earth (into a storage orbit around Earth or out of Earth’s orbit altogether) • Actively remove spacecraft from orbit within 5 years of the end of mission
“Other” objective category, including guidance for constellations, CubeSats, and satellite servicing missions	• Constellations with more than 100 spacecraft have a post-mission disposal success rate of at least 90 percent • CubeSats should comply with the first four objectives listed above • Satellite servicing, rendezvous, and proximity operations missions should not generate debris

Figure 11: Summary of US ODMSP objectives and implementation policy guidance [9]

Among the summary of objectives and implementation described in Figure 11, the ODMSP provided several notable updates from the 2001 version. Most importantly, it reinforces the maximum 25-year post-mission disposal guidance even though some agencies have called to change the maximum to 5 years. Adherence to the 25-year rule has been demonstrated to be one of the best ways to ensure a sustainable space environment. The document also included greater quantitative data and probability requirements regarding the success of post-mission disposal. The updates established a minimum of 90% reliability with a goal of 99%.

Furthermore, it introduced specific practices for space operations among prominent constellations, servicing, and active removal. These practices minimize new debris creation from collisions, explosions, and fragmentation events. Lastly, the ODMSP stated that prominent constellations of 100 or more should have a reliability rate of 90% [48].

U.S. Civil Space Regulatory Agencies

At the convergence of international law, international guidance, national space policy, and us debris mitigation standard practices are several government agencies that oversee space policy implementation. The civil, military, and commercial regulatory entities of NASA, DOD, FCC, FAA, and NOAA all share the regulatory responsibilities in maintaining space law compliance across the United States. Within each agency, a series of policies and regulations help mitigate the orbital debris issue but are disturbed across each agency differently.

NASA is a civil governmental agency that launches and operates its missions but also provides guidance and coordination to other agencies within the US Federal Government. Within NASA's Office of Safety and Mission Assurance (OSMA) at NASA HQ is the Orbital Debris Program Office (ODPO), that "continues to develop an improved understanding of the orbital debris environment and measures that can be taken to control debris growth" [57]. This office provides much information but does not conduct active debris removal missions. The ODPO also leads the development of consensus-based orbital debris mitigation policies with international forums related to orbital debris and informs the creation of the ODMSP [9].

Regarding civil and military missions, NASA has a series of requirements, processes, and a handbook for limiting the creation of orbital debris. The NPR 8715.6B: NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environment, practical in February 2017, further described the authority, procedural requirements, and responsibility within NASA to implement orbital debris mitigation policies [58]. A supplement to NPR 8715.6B, the NASA-STD-8719.14: Process for Limiting Orbital Debris, provides specific technical requirements and helps ensure spacecraft and launch vehicles meet orbital debris standards [59]. Lastly, NASA maintains a Handbook for Limiting Orbital Debris – NASA-HDBK-8719.14 that summarizes the background to aid in the fundamental science and issue of orbital space debris [60].

Regarding national security missions, DOD has to follow the ODMSP by law developed and guided by NASA. At the same time, they also maintain documented space policies of their own to limit space debris. In 2000, DOD 3100.12: Space Support Instruction provided policy, responsibility, and guidelines for space operations that incorporate mitigation measures similar to the ODMSP [61]. Ultimately in 2012, DOD Directive 3100.10 would explicitly state all DOD operations will follow ODMSP guidelines [62]. Furthermore, the Secretary of Defense issued a memorandum in July 2021 to further describe tenets of responsible behavior in space to ensure sustainability due to orbital debris. Among the behaviors are operating in due regard, limiting the generation of long-lived debris, avoiding harmful interference, maintaining safe separation, and communicating any idea to enhance the safety and stability of space [63].

US Commercial Space Regulatory Agencies

Looking at the commercial sector, the ODMSP is implemented through FAA, FCC, and NOAA regulations. At the most basic level - FAA regulates the launch and reentry of space objects, FCC licenses communications spacecraft, and NOAA licenses earth observation spacecraft. In 14 CFR 417.129, FAA regulation requires operators to ensure for a proposed launch, all aspects of the launch vehicle do not make accidental contact or fragment due to using energy sources, and that stored energy is removed by fuel venting, discharging batteries, and removing remaining stored energy [64]. Simply this rule says at the end of the launch; once something is in orbit, demonstrate your plane to ensure the creation of new space debris is mitigated.

FCC implements space debris regulation by ensuring operators have a plan to conduct space operations responsibly to prevent the creation of orbital debris. If approved, they are granted a license and are allowed to use spectrum and communication equipment in orbit. After SPD-3 FCC revamped its orbital debris mitigation regulations and released the final rule in 2020 [65]. The Mitigation of Orbital Debris in the New Space Age rule requires "greater specificity and clarity regarding collision risks and safety measures, spacecraft tracking and data sharing, permissible orbital dwell periods, and casualty risk assessments; clarify that satellite operators should secure satellite commands against unauthorized access and use; and obligate coordination of frequencies during orbit-raising" [66]. Lastly, NOAA is responsible for rules involving licensing private remote sensing spacecraft [67] which can include satellites with cameras, sonar systems, and weather systems [68]. Under 15 CFR part 960, NOAA deferred regulation to the "FCC license requirements regarding orbital debris and spacecraft disposal, and therefore there is no longer any license condition requiring specific orbital debris or spacecraft disposal" [69]. To summarize, the FCC provides the most robust commercial sector regulations under the current regulatory structure. FAA is limited to launch and reentry, and NOAA has given the FCC its authority over orbital debris regulation.

Current State of Play

International State of Play

On an international level, the most significant development in mitigating the creation of new space debris is happening in response to the Russian ASAT test in November 2021 that was conducted irresponsibly with little regard to any norms of behavior that might have been created. On April 18, 2022, The Vice President of the United States announced a US ASAT testing ban and the international push through the UN to codify this ban in international law [70]. Spacefaring nations have received the ban well and noted it might be possible to create an international agreement. On May 9th, 2022, the UN working group on the issue held its first meeting and all significant countries were very interested in seeking an agreement [71]. The Russians were receptive and did not conduct diplomatic games such as walkouts or procedural objects. The Biden Administration hopes the ASAT ban will reach an international agreement; however, some space policy experts do not feel the same way [72].

Additionally, under the UN COPUOS committee, the United States released a statement of its goals concerning COPUOS Scientific and Technical Subcommittee on February 9, 2022. Among the goals were to "Provide clarity and certainty in regulations for non-government space activities, such as orbital debris removal, Increase efforts to mitigate, track, and remediate space debris; and Advance development and implementation of domestic and international best practices to mitigate the creation of space debris and will support efforts to evolve those practices to ensure the continued safety of flight operations in the future” [73]. While these goals are critical to space sustainability, not much has happened beyond high-level talking points.

Among the like-minded international community of Japan, Europe, and the United Kingdom, significant space sustainability advancements have been worked on and announced recently. Europe, through the European Space Agency (ESA), awarded a $104 million contract to ClearSpace to remove a debris object from space by 2025 [74]. ESA has also been a global leader in promoting space sustainability through an annual environmental report [75] and most recently pledged $15.9 million to Astroscale’s ELSA-M mission to remove another piece of debris from orbit by 2024 [76]. The UK Space Agency most recently announced a plan for space sustainability that will encourage space operators to pursue sustainable operations. Their goal is to “set a global commercial framework for the insurability, the licensing, the regulation of commercial satellites so that we drive down the cost for those who comply with the best sustainability standards.” The UK government also announced $6.1 million in funding to Astroscale to further promote their space debris removal services.

Additionally, Charles the Prince of Wales provided global leadership by mentioning the issue and need to maintain sustainability in space by visiting ClearSpace in 2022 [77]. Lastly, JAXA has invested significant resources into active debris removal through a Japanese-based company, Astroscale. In 2025 Astroscale hopes to continue improving their ELSA-M service by removing an upper section of a Japanese rocket orbing around the Earth [78]. Most notably, the United States has not announced any active debris removal missions.

Russia and China are notable outliers to most space sustainability progress. Most recently, Russia threatened to leave the ISS by 2024 but later changed its position to 2028. In July 2022, the Director of ROSCOSM publicly commented on approval to leave astronauts on the space station. So, while progress may be made with the ASAT test ban in the UN, the general space diplomatic relationship is complicated [79]. China has been along the same lines as they do not seem to communicate any debris issues and made headlines after a piece of their rocket crashed into Earth in July 2022. China also did not let anyone know the object's location and was essentially quiet on the issue [80].

Domestic State of Play

The NASA Inspector General recently reviewed NASA’s efforts within the orbital debris mitigation office regarding efforts to characterize the orbital debris environment, protecting missions, limiting and preventing the generation of orbital debris, and coordinating and communicating with federal agencies, commercial entities, and international stakeholders. The Inspector General found that “Despite presidential and congressional directives to NASA over the past decade to develop active debris removal technologies, the Agency has made little to no progress on such efforts” and “A models of the orbital debris environment lack sufficient data, putting the Agency at risk of under or over-protecting spacecraft from the debris.” Among the recommendations, the Inspector General determined that NASA should lead active debris removal, post-mission disposal efforts, promote compliance with debris guidelines, and better understand the 3mm and smaller debris gap [9].

Within the domestic regulatory agencies, FAA is promising further rulemaking that would “update the existing orbital debris mitigation regulations to more closely align with the US Government Orbital Debris Mitigation Standard Practices, limit the growth of orbital debris, and reduce the creation of additional debris caused by on-orbit collisions” [81]. After the FCC updated their orbital debris mitigation rules in 2020, they left out significant regulatory measures due to backlash and pushback from space operators. Among the items the FCC deferred to future rulemaking were no update to the 25-year post-mission removal rule, surety bonds for post-mission disposal, satellite maneuverability above a certain LEO altitude, and aggregate mega constellation collision risk assessment [66]. A bill working its way through Congress could accelerate the FCC’s satellite licensing procedures to promote the space sector [82]. Lastly, FCC Commissioner Simington defended the FCC's authority to create orbital debris rules and supported the Satellite and Telecommunications Streamlining Act previously [83].

The Office of Space Commerce under NOAA, tasked with implementing the transfer of tracking and assessment services from the military to a civilian agency, has undergone significant current events. After a year of absent leadership, the Biden Administration appointed Richard DalBello to lead the office. To better get the OADR ready for commercial use, Congress recently increased the office's budget from 16 million to 87 million under the deadline of 2025 to implement the OADR system. Lastly, DalBello mentioned the need for Congress to assign regulatory authority for activities under Article VI of the OST as no such agency has that power. He also said, “his office is in discussions with the White House and ‘eventually’ will be with Congress as to whether they should take on Article VI responsibilities. ‘That’s a dialogue will we have in the future,’ but the focus now is the transition of civil/commercial SSA from DOD” [84].

In Congress, committee hearings have been centered on space tracking and awareness. The Senate Commerce, Science, and Transportation Subcommittee on Space conducted the Space Situational Awareness, Space Traffic Management, and Orbital Debris: Examining Solutions for Emerging Threats hearing on July 22, 2021. Among the topics were the transfer of tracking capabilities from DOD to NOAA and the need to update orbital debris mitigation rules to align with the ODMSP [85]. Similarly, the House Subcommittee on Space and Aeronautics held the Space Situational Awareness: Guiding the Transition to a Civil Capability hearing on May 12, 2022, that looked at the OADR and how it can be improved [86]. Along with increasing the budget of the Office of Space Commerce under NOAA, House appropriations also directed NASA to spend up to $5 million for technology development to “addressing tall pole technology gaps for large orbital debris, such as grappling tumbling objects. It also calls on the agency to establish a competition through its Centennial Challenges prize program to find ways to detect, track and remove small space debris less than 10 centimeters across” [87].

Although NASA has not conducted significant active debris removal research, the US Space Force has announced the selection of candidates in its Orbital Prime Program. The program aims to develop technologies for orbital debris cleanup and other services. In the first phase, 125 teams were given a $250,000 contract to develop concepts and do early design work. Eventually, “The long-term goal is to select one or more teams two years from now to conduct an in-space demonstration of OSAM technologies, short for on-orbit servicing, assembly, and manufacturing. This includes a broad range of technologies to repair and refuel existing satellites, remove and recycle orbital debris, and manufacture products in space” [88].

At the White House level, advancements have been made since SPD-3 in the form of research and development plans and an implementation plan. Products of the Orbital Debris Research and Development Interagency Working Group of the National Science & Technology Council, with direction from OSTP and the National Space Council, the documents detailed the need to update orbital debris policies. The National Orbital Debris Research and Development Plan, released in January 2021, started conducting listening sessions and seeking expert testimony from space actors [89]. Most recently, these efforts progressed when the National Orbital Debris Implementation Plan was released in July 2022. The plan identified 44 policy recommendations and directives across the pillars of debris mitigation, tracking and characterization, and debris remediation. This document is an essential step in further progressing the effort of space sustainability; however, the results of the plan are yet to be seen [90].

