NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

PROTECTING AMERICA'S HIGH GROUND: A PUBLIC–PRIVATE RESPONSE TO SPACE DEBRIS

by

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June 2021

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2021	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE PROTECTING AMERICA'S HIGH GROUND: A PUBLIC–PRIVATE RESPONSE TO SPACE DEBRIS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Christopher W. Repair			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

The United States is reliant on the capabilities provided by satellite technology for nearly every facet of society. A sustained loss of satellite capabilities due to any service outages will have a significant negative impact on the nation's homeland security. The areas affected include communication, financial transactions, intelligence gathering, internet access, and weather surveillance. Existing domestic and international policy has been insufficient in managing debris growth. The removal of large debris from congested orbits through active debris removal (ADR) is now necessary to prevent future collision events that will damage or destroy operational satellites that may possibly render certain regions of space unusable for generations. To safeguard its satellites and critical services they provide to homeland security, the United States should develop a domestic debris removal program using the established public–private partnership model that NASA has leveraged over the previous 15 years. This model has reduced developments costs and risks of schedule delays, and also stimulates growth in the private space sector and creates additional tax revenues. Furthermore, the commercial sector possesses knowledge and experience in the field of on-orbit servicing, a field with similar technical challenges to debris removal that can provide a foundation for the development of ADR systems. The United States must begin remediation by partnering with the private sector.

14. SUBJECT TERMS			**15. NUMBER OF PAGES**
space debris, debris remediation, public-private partnerships			117
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
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**MASTER OF ARTS IN SECURITY STUDIES
(HOMELAND SECURITY AND DEFENSE)**

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The United States is reliant on the capabilities provided by satellite technology for nearly every facet of society. A sustained loss of satellite capabilities due to any service outages will have a significant negative impact on the nation's homeland security. The areas affected include communication, financial transactions, intelligence gathering, internet access, and weather surveillance. Existing domestic and international policy has been insufficient in managing debris growth. The removal of large debris from congested orbits through active debris removal (ADR) is now necessary to prevent future collision events that will damage or destroy operational satellites that may possibly render certain regions of space unusable for generations. To safeguard its satellites and critical services they provide to homeland security, the United States should develop a domestic debris removal program using the established public–private partnership model that NASA has leveraged over the previous 15 years. This model has reduced developments costs and risks of schedule delays, and also stimulates growth in the private space sector and creates additional tax revenues. Furthermore, the commercial sector possesses knowledge and experience in the field of on-orbit servicing, a field with similar technical challenges to debris removal that can provide a foundation for the development of ADR systems. The United States must begin remediation by partnering with the private sector.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADR	active debris removal
ADRIOS	Active Debris Removal/In-Orbit Servicing
CCP	Commercial Crew Program
CHDS	Center for Homeland Defense and Security
CLPS	Commercial Lunar Payload Services
COTS	Commercial Orbital Transportation Services
CRD2	Commercial Removal of Debris Demonstration
DARPA	Defense Advanced Research Projects Agency
ELSA-d	End-of-Life Service by Astroscale
ESA	European Space Agency
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FCC	Federal Communications Commission
GEO	geosynchronous earth orbit
GPS	global positioning system
IADC	Inter-Agency Debris Coordination Committee
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JSC	Johnson Space Center
LEO	low earth orbit
LiDAR	light detection and ranging
LNT	lethal non-trackable
MEO	medium earth orbit
MEV	Mission Extension Vehicle
NASA	National Aeronautics and Space Administration
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NSpC	National Space Council
ODMSP	Orbital Debris Mitigation Standard Practices
OOS	on-orbit servicing

OSAM	On-Orbit Servicing, Assembly, and Manufacturing
RpK	Rocketplane Kistler
RSGS	Robotic Servicing of Geosynchronous Satellites
RSO	resident space object
SBIR	Small Business Innovation Research
SPD-3	Space Policy Directive 3
SPIDER	Space Infrastructure Dexterous Robot
SSA	space situational awareness
SSL	Space Systems Loral
STM	space traffic management
STTR	Small Business Technology Transfer Programs
TRL	technology readiness level
ULA	United Launch Alliance
UN	United Nations
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
USD	United States dollars
VBN	vision-based navigation

EXECUTIVE SUMMARY

Uncontrolled debris in orbit poses the greatest risk to U.S. satellites in orbit and the capabilities they provide. A sustained loss of services provided by satellite technology will have a significant negative impact on the nation's homeland security. The areas impacted include communication, financial transactions, intelligence gathering, internet access, and weather surveillance.[1] Domestic and international policy decisions have been ineffective in slowing the growth of the debris population. This ineffectiveness has created an orbital environment in which the removal of large debris from congested orbits through active debris removal (ADR) is now necessary to prevent future collision events that will damage or destroy operational satellites and may possibly render certain regions of space unusable for generations. The National Space Council needs to develop a domestic ADR program to begin removing the most dangerous debris objects from orbit to mitigate the threat debris poses to U.S. assets in space.

The United States has been slow to act regarding debris remediation due to policy decisions. The United States was the first nation to generate a list of best practices to reduce debris-generating events known as mitigation standard practices.[2] However, these practices were not mandated and were therefore unenforceable. Complying with these standards may have resulted in a financial burden to satellite operators who may need to carry extra fuel to deorbit their satellite upon its end-of-life. Other nations and the United Nations (UN) eventually adopted mitigation practices as well; however, international community compliance with these practices has been lacking.[3] This lack of compliance

[1] Bryce Space and Technology, *Satellites Key to $5T+ Across U.S. Economy* (Alexandria, VA: Bryce Space and Technology, 2019), 2, https://brycetech.com/reports; Chadwick D. Igl et al., "568 Balls in the Air: Planning for the Loss of Space Capabilities," *Joint Forces Quarterly*, no. 90 (2018): 2, https://www.ndu.edu/Portals/68/Documents/jfq/jfq-90/jfq-90_24-29_igl-et-al.pdf?ver=2018-04-11-125441-307.

[2] J.-C. Liou, "Orbital Debris Briefing" (Washington, DC: Executive Office of the President/Office of Science and Technology Policy (EOP/OSTP) Briefing, December 8, 2017), 4, https://ntrs.nasa.gov/citations/20170011662.

[3] J.-C. Liou, "Orbital Debris Briefing," 9; ESA Space Debris Office, *ESA's Annual Space Environment Report* (Darmstadt, Germany: European Space Agency, 2020), 87, https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf.

has contributed significantly to the current state of the debris population. The United States is aware the debris population is growing and mitigation alone is insufficient, yet no policy action has been taken to combat this threat. The current orbital environment is at risk of experiencing one or more catastrophic collision events, yet no action has been taken to prevent it. Congress must pass a Clean Space Act to establish regulatory authority to enforce mitigation standards and fund a domestic remediation program.

NASA developed the public–private partnership model for the Commercial Orbital Transportation Services (COTS) program. The goal of this effort was to provide cargo resupply services to the international space station (ISS) following the retirement of the space shuttle in 2010.[4] Following directives from the Bush Administration to turn over routine services to the commercial sector, NASA selected Space Exploration Technologies Corporation (SpaceX) and Orbital Sciences Corporation (Orbital Sciences) as partners in developing resupply spacecraft. An analysis conducted within NASA found this program model resulted in significantly lower development costs for the required spacecraft.[5] An example is the development of the SpaceX Falcon 9 booster, which was developed at a cost of one-quarter of the best estimate of previous NASA methods.[6] Furthermore. the fact that the commercial partners retained ownership of the systems developed within the program allowed these systems to be sold commercially. Thus, commercial partners received additional revenue, which created new jobs and tax revenue. Research shows the tax revenue from follow-on commercial sales of these systems has paid for initial public investment in these systems.[7] The success of COTS led to public–private partnerships

[4] National Aeronautics and Space Administration, *Commercial Orbital Transportation Services: A New Era in Spaceflight*, Illustrated (Washington, DC: Government Printing Office, 2014), 2.

[5] Edgar Zapata, "An Assessment of Cost Improvements in the NASA COTS—CRS Program and Implications for Future NASA Missions," in *AIAA Space 2017 Conference* (Orlando, FL: American Institute of Aeronautics and Astronautics, 2017), 23, 24, https://ntrs.nasa.gov/search.jsp?R=20170008895.

[6] National Aeronautics and Space Administration, *Falcon 9 Launch Vehicle NAFCOM Cost Estimates* (Washington, DC: National Aeronautics and Space Administration, 2011), 8–9, https://www.nasa.gov/pdf/586023main_8-3-11_NAFCOM.pdf.

[7] Zapata, "An Assessment of Cost Improvements in the NASA COTS," 25.

being used in the Commercial Crew and Lunar Artemis programs currently under development.[8]

NASA's investment into the commercial space sector has resulted in greater competition and new innovation in a once stagnant sector. Large aerospace companies launching mainly government payloads had dominated the commercial launch industry. The lack of a diverse customer base and competition kept launch prices high.[9] The entry of SpaceX, Blue Origin, Rocket Lab, and others has forced established launch providers, such as United Launch Alliance (ULA), to innovate and evolve to stay competitive.[10] This new marketplace and resulting innovation provide a strong pool of talent for NASA with which to partner. Additionally, the private sector has achieved great success in the related field of on-orbit servicing (OOS), a mission that requires similar capabilities to that of ADR missions. Northrop Grumman's subsidiary SpaceLogistics has demonstrated an operational capability to rendezvous and dock with satellites in geosynchronous earth orbit (GEO) with its mission extension vehicle (MEV).[11] This spacecraft's success has resulted in a partnership with Defense Advanced Research Projects Agency (DARPA) to develop a spacecraft capable of servicing satellites in GEO to provide further evidence that the strength of the commercial sector can be leveraged to pursue complex space capabilities.[12]

The goal of this remediation partnership should be the remediation of U.S.-owned debris objects between 775 km and 1,500 km in altitude. Four separate orbits appear

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[8] Sean Potter, "NASA Astronauts Launch from America in Test of SpaceX Crew Dragon," National Aeronautics and Space Administration, May 30, 2020, http://www.nasa.gov/press-release/nasa-astronauts-launch-from-america-in-historic-test-flight-of-spacex-crew-dragon; and "NASA Announces New Moon Partnerships with U.S. Companies," November 29, 2018, NASA, YouTube, video, 3:20, https://www.youtube.com/watch?v=t2TfS_ckxjA.

[9] Senate Subcommittee on Science, Technology, and Space, *Commercial Space Opportunities* (Washington, DC: U.S. Government Printing Office, 1987), 54, ProQuest; Bruce D. Berkowitz, "Energizing the Space Launch Industry," *Issues in Science and Technology* 6, no. 2 (1989): 79–80.

[10] Irene Klotz, "SpaceX Undercut ULA Rocket Launch Pricing by 40 Percent: U.S. Air Force," Reuters, April 28, 2016, https://www.reuters.com/article/us-space-spacex-launch-ula-idUSKCN0XP2T2.

[11] Elizabeth Howell, "Two Private Satellites Just Docked in Space in Historic First for Orbital Servicing," Space, February 27, 2020, https://www.space.com/private-satellites-docking-success-northrop-grumman-mev-1.html.

[12] Sandra Erwin, "DARPA Picks Northrop Grumman as Its Commercial Partner for Satellite Servicing Program," SpaceNews, March 4, 2020, https://spacenews.com/darpa-picks-northrop-grumman-as-its-commercial-partner-for-satellite-servicing-program/.

between these altitudes that present different risks; however, the literature shows this area of space has the highest likelihood of collision along with producing the most catastrophic collisions regarding the amount of debris generated.[13] Targeting only U.S.-owned debris prevents the violation of established international agreements and will allow for a quicker development of capabilities, as well as for potential future expansion internationally. Between inoperable satellites and derelict rocket bodies, the United States owns 41 objects at these altitudes that pose a collision risk.[14] These objects are the initial target list for the program. While related literature states multiple objects need to be remediated to reduce the risk of collision, this program must focus on the removal of these objects due to their mass and the population density of debris in these orbits.[15] Any capabilities developed in the program can be scaled up later to achieve the desired frequency of remediation missions while pursuing international cooperation to clear foreign debris objects in orbit.

The framework for a domestic ADR program should be a public–private partnership between the National Aeronautics and Space Administration (NASA) and the commercial space sector. NASA has used this model of program management and technology development over the last 15 years. This partnership model, where both NASA and participating commercial partners share the development costs of program spacecraft, has reduced costs through reduced public sector oversight and leveraging private sector innovation and construction efficiency.[16] Additionally, the framework of the partnership allows the commercial partner to retain ownership of the developed systems that allows partners to sell services commercially using these systems.[17] These benefits are not

[13] A. Rossi, A. Petit, and D. McKnight, "Examining Short-Term Space Safety Effects from LEO Constellations and Clusters," v. 2109, in *First International Orbital Debris Conference* (Sugar Land, TX: Lunar Planetary Institute, 2019), 3, https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6010.pdf.

[14] Darren McKnight, Rohit Arora, and Rachel Witner, "Intact Derelict Deposition Study," in *First International Orbital Debris Conference* (Sugar Land, TX: Lunar Planetary Institute, 2019), 6, https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6011.pdf.

[15] Donald J. Kessler et al., "The Kessler Syndrome: Implications to Future Space Operations," *Advances in Astronautical Sciences* 137, no. 8 (2010): 14; Rossi, Petit, and McKnight, "Examining Short-Term Space Safety Effects," 8.

[16] Zapata, "An Assessment of Cost Improvements in the NASA COTS," 23–24.

[17] National Aeronautics and Space Administration, *Commercial Orbital Transportation Services*, 12, 22.

possible in a traditional NASA program when systems are procured from the commercial sector using FAR contracts and specific design specifications.

A partnership with the private sector has the ability to reduce the threat of debris to American satellites. It will also allow the United States to maintain its role as a leader in space and demonstrate good stewardship of the orbital environment. This partnership will also open up new markets and revenue streams in the field of remediation services. The number of commercial satellites being launched is growing, and remediation services may become a large component of the commercial space market. A partnership will allow U.S. companies to take leadership in this effort and keep jobs and tax revenue in the country instead of overseas. The result of this partnership will be a safer environment for U.S. satellites and will jump-start U.S. commercial space companies in the ADR marketplace. Inaction will result in an ever-increasing likelihood that satellite services will be compromised as the number of satellites in orbits grows. The United States needs to begin remediation and should partner with the private sector.