Government inaction within space sustainability has caused companies to band together and form organizations to best work through the orbital debris issue. Established in 2017 by DARPA seed funding, the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) [91], has recommended a set of guidelines to be considered for commercial rendezvous, proximity operations, and on-orbit servicing [92]. The Space Safety Coalition, formed in 2019, has also developed a set of best practices that look at orbital space debris and safety [93]. Lastly, the Space Data Association is an international organization that aims to enhance safety by promoting best practices across the space data industry. This takes form in data accuracy and timeliness of collision warning systems. The association is a promising venture; however, little progress has been made beyond high-level guidance [94]. ISO has been the most influential among standards organizations, as previously described in this report.

KEY CONFLICTS AND CONCERNS

This section explores and highlights fundamental conflicts and concerns related to orbital space debris. The need for global international cohesion in orbital debris mitigation complicates progress as international treaties are slow. Additionally, communication with other countries, voluntary guidelines, active debris removal liability, and poor compliance with the 25-year rule will be explained. This section will explore the domestic level leadership, messaging, lack of sustainable regulatory framework, focus on mitigation, FCC rulemaking, tracking issues, and lack of active debris removal technology.

International Issues

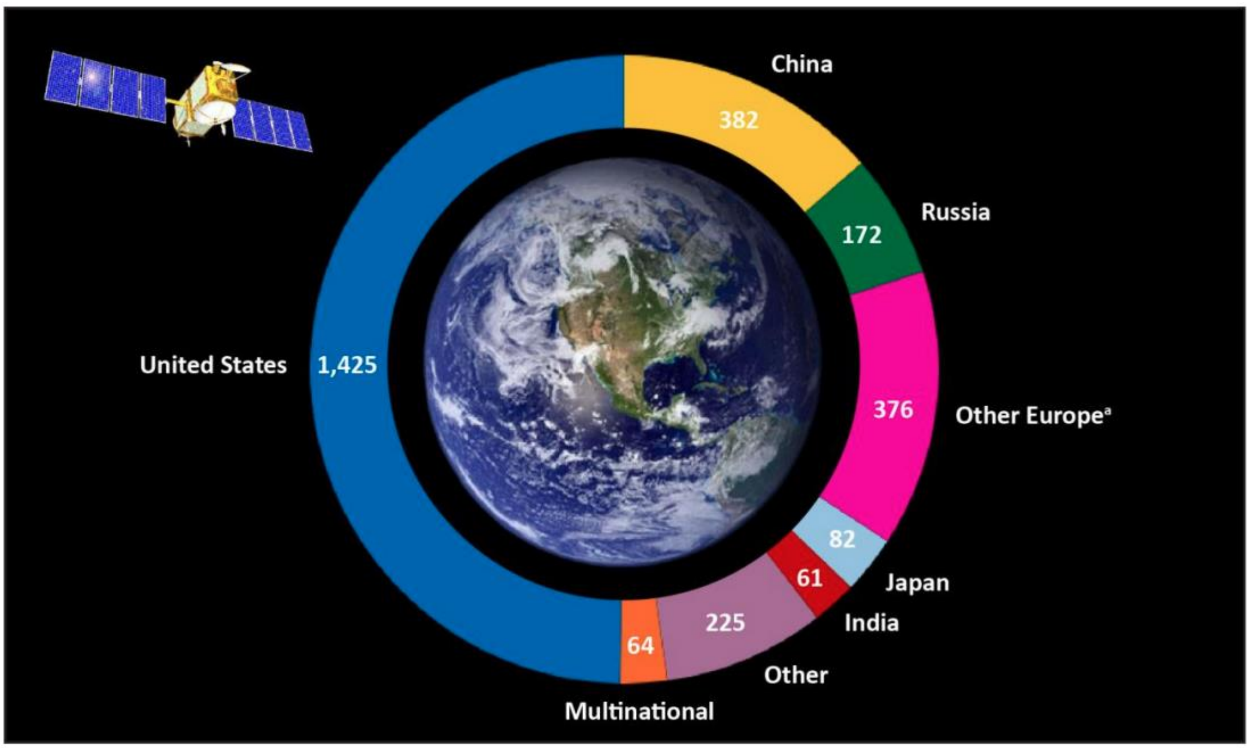

Figure 12: Number of Satellites in Operation by Country (August 2020) [9]

By the very nature of space travel and utilization, the domain encompasses many countries with hundreds of commercial operators. Figure 12 shows the expanse of the space operators. Namely, the countries with the most significant stake in space travel are the United States, China, Europe, and Russia, requiring them to lead in developing sustainable space practices and policies. Conflicts quickly emerge when considering the current state of global affairs where the United States is waging economic war with Russia, and China has threatened to shoot down planes over Taiwan.

Figure 13: Exponential rise in space objects over time [4]

As shown in Figure 13, the number of objects in space has continuously increased over time as countries aim to launch more satellites than ever before. Space experts have described that currently, there are about 4,000 active satellites; however, there are proposals to launch approximately 100,000 additional spacecraft by countries and commercial companies with the increase of mega-constellations. It is abundantly clear by simple intuition a coordinated international approach must be undertaken to adhere to post-mission disposal guidelines, mitigation measures, and active debris removal.

Figure 14: Description of challenges to a sustainable space environment [4]

Approaches to space sustainability must address many issues in the long-term challenges and approaches to ensure sustainability shown in Figure 14. At its most basic level, there is concern that nobody knows how many satellites can operate in orbit without causing issues of interference by spectrum or orbital path. Simply put, there is no consensus on the carrying capacity of Earth orbit, and at the rate of current space launches, the space sector might find out the answer the hard way. There is no international space traffic management system like in air travel to manage the increased use of space. A system would be beneficial to ensure satellites do not collide and help establish road rules in case of potential collision events. While the international community could do all it can to promote sustainable space operations, governments must also consider the emerging trillion-dollar space economy and must balance the need to promote space while regulating safety and ensuring responsible operations [95].

Countries have also been keen on developing unilateral national space policies while incorporating little international cooperation. This hinders developments amongst countries that can eventually grow into international agreements in the United Nations. The failure to cooperate multilaterally promotes the existing policy confusion and patchwork of regulation worldwide. For example, “satellite servicing operations and space traffic management, both of which hold significant economic value but cannot be fully developed without improved cooperation due to their need for shared norms and best practices, much in the same way civil aviation could not function effectively if states did not agree on norms and best practices for air traffic control or flight safety” [36]. Space is a region that must be operated on following all countries as it affects regions worldwide.

After the latest Russian test in November 2021, the incident caused international terror as the astronauts aboard the ISS were forced to prepare to leave the station in an emergency. As previously described, there are ongoing negotiations at the United Nations in the hopes of pursuing an agreement that eliminates the behavior of ASAT testing. Although diplomats have commented on the promising and civil nature of the negotiations, the broader diplomatic context complicates the plan [72]. Most recently, the War in Ukraine [96] and China’s threats toward Taiwan [97] caused great international tension at the meetings. While the Biden Administration hopes to reach an agreement, space experts fear the negotiations will not produce any international result.

The overall approach to mitigation and space sustainability has resulted in the creation of non-binding guidelines such as through the IADC and the United Nations. While these guidelines are essential, they lack actual authority and rely on countries to implement them according to their interpretation and regulations. Hopes to pursue binding agreements are not likely as it is difficult to even agree to ban ASAT testing. The challenge is to seek binding international agreements while ensuring the orbital debris crisis is limited through domestic regulatory regimes [10].

More challenges exist in communicating with other countries as there is no standardized process to communicate in the case of conjunction events of satellites. In some cases, operators telephone each other, while in others, email is used. Most concerningly, countries like China do not communicate with countries like the United States, and messages must be passed through a roundabout pathway to reach their final destination. For a better perspective, on July 31, 2022, the Chinese Long March 5B rocket fell back to Earth. After the ordeal, it was determined China did not share any specific trajectory information even though the object carried a significant risk to life and property [98].

It is widely known the solution to orbital debris relies on 90% compliance with the 25-year rule and removing 5 large objects a year. The active debris removal requirement is being worked on by the UK, ESA, and JAXA but requires better engineering and technology.

Additionally, when removing space debris, the question of Who is responsible? Who pays for services? How much do they pay? How are liability and authority worked out? Lastly, what objects do we remove, and do we work together? These questions are yet to be answered and must be worked through to ensure a sustainable space debris environment.

The 25-year rule, on the other hand, is a commonsense approach and is widely enshrined into mitigation guidelines within the IADC and national laws; compliance with the rule has been significantly poor. NASA's Inspector general found that the "global compliance rate has only averaged between 20 to 30 percent—much lower than the 90 percent required to slow the rate at which debris is generated in LEO" [9]. NASA's Chief Scientist for Orbital Debris, J.C. Liou, expanded on the importance of global compliance to this measure when he said "The takeaway message here is that the global space community must improve compliance with orbital debris mitigation best practices. That is the number one priority" [55].

Domestic Issues

Leadership and Messaging

The United States' approach to solving the orbital debris crisis is picking up steam in mitigation guidelines and regulation, tracking through the OADR, and implementing government-wide policies to address the issue. However, from an outside perspective, citizens will find it difficult to hear about most of the government's actions to address the issue. Most government public relations communication happens broadly in National Space Council meetings chaired by Vice President Harris and through a minor press release by office directors. Even when space topics are addressed, they focus on the current developments but do not discuss long-term sustainability in space.

As a world leader, the United States has great power in the words it uses to develop policy and messaging. Space experts have characterized the US Government's approach to space debris as decades away [74]. The Artemis accords provide a foundation for space sustainability but are simply goals that should be aspired to, not concrete policy and technology impacting the orbital debris crisis. Simply looking at NASA's budget documents provides the context for the actions the government wants to take but lacks active debris removal and remediation services such as what the UK, ESA, and JAXA are pursuing. Within NASA's 2022 strategic plan, the word "debris" is only mentioned twice in the 124-page document. In which the first is related to advancing norms of behavior and adoption of debris mitigation guidelines. The second relates to risk analysis for human spacecraft systems such as the ISS [99]. In the 2023 proposed budget, NASA provides "$30 million for orbital debris research, early-stage technology, and measurement technologies" within that only "$5 million for a new Orbital Debris & Space Situational Awareness initiative within the Living With a Star program" [100].

Simply put, governments talk about space suitability "but at the end of the day we still mostly just see talk" [101]. Change is on the horizon as the National Orbital Debris Implementation Plan has just been released in July 2022. This document is a significant next step to ensure near- and long-term space sustainability, but it simply assigns agencies to look at critical issues. The actual policies and technologies needed to solve the orbital debris crisis are yet to be seen.

Unsustainable Regulatory Framework

Among the issues related to orbital debris, the regulatory framework currently being used is not sustainable. Compliance is relatively easy on the government, civil and military sides as DOD and NASA have to adhere to the ODMSP by law. Similarly, DOD and NASA maintain an above 95% post-mission disposal success rate. In the comical sector, the ODMSP is still a reference but must be incorporated into regulation and not just by following the guidelines. Furthermore, the agencies that regulate the commercial sector are not primarily space agencies. They lack expertise within the area and often seek out NASA officials to inform them on regulations. Essentially FAA regulates launch and reentry, but those events could only last 30 minutes. FAA does a great deal on safety regulation and ensuring space operations are safe going into Earth orbit, but their jurisdiction to regulate evaporates after that. Therefore, their authority to regulate orbital debris by their position is not very strong. NOAA deals with weather satellites and has only recently received the job of looking at space commerce. However, the only regulations NOAA can currently make are concerning Earth imaging satellite systems. Even with that authority, NOAA follows any rules the FCC makes not to duplicate regulations across the agencies.

The FCC is a communications regulator with jurisdiction over technologies like cell phones, Bluetooth, cable, and radio communications. Therefore, when the most important federal regulations around orbital debris are generated by the FCC, they must be well suited for the whole industry and be closely guided by space regulatory and policy experts [102]. NASA's space debris website concurs, saying, "Manufacturers and operators of U.S. spacecraft and upper stages are aware of the hazards of orbital debris and the need to mitigate its growth. Many firms voluntarily adhere to measures designed to limit the growth of orbital debris" the language is in stark contrast to any policy related to compliance through regulatory mechanisms.

Considering the FCC, FAA, and NOAA, their regulations boil down to operators submitting plans to show that they will be responsible during the mission. Article 6 of the outer space treaty states, the activities of non-governmental entities in outer space, including the moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty" [38]. So, actives such as undertaking missions that land on the moon, dock with other satellites, provide servicing, refueling, tracking data, and conjunction assessment are not explicitly regulated in the current regulatory structure. Relegating these types of missions is not a novel topic, as the military must follow transparent processes and procedures do these activities [102]. Debate is still ongoing regarding which agency should regulate the Article 6 services; however, Director DalBello of the Office of Space Commerce has mentioned his office is in talks with the White House to figure out the issue. Additionally, Congress must be involved to grant the agency powers to regulate; currently, not much has been done along those lines [84]. Still, with the regulation in the future, there is also a concern that the regulatory agency will not have enough consensus-based technical standards to implement into law as there is no industry-wide consensus on the Article 6 activities within the orbit.

Mitigation Concerns

As previously described, mitigation events are essential in pursuing near and long-term space sustainability; as spacefaring governments and companies grow, the need for adequate mitigation policy is of the utmost importance. Companies, nonprofits, and students are pursuing space exploration and commercialization because ten years ago, the cost to launch a pound into orbit was $25,000, and now that same pound would cost as little as $1,250. This decrease in cost to orbit, paired with the 50,000 satellites expected to be in orbit within the decade, has simultaneously accelerated the creation of orbital debris [9].

Through expert study at NASA, they determined that in 2005 that the number of debris and objects in space was so high that if no more objects were launched into orbit, a collision would still occur and be a risk for the next 50 years unless significant measures were taken to mitigate orbital debris. However, the truth is the number of debris has increased dramatically over 17 years, and any progress made by the voluntary mitigation standards instituted was negated due to various collisions [9].

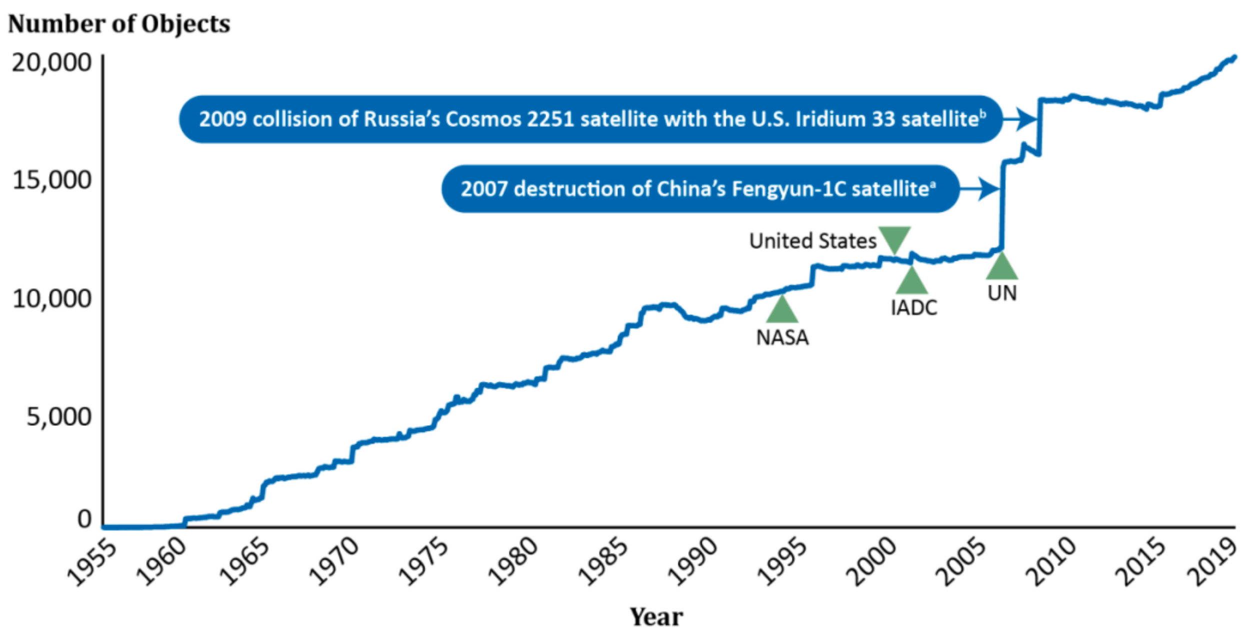

Figure 15: Growth of debris marked with voluntary consensus mitigation guidelines [9]

Figure 15 shows that mitigation efforts have not been adequate to stabilize the orbital debris environment. The green triangles on Figure 15 represent when voluntary consensus mitigation guidelines were implemented. The collision events in 2007 and 2009 negated any progress from mitigation measures, and the situation has reached a tipping point that requires active debris removal [9]. That said, mitigation measures also have their own issues within commercial regulation.

As described in the previous section, mitigation regulation is centered mainly on the FAA for launch and reentry and the FCC that licenses spectrum. These regulations rely on the operators submitting a document detailing how they will be responsible in space. Still, beyond that, there are no incentives for responsibility or forceful enough regulation that mirrors what is done by NASA and DOD through the ODMSP. Often, space objects explode and fragment due to leftover fuel or energy sources, and there is not a precise regulation forceful enough to mitigate this issue. Additionally, ASAT testing is of concern as purposeful collision events add thousands of pieces of debris into orbit. There are efforts to ban the practice, but an internationally binding agreement is yet to be seen.

As the FCC has the most forceful regulations over orbital space debris within the commercial sector of the US Federal Government agencies, it is crucial to describe the conflicts and concerns associated with the commission. As previously described, some experts have noted that the FCC is simply incapable of regulating commercial space debris as it does not have the necessary authority and expertise within the area. There are bills in Congress to clarify this issue, but action is yet to be seen [83]. FCC jumped into a gauntlet of criticism when it announced changes to its license requirements related to debris mitigation. Among the rules implemented in 2020 were roles that “require greater specificity and clarity regarding collision risks and safety measures, spacecraft tracking and data sharing, permissible orbital dwell periods, and casualty risk assessments; clarify that satellite operators should secure satellite commands against unauthorized access and use, and obligate coordination of frequencies during orbit-raising” [66].

After dramatic industry fallout and public comments condemning the proposed rules, the commission deferred several proposed rules for new rule-making. To start, FCC only looks at the probability of collision risk associated with a single satellite, even if the satellites are a part of a mega constellation with over 1000 satellites. Satellite maneuverability requirements at a certain level in LEO were criticized as a burden on operators and smaller satellite companies. The commission also considered reducing the 25-year rule but ultimately did not proceed. Lastly, the FCC punted any surety bond requirements for post-mission disposal from being implemented to ensure higher post-mission disposal compliance [66].

Regarding the dramatic rise of mega-constellations of systems with 1,000 satellites or more such as with SpaceX’s Starlink constellation that has approval for an additional 30,000 satellites, great concern has been shown in regulating the reliability of mega-constellations as a whole. From March 2019 to March 2021, “the number of active and defunct satellites in LEO has increased by over 50% to roughly 5,000 … Starlink now accounts for over half of close encounters between two spacecraft and is projected to be involved in 90% of all close approaches” [103]. With the increase in conjunction events, satellite operators receive alerts daily, and due to propellant limits, they cannot move for every event. This ultimately increases risk and makes mitigation near impossible [104]. Former NASA Administrator Jim Bridenstine explained, “currently observed disposal failure rate of approximately 1.5 percent for the v1.0 satellites, this implies 150 satellites for 10,000 satellites launched, and 225 satellites for 15,000 satellites launched” [105]. With the dramatic rise in mega-constellations expected by the end of the decade, the failure rate is a significant concern relating to mega-constellations.

The 25-year rule compliance is also of concern, as failure to comply with the rule does not allow any form of space debris stabilization through any model scientists have presented at NASA and ESA. A global compliance rate of 90% is required to stabilize the space debris environment. As previously described, current international 25-year compliance is deficient at under 25%. When looking at civil operations in the US government, that number rise to 96% [9]. Obviously, the next question is, what is the commercial compliance rate? That question’s answer is hard to find and has been proved to be hidden from this report. Despite the compliance numbers, governments must enforce the 25-year rule, which has also been proven difficult. For example, the FCC implemented a graveyard requirement at the end of GEO satellites' lifetimes, “but a 2005 ESA study found that only a third of such satellites actually did so, with the others either not pushing out far enough or not moving at all” [5]. Lately, there has also been talk about reducing the 25-year rule to a five or 1-year rule, but there is no clear consensus on the topic as NASA says it would not change anything. Still, other stakeholders, such as DOD, have advocated for lowering the requirement [106].

Tracking and Characterization Concerns

Tracking and characterizing space debris is the next pillar of a sustainable space environment. Essentially tracking information is like the eyes of a driver traveling on a highway. Without eyes, cars will ultimately crash; the same is true regarding space debris. With the expansion of satellites and space objects in orbit ever increasing, concerns regarding tracking quality, update rate, measurement accuracy, data accessibility, conjunction warnings, standards to guide navigation collision events, communication across countries, and the question of a centralized data center all are significant concerns relating to the second pillar of tracking and characterization of debris.

Most of the world uses the US Space Force Space Surveillance Network (SSN) tracking data to help understand the positions of orbiting objects. While Russia, China, and Europe are developing their own or have tracking systems, the US SSN is the backbone of tracking operations worldwide. However, by its very nature as a military function, the military does not consistently track space junk. Instead, they are more worried about watching adversary spacecraft to maintain a military edge. The US provides free basic tracking locations and collision warnings out of concern for all space actors worldwide. Many have pointed out that these warnings are not good enough as they do not track the possibility of debris hitting other debris. To supplement this, satellite operators have often sought fee-based services such as Leo Labs. Their system is automated, real-time, designed for LEO, and transparent, a dramatic improvement from the DOD system [55].

Furthermore, the DOD system updates slowly and not instantaneously. Currently, the Space Force updates positional information every eight hours. In the case of a close pass, that warning time may be too long to mitigate a collision [78].

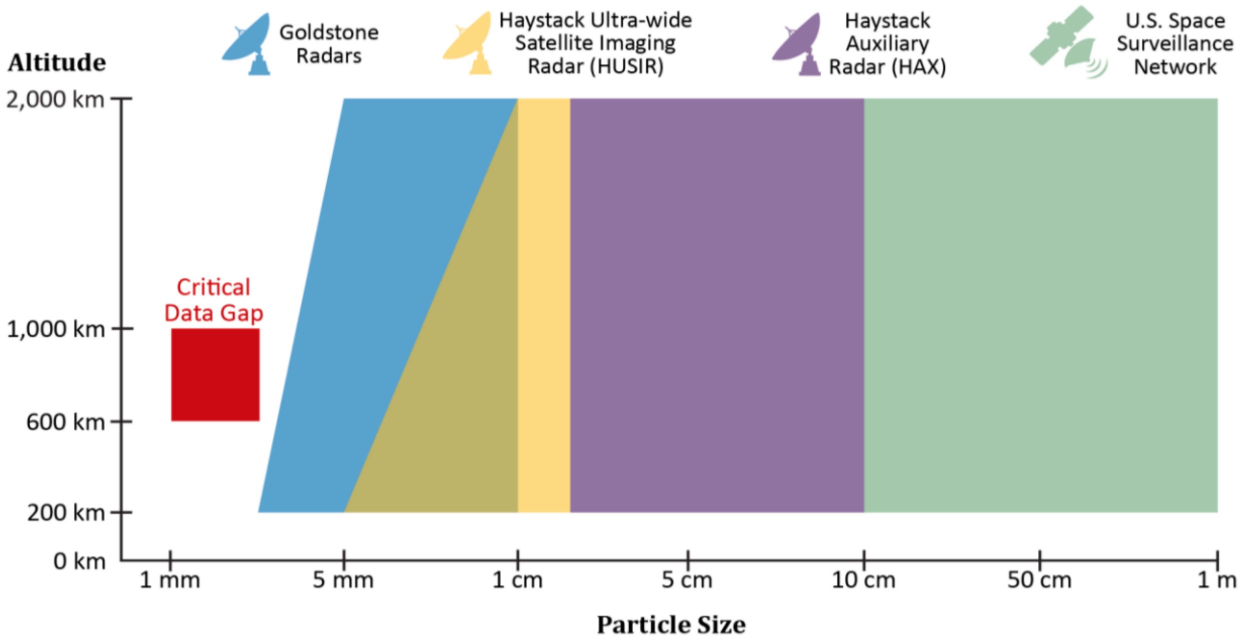

Figure 16: Data gap in low earth orbit [9]

As shown in Figure 16, NASA and DOD also lack sufficient measurements of small debris objects. NASA's issues reside in pieces ranging from 3mm to 1mm depending on altitude, and DOD SSN can only track objects 10 cm or larger. This data gap is of grave concern as in the orbit of the ISS, NASA cannot track debris smaller than 10 cm.

As previously described, SPD-3 started the process of transferring the US Space Force SSN to NOAA's Office of Space Commerce. In this process, an OADR would be created to provide better conjunction alerts, coordination between satellite operators, tracking quality, increased timeliness, commercial data integration, and adaptation to new technologies that will increase the tracking and characterization of space debris [107]. However, with lofty goals, the OADR project has been hit by many challenges. The office's budget originally started at $10 million. After lackluster progress and congressional hearings, its new budget is $87.7 million in FY23, which is a $77.7 million increase from FY21. After not having a director for a significant time, the Biden Administration appointed a director in late April 2022. Concerns still remain as to the degree to which the OADR will use commercially provided data that may provide better capabilities than government-run tracking radar. How precise is the data, and what free services will the OADR provide [108]?