A catastrophic collision in orbit and the resulting fragmentation could impact the space around the planet for generations. This type of collision is not unlike a nuclear meltdown accident or environmental oil spill. Those events have the capability of rendering areas uninhabitable for generations. A series of cascading collisions could do the same to the space around the Earth, only this area would be uninhabitable by satellites. A degradation of services in nearly all aspects of modern life would be the result. Experts are warning the United States about this type of disaster and state immediate action is needed to prevent such an event. Congress and NASA have the resources and the authority to act. It is their responsibility to act in the best interest of the public, as it is negligent to leave America's critical space-based assets vulnerable to this known threat. The U.S. government cannot plead ignorance on this issue. In the event that such a collision event would occur, the public would want to know why more was not done to prevent such a catastrophe; especially one that experts warned was possible. The United States must begin the development of an ADR capability, and the public–private partnership model established by NASA should be the framework for that effort.

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ACKNOWLEDGMENTS

I would like to acknowledge several people who made this thesis possible through their sharing of knowledge and research. Thank you to Dr. Darren McKnight for explaining the scope of the space debris problem and taking the time to share your knowledge with an amateur space enthusiast such as myself. A similar thank you goes to Mr. Scott Simmons, Chair for Space Control Research, OSD (R&E), at the Naval Postgraduate School, who discussed not only the threat of space debris but also the intricacies of the policy challenges that have hampered progress in the field. Thank you to Mr. Ted Muelhaupt, and Mr. Marlon Sorge, of the Aerospace Corporation, who also discussed the challenges of space debris with me and shared current research.

My own research would have been exponentially more challenging if not for the efforts of Greta Marlatt, Research Librarian at the Dudley Know Library at the Naval Postgraduate School (NPS). Your dedication to your profession is matched only by the compassion you display for your students. Thank you for the significant assistance and steadfast encouragement you provided during my time at NPS. A sincere thank you goes to my thesis advisors, Lt. Col. Craig Boucher and Dr. Carolyn Halladay. Your support, patience, and unwavering encouragement created an environment in which I learned just as much about myself as I did about space debris.

Thank you to Center for Homeland Defense and Security (CHDS) alum Dave Park for encouraging me to apply for this program and believing in my potential. Thank you to the other members of the CHDS Cohort 1903/04 for your encouragement and invaluable feedback regarding this project. The time we spent together was challenging, but I value every minute of it. Last, I would like to thank my wife, Lisa; my son, Seth; my daughter, Sarah; my parents, Ken and Helen; and my sister, Nicki. The love and encouragement you gave me throughout this process provided the foundation for me to stand on and reach for the stars.

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I. INTRODUCTION

Satellite technologies have penetrated nearly every level of modern society. As the capabilities of satellites grew, these technologies improved efficiency across many sectors of private industry and government services. The services that satellites in orbit provide include many capabilities critical to U.S. homeland security. I have been passionate about space exploration for many years. Thus, when I began my studies in homeland security, I naturally gravitated to space-related topics. Such key homeland security issues as effective communication during crises and weather observation capabilities in an era of ever-increasing hazardous weather, as well as intelligence services provided to defense officials and policy makers, all depend on satellite technologies. While the high levels of radiation in orbit or state-actors using offensive action can possibly put a satellite out of commission, uncontrolled debris in space is the most immediate threat that may lead to a collision between debris and operational satellites, and perhaps cripple whole networks.

This topic features prominently in the area of space research, but little scholarship examines this threat from a homeland security perspective. Thus, this thesis represents my efforts to research the threat that debris poses to U.S. assets in space and to provide a solution based on evidence gathered from both public and private U.S. space operations.

A. RESEARCH QUESTIONS

After establishing the risk that debris poses to satellites, the next step is to find a solution to this challenge. After examining the relevant research related to debris and the lack of a reason for a concentrated effort to removing it, the following questions were developed:

- How can the United States begin removal operations of orbital debris?
- How does the United States overcome the associated technical, legal, and policy challenges associated with such an endeavor?

B. LITERATURE REVIEW

To generate a strong knowledge base on the issues related to the threat of space debris, my review of the relevant literature spanned the risk space debris poses, the effect of a loss of satellite capabilities on homeland security, domestic and international efforts from both national space agencies and governments, and the efficacy of international agreements regarding space debris. All the research reviewed for this thesis is open source. The literature paints a picture in which both commercial actors and nation-states acknowledge that space debris is a threat to satellites in orbit and the capabilities they provide. Furthermore. my review led to the discovery of success within domestic space programs in partnering with the commercial space sector in recent initiatives. This discovery led me to research the effectiveness of a public–private partnership to address complex challenges. The literature illustrates how this management framework can be successful under the right parameters.

Significant research has been conducted on the growth in the debris population in orbit from both the public and private sector. The foundational document in modern debris research is a 1978 article by Kessler and Cour-Palais. This article states that it is possible for the debris population to grow to a point where a series of cascading collisions may occur that can exponentially increase the amount of debris around the Earth.[1] Once this series of collisions reaches a critical point, the effects become irreversible that then render affected orbits unusable.[2] Subsequent researchers have called this event the "Kessler Syndrome."[3] Research by NASA's Orbital Debris office shows that the amount of debris fragments and total mass in orbit is increasing with "no signs of slowing down."[4] Further

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1 Donald J. Kessler and Burton G. Cour-Palais, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," *Journal of Geophysical Research: Space Physics* 83, no. A6 (1978): 2637, https://doi.org/10.1029/JA083iA06p02637.

2 Joseph Kurt, "Triumph of the Space Commons: Addressing the Impending Space Debris Crisis without an International Treaty," *William & Mary Environmental Law and Policy Review* 40, no. 1 (2015): 309.

3 Louis de Gouyon Matignon, "The Kessler Syndrome and Space Debris," *Space Legal Issues* (blog), March 27, 2019, https://www.spacelegalissues.com/space-law-the-kessler-syndrome/.

4 J.-C. Liou, "Risk from Orbital Debris" (RAS Specialist Discussion Meeting on Space Dust and Debris in the Vicinity of the Earth, London, United Kingdom, November 9, 2018), 7–8, https://ntrs.nasa.gov/api/citations/20180008560/downloads/20180008560.pdf.

research by Kessler, Liou, Rossi, Petit, McKnight, Hakima, and Emami, all illustrate that the volume of debris in orbit has reached a point where debris objects need to be removed to prevent future collision events.[5] These studies illustrate how mitigation efforts, practices designed to limit the amount of debris generated by space operations, have not kept up with debris generating behaviors. A growing body of literature also appears both in journal articles and NASA research showing that the deployment of very-large satellite constellations in low-earth orbit (LEO), such as SpaceX's Starlink constellation that may grow to 42,000 satellites, will increase the likelihood of future collision events and require either more stringent mitigation standards or the implementation of remediation missions.[6] The total number of spacecrafts being launched annually is increasing explosively. According to Bryce Space and Technology, 1,085 spacecraft were launched into orbit in 2020 as of October 31.[7] This figure is approximately double the number from the previous year, which itself was a record.[8] The current state of the debris population and the growing number of satellites in orbit now present a situation in which five debris objects a year must be removed in conjunction with a 90-percent compliance rate to debris mitigation practices.[9]

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[5] Donald J. Kessler et al., "The Kessler Syndrome: Implications to Future Space Operations, 14; A. Rossi, A. Petit, and D. McKnight, "Examining Short-Term Space Safety Effects from LEO Constellations and Clusters," v. 2109, in *First International Orbital Debris Conference* (Sugar Land, TX: Lunar Planetary Institute, 2019), 8, https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6010.pdf, https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6010.pdf; and Houman Hakima and M. Reza Emami, "Assessment of Active Methods for Removal of LEO Debris," *Acta Astronautica* 144 (March 2018): 225, https://doi.org/10.1016/j.actaastro.2017.12.036.

[6] Veronica L. Foreman, Afreen Siddiqi, and Olivier L. de Weck, "Large Constellation Orbital Debris Impacts: Case Studies of OneWeb and SpaceX Proposals," in *Proceedings of the AIAA SPACE and Astronautics Forum and Exposition* (Orlando: American Institute of Aeronautics and Astronautics, 2017), 13–14, https://doi.org/10.2514/6.2017-5200; B. Bastida Virgili et al., "Risk to Space Sustainability from Large Constellations of Satellites," *Acta Astronautica* 126 (September 2016): 154, https://doi.org/10.1016/j.actaastro.2016.03.034; Hugh Lewis et al., "Sensitivity of the Space Debris Environment to Large Constellations and Small Satellites," *Journal of the British Interplanetary Society* 70 (2017): 14; J.-C. Liou et al., "NASA ODPO's Large Constellation Study," *Orbital Debris Quarterly News* 22, no. 3 (2018): 7.

[7] "2020 Year in Review," Bryce Space and Technology, 2020, https://brycetech.com/reports.

[8] Bryce Space and Technology.

[9] Hakima and Emami, "Assessment of Active Methods for Removal of LEO Debris," 1; J.-C. Liou, N. L. Johnson, and N. M. Hill, "Controlling the Growth of Future LEO Debris Populations with Active Debris Removal," *Acta Astronautica* 66, no. 5 (March 2010): 652, https://doi.org/10.1016/j.actaastro.2009.08.005; J.-C. Liou et al., "NASA ODPO's Large Constellation Study," 7.

While the growth in the debris population is well documented, those statistics do not paint a complete picture of the nature of the threat. Not only is the total amount of debris significant, but also the concentration of debris within specific orbital altitudes and the mass of individual debris objects represent the greatest threat of collision in orbit. The literature describes where dangerous debris exists and which states are responsible. Research by McKnight, Arora, and Witner provides statistics on debris location and ownership. Their research found that the United States is responsible for 22.5 percent of the large debris objects in the longest-lived orbits around the Earth.[10] Separate research by Rossi, Petit, and McKnight identify four orbital altitudes that pose a significant risk of collision: 775 km, 850 km, 975 km, and 1,500 km.[11] The literature illustrates that close approaches between debris objects in these four orbits occur 1,000 times annually; with the highest likelihood of collision occurring at 975 km.[12] Within the 975 km orbit, monthly near misses occur with a higher probability of collision than was calculated prior to the collision of the Iridium 33 and Cosmos 2251 satellites in 2009. This event generated 4,500 tracked debris objects and approximately 60,000 lethal non-trackable (LNT) objects.[13]

Each one of these orbits poses a different risk. For example, a collision at 775 km would affect the most operational satellites whereas a collision at 850 km would be the most consequential given the mass of the objects in that orbit.[14] The research by Rossi et al. specifically shows that a collision in the 850 km orbit would have an average mass of up to 18,000 kg that would generate approximately 16,000 new debris objects large enough to track, and another 200,000 LNT objects.[15] These massive objects include rocket bodies, payload adapters, and derelict satellites. Collisions at this altitude, while not as likely as the 975 km orbit, are considered more consequential due to the larger average mass of debris objects, and therefore, the more fragments that would be generated during a collision

[10] Darren McKnight, Rohit Arora, and Rachel Witner, "Intact Derelict Deposition Study" 6.

[11] Rossi, Petit, and McKnight, "Examining Short-Term Space Safety Effects," 3.

[12] Rossi, Petit, and McKnight, 2.

[13] Rossi, Petit, and McKnight, 2.

[14] Rossi, Petit, and McKnight, 3.

[15] Rossi, Petit, and McKnight, 3.

event. Collisions within the 1,500 km altitude have the lowest probability of collision, but debris generated at this altitude would be the longest lived of the four altitudes.[16] As a whole, this literature provides the needed data on where remediation missions would be the most effective, which is an important component of any future remediation efforts.

A significant body of research is available on the economic value the services the satellite industry provides to the global economy at large. Satellite technology has penetrated many aspects of modern society. With increased reliance on the capabilities these technologies provide, the repercussions of any loss of these capabilities increases as well. Bryce Space and Technology has conducted several studies on spending and economic drivers related to satellite technology. A 2019 report from Bryce found that satellite technology was a driver in $5 trillion in annual revenues across the U.S. economy.[17] The satellite capabilities found to strongly impact the economy include wireless communications services, satellite television distribution, precision timing services for financial institutions, global positioning system (GPS) navigation capabilities, and weather surveillance.[18] This report demonstrates that several sectors of the U.S. economy would be negatively impacted if significant collision events occurred limiting the United States' access to space.

The literature reviewed for this thesis also demonstrated that satellites are key to U.S. national security. In a 2018 article by Igl, Smith, Fowler, and Angermann, the authors found that the U.S. Department of Defense relied on satellite capabilities for communication, precision targeting, navigation, and imagery for intelligence.[19] In addition, the authors also illustrated how potential adversaries in Russia and China have identified U.S. reliance on satellites for military capabilities and have established plans to

[16] Rossi, Petit, and McKnight, 3.

[17] Bryce Space and Technology, *Satellites Key to $5T+ Across U.S. Economy*, 2.

[18] Bryce Space and Technology, 2.

[19] Chadwick D. Igl et al., "568 Balls in the Air: Planning for the Loss of Space Capabilities," *Joint Forces Quarterly*, no. 90 (2018): 2, https://www.ndu.edu/Portals/68/Documents/jfq/jfq-90/jfq-90_24-29_igl-et-al.pdf?ver=2018-04-11-125441-307.

neutralize these capabilities at the outset of hostilities.[20] Satellites are not only critical to national security by way of defense but also several sectors identified as critical infrastructure by the Department of Homeland Security rely on satellites technologies.[21] A journal article by Gheorghe et al. expands on this topic further by stating that reliance on satellites has become so prevalent in modern society that satellite constellations themselves should be identified as critical infrastructure.[22] This literature demonstrates that a loss of satellite capabilities can have serious national security implications that affect the United States' defense capabilities and functions of identified critical infrastructure.

Outside of the disruption to the nation's defense and homeland security, a sustained GPS outage can cause significant damage to the American economy. Many U.S. industries rely on the capabilities provided by GPS. In other words, any sustained disruption of service will have ripple effects across all sectors of the economy. Leveson's report on the value GPS provides to the civilian market states that commercial agriculture, construction, surveying, timing services, and all modes of commercial transportation comprise an approximate $55.7 billion benefit to these industries.[23] Research by the Boston Consulting Group affirms Leveson's research and shows that GPS capabilities drove $1.6 trillion in U.S. revenue in 2012.[24] In a 2012 report, Pham quantified the financial losses that would occur if GPS capabilities were lost and showed that a 50 percent loss of GPS capabilities would result in a $48.3 billion loss to the economy; a total loss would result in a $96 billion

[20] Igl et al., 2.