Conjunction warnings also raise concerns about the quality of data used, uncertainly, need for speed, small debris clouds, risk of collision standardization, and communication standard process after a conjunction notification. Calculating collision risk is increasingly tricky as more congestion has caused difficulties in calculating collision probability. Currently, there is no standardized method to determine the quality of an operator's data and if their assessment is accurate enough to cause a satellite to perform an evasive maneuver. Apart from this is the lack of transparency on the part of satellite operators. For example, SpaceX's Starlink uses one assessment algorithm, and NASA uses something else. In the event of a close pass, SpaceX could be worried about a collision, but under NASA's algorithms, they are not worried. This confusing lack of clarity causes many issues when determining if objects are likely to hit each other.

Furthermore, the quality of data decreases as debris reaches less than 10 cm levels because operators seek data from many sources. Each source has a probability mechanism that creates a mathematical cloud of debris. Some clouds may be more precise than others, further creating concerns [5]. The overall risk is an issue that currently does not have a clear answer as multiple stakeholders have different definitions [105].

After operators are warned of a possible conjunction event, there is no standardized procedure to determine what should happen. Essentially, the Space Force SNN tells both operators of the possibility, and resolving the conflict is left up to them. While this notification is good, it also increases the concern of both operators being attentive. Due to the lack of standardized procedure, the encounter could be over the phone, done by email, automatically, or even through fax. Furthermore, when communicating with countries like China that do not like to share much information, they often wall themselves off and do not care to conduct collision prevention discussions.

Lastly, space object tracking and characterization are necessary to cross the international domain. With thousands of more satellites planned to be launched, some experts have noted the need for an international data center. This would combine the patchwork of commercial and national systems into one place as a central trusted authority. In which quality data and advice can be provided. Some policy experts have commented a more decentralized peer-to-peer approach may be the best option. However, the idea of creating an international body that coordinates space traffic worldwide is still debatable.

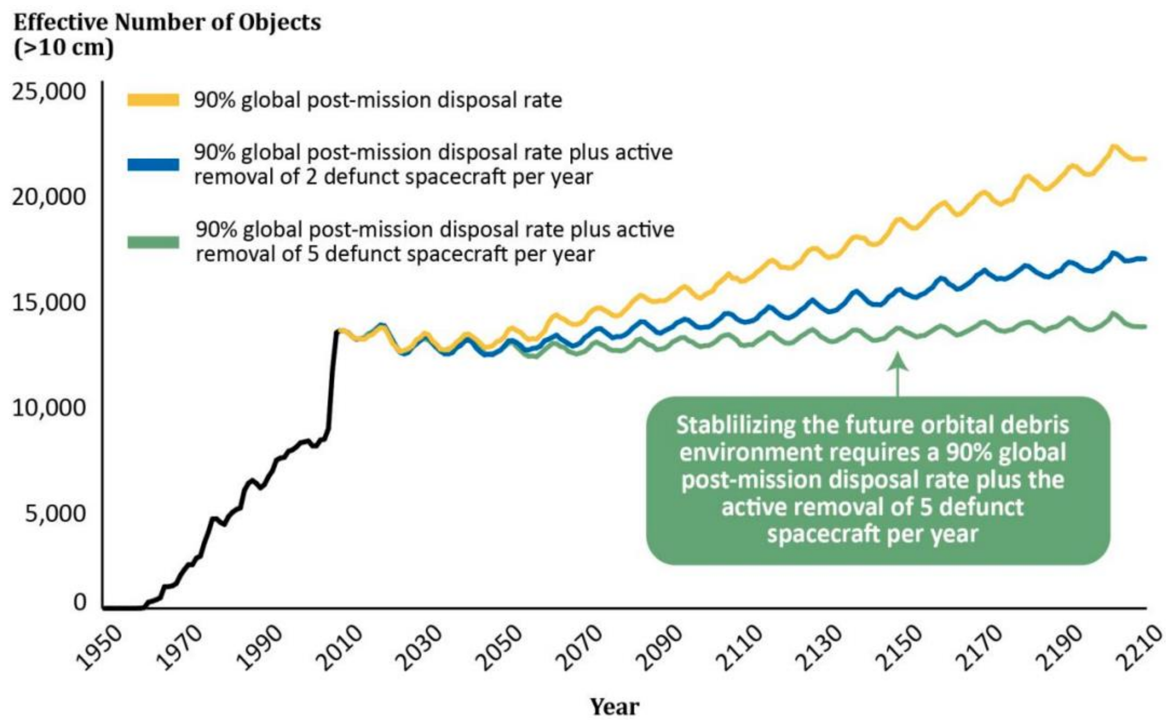

Figure 9: Estimated Impacts of Successful Post-Mission Disposal and Active Debris Removal Activities on LEO's Orbital Debris Environment [9]

The last necessary pillar of space sustainability involves active debris removal and remediation missions. In a basic sense, this means taking large items out of orbit either into the atmosphere or into higher graveyard orbits. Remediation involves operations that extend the life of a satellite or repurpose and reuse it. As shown in Figure 9, there is a global consensus that stabilizing the space debris environment requires 90% compliance with post-mission disposal guidelines and removing five space objects a year from orbit.

Currently, the process of removing five space objects a year has developed past a pipe dream, and actual missions are underway to remove defunct satellites from orbit by 2025. These demonstration missions are far away from what is needed to maintain removal services for near and long-term space sustainability. The United States likes to advocate that they are pursuing active debris removal research; however, most of their efforts have not been sustainable enough for any real hope.

To start, active debris removal has solid policy background but is hamstrung by a lack of coordination, explicit authorization, and necessary appropriations. President Obama's broad directive in the 2010 National Space Policy called on NASA and DOD to research remediation technologies; however, no agency was given authority to develop a US government-led active debris removal mission [109]. This was confusing at the time because the White House OSTP issued a framework for active debris removal in 2014 to NASA officials. Specifically, no action was taken due to a lack of funding, administrator priorities, and national security concerns [9]. In a 2014 memorandum, NASA's Associate Administrator directed NASA to only develop ADR technologies to a technical readiness level (TRL) 4.18. This level means research is limited to lab-based testing [109]. The memorandum also acknowledged a lack of direct codifications and simply that the agency had no plans to establish an operational role in ADR.

Furthermore, in 2017, the NASA Transition Authorization Act directed NASA and OSTP to address reporting requirements from the 2010 Authorization Act. Apart from the report, an inter-agency working group found that mitigation measures alone are insufficient and further explained the difficulties of policy, law, and international conditions that would make ADR difficult. Still, the working group did not develop a documented strategy. SPD-3 would provide greater impetus for NASA to do something. Still, the agency advised that "developing an active debris removal system would be a costly and complex endeavor that NASA would not be interested in taking on, especially absent additional funding" [9]. The most tangible product of 10 years of directives is OSAM-1, set to launch in 2025 to demonstrate "rendezvous with, grasp, refuel, and relocate the Landsat 7 satellite to extend its life" [9].

Combined with a lack of Congressional mission authorization and minimum investment in ADR technology, the US government is pursuing the bare minimum to maintain compliance with executive orders and budget authorizations. Essentially, the US Government's reason for limited ADR development is that it is too costly and confusing. The development challenges include engineering problems such as rotating objects, grabbing large rocket bodies, docking with different types of satellites, and standardizing docking mechanisms. While engineering problems should not be of much concern to NASA, as informed by the history of ADR development, NASA believes that it is too complicated [21].

Policy and legal issues arise regarding the legal feasibility of removing defunct objects from space. Often the issue is plagued with the chain of custody, the owner's permission, and what happens if something goes wrong. As all space objects are the property of the launching country, grabbing someone else satellite or object may be seen as an act of war and hence an insurmountable roadblock. Often the issue turns to the conclusion that an international treaty is needed to handle ADR capabilities [101]. Policy questions such as what agency does it? How much does it cost? How is ADR paid for in terms of simply tax dollars or collected fees? How can an ADR space economy be created that encourages a fleet of companies to produce services? And, since the government cannot do everything, how does long-term funding work?

Lastly, the path to near and long-term sustainability by its nature needs to be an international approach. Currently, the same legal issues looking at domestic policy are even more exacerbated when considering an outside country deorbiting a non-domestic object. Is it an act of war? How does chain of custody work? And who pays for the service is among the most significant concerns. ADR technologies are essential to maintain a safe and operational orbital environment; however, issues in engineering and policy remain to be answered [110].

POLICY RECOMMENDATIONS

This section will provide policy recommendations to pave the way to space sustainability both in the short term to stabilize the orbital debris issue and in the long term to ensure that space remains sustainable for decades to come. Furthermore, policy recommendations will be divided into leadership, regulatory authority, mitigation, tracking, and removal categories.

Short Term – Stabilization

Leadership and International Support

The path to solving the orbital debris crisis requires countries to lead the way both domestically and internationally. As space is not owned by one country, solving the issue is one that requires global coordination and cohesion. There are currently efforts to encourage this in the United Nations and through the IADC; however, these efforts have proven insufficient. As global tensions rise with the central space powers of the United States, Russia, and China, it is becoming increasingly challenging to cooperate multilaterally. While essential multilateral communication remains difficult, creating a binding agreement is also not currently possible under the global diplomatic climate.

Sometimes the best way to create international agreements is to lead the way and peer pressure other countries through international forums using the progress a group of countries creates. It is **recommended that the United States counties efforts to add more signatories to the Artemis Accords** that highlight the importance of space sustainability. Additionally, the **United States should promote methods to reduce space debris**, just as the UK Space Agency and ESA do through public relations and multilateral forums.

To best lead the way to stabilizing the orbital debris environment, the United States needs bold action partnered with presidential authority. The orbital space debris issue is similar to climate change. On a broad scale, the issue and significant executive and legislative action are needed across multiple government sectors and the country. The White House Orbital Debris Implementation Plan is a foundational and necessary step to leading the way to stabilization; however, the actual implementation and effects of the plan are yet to be seen. To best oversee the implementation of orbital debris policy across the government, it is **recommended that the President appoint an executive branch czar to oversee orbital debris implementation**.

Solving major issues require a clear chain of command. From COVID-19 to infrastructure and climate change, the President has appointed czars to oversee these issues with notable success. It is also **recommended the orbital debris czar works hand in hand with the National Space Council and OSTP to oversee all departments across the federal government and become the lead spokesperson** on the orbital debris issue both domestically and internationally. Additionally, it is **recommended that the United States works multilaterally to encourage like-minded nations to appoint orbital debris executive czars** to best coordinate across the globe.

Lastly, it is **recommended that the United States czar for space debris leads a government-wide movement to educate the public** about the importance of space and why we should all care about stabilizing the orbital debris environment. Often space can be thought of as something that countries do for fun via exploration; however, the public is often unaware of the critical infrastructure orbiting the Earth that allows communication, GPS, and commerce across the globe. The White House and NASA would be best suited to lead this campaign through high school and public outreach initiatives, including raising the issue to the Presidential level. This combination of outreach and executive discussion will help raise the orbital debris issue to a mainstream level and accelerate the multilateral discussions that are needed through the United Nations and other international forums.

Commercial Regulation

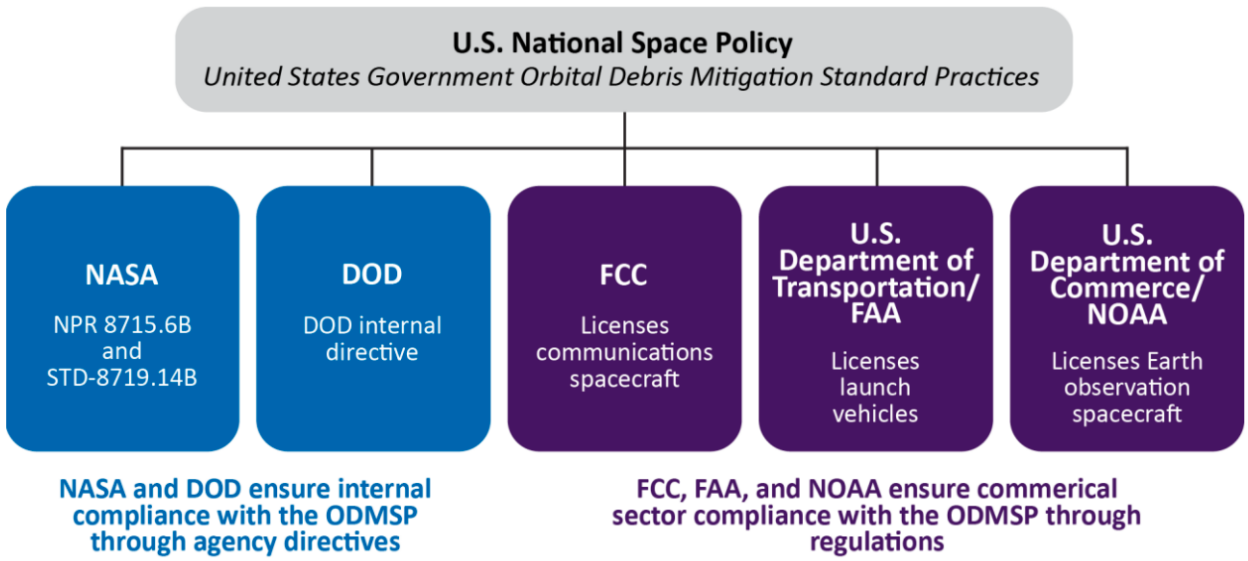

Figure 10: US Government Orbital Debris Mitigation Policy Implementation Framework [9]

As described and shown in Figure 10, the current regulatory framework can be separated into two sections by commercial and government missions. Although all US government missions, rockets, and satellites must adhere to the US National Space Policy and ODMSP, they are applied differently according to what the space object is used for. Regulation within the US government is strictly controlled through internal compliance with the ODMSP within NASA and DOD; however, the commercial sector relies on the three commercial regulators of the FCC, FAA, and NOAA to implement policies across the entire commercial market.

Currently, the FCC has the most regulatory authority concerning commercial sector adherence to the ODMSP; however, regulations are limited to ensuring operators have a plan to be safe and responsible. Additionally, at its basic level, the FCC is a regulator of communications equipment and hence has limited knowledge of space operations. Furthermore, there is no regulatory authority that authorizations missions within orbit such as proximity operations, removal services, and lunar missions. Article VI of the Outer Space Treaty states that countries must regulate these activities; however, no such power currently exists within the government.

It is **recommended that Congress assign commercial regulatory authority to an agency within the US government**. To best assign this authority that must regulate the exponential growth of the space industry and the rising threat of orbital debris, the **Congressional Research Service should produce a report on the gaps within current commercial regulation and identify possible agencies to assign commercial and regulatory power**. CRS should also ensure their recommendations consider necessary expert-level personnel and experience to best regulate the commercial sector. Furthermore, **Congress should conduct hearings on assigning commercial regulatory authority to an agency and regulatory schemes to best mitigate the orbital debris issue**. Assigning commercial and regulatory powers with adequate funding and personnel is necessary to stabilize the orbital debris environment and must be looked at as a short-term issue to mitigate the possibility of disasters and accidents occurring in orbit. Furthermore, the **Federal government should work with standards organizations to develop consensus-based standards that will eventually be incorporated into federal regulation**.

Mitigation

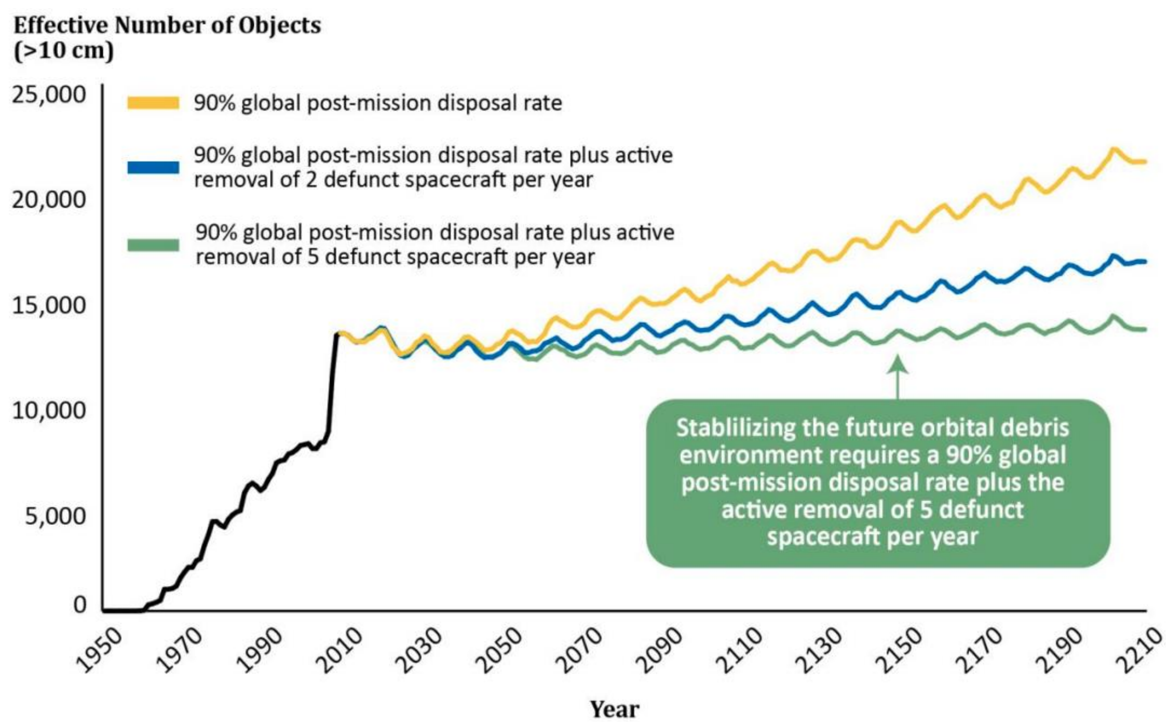

Figure 9: Estimated Impacts of Successful Post-Mission Disposal and Active Debris Removal Activities on LEO's Orbital Debris Environment [9]

The next pillar to solving the orbital debris problem involves mitigation techniques. Simply put, mitigation looks to reduce the chance of collision with other objects in space. The

US government does an adequate job of mitigating the creation of space debris through regulations and internal guidelines. However, the government's efforts do not address the issues of post-mission disposal, mega constellations, and debris responsibility. As Figure 9 shows, stabilizing the orbital debris environment involves reducing the creation of more space debris and ensuring space operators and countries adhere to the 25-year post-mission disposal rule.

The US government adheres to the globally recognized 25-year rule through multiple documents such as the updated ODSMP. For civil and military missions, the compliance rate is near 96%; however, when looking for commercial sector compliance, there is no compliance rate to even reference. It is widely understood that commercial 25-year compliance is low even though data does not exist. Furthermore, the global compliance rate falls below 20%, which is far below the necessary 90% post-mission disposal rate to stabilize the orbital debris environment.

It is **recommended that the Government Accountability Office (GAO) investigate the FCC's enforcement of the 25-year rule among commercial companies**. This action will allow policy leaders to identify a baseline for the commercial sector compliance rate and if more enforcement is necessary. Additionally, the **Congressional Research Service should investigate stricter regulations and economic incentives for space operators to successfully adhere to the 25-year rule**. Furthermore, **Congress should hold a series of hearings to oversee 25-year rule compliance and what can be done to improve adherence to the rule**. Lastly, **Congress should hold hearings, and NOAA Office of Space Commerce should convene the necessary stakeholders to gather input on whether the 25-year rule should be modified regarding changing the time frame to less than 25 years,** such as five years or one year. These actions will pave the path to stabilizing the orbital debris environment as a central pillar of the solution involves simply disposing of things that are no longer needed in space.

Quantifying the number of orbital debris stakeholders should also be investigated. **The National Space Council and Interagency Space Debris Working Group should produce a report to identify what companies and countries are responsible for the current civil, commercial, and international debris currently in space**. This action will finally show which companies are being responsible in orbit and provide greater transparency rather than relying on hearsay from space stakeholders. Furthermore, **NOAA should publish all stakeholders' Space Sustainability Rating**, which rates an operator's orbital sustainability initiatives and history of sustainable responsibility [111]. Publishing this transparent rating will allow stakeholders to self-regulate by providing internal pressure to gain a better rating. Additionally, **NOAA OSC should identify a series of economic incentives paired with the rating space stakeholder's archive**. These actions will provide excellent transparency and pressure for operators to comply with orbital space debris mitigation rules without forcing the heavy hand of government requirements on operators.

As the orbital highways become increasingly congested and traffic will increase by ten times the current level by 2030, mega-constellations like SpaceX's Starlink are a significant threat to mitigation techniques. Currently, the FCC authorizes mega constellations by looking at the failure rate of an individual satellite rather than considering the system of 1,000 satellites as a whole. When there is a failure rate of 5% will, 1000 satellites, about 50 will fail; however, with an estimated 42,000 more satellites expected to be launched in the next eight years, allowing a 5% failure rate is entirely unacceptable. It is **recommended that the FCC revise its orbital space debris regulations to consider mega constellation failure rate as an aggregate system rather than individual components**. **Further study by NASA with input from stakeholders through NOAA OSC should also focus on the theoretical carrying capacity of satellites within orbit** as space will continue to be used exponentially.

Lastly, the United States is working to form a binding agreement within the UN COPUOS to formally ban the use of ASAT testing demonstrations across international borders. It is **recommended the United States continue this effort** as stopping the intentional creation of thousands of pieces of space debris should be of utmost importance. If no binding agreement comes from the discussions of the UN, it is **recommended the United States work multilaterally to gain international support in this effort**.

Tracking

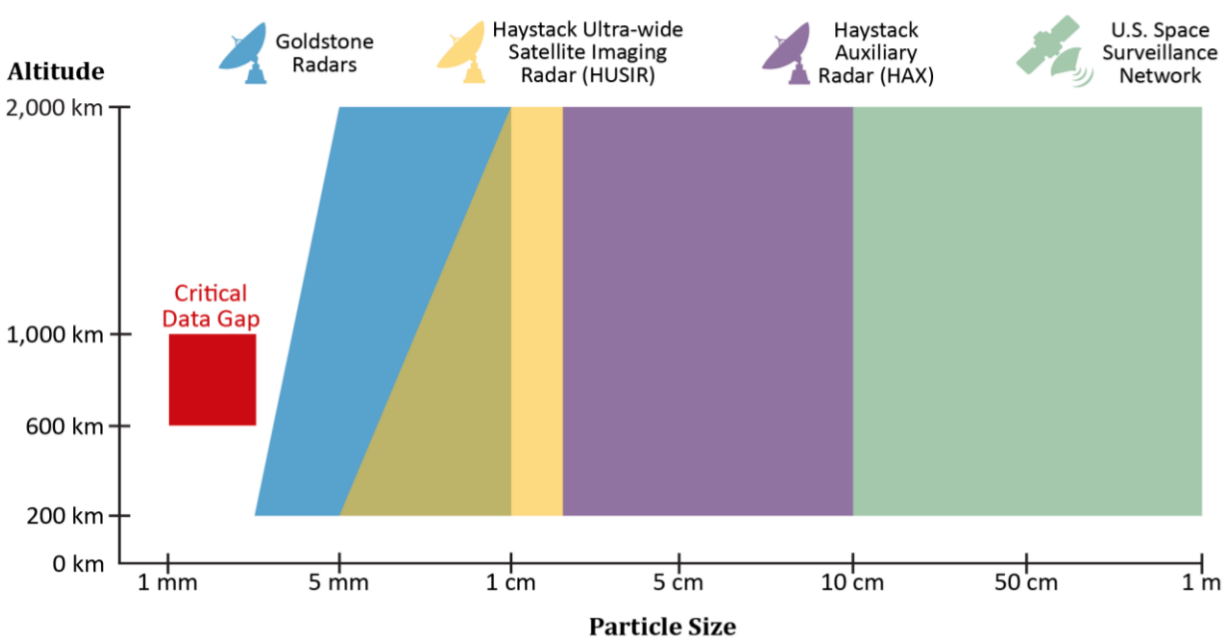

Figure 16: Data gap in low earth orbit [9]

The second pillar to stabilizing the orbital debris problem is to improve the tracking and communication abilities of space objects and satellites. Just as it would be dangerous to drive a car with your eyes shut and the disasters that would happen if airplanes could not talk to each other, satellite operators encounter the same issues. Operators must track their objects to know where they are relative to other objects. If a conjunction event occurs, satellite operators must also talk to each other to mitigate the chance of collisions.

Currently, the US government provides basic open-access tracking information to the entire world free of cost. Since President Trump signed SPD-3, the satellite tracking infrastructure operated by the US Space Force has been transferred to NOAA OSC to a system called the OADR. The OADR is only in a prototype phase, but progress has been encouraging as Congress has funded the system at adequate levels for growth. It **is recommended that Congress and NOAA continue to fund the OADR at its 2023 levels and not reduce the project's budget**. Additionally, **NOAA should continue prioritizing tracking, data processing, sharing, and filtering debris catalogs** [109]. In the meantime, while the OADR is still under development, the US Space Force and NASA have noted a critical data gap in tracking objects less than 3 mm. As shown in Figure 16, this data gap is large enough to threaten multiple satellite systems in LEO, including the ISS. To reduce the critical data gap, the **US Space Force and NASA should invest in tracking capabilities through research and development that can track objects less than 3 mm**. **Congress should fully fund this initiative** as it is critical to the safety of satellites threatened by space debris.

Furthermore, operators have supplemented the data they use from the US Space Force from various commercial companies that provide similar object-tracking services. However, not all companies cannot afford outside data sources. In that case, they are subject to the Space Forces' slow 8-hour tracking updates, basic tracking information of large objects, and not small pieces of space debris. To level the playing field and ensure operators have an essential availability of tracking information, the **government and OSC should explore contracting private companies such as Leo labs to provide better services**. This change would give operators better vision as tracking data has higher resolution and updates within minutes. The OADR will provide similar services; however, the results are yet to be seen.