[21] Paul Tullis, "The World Economy Runs on GPS. If It Fails, We're Screwed," Bloomberg, July 25, 2018, https://www.bloomberg.com/news/features/2018-07-25/the-world-economy-runs-on-gps-it-needs-a-backup-plan.

[22] Adrian V. Gheorghe et al., "New Dimensions for a Challenging Security Environment: Growing Exposure to Critical Space Infrastructure Disruption Risk," *International Journal of Disaster Risk Science* 9, no. 4 (December 2018): 555, https://doi.org/10.1007/s13753-018-0197-2.

[23] Irv Leveson, *GPS Civilian Economic Value to the U.S., Interim Report* (Beltsville, MD, Reston VA: ASRC Federal Research and Technology Solutions, Inc., 2015), 69, https://www.performance.noaa.gov/wp-content/uploads/2015-08-31-Phase-1-Report-on-GPS-Economic-Value.pdf.

[24] Heikki Henttu, Jean-Manuel Izaret, and David Potere, *Geospatial Services: A $1.6 Trillion Growth Engine for the U.S. Economy* (Boston: The Boston Consulting Group, 2012), 2, https://www.bcg.com/documents/file109372.pdf.

reduction.[25] The combined body of research reviewed for this thesis demonstrates the U.S. economy greatly relies on satellite-based technologies, and losing these capabilities will significantly impact several sectors. The GPS satellites themselves reside in an orbital region designated as medium earth orbit (MEO), at an approximate altitude of 20,000 km.[26] The risk of collision with debris in this orbital region is lower than in LEO given the quantity of debris present at this altitude is lower.[27] The risk to the GPS constellation itself would come from a loss of access to that orbital region if lower altitudes experienced significant collision events. If the LEO regions of space cannot be safely traversed, the federal government will be unable to replace ageing GPS satellites and the ability to maintain full capabilities will be compromised.[28]

While the body of literature regarding space debris is growing and generally agrees it is a threat, literature on the efficacy of international agreements and treaties regarding space debris agree that these agreements are outdated and in need of revision. The most significant document with regard to debris ownership is the United Nation's Outer Space Treaty of 1967, which establishes that ownership of any object placed in space is retained by the owning state, regardless of the condition of the object, even after it returns to Earth.[29] The Outer Space Treaty also establishes that the owning state is liable for any damages an object may cause to another object or territory.[30] An attempt to clarify ownership and liability is found in the Registration Convention of 1976 and the Liability Convention of 1972, but a growing body of literature identifies that these treaties and conventions have not kept pace with the evolving space sector, specifically the growing

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[25] Nam D. Pham, *The Economic Benefits of Commercial GPS Use in the United States* (Washington, DC: NDP Consulting, 2012), 20, https://www.gps.gov/governance/advisory/meetings/2012-08/pham.pdf.

[26] "Space Segment," GPS, accessed December 4, 2020, https://www.gps.gov/systems/gps/space/.

[27] Joseph N. Pelton, "The Space Debris Threat and the Kessler Syndrome," in *Space Debris and Other Threats from Outer Space*, ed. Joseph N. Pelton, SpringerBriefs in Space Development (New York: Springer, 2013), 19, 21, https://doi.org/10.1007/978-1-4614-6714-4_2.

[28] Pelton, 21.

[29] General Assembly, "Outer Space Treaty," Article VIII, United Nations, 1967, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html#a7.

[30] General Assembly, Article VII.

commercial space market.[31] While this scholarship suggests that updates need to be made to these documents, the United Nations currently has no plan to do so. Any future remediation efforts will have to navigate these treaties and conventions.

While conducting research on recent successful projects at NASA, partnerships with the private sector were found to be a driver of success in these programs. This discovery led to research on the efficacy of a public–private framework in solving complex issues. This research was conducted to establish whether NASA's success was an outlier or if it aligned with the existing literature on this management framework. During the literature review of public–private partnerships, several benefits of this approach were identified. Generally, the literature shows that public–private partnerships must leverage the strengths of both sides to be successful. In examining the history of these arrangements, Bovaird highlights three strengths of such partnerships: economies of scale, economies of scope, and opportunities of mutual learning.[32] Bovaird asserts that these three strengths can make a partnership between the private and public sectors stronger in a particular endeavor than if pursued individually.[33] Challenges to these partnerships include the fear of losing employment due to restructuring, the loss of control from a management perspective for both sides, and the fear that profits will come ahead of the public good.[34] Research by Busch and Givens highlights similar strengths and weaknesses discussed by Bovaird in an analysis of public–private partnerships in homeland security.[35] The scholars find that the government benefits from partnering with private-sector contractors in areas,

[31] Kurt, "Triumph of the Space Commons," 312; Joshua Tallis, "Remediating Space Debris: Legal and Technical Barriers," *Strategic Studies Quarterly* 9, no. 1 (Spring 2015): 89. https://www.airuniversity.af.edu/Portals/10/SSQ/documents/Volume-09_Issue-1/tallis.pdf; Frans von der Dunk, "Too-Close Encounters of the Third Party Kind: Will the Liability Convention Stand the Test of the Cosmos 2251-Iridium 33 Collision?," *Proceeding of the International Institute of Space Law* 28 (2010): 206.

[32] Tony Bovaird, "Public–Private Partnerships: From Contested Concepts to Prevalent Practice," *International Review of Administrative Sciences* 70, no. 2 (2004): 207, https://doi.org/10.1177/0020852304044250.

[33] Bovaird, 207.

[34] Bovaird, 203–4.

[35] Nathan E. Busch and Austen D. Givens, "Public–private Partnerships in Homeland Security: Opportunities and Challenges," *Homeland Security Affairs* 8, October 2012, https://calhoun.nps.edu/handle/10945/25017.

such as hiring, technological innovation, resource utilization, and the use of specialists to fulfill specific needs.[36] Specific challenges to these relationships include differing management styles between public and private organizations, legal and ethical challenges, and transparency issues.[37] These challenges mirror some of the challenges that Bovaird highlighted.

A unique feature of public–private partnerships is that each party brings different strengths and experiences into the arrangement that can be built upon for future efforts in shared learning. Several scholars confirm the role of shared learning in successful partnerships. Research by Poland examined partnerships between police departments and their surrounding communities to improve trust in law enforcement and reduce crime.[38] The literature highlights three factors contributing to successful partnerships: the ability to learn from the other party, displaying flexibility, and creating a plan toward a common goal.[39] Berry et al. also highlighted several of the successful factors identified by Poland in their research of effective community-law enforcement partnerships. The scholars have found that such factors as strong leadership, effective communication, proximity of operations, and consistent sharing of data between the parties lead to successful partnerships.[40]

One aspect of the public–private partnership NASA implemented was the resulting effort would not have been possible if either side had acted independently. I looked for literature providing examples of partnerships that achieved results that exceeded what either party could have realized independently. Research by Lucas highlights such a situation in the World Health Organization's partnership with private pharmaceutical

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[36] Busch and Givens, 6–7.

[37] Busch and Givens, 210–12.

[38] Mark J. Poland, "Relationship Policing: Implementing a New Model of Thinking for Law Enforcement to Build Formal Community Partnerships" (master's thesis, Naval Postgraduate School, 2019), v, https://calhoun.nps.edu/handle/10945/63494.

[39] Poland, 58.

[40] Geoff Berry et al., *The Effectiveness of Partnership Working in a Crime and Disorder Context: A Rapid Evidence Assessment* (Croydon, UK: Home Office, 2011), 22, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/116549/horr52-report.pdf.

companies for research and training in tropical diseases.[41] This research demonstrates that significant technical and organizational challenges can be overcome when public–private partnerships take advantage of the strengths of the parties involved.[42] This partnership overcame the lack of financial incentives on the part of private-sector drug companies and the lack of technical knowledge on the part of the World Health Organization.[43] By leveraging the strength of each organization involved, the resulting program successfully accomplished a goal that neither could have independently, that of combatting tropical disease. This conclusion is another common theme in the literature; the private sector often has the technical capability to solve complex problems or pursue innovative technology, yet it will not pursue a program it deems unprofitable.

Another body of work has found that public–private partnerships can reduce government spending to an extent. Research by Pearlman and Scerbo demonstrates the ability of local governments to reduce energy costs by partnering with private enterprise.[44] They highlight a specific example in which one community reduced energy usage through a partnership with a private renewable energy firm through tax credits, competitive bidding, and fixed-rate billing.[45] In examining this example, Pearlman and Scerbo demonstrate that a competitive bidding process and tax credits are a way to reduce government spending by partnering with the private sector. Additional benefits can be found at higher levels of governments as well. San Miguel and Summers, on the other hand, demonstrate that leveraging improved private sector strengths at higher levels of government comes at a higher financial cost. In their research regarding public–private partnerships in defense acquisitions in the United Kingdom, San Miguel and Summers

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[41] Adetokunbo O. Lucas, "Public–private Partnerships: Illustrative Examples," in *Public–private: Partnerships for Public Health* (Cambridge, MA: Harvard Center for Population and Development Studies, 2002), 19, http://health21initiative.org/wp-content/uploads/2017/08/2001-Harvard-PPPs-for-Global-Health.pdf.

[42] Lucas, 19.

[43] Lucas, 20.

[44] Stephen B. Pearlman and Ryan J. Scerbo, "Public–private Partnership for Renewable Energy: A Case Study," *New Jersey Law Journal* 199, no. 10 (March 2010): 1, https://www.decotiislaw.com/assets/db/12674664673545.pdf.

[45] Pearlman and Scerbo, 1.

examined the use of privately financed initiatives as opposed to strictly government-financed procurement.[46] A significant drawback to this approach was the increased cost over publicly funded programs.[47] Private-sector financing was found to be more expensive. However, by having the private partner acquire the financing, the risk of failure is transferred from the public purchaser to the private developer.[48] The military loses no financial capital if the manufacturer cannot fulfill the contract. San Miguel and Summers found that this process reduced schedule delays and cost overruns and recommended it be used by the U.S. Department of Defense.[49]

In a similar case study analyzing the use of privately financed initiatives in defense procurement, Jankowski, McGee, and Lehmann found the same benefit to the government agency in terms of protections.[50] This type of partnership defers the risk of failed deadlines or unmet contractual requirements to the contractor, which provides the government buyer some protection from delays and cost overruns.[51] Conversely, this style of contract also protects the manufacturer against design changes from the purchasing agency. After a contract has been signed, the purchaser will pay for any changes made to the schedule or product.[52] These examples in defense procurement demonstrate that properly structured partnerships between the public and private sectors protect both parties and improve efficiency in terms of delivering hardware on time and on budget.

This unique environment presents a distinct challenge when debris in orbit remains in place for decades or longer. Decades of neglect have resulted in an orbital environment in which the removal of existing debris is necessary to prevent future collisions that place

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[46] Joseph G. San Miguel and Donald E. Summers, *Public–private Partnerships for Government Financing, Controlling Risk, and Value-for-Money: The UK Experience*, NPS-FM-06-036 (Monterey, CA: Naval Postgraduate School, 2006), 32, https://calhoun.nps.edu/handle/10945/33775.

[47] San Miguel and Summers, 32.

[48] San Miguel and Summers, 32.

[49] San Miguel and Summers, 32.

[50] Patrick Jankowski, Matthew Lehmann, and Michael P. McGee, “Financing the DOD Acquisition Budget: Innovative Uses of Public–private Partnerships” (MBA professional report, Naval Postgraduate School, 2006), 18, https://calhoun.nps.edu/handle/10945/10129.

[51] Jankowski, Lehmann, and McGee, 18.

[52] Jankowski, Lehmann, and McGee, 19.

U.S. satellites at risk. A lack of research and development into technologies specific to debris removal is a challenge to implementing any remediation program, due in part to national policies recommending other means to mitigate the risk of debris. Furthermore. the challenges in debris ownership and liability as defined in existing international agreements all present obstacles in implementing a remediation program.

C. PROBLEM STATEMENT

Neglect on the part of all space-faring nations has resulted in an orbital environment with a growing population of uncontrolled debris. The impact speeds of collisions with orbital debris result in significant to catastrophic damage both to the debris and the impacted objected. Due to the physics involved, debris in the higher regions of LEO and above will stay in orbit for decades or longer. As the launch rate of satellites into orbit increases, the population of orbital debris has grown at a much higher rate.[53] The debris, however, is not naturally decaying in altitude as quickly as it is being generated. This situation has resulted in the debris population reaching a critical mass in the higher altitudes of LEO; removal of several objects is now necessary to reduce the risk of future catastrophic collisions.[54] Given the high altitudes and mass of the objects involved in these potential collisions, the effects of the collision will be long lasting.[55] This influx of new debris into the orbital region increases the risk of future collisions, possibly setting off a "Kessler Syndrome" event that can result in the damage and destruction of many operational satellites, a loss of their capabilities, and limited access to affected orbits.[56]

The United States has been slow to act regarding debris remediation due to policy decisions. The United States was the first to generate a list of best practices to reduce

[53] J.-C. Liou, "The 2019 U.S. Government Orbital Debris Mitigation Standard Practices," in *57th Session of the Scientific and Technical Subcommittee Committee on the Peaceful Uses of Outer Space* (Vienna, Austria: United Nations, 2020), 2, https://www.unoosa.org/documents/pdf/copuos/stsc/2020/tech-24E.pdf

[54] Donald J. Kessler et al., "The Kessler Syndrome: Implications to Future Space Operations," 14.

[55] Rossi, Petit, and McKnight, "Examining Short-Term Space Safety Effects," 8; McKnight, Arora, and Witner, "Intact Derelict Deposition Study," 8.

[56] Donald J. Kessler et al., "The Kessler Syndrome: Implications to Future Space Operations," 1–2.

debris-generating events known as mitigation standard practices.[57] However, these practices were not mandated and were therefore unenforceable. Complying with these standards may have resulted in a financial burden to satellite operators who may need to carry extra fuel to deorbit their satellite upon its end-of-life. Other nations and the United Nations eventually adopted mitigation practices as well, but these were also unenforceable suggestions.[58] The lack of compliance to these practices has contributed significantly to the current state of the debris population. The United States is aware the debris population is growing, and mitigation alone is insufficient, yet no policy action has been taken to enforce mitigation standards or remove debris. The current orbital environment is at risk of experiencing one or more catastrophic collision events due to government inaction.

D. RESEARCH DESIGN

The purpose of this thesis is to identify a process that will allow the United States to begin debris remediation missions. This process will need to overcome the identified barriers and challenges that have prevented these actions from being taken in the past. I employ comparative analysis methods while reviewing the relevant literature related to the increase in space debris to determine the threat debris poses to operational satellites. This analysis includes literature from public space agencies, academia, and private researchers. This analysis concludes that remediation is now necessary to reduce the risk of future collision events. A contextual analysis on domestic policies and international treaties is used to determine what actions have been taken to address the threat of space debris.

To determine which organization or company is best suited to lead a remediation effort involves exploring the literature regarding domestic space operations using a comparative analysis method. These programs are reviewed to ascertain whether the desired technical outcome can be achieved, can stay within the allotted budget, and how close they can maintain their established schedule. The selection of these metrics is intended to look for commonalities in these programs that can be reproduced within a remediation program. This analysis reveals the public–private partnerships between NASA

57 J.-C. Liou, "Orbital Debris Briefing," 4.

58 Kurt, "Triumph of the Space Commons," 312.

and the commercial sector has produced reduced development and operational costs and lower risk to schedule delays. Upon making this observation, the literature review is expanded to include case studies of the use of public–private partnerships in other sectors to determine the efficacy of the program model.

The output of the thesis is policy recommendations to allow for the development of a domestic remediation program. These recommendations are tailored to overcome the barriers that have prevented previous actions from being taken, including domestic and international policy actions. This thesis also provides recommendations to the program structure based on the identified strengths of both the public and private sector, and how these strengths can be leveraged within a public–private partnership framework.

E. OVERVIEW OF CHAPTERS

Chapter II of this thesis illustrates the barriers that have prevented any remediation efforts from being established within the United States. These challenges come from both policy and management actions that result in an environment in which neither the public nor the private sector can effectively develop a remediation program independently. Chapter III provides evidence that the recent growth in competition and innovation in the commercial space industry has resulted in a much more capable sector. This chapter also provides evidence that the partnership between NASA and the commercial space industry in the Commercial Orbital Transportation Services (COTS) program produced results that neither sector was capable of achieving independently that also resulted in the further growth of the commercial sector as a whole.

Chapter IV discusses the state of the art regarding debris remediation technologies, both domestically and internationally. These early efforts provide a foundational knowledge base that the United States can build upon while leveraging the power of the public–private partnership model established during COTS. This chapter also illustrates the policy actions from both NASA and the federal government as a whole that are needed to begin such a program.

Chapter V provides a framework to build a domestic remediation capability using the public–private partnership model NASA has successfully leveraged for almost 15 years. This chapter also identifies the specific policy decisions that need to happen to bring about the start of a remediation program. Lastly, this chapter discusses the potential for future cooperation between the United States and other nations and proposes actions that may bring about new international agreements that will allow for a direct path for the large-scale remediation efforts needed to minimize the threat from debris.

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II. CHALLENGES TO DEBRIS REMOVAL

This chapter identifies specific challenges that have prevented the United States from developing a remediation program. These issues are domestic and international in nature. They relate to both policy decisions and management practices that created an environment in which neither public space agencies nor the commercial sector could effectively pursue remediation. Any future remediation program will have to address these challenges before beginning operations.

A. APPLICABLE INTERNATIONAL TREATIES AND CONVENTIONS

The United Nations Outer Space Treaty has two specific articles and related conventions that pose a challenge for debris remediation efforts. Article VIII of the treaty specifies that the registered owner of the object retains ownership, regardless of the status of that object, and the object returning to Earth does not affect this ownership.[59] The article also states that fragments of an object are still the property of the registered owner.[60] The 1974 Registration Convention added the launching state could be considered the owner of payloads launched into space. In situations in which the owner of the spacecraft and the launching state are not the same, the two entities will determine between the two which one is the registered owner.[61] Whether the object is functional, intact, or in several pieces, has no bearing on ownership. This article makes it illegal for any party other than the owning state to manipulate an object in space; at least without clear permission from the owning state.[62] Article VIII pertains to future remediation missions in that any state owning a spacecraft performing removal missions would be in violation of the Outer Space Treaty if it manipulated any object owned by another state. Due to sensitive technologies and national security concerns involving many satellites in orbit, states are hesitant to allow

[59] General Assembly, "Outer Space Treaty," Article VIII.

[60] General Assembly, Article VIII.

[61] General Assembly, "Registration Convention," Articles I, II, United Nations, November 12, 1974, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introregistration-convention.html.

[62] Michael W. Taylor, "Orbital Debris: Technical and Legal Issues and Solutions" (master's thesis, Montreal, McGill University, 2006), 80, https://fas.org/spp/eprint/taylor.pdf.

other states access to their assets in orbit, which makes permission to remediate these objects by another state unlikely.[63]

To avoid any violations of the Outer Space Treaty, the United States should begin by only remediating U.S.-owned debris objects. No new convention has occurred at the United Nations to address the debris problem, and even strong proponents of the United Nations have doubts in its ability to create any updated international treaties with regard to space debris and ownership.[64] This lack of progress in addressing debris ownership through international agreements presents a challenge to any U.S. remediation effort. Any U.S. spacecraft that comes in contact without permission with a foreign-owned debris object would be in breach of the Outer Space Treaty. By focusing on remediating U.S. debris only, the United States can avoid any potential international incidents. Furthermore. in the case of a collision, the literature demonstrates that many U.S.-owned debris objects in the orbits are identified as causing significant disruption.[65]

Focusing on remediating only U.S.-owned objects will also allow the program to narrow its attention to bring these capabilities to maturity. This focus can also lay a foundation upon which future large-scale remediation efforts can be built. The participating commercial partners will be well-positioned to lead in commercial remediation services upon demonstrating a viable remediation capability. Additionally, as reliability improves and the technology matures, the United States can explore international cooperation. A domestic-only approach can improve remediation systems and techniques to build confidence into the systems from potential international partners or customers.

B. NO FOCUS ON DEBRIS REMOVAL

The lackadaisical approach taken by all space-faring nations to debris generating activities has resulted in the growth of the space debris population. The creation of

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[63] James A. Vedda, *Orbital Debris Remediation through International Engagement*, Crowded Space Series (El Segundo, CA: The Aerospace Corporation, 2017), 3, https://aerospace.org/sites/default/files/2018-05/DebrisRemediation.pdf.

[64] Kurt, "Triumph of the Space Commons," 314.

[65] Rossi, Petit, and McKnight, "Examining Short-Term Space Safety Effects," 3.

mitigation guidelines by the United States and other nations is one method to control the growth in the debris population. These mitigation guidelines are an established set of practices, that when followed, should prevent the creation of more debris. Given that research by the European Space Agency (ESA) shows international intentional compliance with the standards is poor since less than half of the payloads launched in the last decade reside in an orbit that complies with mitigation guidelines, the efficacy of mitigation guideline at this point is questionable.[66] For the payloads that require a maneuver to move to a compliant altitude, only 30 percent perform maneuvers to comply with an approximate 20 percent success rate.[67]

The United States led in developing debris mitigation practices to limit debris-generating events, with NASA being the first agency to establish such practices. The agency's initial effort occurred in 1993 with NASA Management Instruction 1700.8, which directed mission planners to limit the risks of their programs generating debris or causing collisions.[68] Examples of recommend actions from this document include the depletion of on-board energy storage devices after a spacecraft's end-of-life to limit the risk of explosion and limited orbital lifetimes to 25 years after end of mission.[69] Two years later, NASA published a safety standard document providing guidance on how to comply with 1700.8 in the areas of normal operation, explosions and break-ups, collisions, post-mission disposal, and atmospheric reentry.[70] In 2001, the Orbital Debris Mitigation Standard Practices (ODMSP) was created to limit debris generation across all U.S. government agencies.[71]

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[66] ESA Space Debris Office, *ESA's Annual Space Environment Report*, 87.

[67] ESA Space Debris Office, 87.

[68] National Aeronautics and Space Administration, *NASA Safety Standard: Guidelines and Assessment Procedures for Limiting Orbital Debris*, 1–1.

[69] National Aeronautics and Space Administration, 1–1.

[70] National Aeronautics and Space Administration, ii.

[71] U.S. Government, *Orbital Debris Mitigation Standard Practices, November 2019 Update* (Washington, DC: U.S. Government, 2019), 1, https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf.

The Inter-Agency Space Debris Coordination Committee (IADC) established the first set of internationally accepted mitigation guidelines in 2002.[72] The IADC is the internationally recognized authority on space debris.[73] The United States followed suit in developing mitigation guidelines for all domestic space launches in 2007.[74] Research conducted by J.-C. Liou, Chief Scientist for Orbital Debris at NASA, shows that NASA's mitigation practices, followed by other U.S. agencies, are, "more quantitative and strict than the IADC and the UN SD mitigation guidelines."[75] However, even though the United States has been a leader in creating mitigation practices, it trails only Russia in owning the highest amount of debris in dangerous orbits.[76]

While the United States should be commended for attempting to slow future debris growth through mitigation practices, national space policies have lacked clear direction to take any action to remove debris from orbit. A review of the literature in the field found that several experts believe remediation is now necessary to protect satellites in crowded orbits and avoid disastrous collision events.[77] No U.S. policy has mandated a remediation effort in response to the threat of debris. While several national space policies mentioned space debris and encouraged behaviors to limit its growth and encourage other states to do so as well, the U.S. government directed no further action outside of compliance to mitigation practices until 2018.

The Trump Administration was the first to call for action beyond international cooperation and adherence to mitigation practices, and specifically called for remediation efforts. The White House released Space Policy Directive-3 (SPD-3) in 2018 that directed several government agencies to act to protect U.S. assets in space. This policy called on the United States to make improvements in Space Traffic Management (STM), Space

[72] J.-C. Liou, "Orbital Debris Briefing," 9.

[73] Liou, 9.

[74] Liou, 10.

[75] Liou, 12.

[76] McKnight, Arora, and Witner, "Intact Derelict Deposition Study," 6.

[77] Kessler et al., "The Kessler Syndrome," 14; Rossi, Petit, and McKnight, "Examining Short-Term Space Safety Effects," 8; Hakima and Emami, "Assessment of Active Methods for Removal of LEO Debris," 1.

Situational Awareness (SSA), and encouraged growth in the commercial sector to protect the nation's space-based capabilities.[78] This policy directive resulted in a 2019 update to NASA's ODMSP, which provided encouragement, but not a mandate, to remove satellites from orbit immediately following the end of its mission as opposed to a 25-year window.[79] The new guidelines also suggested post-mission-disposal systems have a demonstrated 90-percent reliability.[80] SPD-3 acknowledged that mitigation practices alone have been unable to keep pace with the rapid growth in global space operations and called for the pursuit of remediation efforts in conjunction with regular updates to mitigation practices.[81] SPD-3 does not put a compliance mechanism in place with regard to mitigation practices. Not all satellite operators followed past less-restrictive mitigation practices to the letter. Thus, it is illogical to assume that the more-restrictive ODMSP established by SPD-3 will result in a higher compliance rate.

NASA, nor any other federal agency, have responded to the call to pursue remediation efforts. The recommendation to begin this work means acknowledging the threat debris poses to critical space-based infrastructure at the highest levels of government. SPD-3 fell short of mandating action; it is still just a suggestion on the part of the government. The literature shows that not only is remediation necessary to prevent future collisions, it also shows that satellite operators have not been complying with agreed upon mitigation practices. Any policy action that does not address either of these challenges is no more likely to succeed than any preceding policy. U.S. satellites are put at risk and the nation's security and economic prosperity jeopardized by a lack of clear direction and mandated mitigation practices. The scientific community and experts within NASA acknowledge that remediation efforts are needed in conjunction with strict adherence to

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[78] Donald J. Trump, *Space Policy Directive-3, National Space Traffic Management Policy* (Washington, DC: White House, 2018), §1, https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/.

[79] J.-C. Liou, "The 2019 U.S. Government Orbital Debris Mitigation Standard Practices," 7.

[80] J.-C. Liou, "Orbital Debris Mitigation and U.S. Space Policy Directive-3," in *56th Session of the Scientific and Technical Subcommittee Committee on the Peaceful Uses of Outer Space* (Vienna, Austria: United Nations, 2019), 10, https://www.unoosa.org/documents/pdf/copuos/stsc/2019/tech-30E.pdf.

[81] Trump, *Space Policy Directive-3*, 5(a)(iii).

mitigation standards. The White House also acknowledged this need, yet the United States still has not made any progress in this field.

C. INEFFICIENT PROJECT MANAGEMENT AT NASA

Any future efforts by NASA will have to overcome the challenges the agency has faced from a program management standpoint. While many acknowledge the technical achievement of programs, such as Apollo, the space shuttle, and the ISS, NASA has often faced schedule delays and cost overruns related to its efforts. Many of these challenges have occurred across a wide range of programs, which highlights a cultural weakness within the agency.[82] These challenges have plagued both manned and unmanned missions. Any attempted remediation efforts would have to overcome this obstacle.

The operational structure of the space shuttle program is an early example of NASA's inefficient management. Research by Bromberg shows that in 1991 alone, NASA spent $4.3 billion on its fleet of orbiters; this figure was nearly one-third of the agency's budget.[83] While some upgrades were performed to the fleet at that time, much of that cost went to maintenance on the shuttles themselves. After being advised by the Clinton Administration in 1995 that its budget would be reduced by $5 billion over the next five years, the Agency knew the current model of shuttle operations was not sustainable.[84] The management structure handling space shuttle operations oversaw 86 separate contracts with 56 different vendors.[85] This management structure caused gross inefficiency, increased program costs, and required significant management staffing. The management team needed to oversee shuttle operations stood at 3,000 people at this time.[86] Inefficiency

[82] Paul K. Martin, *NASA Cost and Schedule Overruns: Acquisitions and Program Management Challenges* (Washington, DC: NASA Office of Inspector General, 2018), 1, https://oig.nasa.gov/docs/CT-18-002.pdf.

[83] Joan Lisa Bromberg, *NASA and the Space Industry* (Baltimore, MD: Johns Hopkins University Press, 1999), loc. 2469 of 3428, Kindle.

[84] Bromberg, loc. 2476.

[85] Carl E. Behrens, *Space Launch Vehicles: Government Activities, Commercial Competition, and Satellite Exports*, CRS Order Code IB93062 (Washington, DC: Congressional Research Service, 2006), CRS-4, https://apps.dtic.mil/dtic/tr/fulltext/u2/a456523.pdf.