Additionally, as companies supplement their data with other tracking providers, there is no mechanism to ensure that these tracking companies provide accurate and reliable information. For example, one satellite operator could gather two data sets from different companies. One data set could say that the object will hit the satellite, while the other says it will pass hundreds of miles away. This difference accounts for operators not fully understanding the risk of orbiting in space as they can gather information from both situations. It is **recommended that data quality be standardized and orbit abortions be transparent to ensure all tracking providers provide accurate information**. **NOAA, FCC, and FAA should work with standards organizations** already in the space community, such as the Space Data Association and a reputable standards organization like ASTM International, to **create a consensus-based standard for all operators to use**. Additionally, once a standard is created, the **government should consider using it to regulate space-tracking companies**.

More issues arise when two objects in a path hit each other. Currently, the Space Force sends a notification to the two parties, and those parties have to de-escalate the situation. This escalation can be made difficult through differences in tracking information and a lack of standardized operating procedures to mitigate a collision. It is **recommended that standards organizations like ASTM international work with satellite tracking providers and other**

stakeholders to develop a standardized de-escalation method similar to how airplane pilots have procedures in the case of emergencies.

Removal

The last pillar to stabilizing the orbital debris environment is removing defunct spacecraft, satellites, and rocket bodies from orbit. As shown in Figure 9, both NASA and ESA have determined that stabilizing the orbital debris environment will require the removal of only five large pieces of debris a year, paired with a 90% post-mission disposal rate. Although the United States government has provided policies to start developing removal technologies, such as in President Obama's 2010 National Space policy, the federal government lacks an organized and fully funded orbital debris removal program. Most notably, NASA has only developed removal and servicing technologies for TRL 4, which only allows lab testing, and, in reality, this research does nothing to improve the situation. Simply put, the federal government is investing in removal technologies at the minimum amount to comply with Presidential directives. Part of this lackluster development is the simple fact that the Presidential directives to develop removal technologies are unfunded mandates that lack clear directives and authority from Congress and Executive agencies.

Realizing the need to develop satellite and space debris removal technologies, multiple companies such as Astroscale and ClearSpace have been awarded contracts by space agencies such as ESA, UK Space Agency, and JAXA. While these companies have been relatively successful in developing removal technologies, there is a lack of actual removal missions that will help achieve the five object-a-year removal requirement to stabilize the orbital debris environment. These companies and space agencies should be commended for their progress; however, significant engineering work must be done to improve removal technologies that can deorbit large space debris.

In cases where challenges seem too steep within monetary and engineering constraints, it is the government's job is to trailblaze a path for commercial entities to follow. To spur innovation and solve engineering challenges of removing space debris, it is **recommended that the United States government fully authorize a flagship large-body debris removal mission**. In this effort**, Congress should grant clear mission authority to NASA** and **authorize adequate appropriations to develop removal capabilities that will ultimately deorbit a defunct US rocket body**. At the current exponential rise in space debris expected by 2030, the United States government cannot treat removal missions as a long-term issue. NASA is one of the world's most outstanding engineering organizations; it is time to allow the team of engineers at NASA to deorbit a defunct rocket body as the first step to the continued need to remove five objects a year from orbit.

Under the direction of the National Space Council and NOAA OSC, Congress should authorize a public-private partnership to allow the commercial sector to fill in the technological gaps NASA's large debris removal mission would not address. Just as NASA has successfully done with the commercial orbital transportation services initiative, Congress should fully fund this project to leverage the immense engineering and problem-solving talent of the United States aerospace industry. **NASA is also recommended to share its advice and findings with companies selected for the commercial debris removal program** [109].

When talking about removing objects from orbit, many space experts have explained that the liability and ownership issue is impossible to the point that a new treaty would be required even to allow these types of missions. However, space policy experts at the Aerospace Cooperation have explained a simple solution incorporating a bottom-up approach. It is **recommended that the United States help solve the liability hurdle by developing a consent-based contract between the debris owner and removal provider**. Under the private-public orbital debris removal project, **NOAA OSC should facilitate liability contracts and regulate the approval of active debris removal missions** [101].

Satellites and space debris come in all different shapes and sizes. Therefore, deorbiting an object could require a different attachment mechanism for any two objects. Ultimately this will cause issues as removing objects in orbit that do not fit within a removal satellite's specifications will be difficult. For example, imagine the problems that would occur if a trailer hitch was different for all trucks. If some used a sphere while others used a cube and some a pyramid. Any industry stakeholder that relies on the sphere trailer hitch would have to develop entirely different manufacturing methods to account for the differences when attaching to a cube trailer hitch. The same analogy is relevant to defunct satellites. As removal technologies develop, it is **recommended the FCC require standardized servicing interfaces for all satellites put into orbit**. This simple solution would allow multiple companies to use the same docking technology to remove defunct objects without developing entirely new systems each time a mission is launched. **Standards organizations should develop a consensus-based standard of removal interfaces that can be incorporated into the next generation of satellites**. Additionally, to promote standardization, the **Federal Government should provide preferential contracting to operators that use the interface and grant business incentives to promote further adoption** [109].

As removal missions will become increasingly necessary for decades to come, it is evident that they require millions of dollars to fund removal missions and research and development. Startups like Astroscale and ClearSpace have been funded almost entirely through government contracts. The market for removal and remediation services does exist; however, it will require an injection of government assistance to overcome the significant monetary hurdles needed to develop removal and remediation technologies. It is **recommended that the United States Department of Commerce lead an economic study to determine costs, economic incentives, and funding sources that can be used to stimulate an active debris removal and remediation market** [109]. Additionally, it is **recommended that the economic study investigate the establishment of an orbital licensing fee that will fund orbital debris removal missions and development** [103]. The development of the economic study will provide a plan for long-term funding to stabilize the orbital debris environment.

Long Term – Sustainability

International Partners

Just as solving climate change requires international cohesion and coordination, paving the path to a sustainable space environment for the next one hundred years requires similar international coordination. The most direct path to reducing the threat of orbital space debris would be to create an internationally binding treaty that holds countries responsible for the space debris they create. Currently, international coordination to solve the orbital space debris crisis is done through voluntary guidelines that do not have strong teeth and only rely on the international community to be responsible and adopt the guidelines. The climate for a space debris mitigation treaty has proven challenging as diplomatic tensions between the United States, Russia, and China has continued to escalate. Although the path to a binding agreement may be difficult, it is crucial to set the groundwork at a multilateral level in preparations for an agreement that encompasses all spacefaring nations.

It is **recommended that the United States, led by the State Department, work with like-minded nations such as the UK and Japan to bridge the challenging obstacles in international coordination to reduce the space debris threat**. Building on a domestic space debris removal program, **the United States should consider partnering with international space agencies to fund, develop, and remove international objects**. This action of international coordination will pave the way for space debris ownership and liability issues to be worked out with a pair of countries before agreements can be made with all space-faring nations.

Additionally, it is **recommended that the United States lead an effort to adhere to the 25-year post-mission disposal rule**. Currently, international compliance remains less than 20% and is far below the needed 90% compliance to maintain a sustainable space environment. Building on the 25-year compliance rate report described in the previous sections, the United States should work multilaterally to improve regulations and policies to better adhere to the 25-year rule.

Just as the journey of making a safe and stable climate has improved drastically over the past two decades through the Paris agreement, a similar **flagship international agreement should be developed to legally bind spacefaring countries to a set agreement that reduces space debris**. Ideally, the agreement would provide a roadmap and benchmarks for all countries to improve their 25-year compliance rate to ensure objects are responsibly disposed of. Furthermore**, in partnership with a National Academy of Science study, the agreement should incorporate possible changes to ownership rules of old space objects that countries deem too old and useless such that any country could remove them from orbit**. Lastly, **the agreement should incorporate a framework for funding space debris removal missions** as no single country should foot the cost of maintaining a sustainable space environment.

Infrastructure and Coordination

The number of operators and satellites in space is expected to increase by a factor of 10 by 2030. When thinking about the future, it is evident that this number will keep increasing and significantly strain the existing domestic and international space regulation infrastructure. Currently, many federal agencies in the United States have a piece of the space sector. This fact is easily shown as the current National Space Council is represented by more than fifteen different departments or offices within the Federal Government. While a disaster has not yet occurred where consolidation of these agencies would be recommended, **Congress and the Congressional Research Service should identify possible responsibilities for a cabinet-level space department**. Congress should learn from the lessons of creating the Department of Homeland Security and plan into a department of space consolidation now and not wait for a significant causation event to take place like a rocket hitting the ISS and causing it to break apart.

Lastly, it is also **recommended that the State Department conduct preliminary conversations about the need for an international space traffic management agency operated by the United Nations**. Currently, no such entity coordinates the international space highways to ensure they remain open and safe. Forming an international space agency within the United Nations would allow better communication between countries regarding orbit planning, tracking, and debris removal services.

Final Recommendations

Stabilizing the orbital debris environment is one that requires significant coordination and support from various agencies within the federal government and across the globe. As shown in previous sections, the path to space sustainability rests on the pillars of maintaining a 90% post-mission disposal rate per the 25-year rule and removing five space objects a year from orbit. At a global level, space operators are not completing these objectives to a high standard, further exacerbating the space debris environment. It is **recommended that the United States focus on solving domestic issues in the short term and, in the long term, lead international efforts to reduce further the thousands of pieces of space debris orbiting the Earth.**

To lead the way and to stabilize the space debris environment while also planning for long-term sustainability, the **United States must lead the way by allowing NASA to develop a flagship removal mission** to dispose of a defunct rocket body as current technologies are not progressing fast and efficient enough to reach the five object disposal requirement set out by NASA and ESA. This fully funded and authorized flagship mission will advance current technologies and trailblaze the path for commercial companies to develop removal technologies for their future. To energize this process, the **United States Congress, in partnership with the Department of Commerce and NASA, should develop a private-public partnership** to leverage the power of the domestic aerospace industry through contracts and research grants that aim to develop orbital debris removal technologies further. Lastly, **the United States should conduct an economic study to determine the costs and economic incentives needed to improve removal services**.

Furthermore, it is **recommended that the United States determine the 25-year post-mission disposal rate for the commercial sector and develop a report that will quantify operators' compliance rates**. The GAO should do this as adherence to the rule is already mandated by regulations. Additionally, **Congress should hold congressional hearings to investigate the 25-year rule compliance rate across the government and determine if policy changes need to be made**. It is also **recommended that following the report's publication, the FCC and other regulatory authorities develop policies to increase 25-year post-mission disposal compliance across the commercial sector**.

Lastly, as space operators continue to launch thousands of satellites into orbit through mega-constellations and new space operators, it is **recommended that Congress and the GAO identify the regulatory gaps within space regulation and identify an agency to take over commercial space regulation**. Currently, the United States relies mainly on the FCC to regulate space debris mitigation. An agency that regulates spectrum should not have to push its authority into the commercial space sector. Therefore, it is of the utmost importance for Congress to assign commercial space regulatory authority to an agency that has experience within the space industry.

REFERENCES

[1] "What Are Satellites Used For?," Union of Concerned Scientists, 15 January 2015. [Online]. Available: https://www.ucsusa.org/resources/what-are-satellites-used. [Accessed 2022].

[2] "Everyday benefits of space exploration," Government of Canada, 11 12 2020. [Online]. Available: https://www.asc-csa.gc.ca/eng/about/everyday-benefits-of-space-exploration/. [Accessed 2022].

[3] The European Space Agency, "About space debris," European Space Agency, 2022. [Online]. Available: https://www.esa.int/Space_Safety/Space_Debris/About_space_debris.

[4] UNOOSA and ESA, "UNOOSA and ESA space debris infographics and podcasts," UNOOSA, 2021 February 2021. [Online]. Available: https://www.unoosa.org/oosa/en/informationfor/media/unoosa-and-esa-release-infographics-and-podcasts-about-space-debris.html. [Accessed 2022].

[5] D. Finkleman, "The Dilemma of Space Debris," American Scientist, 2014. [Online]. Available: https://www.americanscientist.org/article/the-dilemma-of-space-debris. [Accessed 2022].

[6] NASA Orbital Debris Program Office, "Photo Gallery," NASA, 2019. [Online]. Available: https://www.orbitaldebris.jsc.nasa.gov/photo-gallery/. [Accessed 2022].

[7] iridium, "Satellites 101: LEO vs. GEO," iridium, 11 September 2018. [Online]. Available: https://www.iridium.com/blog/2018/09/11/satellites-101-leo-vs-geo/#:~:text=Unlike%20GEO%20satellites%2C%20LEO%20satellites,typically%20flies%20around%207%2C000%20mph.. [Accessed 2022].

[8] P. Hollinger and S. Learner, "How space debris threatens modern life," Financial Times, 8 June 2022. [Online]. Available: https://ig.ft.com/space-debris/. [Accessed 2022].

[9] NASA Office of Inspector General, "NASA'S Efforts to Mitigate the Risks Posed by Orbital Debris," 27 January 2021. [Online]. Available: https://oig.nasa.gov/docs/IG-21-011.pdf. [Accessed 2022].