[86] Bromberg, *NASA and the Space Industry*, loc. 2476.

in managing the shuttle caused ripple effects across the agency. Less funding was available for other programs since so much of the annual budget was used to keep the shuttle program operational.[87]

Testimony from NASA Inspector General Paul K. Martin to the House Subcommittee on Science, Space, and Technology in 2018 identified an overly optimistic mindset within NASA to contributing to these delays and cost overruns.[88] Martin identifies a culture within the agency that identifies program success based on technical accomplishment, with schedules and cost often overlooked in the pursuit of this goal.[89] This culture created a management environment that often generated unrealistic cost and schedule projections that led to the presumption that if budget shortfalls occurred, the Agency or Congress would provide more funding.[90] Martin uses the term "Hubble psychology" to explain this management style. He explains that it is an "an expectation among Agency personnel that projects that fail to meet initial cost and schedule goals will receive additional funding and subsequent scientific and technological success will overshadow budgetary and schedule problems."[91] The Hubble Telescope, the poster-child for this philosophy, also experienced delays and overruns. Martin warns moreover that this same philosophy of being "too big to fail" can also be applied to current programs, such as the James Webb Space Telescope, the Orion crew capsule, and the Space Launch System.[92] According to Martin, the moon landing, the recovery of the Apollo 13 astronauts, and the on-orbit repair of the Hubble Space Telescope have benefitted from this optimistic approach to program management that also resulted in significant technical achievements.[93] However, Martin highlights that when cost overruns occur on large projects, other programs and missions within the agency suffer due to the shifting of

[87] Bromberg, loc. 2476.

[88] Martin, *NASA Cost and Schedule Overruns*, 2.

[89] Martin, 2.

[90] Martin, 2.

[91] Martin, 2.

[92] Martin, 2.

[93] Martin, 2.

funding away from smaller projects to keep large ones solvent.[94] While this method may keep the large programs moving, it negatively impacts the rest of the agency and may lead Congress to have less confidence in NASA to deliver projects on time and on budget.

The cancellation of a large program, the Constellation, a NASA program intended to return astronauts both to LEO, as well as the moon following the retirement of the space shuttle, is another specific example of poor management. The program began in 2005 under the Bush Administration, but President Obama cancelled the project in 2010 due to program management challenges.[95] Contrary to the programs highlighted earlier by Martin, Constellation's challenges were deemed too big to overcome. A 2011 report by NASA highlighted some of the lessons learned from the challenges of the Constellation program, and several relate to inefficient management.[96]

NASA recognized that too much oversight was being placed on contractors building the spacecraft, and example being the Orion crew capsule. Significant manpower, which results in a fixed cost to the program budget, was devoted to ensuring that contractors performed certain construction tasks, such as soldering or wiring procedures, to specific NASA standards.[97] When the program was cancelled, a review found that these processes brought questionable value to the program. The manufacturing processes of large aerospace contractors were found to be sufficient and did not require this level of oversight.[98] Additionally, according to NASA, adherence to the original design specifications throughout the construction of the Orion crew capsule resulted in a vehicle that was "overly constrained, too heavy, and had performance challenges."[99] The spacecraft began to improve only after being allowed to deviate from the original design specifications. After reviewing the design and specifying only the systems needed for

[94] Martin, 2.

[95] Jennifer L. Rhatigan, *Constellation Program: Lessons Learned*, vol. 1 (Washington, DC: National Aeronautics and Space Administration, 2011), 2–3, 11, https://history.nasa.gov/SP-6127.pdf.

[96] Rhatigan, 11.

[97] Rhatigan, 13.

[98] Rhatigan, 14.

[99] Rhatigan, 15.

mission success and crew sustainability, no additional specifications were necessary to reduce the risk to spacecraft or crew.[100] The Constellation review report recommended a similar approach of streamlining design specifications for future spacecraft construction programs.[101]

The efforts to develop and construct the elements of the Constellation program were divided among several NASA centers to provide work and funding to as much of the NASA workforce as possible.[102] While well intentioned, this decision led to poor communication and confusion concerning the roles and responsibilities of the different facilities.[103] Upon review of the program, this diversification may have benefitted the different centers, but did not benefit the program as a whole.[104] As the program evolved, necessary changes were not identified by all the various centers working on the project, which then led to the program's lack of cohesion and efficiency.[105] This inefficiency, along with the other management challenges identified in the Constellation report, created an environment in which adherence to schedules and budgets was not possible. NASA indeed fell victim to the overly optimistic mindset identified by NASA Inspector General Paul Martin.

If NASA is to be involved in the development or operation of a debris remediation program, the lessons learned from the Constellation program need to be incorporated into program management to avoid a similar fate. NASA has a track record of significant technical achievement. The lunar landings and the space shuttle program are prime examples of these accomplishments. However, these programs were deemed a national imperative that resulted in a culture in which technical progress was to be achieved regardless of the costs involved. The evidence shows that this mindset has penetrated many large programs in NASA; inefficient management practices are commonplace. While many programs survive being over budget and behind schedule, the Constellation program was

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[100] Rhatigan, 15.

[101] Rhatigan, 16.

[102] Rhatigan, 16.

[103] Rhatigan, 17, 22.

[104] Rhatigan, 17.

[105] Rhatigan, 22.

cancelled due management deficiencies and the resultant delays and overruns. Additionally, cost overruns can damage other NASA programs due to the re-prioritizing of funding to keep large programs on track.[106] Management styles need to evolve if NASA is to create an environment that enables both technical achievement and on-budget performance for remediation efforts.

D. STAGNANT COMMERCIAL SPACE SECTOR

NASA and the U.S. Air Force's actions led to an environment in which the U.S. commercial space sector relied on government business to sustain itself. Significant oversight and adherence to government manufacturing standards crippled the industry's ability to innovate. In addition, the lack of a significant customer base outside of government launches provided little incentive to deviate from these practices. The commercial industry was incapable of large initiatives outside of government projects due to this relationship between the public and private sectors. Debris remediation efforts were also not possible unless a government agency contracted with the commercial sector to do so.

Beginning the in the 1960s and progressing through the 1980s, the United States' policies related to space exploration led to a stagnant commercial space sector. This period saw significant technical achievements, such as the Apollo and space shuttle programs, but NASA developed these efforts while contractors were used to construct hardware but with significant oversight and retained no ownership of the designs to generate additional revenue.[107] In the late 1980s, the commercial launch sector began placing payloads into orbit. However, NASA and the Air Force's decisions resulted in a marketplace dominated by large defense contractors and restricted by ineffective national policies. This limited market resulted in a commercial space sector reliant on government payloads to sustain itself and was incapable of innovation and efficiency, both key factors to successful large-scale space programs.

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[106] Martin, *NASA Cost and Schedule Overruns*, 2.

[107] National Aeronautics and Space Administration, *Commercial Orbital Transportation Services*, 2–3, 22.

The 1984 Commercial Space Launch Act was an early effort to grow the commercial space industry. This act specifies that commercial launch capability is complementary to government launching services. A capable commercial space sector allows the United States to stay competitive internationally, while providing economic and national security benefits.[108] The timing of this legislation was not beneficial to any potential commercial launch operators, NASA was offering launch services for payloads below-cost on the space shuttle.[109] Congress passed legislation to grow the commercial sector, but NASA undercut their efforts to draw customers to the then-new space shuttle. Fears of schedule delays in using the shuttle caused several commercial launch customers to overseas launch companies, which resulted in a loss of launch revenues and challenges to bring these sales back domestically.[110]

Following the accidental loss of the space shuttle *Challenger* in January 1986, the Reagan Administration directed NASA to cease launching commercial payloads on any future shuttle missions.[111] This tragedy created an opportunity for the commercial launch sector. By eliminating the largest domestic competitor to launching commercial payloads, the burgeoning commercial launch sector should have had a path toward growth and solvency. Instead, the federal government's practices continued to hamper progress in the following years.

Federal agencies elected to procure boosters from commercial builders to launch government payloads; they were buying the whole rocket instead of purchasing a launch service.[112] The Air Force believed this method would allow for commercial sector growth. Manufacturers were required to build all launch vehicles to the stringent standards required

[108] Daniel Akaka, "To Facilitate Commercial Space Launches, and Other Purposes," Public Law 98-575, 10 (1984), § 2 (4), (5), https://www.govtrack.us/congress/bills/98/hr3942/text.

[109] Bruce D. Berkowitz, "Energizing the Space Launch Industry," *Issues in Science and Technology* 6, no. 2 (1989): 80.

[110] Berkowitz, 78.

[111] Philip M. Boffey and Special to the New York Times, "Commercial Launching by NASA Ordered Shifted to Private Sector," *New York Times*, sec. U.S., August 16, 1986, https://www.nytimes.com/1986/08/16/us/commercial-launching-by-nasa-ordered-shifted-to-private-sector.html.

[112] Berkowitz, "Energizing the Space Launch Industry," 79.

by military.[113] The intent of this requirement was to lower the unit cost for military-procured boosters that would then create redundancy by having commercial boosters available to launch government payloads if needed.[114] The Air Force was dictating to commercial rocket manufacturers how they should build rockets for non-Air Force launches. By limiting commercial space companies into manufacturing only government-approved hardware, technological progress in the industry was slow. Given that the federal government was the customer for 90 percent of all space hardware and service purchases, the commercial sector was unable to innovate.[115]

By procuring the boosters in this way, government operators imposed a significant administrative burden on contractors and oversight on the construction of these systems.[116] These efforts were intended as a quality control measure and historically achieved good results in terms of safe launches; however, these results came at a high cost.[117] Building components to the specified standard results in higher manufacturing costs, and the required oversight by the government purchaser brings significant personnel costs for reviewing officials.[118] As suggested by Bromberg, the Air Force and NASA kept using this style of procurement to protect those budgets and management oversight jobs.[119] This process also limited the commercial builder's ability to innovate; any changes to a component or design would be subject to review and inspection, which caused delays of up to two years.[120]

The government further frustrated commercial launch companies by limiting access to its launch facilities. These companies did not possess their own launch facilities but relied on access to federal facilities to launch their rockets. As the commercial space

113 Bromberg, *NASA and the Space Industry*, loc. 2073.

114 Bromberg, loc. 2073.

115 Senate Subcommittee on Science, Technology, and Space, *Commercial Space Opportunities*, 54.

116 Berkowitz, "Energizing the Space Launch Industry," 79.

117 Berkowitz, 79.

118 Berkowitz, 79.

119 Bromberg, *NASA and the Space Industry*, loc. 2172.

120 Berkowitz, "Energizing the Space Launch Industry," 80.

industry was attempting to grow in the 1980s, commercial launches faced unpredictable launch schedules at federal launching facilities; government launches were given priority in scheduling.[121] Berkowitz highlights how this unpredictability posed a challenge to the U.S. commercial space sector in providing reliable launch services to clients. Commercial launch providers were limited to flying when the government had an available window; government launches could also bump commercial launches off the schedule.[122] It was difficult to provide firm launch dates to customers compared to commercial launch providers overseas.[123]

Following the release of a new Commercial Space Initiative in 1988 by the Reagan Administration, NASA changed its philosophy from procuring boosters themselves and began pursuing the procurement of launch services from the commercial launch industry.[124] However, NASA and the Air Force's decisions stacked the deck in favor of large defense contractors in the young commercial launch market. Despite the regulation-heavy environment in which the commercial booster industry was operating, by spring 1988, three major defense contractors were now manufacturing boosters for the U.S. Air Force: McDonnel Douglas, Martin Marietta, and General Dynamics.[125] NASA, in an effort to rebuild domestic launch capability quickly following the events of the *Challenger* accident, chose to work directly with the boosters' manufacturers to procure launch services in lieu of contracting launches to third-party enterprises.[126]

In 1989, the commercial launch industry took flight when the Department of Transportation's Office of Commercial Space Transportation licensed its first launch.[127] The groundwork laid by the Air Force and NASA put the three large defense contractors

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[121] Berkowitz, 81.

[122] Berkowitz, 81.

[123] Berkowitz, 81.

[124] Bromberg, *NASA and the Space Industry*, loc. 2185.

[125] Bromberg, loc. 2151.

[126] Bromberg, loc. 2105, 2195.

[127] Federal Aviation Administration, *Origins of the Commercial Space Industry* (Washington, DC: Federal Aviation Administration, n.d.), 2, accessed November 8, 2020, https://www.faa.gov/about/history/milestones/media/commercial_space_industry.pdf.

in a prime position to dominate the new marketplace. Between 1989 and 2003, these contractors had launched 107 of the 154 commercial payloads.[128] Even less competition occurred in the government's national security launches. Boosters of the Titan (Martin Marietta, later Lockheed Martin), Atlas (Martin Marietta, later Lockheed Martin), and Delta (then Lockheed Martin, now Boeing) families were placing government payloads into orbit.[129] The exception was the aircraft-launched Pegasus booster, manufactured by Orbital Sciences, which was used for smaller launches.[130]

In 1994, the Air Force began a program to develop a new generation of boosters to orbit national security payloads.[131] This program resulted in the Air Force paying for the creation of the Lockheed Martin Atlas V and the Boeing Delta IV boosters.[132] Both these boosters are based on the previous generation of Atlas and Delta boosters, which date back to the 1960s. Lockheed Martin and Boeing joined forces in booster development in 2005 and created United Launch Alliance (ULA). This new company manufactured the Delta and Atlas boosters and provided launching services for the government. ULA maintained a monopoly on national security launches until 2015.[133]

In the roughly 30-year stretch from the loss of the *Challenger* to 2003, the commercial launch industry established itself by launching for both commercial and government customers. However, the restrictions imposed by solely backing the large defense contractors in the latter half of the 1980s, erratic scheduling tempo due to priority being place on national security launches, and a lack of competition and therefore innovation, resulted in an industry that saw little progress. Smaller companies, such as Sea

[128] "Licensed Launches," FAA, Commercial Space Data, November 8, 2020, https://www.faa.gov/data_research/commercial_space_data/launches/?type=Licensed.

[129] Forrest McCartney et al., *National Security Space Launch Report*, MG-503-OSD (Santa Monica, CA: RAND, 2006), xiv, https://www.rand.org/pubs/monographs/MG503.html.

[130] McCartney et al., xiv; Bromberg, *NASA and the Space Industry*, loc. 2182.

[131] McCartney et al., xiv.

[132] McCartney et al., xv.

[133] Vidya Sagar Reddy, "The SpaceX Effect," *New Space* 6, no. 2 (2018): 126–27, https://doi.org/10.1089/space.2017.0032.