[10] N. Khlystov, "We have a space debris problem. Here’s how to solve it," World Economic Forum, 3 April 2018. [Online]. Available: https://www.weforum.org/agenda/2018/04/we-have-a-space-debris-problem-heres-how-to-solve-it/. [Accessed 2022].

[11] M. Garcia, "Space Debris and Human Spacecraft," NASA, 27 May 2021. [Online]. Available: https://www.nasa.gov/mission_pages/station/news/orbital_debris.html. [Accessed 2022].

[12] Aerospace, "Space Debris 101," The Aerospace Corporation, 2015. [Online]. Available: https://aerospace.org/article/space-debris-101. [Accessed 2022].

[13] E. Berger, "Earth’s orbital debris problem is worsening, and policy solutions are difficult," WIRED Media Group, 25 May 2022. [Online]. Available: https://arstechnica.com/science/2022/05/earths-orbital-debris-problem-is-worsening-and-policy-solutions-are-difficult/. [Accessed 2022].

[14] S. Odenwald, "Starlink satellite streaks: How big of a problem are they?," Astronomy, 25 March 2022. [Online]. Available: https://astronomy.com/news/2022/03/starlink-satellite-streaks-how-big-a-problem-are-they. [Accessed 2022].

[15] Aerospace, "PAVING AN INTEGRATED APPROACH FOR SPACE’S TRAFFIC JAM PROBLEM," The Aerospace Corporation, 30 March 2022. [Online]. Available: https://aerospace.org/article/paving-integrated-approach-spaces-traffic-jam-problem. [Accessed 2022].

[16] M. Polyakov, "We’re polluting our future home – before we even live there. Here’s why we need to clean up our space junk.," World Economic Forum, 5 May 2021. [Online]. Available: https://www.weforum.org/agenda/2021/05/why-we-need-to-clean-up-space-junk-debris-low-earth-orbit-pollution-satellite-rocket-noosphere-firefly/. [Accessed 2022].

[17] Iberdrola, "Space debris: is it time to start taking care of the cosmos?," Iberdrola, S.A., 2022. [Online]. Available: https://www.iberdrola.com/sustainability/space-debris. [Accessed 2022].

[18] "The Persistent Problem of Orbital Debris," Secure World Foundation, 17 October 2018. [Online]. Available: https://swfound.org/space-sustainability-101/the-persistent-problem-of-orbital-debris/. [Accessed 2022].

[19] A. Tellis, "India’s ASAT Test: An Incomplete Success," Carnegie Endowment for International Peace, 15 April 2019. [Online]. Available: https://carnegieendowment.org/2019/04/15/india-s-asat-test-incomplete-success-pub-78884. [Accessed 2022].

[20] United Nations Climate Action, "The Paris Agreement," United Nations, 2021. [Online]. Available: https://www.un.org/en/climatechange/paris-agreement. [Accessed 2022].

[21] J. O'Callaghan, "Hope for solving space debris," Aerospace America - AIAA, April 2022. [Online]. Available: https://aerospaceamerica.aiaa.org/features/hope-for-solving-space-debris/. [Accessed 2022].

[22] The European Space Agency, "Mitigating space debris generation," The European Space Agency, 2015. [Online]. Available: https://www.esa.int/Space_Safety/Space_Debris/Mitigating_space_debris_generation. [Accessed 2022].

[23] M. Smith, "SPACE DEBRIS EFFORTS MAKING PROGRESS IN THE ADMINISTRATION AND WITH HOUSE APPROPRIATORS," Space and Technology Policy Group, LLC, 27 June 2022. [Online]. Available: https://spacepolicyonline.com/news/space-debris-efforts-making-progress-in-the-administration-and-with-house-appropriators/. [Accessed 2022].

[24] J. Wahl, "Active Debris Removal: It’s Complicated," Georgetown University Space Initiative, 16 March 2021. [Online]. Available: https://www.guspaceinitiative.org/contentmaster/active-debris-removal-its-complicated. [Accessed 2022].

[25] "Astroscale’s ELSA-d Mission Successfully Completes Complex Rendezvous Operation," Astroscale, 4 May 2022. [Online]. Available: https://astroscale.com/astroscales-elsa-d-mission-successfully-completes-complex-rendezvous-operation/. [Accessed 2022].

[26] J. Foust, "The growing case for active debris removal," The Space Review, 29 March 2021. [Online]. Available: https://www.thespacereview.com/article/4150/1. [Accessed 2022].

[27] ClearSpace, "ClearSpace-1 Is A Pioneering Mission To Remove Debris From Earth Orbit," ClearSpace, 2022. [Online]. Available: https://clearspace.today/. [Accessed 2022].

[28] United Nations Office for Outer Space Affairs, "Committee on the Peaceful Uses of Outer Space," UNOOSA, 2022. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/copuos/index.html. [Accessed 2022].

[29] B. Weeden, "US space policy, organizational incentives, and orbital debris removal," The Space Review, 30 October 2017. [Online]. Available: https://www.thespacereview.com/article/3361/1. [Accessed 2022].

[30] Reagan Administration, "Presidential Directive on National Space Policy," 11 February 1988. [Online]. Available: https://spp.fas.org/military/docops/national/policy88.htm#:~:text=The%20policy%20states%20the%20unique,critical%20aspects%20of%20manned%20spaceflight.. [Accessed 2022].

[31] George H. W. Bush Administration, "National Space Policy," 2 November 1989. [Online]. Available: https://aerospace.csis.org/wp-content/uploads/2019/02/NSPD-1-Bush-I-National-Space-Policy.pdf. [Accessed 2022].

[32] Committee on Space Debris Aeronautics and Space Engineering Board Commission on Engineering and Technical Systems national Research Council, "Orbital Debris: A Technical Assessment," 1995. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/library/a-technical-assessment.pdf. [Accessed 2022].

[33] The National Science and Technology Council Committee on Transportation Research and Development, "Interagency Report on Orbital Debris," November 1995. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/library/iar_95_document.pdf. [Accessed 2022].

[34] U.S. Government, "Orbital Debris Mitigation Standard Practices, November 2019 Update," 2019. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf. [Accessed 2022].

[35] Inter-Agency Space Debris Coordination Committee, "IADC Space Debris Mitigation Guidelines," March 2020. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf. [Accessed 2022].

[36] S. Goguichvili, A. Linenberger and A. Gillette, "The Global Legal Landscape of Space: Who Writes the Rules on the Final Frontier?," 2021 October 2021. [Online]. Available: https://www.wilsoncenter.org/article/global-legal-landscape-space-who-writes-rules-final-frontier. [Accessed 2022].

[37] C. Johnson, "Legal Aspects of Space Debris," 8 September 2021. [Online]. Available: https://swfound.org/media/207257/legal-aspects-of-space-debris-9-sept.pdf. [Accessed 2022].

[38] United Nations, "Treaty on Principles Governing the Activities of States in the Exloration and Use of Outer Space, including the Moon and Other Celestial Bodies," 1967. [Online]. Available: https://www.unoosa.org/pdf/publications/STSPACE11E.pdf. [Accessed 2022].

[39] United Nations, "Convention on International Liability for Damage Caused by," 1972. [Online]. Available: https://www.unoosa.org/pdf/publications/STSPACE11E.pdf. [Accessed 2022].

[40] E. Kisiel, "LAW AS AN INSTRUMENT TO SOLVE THE ORBITAL," *Environmental Law,* vol. 51, no. 1.

[41] United Nations, "Convention on Registration of Objects Launched into Outer Space," 1974. [Online]. Available: https://www.unoosa.org/pdf/publications/STSPACE11E.pdf. [Accessed 2022].

[42] United Nations, "Space Debris Mitigation Guidelines of the Committe on the Peaceful Uses of Outer Space," December 2007. [Online]. Available: https://www.unoosa.org/pdf/publications/st_space_49E.pdf. [Accessed 2022].

[43] Space Foundation Editorial Team, "Space Briefing Book: Space Sectors," Space Foundation, [Online]. Available: https://www.spacefoundation.org/space_brief/space-sectors/. [Accessed 2022].

[44] United States Code, "Title 51 - NATIONAL AND COMMERCIAL SPACE PROGRAMS," U.S. Government Publishing Office, 2011. [Online]. Available: https://www.govinfo.gov/content/pkg/USCODE-2011-title51/html/USCODE-2011-title51.htm. [Accessed 2022].

[45] Space Foundation Editorial Team, "SPACE BRIEFING BOOK: U.S. Space Laws, Policies and Regulations," Space Foundation, 2020. [Online]. Available: https://www.spacefoundation.org/space_brief/us-space-law/#:~:text=The%20law%20was%20designed%20to,damages%20beyond%20the%20company%27s%20required. [Accessed July 2022].

[46] Obama Administration, "National Space Policy of the United States of America," 28 June 2010. [Online]. Available: https://history.nasa.gov/national_space_policy_6-28-10.pdf. [Accessed 2022].

[47] Trump Administration, "Space Policy Directive-3, National Space Traffic Management Policy," 18 June 2018. [Online]. Available: https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/. [Accessed 2022].

[48] C. Weeden, "Moving the Space Sustainability Needle? Assessing the new NASA Orbital Debris Mitigation Standard Practices," Astroscale, 28 January 2020. [Online]. Available: https://astroscale.com/moving-the-space-sustainability-needle/. [Accessed July 2022].

[49] S. Erwin, "Office of Space Commerce rolls out prototype space catalog for traffic management," SpaceNews, 12 February 2022. [Online]. Available: https://spacenews.com/office-of-space-commerce-rolls-out-prototype-space-catalog-for-traffic-management/. [Accessed July 2022].

[50] M. Dodge, "REGULATING ORBITAL DEBRIS: THE FEDERAL COMMUNICATIONS COMMISSION TACKLES SPACE JUNK," 2021. [Online]. Available: https://law.und.edu/_files/docs/ndlr/pdf/issues/96/2/96ndlr181.pdf. [Accessed 2022].

[51] T. Administration, "NASA: The Artemis Accords," NASA, 2020. [Online]. Available: https://www.nasa.gov/specials/artemis-accords/index.html. [Accessed July 2020].

[52] Office of the spokesperson, "Kingdom of Saudi Arabia Signs the Artemis Accords," US Department of State, 16 July 2022. [Online]. Available: https://www.state.gov/kingdom-of-saudi-arabia-signs-the-artemis-accords/. [Accessed July 2022].

[53] B. Administration, "United States Space Priorities Framework," December 2021. [Online]. Available: https://www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework-_-December-1-2021.pdf. [Accessed July 2022].

[54] J. Foust, "White House releases space priorities framework," SpaceNews, 1 December 2021. [Online]. Available: https://spacenews.com/white-house-releases-space-priorities-framework/. [Accessed July 2022].

[55] T. Hitchens, "Breaking Defense," 18 May 2020. [Online]. Available: https://breakingdefense.com/2020/05/most-satellite-operators-fail-to-follow-space-debris-rules-nasa/#:~:text=Last%20December%2C%20the%20National%20Space,military%20and%20the%20Intelligence%20Community.. [Accessed July 2022].

[56] US Government, "Orbital Debris Mitigation Standard Practices, November 2019 Update," November 2019. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf. [Accessed July 2022].

[57] "NASA Orbital Debris Program Office," NASA, 2022. [Online]. Available: https://orbitaldebris.jsc.nasa.gov/. [Accessed July 2022].

[58] Office of Safety and Mission Assurance, "NPR 8715.6B: NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments," NASA, 16 February 2017. [Online]. Available: https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8715&s=6B. [Accessed July 2022].

[59] NASA, "NASA-STD-8719.14: Process for Limiting Orbital Debris," NASA Technical Standards System, 5 November 2021. [Online]. Available: https://standards.nasa.gov/sites/default/files/standards/NASA/C/0/nasa-std-871914c.pdf. [Accessed July 2022].

[60] NASA Headquarters Office of Safety and Mission Assurance with the Orbital Debris Program Office at Johnson Space Center, "Handbook for Limiting Orbital Debris – NASA-HDBK-8719.14," 30 July 2008. [Online]. Available: https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/1/nasa-hdbk-871914_baseline_with_change_1.pdf. [Accessed July 2022].

[61] Department of Defense: Arthur Money, "DOD Instruction: Number 3100.12 Space Support," 14 September 2000. [Online]. Available: https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/310012p.pdf. [Accessed July 2022].

[62] Deputy Secretary of Defense: Ashton B. Carter, "DOD Directive: Space Policy Number 3100.10," 18 October 2012. [Online]. Available: https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodd/310010.pdf?ver=2019-02-04-130744-620. [Accessed July 2022].

[63] Secretary of Defense: Lloyd Austin, "Memo: Tenets of Responsible Behavior in Space," 7 July 2021. [Online]. Available: https://media.defense.gov/2021/Jul/23/2002809598/-1/-1/0/TENETS-OF-RESPONSIBLE-BEHAVIOR-IN-SPACE.PDF. [Accessed July 2022].