Launch, Orbital ATK, and Astrotech, were not drawing as much business as the larger defense contractors.[134]

E. CONCLUSION

The current amount of debris in orbit is the result of space-faring nations neglecting their responsibilities to protect the orbital environment in limiting debris-generating activities. The United States created mitigation guidelines to prevent debris-generating activities, but these efforts have fallen short of their intended purpose due to a lack of compliance on the part of satellite operators. National space policies and international mitigation guidelines have failed to curb the growth in the debris population. Furthermore. they have failed in calling for remediation efforts to remove dangerous debris objects currently in orbit.

A domestic program to remediate space debris must overcome several barriers to succeed. These barriers are formed from outdated international treaties that have failed to keep pace with the growth of the global space industry, along with policy decisions and management practices that have hindered the nation's space programs. Management challenges have been overcome with brute force efforts; examples include the Apollo spacecraft and the space shuttle. These programs were deemed national imperatives with significant national security considerations. This management model is unsustainable given the high costs associated with such programs.

The resulting damage from a prolonged disruption of satellite capabilities are just as grave a concern as the Soviets posed during the Cold War. Taking the steps to overcome these challenges to secure U.S. assets in space is imperative to homeland security. These challenges are not the technical mountains that NASA summited developing the Apollo spacecraft or the space shuttle but are a matter of sound policy and management decisions that may be solved through a partnership with the commercial space industry. The solutions to these challenges are within U.S. capabilities; it simply must decide to act.

[134] FAA, Commercial Space Data, "Licensed Launches."

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III. STRENGTHS OF PUBLIC–PRIVATE PARTNERSHIPS

The previous chapter illustrated some of the challenges a domestic remediation program would have to overcome. This chapter highlights recent progress made in domestic space operations. A growth in innovation, efficiency, and competition has resulted in a diverse and robust commercial space sector. The arrival of companies with new business philosophies, and successful partnerships between NASA and the commercial sector, has led to the evolution of the commercial space sector. While both sectors have been reliant on one another since space operations began, the new framework of partnership is leveraging the strengths of both sectors and proving beneficial to both sides. This evidence demonstrates the potential of a synergistic relationship between NASA and the commercial space sector; together they can accomplish more than acting separately.

A. COMMERCIAL SECTOR COMPETITION AND GROWTH

The previous chapter illustrated how large aerospace contractors dominated the commercial launch sector, and effectively formed a monopoly on national security launches and lofting most of the commercial payloads as well. The commercial launch market began to change once SpaceX entered the marketplace in 2006.[135] SpaceX utilized several methods to reduce costs, improve efficiency, and increase performance in pursuit of gaining customers and building toward their larger exploration goal, the colonization of Mars.[136] Lean business practices, in-house manufacturing, and reusability were innovations that SpaceX brought to the commercial launch sector, and in doing so, sent ripples across the industry and forced its competition to adapt. These pursuits ultimately ended ULA's monopoly on national security launches and created a competitive marketplace for both commercial and government launches.

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135 *Encyclopedia Britannica*, s.v. "SpaceX, spacecraft, rockets, & facts," June 1, 2020, https://www.britannica.com/topic/SpaceX.

136 Tim Fernholz, "The Right Stuff: What It Took for Elon Musk's SpaceX to Disrupt Boeing, Leapfrog NASA, and Become a Serious Space Company," Quartz, October 14, 2014, https://qz.com/281619/what-it-took-for-elon-musks-spacex-to-disrupt-boeing-leapfrog-nasa-and-become-a-serious-space-company/.

To reduce costs, SpaceX pursued reusability for its Falcon 9 booster. The rationale for reusability was to recoup as much of the manufacturing cost as possible of the booster to provide savings for future launches; customers would not have to pay for the manufacture of a new booster with every launch. SpaceX CEO Elon Musk equates disposing of a rocket booster after one use to purchasing a new commercial airliner for each flight.[137] This type of business model would bankrupt the airline industry. SpaceX changed the commercial launch sector by applying this same logic. To accomplish this task, the Falcon 9 first stage booster reenters the atmosphere after depositing its payload in orbit, then slows by firing its engine and steers itself using fins to a designated landing zone.[138] Once the booster is recovered, it can be refurbished and launched again at a cost of approximately half of the original manufacture price.[139] This approach translates to significant cost savings that can then be passed on to launch customers.

The efforts to increase efficiency and reduce costs resulted in an approximate cost of $57 million for the Falcon 9 booster.[140] To put that figure in perspective, ULA's similar booster, the Atlas V, cost $184 million when the Falcon 9 entered the market.[141] This price reflects the different philosophies the companies were using. SpaceX took the approach to reduce costs as much as possible that resulted in innovations in reusability and vertical integration. ULA had designated reliability above all other factors in its designs, an attribute deemed critical by ULA's primary customer, the U.S. government.[142] ULA has been successful in its pursuit of reliability; the company conducted its 140th consecutive

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[137] Carl Hoffman, "Elon Musk, the Rocket Man with a Sweet Ride," *Smithsonian Magazine*, December 2012, https://www.smithsonianmag.com/science-nature/elon-musk-the-rocket-man-with-a-sweet-ride-136059680/.

[138] Rod Pyle, *Space 2.0: How Private Spaceflight, a Resurgent NASA, and International Partners Are Creating a New Space Age* (Dallas, TX: BenBella Books, 2019), loc. 1920–1929 of 6237, Kindle.

[139] Jeff Foust, "SpaceX Gaining Substantial Cost Savings from Reused Falcon 9," SpaceNews, April 5, 2017, https://spacenews.com/spacex-gaining-substantial-cost-savings-from-reused-falcon-9/.

[140] Andrew Chaikin, "Is SpaceX Changing the Rocket Equation?," *Air & Space Magazine*, 2, January 2012, https://www.airspacemag.com/space/is-spacex-changing-the-rocket-equation-132285884/.

[141] Phillip Swarts, "ULA Debuts Online Pricing Tool for Atlas Launches," SpaceNews, December 1, 2016, https://spacenews.com/ula-debuts-online-pricing-tool-for-atlas-launches/.

[142] Loren Grush, "ULA Alludes to SpaceX's Rocket Explosion in Competition for Military Contract," The Verge, September 22, 2016, https://www.theverge.com/2016/9/22/13015370/united-launch-alliance-spacex-rocket-explosion-contract.

successful launch in August 2020.[143] However, the lack of competition did not put any pressure on ULA to reduce costs; it tailored its services to meet the needs of its primary customer. Once SpaceX demonstrated Falcon 9 as a viable alternative to the Atlas V, ULA reassessed its manufacturing procedures and trimmed its payroll to compete, reducing the unit cost of the Atlas V to $109 million.[144]

Statistics from the Federal Aviation Administration (FAA) show that from 2004 to October 2020, large aerospace companies (including ULA after its conception in 2005) accounted for only 32 of the 209 licensed commercial launches flown.[145] Additionally, since SpaceX began delivering commercial payloads in 2008, large aerospace companies account for only 18 of 173 commercial launches.[146] SpaceX, along with other operators, such as Rocket Lab, Blue Origin, and Orbital Sciences, have become major players in the commercial launch sector, and have effectively ended the monopoly on commercial launches held by large aerospace contractors. Reusability is now utilized by Blue Origin and Rocket Lab, with ULA pursuing this capability in its new Vulcan booster.[147] This change in the market is generating competition and driving innovation, resulting in reduced costs to customers and enhanced capabilities available for purchase.

SpaceX was also able to break the monopoly held by ULA for national security launches after suing the U.S. Air Force in 2014.[148] The basis of the lawsuit was that the ULA contracts were uncompetitive and amounted to a federal subsidy to the aerospace contractors.[149] This argument had merit given that the government was paying additional

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143 Greg Avery, "ULA CEO Tory Bruno: Here's How We Beat SpaceX for Space Force's Big Contract," *Denver Business Journal*, August 20, 2020, https://www.bizjournals.com/denver/news/2020/08/20/united-launch-alliance-space-force-spacex-contract.html.

144 Irene Klotz, "SpaceX Undercut ULA Rocket Launch Pricing by 40 Percent: U.S. Air Force,"

145 FAA, Commercial Space Data, "Licensed Launches."

146 FAA, Commercial Space Data.

147 William Harwood, "Rocket Lab Recovers Booster in Major Step toward Reusability," CBS News, November 20, 2020, https://www.cbsnews.com/news/rocket-lab-booster-recovery-reusability/.

148 Mike Gruss, "Senators Decry Planned Reduction in Competitively Awarded EELV Missions," SpaceNews, April 3, 2014, https://spacenews.com/40097senators-decry-planned-reduction-in-competitively-awarded-eelv-missions/.

149 Pyle, *Space 2.0*, 1757–1766.

fees to ULA to maintain its launch infrastructure even when no launches were occurring as a matter of national security.[150] By allowing competition and multiple companies to launch national security payloads, redundancy would be built into the launch capability; the United States would still be able to perform launches in the event that one launch provider was unavailable. Additionally, SpaceX argued it could provide launch services at a 50-percent reduction compared to ULA's cost estimates.[151] The lawsuit was settled in 2014 and SpaceX was contracted for national security payloads, conducting its first launch in February 2015.[152]

The market share of launches for the federal government is showing further indications of increased competition. The Pentagon signed contracts for national security payloads for launches between 2022 and 2027; ULA was awarded 60 percent of the launches, and SpaceX received 40 percent.[153] Northrop Grumman and Blue Origin also bid on these contracts but were not selected; however, these companies supply solid rocket boosters (Northrop Grumman) and the main engines (Blue Origin) for ULA's Vulcan booster.[154] Four companies competing for national security launches show significant growth in competition since SpaceX sued the Air Force to gain entry into this segment. The launch statistics since 2004 clearly demonstrate that the commercial sector has increased the diversity of launch providers being utilized for both commercial and government payloads. A healthy and competitive marketplace for launch services in the United States now exists, and this competition is driving new investment in the sector. According to statistic from the Department of Commerce, global investment in space

[150] Eric Berger, "Air Force Budget Reveals How Much SpaceX Undercuts Launch Prices," Ars Technica, June 15, 2017, https://arstechnica.com/science/2017/06/air-force-budget-reveals-how-much-spacex-undercuts-launch-prices/; Sandra Erwin, "Air Force Awards ULA $1.18 Billion Contract to Complete Five Delta 4 Heavy NRO Missions," SpaceNews, September 30, 2019, https://spacenews.com/air-force-awards-ula-1-18-billion-contract-to-complete-five-delta-4-heavy-nro-missions/.

[151] Pyle, *Space 2.0*, 1776.

[152] Pyle, 1781–1790.

[153] Stephen Clark, "ULA, SpaceX Win Landmark Multibillion-Dollar Launch Agreements with Pentagon—Spaceflight Now," *Spaceflight Now* (blog), August 7, 2020, https://spaceflightnow.com/2020/08/07/ula-spacex-win-landmark-launch-agreements-with-pentagon/.

[154] Clark.

technologies totals $17.5 billion in 2020, with 62 percent of that total being invested in the domestic commercial space sector.[155]

The arrival of SpaceX and the resulting market competition has resulted in a healthy commercial space sector in which several companies are now key players in the market. This diversity is vital to any successful ADR program. For a partnership to be successful, project management must utilize the strengths of both sectors. The commercial space sector is showing strong innovation, along with a reduction in costs and increased efficiency. As the number of viable companies enters the marketplace, competition grows. This growth creates an environment in which NASA will have several capable partners to choose from in any partnership; the days of relying on the legacy aerospace contractors are over. Leveraging the growth of the commercial sector and its enhanced capabilities will be a key factor in the success of a public–private partnership to remediate space debris.

B. IMPROVED PROGRAM MANAGEMENT

This section provides evidence illustrating that when NASA reduces management oversight of large projects, significant cost savings can occur. A change in program management for NASA's fleet of space shuttles is a prime example of how a reduced management footprint can reduce costs. In 1995, the results from an outside review panel examining shuttle operations made recommendations to NASA to reduce costs and increase program efficiency.[156] One of the review panel's recommendations was to move all shuttle program operations under one contractor to reduce operational costs.[157] In 1996, NASA signed a six-year, $7 billion contract with United Space Alliance to maintain its fleet of shuttles. Congressional Research Services reports that this new management structure resulted in a $1 billion a year reduction in shuttle operations.[158] While this

[155] "Update on Artemis Program to the Moon at the Eighth National Space Council Meeting," December 9, 2020, NASA, YouTube, video, 59:37, https://www.youtube.com/watch?v=oG2JwwOphLQ.

[156] Bromberg, *NASA and the Space Industry*, loc. 2476; Christopher C. Kraft, *Report of the Space Shuttle Management Independent Review Team* (Washington, DC: National Aeronautics and Space Administration, 1995), https://www.spaceflight.nasa.gov/shuttle/reference/green/kraft.pdf.

[157] Kraft, 15.

[158] Behrens, *Space Launch Vehicles*, CRS-4.

arrangement reduced NASA's management structure and reduced costs, it does not represent the full potential of a partnership between the agency and the commercial sector.

A public–private partner structure has the ability to overcome the management challenges identified by Inspector General Martin and the lessons learned report from the Constellation program. The evidence cited to illustrate this strength is found in the successful partnership between NASA and the commercial space sector in the COTS program. The purpose of COTS was to enable resupply missions for cargo to the ISS following the retirement of the space shuttle.[159] Additionally, the program was intended to stimulate the commercial space sector with public sector investment in developing commercial space transportation services that could be used by both private and government customers.[160] By using a new management and contract structure, the agency successfully leveraged the strength of lean business practices found in the private sector combined with a reduced management footprint to reduce government spending and financial risk.[161] The new partnership framework established in COTS resulted in a synergistic relationship between the two sectors, where the net result of the partnership was a stronger product than could have been developed independently.

COTS utilized limited government investment and a non-contract approach to avoid the management pitfalls in previous NASA efforts.[162] For both the Constellation and space shuttle programs, the management structure was large due to heavy oversight of the contractors involved in the program. This approach resulted in significant personnel costs in oversight roles that added significant fixed costs to both program budgets. The COTS structure required a much smaller program office and oversight structure due to the unique nature of the partnership between the two sectors. NASA sought to share the development costs for cargo resupply spacecraft with commercial partners, after which NASA would

[159] National Aeronautics and Space Administration, *Commercial Orbital Transportation Services*, 2.

[160] National Aeronautics and Space Administration, 17.

[161] Edgar Zapata, "An Assessment of Cost Improvements in the NASA COTS," 23–24.

[162] National Aeronautics and Space Administration, *Commercial Orbital Transportation Services*, 11, 13.

then purchase resupply services from the commercial partner. In the end, NASA was buying resupply missions, not the actual spacecraft.[163]

Since NASA was not procuring spacecraft, the agency was able to avoid using FAR procurement contracts and the associated oversight and management costs.[164] The result of this structure allowed for a significantly smaller management footprint than other NASA programs; the COTS management office consisted of only 14 personnel.[165] This change drastically reduced the fixed-cost of program management, which peaked at five percent of total program budget.[166] With lower management costs, more of the initial $500-million dollar program budget could be devoted to developing the spacecraft instead of paying for unnecessary oversight. The work of NASA personnel could then be focused at one location, instead of being distributed across several NASA centers, which was another identified challenge of the Constellation program. The Johnson Space Center (JSC) in Houston, TX, is the base center of operations for the ISS. NASA chose this facility as the home of COTS given that most of the knowledge and talent needed for the program was there.[167]

To allow for design innovation and to leverage the strengths of the commercial sector, NASA requested proposals for specific mission capabilities from the commercial sector in lieu of requesting specific designs. One of the drawbacks of the Constellation program cited in the after-action report was the development of the Orion crew capsule. When the Orion was built to NASA design requirements, the resulting spacecraft underperformed. This realization resulted in delays and increased costs. For COTS, NASA announced a request for proposals from the commercial sector to submit plans to fulfill mission requirements, such as pressurized or un-pressurized cargo delivery to the ISS; NASA did not dictate the designs of the spacecraft submitted by industry.[168] This leeway given in system design allowed bidding contractors to tailor their proposals to match the

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[163] National Aeronautics and Space Administration, 12.

[164] National Aeronautics and Space Administration, 13–14.

[165] National Aeronautics and Space Administration, 39.

[166] National Aeronautics and Space Administration, 37.

[167] National Aeronautics and Space Administration, 16–17.

[168] National Aeronautics and Space Administration, 18–19.

strengths of their capabilities instead of NASA's design requirements. The purpose of this design approach was not only to encourage participation from the private sector but reduce development costs as well.[169] Proposals would be rated based on the technology proposed, the business plan to accomplish program goals, and access to finances to fund development costs.[170]

NASA incorporated personnel with expertise in venture capital investment into the program office to review the submitted proposals from industry effectively to avoid falling into the previously identified pitfall of excessive optimism at the expense of program costs identified by Inspector General Martin. A strong business plan and sufficient access to funding was identified as a critical component of program success. If a partner could not provide adequate funding, development could not progress regardless of the technical capabilities of the design.[171] A balanced review of all the components of the submitted proposals was necessary to ensure program success.

NASA experienced both failure and success related to selecting commercial partners based on evaluating the financial strength of potential partners. The initial partners selected for COTS were SpaceX and Rocketplane Kistler (RpK). SpaceX's proposal was the first selected based on its technical strengths, impressive plan for development, and strong finances.[172] RpK's proposal was well received by NASA due to its impressive modular spacecraft system and strong business plan.[173] However, RpK did not have the finances on hand to finance its end of the development costs; it would rely on outside investment to raise the funds.[174] Once again, NASA fell victim to viewing technical capabilities as the key to mission success. NASA did not place equal weight to the funding aspect of the program.

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[169] National Aeronautics and Space Administration, 17.

[170] National Aeronautics and Space Administration, 27.

[171] National Aeronautics and Space Administration, 21.

[172] National Aeronautics and Space Administration, 29.

[173] National Aeronautics and Space Administration, 30.

[174] National Aeronautics and Space Administration, 61.

RpK's financial position presented challenges six months into the program. The company failed to raise adequate funding by the first program milestone in September 2006.[175] NASA granted extensions and allowed funding to be deferred to later milestone dates to allow more time for RpK to raise funds, but RpK was unable to secure the necessary capital and NASA terminated the partnership in August 2007.[176] NASA learned from this lapse in judgement, and during a second round of bidding to find a new partner, chose Orbital Sciences.[177] The proposal from Orbital Sciences was strong from a technical and business standpoint. However, program officials acknowledge that a significant factor in their selection was the company had the necessary finances on hand to fully fund development.[178]

The framework of the partnership and the selection of SpaceX and Orbital Sciences resulted in a successful program to develop two resupply systems for the ISS. Total development costs for the COTS program were $1.9 billion, with NASA contributing 47 percent of these costs. SpaceX and Orbital Sciences contributed $454 million and $590 million, respectively to develop their delivery systems.[179] In this co-financed partnership, NASA gained access to two independent methods to resupply the ISS while not having to develop the program using only public funding. Second, the commercial sector received significant investment capital and developed space transport systems that could be used by both government and private customers due to the commercial partners retaining ownership of the developed systems.[180]

By leveraging the lean manufacturing and management practices found in the commercial space industry, the resupply spacecraft were developed at a significantly lower cost than if NASA had used traditional procurement methods. An example is the development costs for SpaceX's Falcon 9 booster. A 2010 Cost Assessment study

[175] National Aeronautics and Space Administration, 61.

[176] National Aeronautics and Space Administration, 61–62.

[177] National Aeronautics and Space Administration, 33.

[178] National Aeronautics and Space Administration, 33, 66.

[179] National Aeronautics and Space Administration, 58, 76.

[180] National Aeronautics and Space Administration, 12, 22.

estimated the cost of developing the Falcon 9 by NASA using traditional methods to be approximately $4 billion dollars.[181] The study also found that the SpaceX approach using cost-plus Federal Acquisition Regulation (FAR) contracts would cost $1.7 billion.[182] Once NASA verified the funds actually spent by SpaceX to develop this booster, the total was found to be $443 million.[183] SpaceX was able to deliver a booster at a cost of 26 percent the amount of NASA's most optimistic estimate.

With SpaceX retaining ownership of the rocket, additional benefits to both SpaceX and the government resulted. As of November 2020, the Falcon 9 has flown 96 times, 88 of which have been with commercial payloads.[184] The COTS partnership led to the development of technology that SpaceX and Orbital Sciences can utilize for additional revenue streams, an arrangement that allows for long-term benefits for both sides of the partnership. Research by Zapata shows that the tax revenue generated from Falcon 9 launches between 2008 and 2017 exceeds the federal investment in developing the booster.[185] The example of the Falcon 9 demonstrates that investing public funds into private sector space technology provides economic benefits to both sides of the partnership. The systems developed in COTS will continue to generate revenue for both sides of the partnership for years to come.

Management teams from both NASA and the commercial partners were kept well informed of the progress by establishing a schedule for technology reviews about fixed program milestones. Funding would be distributed to the commercial partner upon satisfaction of the milestone requirements.[186] This process, in conjunction with a smaller NASA management team, allowed for clear expectations to be established on both sides of the partnership. The identified deficiency of some of the centers being unaware of changes

[181] National Aeronautics and Space Administration, *Falcon 9 Launch Vehicle NAFCOM Cost Estimates*, 8.

[182] National Aeronautics and Space Administration, 8.

[183] National Aeronautics and Space Administration, 9.

[184] FAA, Commercial Space Data, "Licensed Launches"; "Falcon-9," SpaceX, accessed November 11, 2020, http://www.spacex.com.

[185] Zapata, "An Assessment of Cost Improvements in the NASA COTS," 25.

[186] National Aeronautics and Space Administration, *Commercial Orbital Transportation Services*, 22.

or other challenges when working on the Constellation project was thus alleviated. Furthermore. by being able to withhold NASA funding from an underperforming commercial partner, RpK, for example, NASA could hold partners accountable for delays and overruns or terminate the agreement altogether.[187] This framework resulted in more accountability for the commercial partners given they were contributing significant financing and were not afforded the protection of traditional FAR procurement contracts.

NASA deemed the COTS partnership a success, so much so that managing directives for large programs were changed to encourage program managers to use a similar framework when possible.[188] NASA is now using similar public–private partnership frameworks for the Commercial Crew (CCP) and the Commercial Lunar Payload Services (CLPS) programs. CCP is a partnership with SpaceX and Boeing to transport astronauts to the ISS. SpaceX has already delivered astronauts to the ISS as part of this program in a May 2020 demonstration flight of the Crew Dragon capsule, followed by the first operational launch on November 15, 2020.[189] The Crew Dragon is an evolution of the Dragon cargo capsule developed during COTS, which further illustrates the innovation and efficiency found in the commercial sector.[190] Like the Falcon 9 booster, Crew Dragon will be used outside of NASA missions; the company has announced agreements with Space Adventures and Axiom Space to launch passengers into LEO and to the ISS.[191] Phil McAlister, Director of Commercial Spaceflight for NASA, summarized the implication of this arrangement, "this is the kind of outcome envisioned when we initiated CCP: enabling a new commercial market in which the U.S. companies provide services; and making

[187] National Aeronautics and Space Administration, 22.

[188] National Aeronautics and Space Administration, 99.

[189] Sean Potter, "NASA Astronauts Launch from America in Test of SpaceX Crew Dragon"; Jeff Foust, "SpaceX Launches First Operational Crew Dragon Mission to ISS," SpaceNews, November 16, 2020, https://spacenews.com/spacex-launches-first-operational-crew-dragon-mission-to-iss/.

[190] Mike Wall, "Here's How Much NASA Is Paying per Seat on SpaceX's Crew Dragon & Boeing's Starliner," Space, November 16, 2019, https://www.space.com/spacex-boeing-commercial-crew-seat-prices.html.

[191] Phil McAlister, *Commercial Crew Program Status to NAC* (Washington, DC: National Aeronautics and Space Administration, 2020), 15, https://www.nasa.gov/sites/default/files/atoms/files/ccp_status_to_nac_-_may_2020_1.pdf.

NASA 'one of many customers'."[192] The commercialization of the developed technologies provides an environment in which increased launch rates can result in greater manufacturing efficiency and safety performance.[193] This increased launch tempo would not be possible if the systems were limited to NASA missions only.[194]

Following in the footsteps of COTS and CCP, CLPS is a program in which NASA is acquiring services from the commercial sector, but not the spacecraft themselves, but instead for delivery missions to the surface of the moon under the Artemis program. NASA Administrator Jim Bridenstine explains, "When we go to the moon, we want to be one customer of many customers, in a robust marketplace, between the Earth and the moon."[195] This model of partnership is intended to foster competition in cost and innovation between the participating companies.[196] Nine companies were selected in November 2018 for eligibility to bid on delivery services to the surface of the moon, with five more companies added one year later.[197] These companies are bidding on indefinite-delivery/indefinite-quantity contracts worth a maximum $2.6 billion for combined services running through 2028.[198] The companies selected for these missions are not legacy defense contractors or the major commercial players in the private launch industry, but smaller companies that NASA hopes will provide fresh perspective and ideas. Chris Cuthbert, Director of CLPS, explains, "NASA is committed to working with industry to enable the next round of lunar exploration. The companies we have selected represent a diverse community of exciting

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[192] McAlister, 15.

[193] Zapata, "An Assessment of Cost Improvements in the NASA COTS," 24.

[194] Zapata, 24.

[195] "NASA Announces New Moon Partnerships with U.S. Companies," 3:11.

[196] NASA, 3:20.

[197] "NASA Announces New Partnerships for Commercial Moon Deliveries," National Aeronautics and Space Administration, November 29, 2018, https://www.nasa.gov/press-release/nasa-announces-new-partnerships-for-commercial-lunar-payload-delivery-services; "New Companies Join Growing Ranks of NASA Partners for Artemis Program," National Aeronautics and Space Administration, November 18, 2019, https://www.nasa.gov/press-release/new-companies-join-growing-ranks-of-nasa-partners-for-artemis-program.

[198] Brian Dunbar, "Commercial Lunar Payload Services Overview," National Aeronautics and Space Administration, November 18, 2019, http://www.nasa.gov/content/commercial-lunar-payload-services-overview.

small American companies, each with their own unique, innovative approach to getting to the Moon."[199]

The amount of government money put into developing private sector technologies during COTS was significant. Moreover, the processes through which the commercial sector was manufactured these systems led to lower costs to the government and strengthened the domestic commercial space sector, which resulted in more jobs and tax revenue for the nation. Additionally, these achievements could not have been accomplished by the commercial sector acting independently. The infusion of public investment into SpaceX during COTS and the resulting contracts to resupply the ISS allowed the company to pursue improvements to the Falcon 9 and develop the Crew Dragon capsule.[200] This model has also led NASA to invest in many smaller space companies in the CLPS effort, which demonstrates that NASA is trying to develop the commercial sector as whole instead of just the major companies. The COTS partnership truly is an example in which the sum is greater than the parts of the whole and has created a ground shift in how NASA manages programs.

C. CONCLUSION

The uncompetitive and stagnant commercial space sector has evolved into an innovative and vibrant marketplace. A significant portion of the evidence provided is a result of the COTS partnership between the two sectors. While the commercial sector was slowly growing before COTS, the infusion of public investment resulted in significant growth and increased capabilities of the sector. The structure of the partnership allowed technologies to be built in a lean manner, with a focus on innovation instead of NASA design specifications. This environment led to breakthroughs in manufacturing and technologies, such as reusability. Furthermore. it brought competition to the market that

[199] "NASA Selects First Commercial Moon Landing Services for Artemis," National Aeronautics and Space Administration, May 31, 2019, https://www.nasa.gov/press-release/nasa-selects-first-commercial-moon-landing-services-for-artemis-program.

[200] Eric Berger, "Without NASA There Would Be No SpaceX and Its Brilliant Boat Landing," Ars Technica, April 11, 2016, https://arstechnica.com/science/2016/04/without-nasa-there-would-be-no-spacex-and-its-brilliant-boat-landing/.

then reduced launch costs for both private and government customers. In a similar fashion to the research by Berry et al. on partnerships reviewed for this thesis, COTS was successful because of strong leadership, effective communication, proximity of operations, and consistent sharing of data between partners.[201] All these factors were found to be program challenges within NASA's Constellation program. The proper execution of a public–private framework overcame these barriers.

In a similar manner to Lucas's research on partnerships to combat tropical disease, NASA's partnership with the commercial sector produced results that neither side of the partnership could have attained independently. Lucas highlights how private pharmaceutical companies lacked the financial incentive to act and how the World Health Organization did not possess the talents to provide research and training to combat these diseases.[202] Only when the two sides worked together could they create a successful program to combat tropical diseases. Resupply services to the ISS presented a similar challenge. The commercial sector did not have the financial resources, nor the incentive, to develop these capabilities independently. NASA could have acted independently but was seeking a more efficient solution to the problem. The private sector provided the efficient manufacturing and design processes, while NASA provided access to research data and facilities. The result is a program produced at a fraction of the cost if NASA had acted independently, which also provided a boost to the commercial space sector in the form of public investment.