[64] FAA, "14 CFR 417.129," National Archives Code of Federal Regulations, 25 August 2006. [Online]. Available: https://www.ecfr.gov/current/title-14/chapter-III/subchapter-C/part-417/subpart-B/section-417.129. [Accessed July 2022].

[65] Federal Communications Commission, "Mitigation of Orbital Debris in the New Space Age," 24 April 2020. [Online]. Available: https://docs.fcc.gov/public/attachments/FCC-20-54A1.pdf. [Accessed July 2022].

[66] G. John, "Orbital debris mitigation standards evolve with new FCC rules and further proposed rulemaking," Hogan Lovells, 1 September 2020. [Online]. Available: https://www.engage.hoganlovells.com/knowledgeservices/news/orbital-debris-mitigation-standards-evolve-with-new-fcc-rules-and-further-proposed-rulemaking. [Accessed July 2022].

[67] A. Balakrishnan, "U.S. Policies Relevant to Orbital Debris," October 2020. [Online]. Available: https://www.ida.org/-/media/2cae5ff293304c8eac2d1167a03d26f6.ashx. [Accessed July 2022].

[68] USGS, "What is remote sensing and what is it used for?," U.S. Department of the Interior, 2022. [Online]. Available: https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used. [Accessed July 2022].

[69] D. o. C. NOAA, "15 CFR Part 960 Docket No.: 200407-0101," 20 May 2020. [Online]. Available: https://www.nesdis.noaa.gov/s3/2021-08/15%20CFR%20Part%20960%20Regs%202020.pdf. [Accessed July 2022].

[70] K. Harris, "FACT SHEET: Vice President Harris Advances National Security Norms in Space," The White House, 18 April 2022. [Online]. [Accessed July 2022].

[71] J. Foust, "Parallel Paths for Space Sustainability," SpaceNews, 24 June 2022. [Online]. Available: https://spacenews.com/parallel-paths-for-space-sustainability/. [Accessed July 2022].

[72] T. Hitchens, "UN talks on space norms surprisingly collegial, but fireworks to come: Sources," Breaking Defense, 31 May 2022. [Online]. Available: https://breakingdefense.com/2022/05/un-talks-on-space-norms-surprisingly-collegial-but-fireworks-to-come-sources/. [Accessed July 2022].

[73] V. Vikmanis-Keller, "59th Session of the COPUOS Scientific and Technical Subcommittee | Agenda Item 8: Space Debris," U.S. MISSION TO INTERNATIONAL ORGANIZATIONS IN VIENNA, 9 February 2022. [Online]. Available: https://vienna.usmission.gov/2022-copuos-stsc-space-debris/?_ga=2.72647963.964747685.1656487687-526996877.1656487687. [Accessed July 2022].

[74] S. Erwin, "Space debris expert warns U.S. 'woefully behind' in efforts to clean up junk in orbit," SpaceNews, 6 January 2022. [Online]. Available: https://spacenews.com/space-debris-expert-warns-u-s-woefully-behind-in-efforts-to-clean-up-junk-in-orbit/. [Accessed July 2022].

[75] "Space Saftey: Space Debris," ESA, 2022. [Online]. Available: https://www.esa.int/Space_Safety/Space_Debris. [Accessed 2022 July].

[76] H. Vardhan, "Astroscale To Launch Its ESA-backed World's First Space Debris Removing Mission In 2024," Republicworld.com, 21 June 2022. [Online]. Available: https://www.republicworld.com/science/space/astroscale-to-launch-its-esa-backed-worlds-first-space-debris-removing-mission-in-2024-articleshow.html. [Accessed July 2022].

[77] J. Foust, "U.K. government announces new space sustainability measures," SpaceNews, 25 June 2022. [Online]. Available: https://spacenews.com/u-k-government-announces-new-space-sustainability-measures/. [Accessed July 2022].

[78] J. O'Callaghan, "Hope for solving space debris," Aerospace America, April 2022. [Online]. Available: https://aerospaceamerica.aiaa.org/features/hope-for-solving-space-debris/. [Accessed July 2022].

[79] E. Howell, "Russia wants to build its own space station, as early as 2028," Space.com, 26 July 2022. [Online]. Available: https://www.space.com/russian-space-station-ross-2028-timeline. [Accessed July 2022].

[80] "Debris from China's rocket booster falls to Earth," AlJazeera, 31 July 2022. [Online]. Available: https://www.aljazeera.com/news/2022/7/31/debris-from-chinas-rocket-booster-falls-to-earth. [Accessed July 2022].

[81] FAA, "Orbital Debris Mitigation Methods for Launch Vehicle Upper Stages (Orbital Debris)," Reginfo.gov, Fall 2017. [Online]. Available: https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=201710&RIN=2120-AK81. [Accessed July 2022].

[82] J. Rainbow, "Bipartisan legislation seeks to reform FCC satellite licensing rules," SpaceNews, 14 February 2022. [Online]. Available: https://spacenews.com/bipartisan-legislation-seeks-to-reform-fcc-satellite-licensing-rules/. [Accessed July 2022].

[83] N. Simington, "Simington Addresses Texas Public Policy Foundation," 4 March 2022. [Online]. Available: https://www.fcc.gov/document/simington-addresses-texas-public-policy-foundation. [Accessed July 2022].

[84] M. Smith, "SPACE DEBRIS EFFORTS MAKING PROGRESS IN THE ADMINISTRATION AND WITH HOUSE APPROPRIATORS," SpacePolicOnline.com, 27 June 2022. [Online]. Available: https://spacepolicyonline.com/news/space-debris-efforts-making-progress-in-the-administration-and-with-house-appropriators/. [Accessed July 2022].

[85] "Space Situational Awareness, Space Traffic Management, and Orbital Debris: Examining Solutions for Emerging Threats," US Senate, 22 July 2021. [Online]. Available: https://www.commerce.senate.gov/2021/7/space-situational-awareness-space-traffic-

management-and-orbital-debris-examining-solutions-for-emerging-threats/819ef822-3e6d-4ab1-9a56-31c6d60969c9. [Accessed July 2022].

[86] "RESCHEDULED: SPACE SITUATIONAL AWARENESS: GUIDING THE TRANSITION TO A CIVIL CAPABILITY," US House of Representatives, 12 May 2022. [Online]. Available: https://science.house.gov/hearings/space-situational-awareness-guiding-the-transition-to-a-civil-capability. [Accessed July 2022].

[87] J. Foust, "House appropriators partially restore funding for planetary defense mission," SpaceNews, 27 June 2022. [Online]. Available: https://spacenews.com/house-appropriators-partially-restore-funding-for-planetary-defense-mission/. [Accessed July 2022].

[88] S. Erwin, "Space Force selects 125 industry proposals for on-orbit servicing technologies," SpaceNews, 2 May 2022. [Online]. Available: https://spacenews.com/space-force-selects-125-industry-proposals-for-on-orbit-servicing-technologies/. [Accessed July 2022].

[89] T. Administration, "NATIONAL ORBITAL DEBRIS RESEARCH AND DEVELOPMENT PLAN," January 2021. [Online]. Available: https://trumpwhitehouse.archives.gov/wp-content/uploads/2021/01/National-Orbital-Debris-RD-Plan-2021.pdf. [Accessed July 2022].

[90] B. Administration, "NATIONAL ORBITAL DEBRIS IMPLEMENTATION PLAN," July 2022. [Online]. Available: https://www.whitehouse.gov/wp-content/uploads/2022/07/07-2022-NATIONAL-ORBITAL-DEBRIS-IMPLEMENTATION-PLAN.pdf. [Accessed July 2022].

[91] CONFERS, "About," Advanced Technology International (ATI), 2022. [Online]. Available: https://www.satelliteconfers.org/about-us/. [Accessed July 2022].

[92] Consortium for Execution of Rendezvous and Servicing Operations, "CONFERS Recommended Design and Operational Practices," October 2021. [Online]. Available: https://www.satelliteconfers.org/wp-content/uploads/2021/11/CONFERS_Operating_Practices_Revised-Oct-21.pdf. [Accessed July 2022].

[93] Space Saftey Coalition, "Best Practices for the Sustainability of Space Operations," 16 September 2019. [Online]. Available: https://spacesafety.org/wp-content/uploads/2022/03/Endorsement-of-Best-Practices-for-Sustainability_v46.pdf. [Accessed July 2022].

[94] Space Data Association, "Welcome to the Space Data Association," Space Data Association LTD, 2022. [Online]. Available: https://www.space-data.org/sda/. [Accessed July 2022].

[95] D. Messier, "EXPERTS SAY URGENT ACTION REQUIRED ON SPACE SAFETY AS NUMBER OF SATELLITES SOARS AND ORBITAL DEBRIS PROLIFERATES," New Space Global, 4 June 2022. [Online]. Available: https://newspaceglobal.com/experts-say-urgent-action-required-on-space-safety-as-number-of-satellites-soars-and-orbital-debris-proliferates/. [Accessed July 2022].

[96] M. Langrand, "Geneva launches efforts to set some ground rules in space," Geneva Soutions, 11 May 2022. [Online]. Available: https://genevasolutions.news/science-tech/geneva-launches-efforts-to-set-some-ground-rules-in-space. [Accessed July 2022].

[97] "Pelosi to leave for Asia amid Chinese threats over Taiwan stop," Politico, 29 July 2022. [Online]. Available: https://www.politico.com/news/2022/07/29/pelosi-taiwan-china-00048749. [Accessed July 2022].

[98] B. Nelson, "NASA Administrator Statement on Chinese Space Debris," NASA, 30 July 2022. [Online]. Available: https://www.nasa.gov/press-release/nasa-administrator-statement-on-chinese-space-debris. [Accessed July 2022].

[99] NASA, "NASA Strategic Plan 2022," 2022. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/fy23_nasa_budget_request_full_opt.pdf. [Accessed July 2022].

[100] NASA, "FY 2023 Budget Estimates," 2022. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/fy23_nasa_budget_request_full_opt.pdf. [Accessed July 2022].

[101] J. Foust, "Industry looks to decentralized approaches to space sustainability," SpaceNews, 25 May 2022. [Online]. [Accessed July 2022].

[102] T. Hitchens, "Unclear And Contradictory Rules Bedevil Commercial Space Firms: Study," Breaking Defense, 15 October 2021. [Online]. [Accessed July 2022].

[103] M. Runnels, "On Clearing Earth’s Orbital Debris & Enforcing the Outer Space Treaty in the U.S.," American Bar Association, 13 January 2022. [Online]. [Accessed July 2022].

[104] T. Pultarova, "SpaceX Starlink satellites responsible for over half of close encounters in orbit, scientist says," Space, 18 August 2021. [Online]. Available: https://www.space.com/spacex-starlink-satellite-collision-alerts-on-the-rise. [Accessed July 2022].

[105] A. Datta, "Former NASA chief Jim Bridenstine Makes a Case for Sustainability of Space," GEOSPATIAL MEDIA AND COMMUNICATIONS, 26 March 2022. [Online]. Available: https://www.geospatialworld.net/blogs/jim-bridenstine-space-sustainability-regulatory-framework/. [Accessed July 2022].

[106] J. Foust, "Orbital debris mitigation guidelines still useful, if complied with," SpaceNews, 15 January 2020. [Online]. Available: https://spacenews.com/orbital-debris-mitigation-guidelines-still-useful-if-complied-with/#:~:text=Guidelines%20for%20mitigating%20orbital%20debris,of%20collisions%20that%20would%20create. [Accessed July 2022].

[107] U. D. O. D. Howard, "Open Architecture Data Repository," 28 April 2021. [Online]. Available: https://www.unoosa.org/documents/pdf/copuos/stsc/2021/tech-55E.pdf. [Accessed July 2022].

[108] C. Zur and S. Kordella, "Biden budget prioritizes space sector," The Hill, 21 June 2022. [Online]. Available: https://thehill.com/opinion/technology/3531566-biden-budget-prioritizes-space-sector/a. [Accessed 2022 July].

[109] ASTROSCALE U.S. INC., "Comments of Astroscale U.S. INC. In the Matter of Orbital Debris Research and Development Plan Before the Science and Technology Policy Office," January 2021. [Online]. Available: https://astroscale-us.com/wp-content/uploads/2022/01/Comments-of-Astroscale-U.S.-Inc-to-OSTP.pdf.

[110] T. Way and J. Koller, "Active Debris Removal: Policy and Legal Feasibility," April 2021. [Online]. Available: https://csps.aerospace.org/sites/default/files/2021-08/Way_Koller_ADR_20210422.pdf. [Accessed July 2022].

[111] Space Sustainability Rating, SSR - Space Sustainability Rating, July 2022. [Online]. Available: https://spacesustainabilityrating.org/.

[112] NATIONAL SCIENCE AND TECHNOLOGY COUNCIL ORBITAL DEBRIS INTERAGENCY WORKING GROUP, "National Orbital Debris Implementation Plan," July 2022. [Online]. Available: https://www.whitehouse.gov/wp-content/uploads/2022/07/07-2022-NATIONAL-ORBITAL-DEBRIS-IMPLEMENTATION-PLAN.pdf. [Accessed 2022].