The scholarship from San Miguel and Summers, along with Jankowski et al., highlights how public–private partnerships have the ability to provide protection to public agencies not possible outside of this framework. The ability to terminate agreements with underperforming commercial partners provides a protection to public agencies not found in traditional procurement efforts.[203] The COTS partnership aligns with this research given the program's ability to terminate its agreement with RpK. Instead of facing delays while

201 Berry et al., *The Effectiveness of Partnership Working in a Crime and Disorder Context*, 32.

202 Lucas, "Public–private Partnerships," 20.

203 San Miguel and Summers, *Public–private Partnerships for Government Financing*, 32; Jankowski, Lehmann, and McGee, "Financing the DOD Acquisition Budget," 18.

RpK was procuring outside financing, NASA was able to terminate the agreement and move on to another partner quickly to preserve the development schedule and prevent wasting further public sector funds on an underperforming partner. In light of the COTS program and comparing it to the existing literature on the strengths of public–private partnerships, the program's successes align with the established research.

The commercial sector has proven to be efficient and innovative, and willing to contribute funding for technology development to use these capabilities for commercial purposes. These factors provide an environment that NASA can leverage in a partnership to begin remediation. The precedent has been set that partnerships are effective; NASA is using the method for its two current flagship programs, Commercial Crew and Lunar Artemis. NASA could attempt to begin remediation missions using traditional procurement methods. Traditional procurement methods appear to be a step backwards in terms of progress given the advances that have been made using the public–private partnership framework. Furthermore. the threat of space debris needs to be addressed quickly, and the efficiency provided in the partnership framework provides an option less likely to face schedule delays and cost overruns. By leveraging the vision and innovation of the private sector, solutions that NASA may not have envisioned may be presented. The funding and access to research facilities that NASA brings, paired with the efficiency and innovation of the private sector, provide the highest chance of success for any remediation efforts.

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IV. STATE OF REMEDIATION TECHNOLOGY AND FUTURE EFFORTS

The United States is currently not undertaking any active debris remediation efforts. However, the United States has made significant progress in the related field of on-orbit servicing (OOS). While not directly intended to remove debris objects from orbit, some of the key technologies that will enable a spacecraft to perform OOS missions can be utilized for remediation efforts. The successes in this emerging field, mostly due to the performance of a commercial spacecraft, provide a foundation of knowledge and experience upon which future remediation efforts can build.

While the United States has taken the lead in developing OOS capabilities, other states have begun developing dedicated remediation programs. These efforts are still in the early stages of development and are far from being operational. However, these programs challenge U.S. leadership in a field that will be relevant to both the public and private sectors globally. The threat of debris endangers capabilities ranging from intelligence, communication, defense, and infrastructure. As the threat continues to grow due to continuous launches, states and private companies that develop a remediation capability will have a significant advantage in securing contracts to remove debris. To ensure U.S. satellites are protected by U.S. spacecraft, and to secure the economic growth of the domestic commercial space sector, a domestic remediation effort must begin.

A. OVERVIEW OF ACTIVE DEBRIS REMEDIATION

Active debris remediation (ADR) is the process of physically capturing debris in space and removing it from orbit.[204] This process is beyond the maneuvers a satellite may make at the end of its service life to deorbit and reenter the atmosphere in compliance with mitigation protocols.[205] ADR missions will require a removal spacecraft to rendezvous with debris objects, and then physically move the object to where it either reenters the

[204] J.-C. Liou, "An Active Debris Removal Parametric Study for LEO Environment Remediation," *Advances in Space Research* 47, no. 11 (June 2011): 1865, https://doi.org/10.1016/j.asr.2011.02.003.

[205] Liou, 1865.

atmosphere or is moved to a "graveyard" region where it cannot collide with operational satellites.[206] The literature reviewed for this thesis established that this process is now necessary in conjunction with adherence to mitigation practices to prevent significant collision events in the future. Furthermore. the literature illustrates the massive debris objects found in the orbital altitudes between 775 km and 1,500 km in orbital altitude are particularly dangerous.[207] The mass of the debris found at these altitudes poses a significant risk due to the large amount of fragmentation that the destruction of such a large object would produce.[208] A collision at these altitudes would pose a risk to satellites in these altitudes for many years due to the height of these orbits. The fragments produced in any collision could take decades, or even hundreds of years, to deorbit.[209]

Currently, no operationally capable technology exists to perform ADR missions of any scale. Several technologies are being considered to remediate debris objects, including but not limited to, nets, harpoons, drag-augmentation devices, robotic arms, and lasers.[210] The manner in which remediation missions are conducted will vary depending on the technology used to remediate the target. Methods, such as using nets, harpoons, or robotic arms, to capture debris targets will require remediating spacecraft to rendezvous and maneuver in close proximity of targets to capture them. Once these objects are captured, the remediating spacecraft can either deorbit them so they reenter the atmosphere or move them to an orbit where they no longer present a collision risk to operational satellites.[211] Getting into position to dock with or capture a debris target will require precise maneuvering to prevent damage to the remediating spacecraft and the target, an event that may generate additional debris. A debris target tumbling in multiple axes will further

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[206] Liou, 1865.

[207] Rossi, Petit, and McKnight, "Examining Short-Term Space Safety Effects," 3.

[208] Rossi, Petit, and McKnight, 8.

[209] Darren McKnight, "STM—Do Not Build on a Weak Foundation" (presentation, Department of Commerce, Washington, DC, August 29, 2020), 4.

[210] Heiner Klinkrad and Nicholas L. Johnson, "Space Debris Environment Remediation Concepts," in *5th European Conference on Space Debris*, vol. 672, 4–5, 2009, https://ui.adsabs.harvard.edu/abs/2009ESASP.672E..50K/abstract; Hakima and Emami, "Assessment of Active Methods for Removal of LEO Debris," 231–35.

[211] Hakima and Emami, "Assessment of Active Methods for Removal of LEO Debris," 231, 234.

complicate rendezvous maneuvers; a remediating spacecraft will have to synchronize its movements to mirror the target to successfully make contact.[212]

Early research on the use of some of these methods of debris capture has begun and is discussed later in this chapter. These systems are far from the maturity level needed to remediate the massive debris objects residing in the higher altitudes of LEO.[213] However, breakthroughs have been made, specifically in the United States, in related technologies that will be needed for remediation missions. The systems needed to perform rendezvous and docking maneuvers have not only been researched domestically, but a U.S. commercial space company has reached a level of operational readiness with these systems that has opened up a new field of space commerce.

B. ON-ORBIT SERVICING AND PUBLIC–PRIVATE PARTNERSHIPS

The United States has made significant progress in the field of OOS. While these efforts do not pursue the remediation of debris, the work completed within these projects can provide a technological springboard for a future public–private partnership in ADR. OOS is a developing field in satellite technology with significant implications for debris reduction efforts. The Aerospace Corporation defines OOS as, “on-orbit activities conducted by a space vehicle that performs up-close inspection of, or results in intentional and beneficial changes to, another resident space object (RSO).”[214] In more general terms, it concerns the repairing or refueling of satellites in orbit to extend their mission lifetimes. The space shuttle and astronauts were used in this role from 1984 to the 2009, with the five servicing missions to the Hubble Space Telescope being the most visible.[215]

[212] Hakima and Emami, 229, 234.

[213] Hakima and Emami, 236.

[214] Joshua P. Davis, John P. Mayberry, and Jay P. Penn, *On-Orbit Servicing: Inspection, Repair, Refuel, Upgrade, and Assembly of Satellites in Space* (El Segundo, CA: The Aerospace Corporation, 2019), 2, https://aerospace.org/sites/default/files/2019-05/Davis-Mayberry-Penn_OOS_04242019.pdf.

[215] NASA Goddard Spaceflight Center, *On-Orbit Satellite Servicing Study: Project Report* (Greenbelt, MD: NASA Goddard Spaceflight Center, 2010), 15–20, https://nexis.gsfc.nasa.gov/images/nasa_satellite%20servicing_project_report_0511.pdf.

The development of OOS capabilities apply to space debris remediation in two significant ways. First, the ability to refuel or repair satellites in orbit will prevent these satellites from becoming derelict and contributing to the overall mass of debris. Second, many of the capabilities needed to perform OOS parallel the needs of ADR platforms. The ability to rendezvous and conduct proximity operations with target objects is a requirement of both missions. This section highlights two U.S.-based programs either dedicated or related to the OOS mission. These efforts are not committed to the ADR mission, but the progress made in these programs can be readily applied to any future remediation program.

1. SpaceLogistics Mission Extension Vehicle

The SpaceLogistics (a subsidiary of Northrop Grumman) MEV is marketed as a space servicing vehicle; its purpose is to dock with satellites in orbit that have lost the ability to maneuver and extend their useful time in orbit.[216] This service benefits customers by eliminating or delaying the expense of designing and manufacturing a replacement spacecraft to fulfill a necessary function. The capabilities needed to perform this mission, an example being the ability to rendezvous with derelict objects, is also needed for debris remediation missions. These capabilities have passed their development and demonstration phase and have achieved operational status, or as determined by NASA to be the highest technology readiness level (TRL).[217] The early successes of the MEV spacecraft provide a foundation for not only the emerging OOS market, but also a launching pad in which remediation capabilities can be developed.

The first spacecraft of this series, MEV-1, was launched on October 9, 2019 and rendezvoused with its target, Intelsat's IS-901, in GEO on February 25, 2020.[218] The

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[216] "Space Logistics Services," *Northrop Grumman* (blog), accessed July 22, 2020, https://www.northropgrumman.com/space/space-logistics-services.

[217] Thuy Mai, "Technology Readiness Level," National Aeronautics and Space Administration, October 28, 2012, http://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html. The readiness level of a technology is rated on a 9-point scale, with TRL-9 being the highest point. This rating, which MEV has reached, is commensurate of a "flight proven" technology.

[218] Chris Gebhardt, "Northrop Grumman Makes History, Mission Extension Vehicle Docks to Target Satellite," *NASASpaceFlight* (blog), February 26, 2020, https://www.nasaspaceflight.com/2020/02/northrop-grumman-history-mission-extension-vehicle-docks-satellite/; Elizabeth Howell, "Two Private Satellites Just Docked in Space in Historic First for Orbital Servicing."

docking took place 180 miles above the GEO region, where IS-901 had been placed after being taken out of service in anticipation of this mission.[219] This meeting also represented the first time two commercial spacecraft docked in space.[220] According to a press release from SpaceLogistics parent company, Northrop Grumman, MEV-1 will provide station-keeping services for IS-901 for five years and then place it in a decommissioning orbit.[221] MEV-1 will then move on to another client satellite to provide additional station-keeping services for at least 10 additional years.[222]

SpaceLogistics has continued the momentum of MEV-1 with the successful launch of MEV-2 in August 2020.[223] The client satellite for MEV-2 is another Intelsat satellite in GEO, IS-1002.[224] Due to the successful rendezvous and docking of MEV-1 with IS-901, MEV-2 will dock with IS-1002 at orbital altitude as opposed to the higher altitude of the MEV-1/IS-901 docking.[225] The MEVs represent a crucial first step for in-orbit servicing. SpaceLogistics is pursuing a follow-on for MEVs to enhance their servicing capability. This new effort involves a robotic spacecraft that will dock with satellites and attach pods to client satellites to provide station-keeping services.[226] While the on-orbit servicing

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219 Howell.

220 "Northrop Grumman Successfully Completes Historic First Docking of Mission Extension Vehicle with Intelsat 901 Satellite," Northrop Grumman Newsroom, February 26, 2020, https://news.northropgrumman.com/news/releases/northrop-grumman-successfully-completes-historic-first-docking-of-mission-extension-vehicle-with-intelsat-901-satellite.

221 Northrop Grumman Newsroom.

222 Northrop Grumman Newsroom.

223 Tobias Corbett, "Ariane 5 Launches Mission Extension Vehicle, Two Communications Satellites to Orbit," *NASASpaceFlight* (blog), August 14, 2020, https://www.nasaspaceflight.com/2020/08/ariane-5-launch-va253/.

224 "Northrop Grumman's Second Mission Extension Vehicle and Galaxy 30 Satellite Begin Launch Preparations in French Guiana," Northrop Grumman Newsroom, June 30, 2020, https://news.northropgrumman.com/news/releases/northrop-grummans-second-mission-extension-vehicle-and-galaxy-30-satellite-begin-launch-preparations-in-french-guiana.

225 Gebhardt, "Northrop Grumman Makes History, Mission Extension Vehicle Docks to Target Satellite."

226 Caleb Henry, "Northrop Grumman's MEV-1 Servicer Docks with Intelsat Satellite," SpaceNews, February 26, 2020, https://spacenews.com/northrop-grummans-mev-1-servicer-docks-with-intelsat-satellite/.

industry is still in its infancy, Northrop Grumman claims multiple clients are interested in this new system.[227]

The success of the MEV has also caught the attention of DARPA. On March 4, 2020, less than a month after the successful docking of MEV-1, DARPA named Northrop Grumman as a partner in the Robotic Servicing of Geosynchronous Satellites (RSGS) program.[228] The goal of the RSGS is to developing a robotic servicing vehicle to extend the service life and enhance the resiliency of U.S.-government and commercial satellites in GEO.[229] The RSGS spacecraft will be able to repair or add components to satellites to extend their service lives or add additional capabilities.[230] Northrop Grumman is replacing Space Systems Loral (SSL), a subsidiary of Maxar Technologies, which dropped out of the partnership due to financial concerns.[231] DARPA and the U.S. Naval Research Laboratory (NRL) will provide the robotic components along with the rest of the servicing payload, which include sensors and tools developed the NRL. Northrop Grumman will provide the bus technologies sourced from MEV to build the actual spacecraft, along with launch services and operational management.[232] While the MEV itself was developed within the commercial sector, DARPA saw the value of its capabilities and is incorporating Northrop Grumman's expertise into the RSGS effort. Construction and testing of the servicing components are expected to begin in 2021, with a target launch date for the spacecraft in 2023.[233] The spacecraft is then expected to begin servicing missions in GEO in 2024.[234]

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[227] Henry.

[228] Sandra Erwin, "DARPA Picks Northrop Grumman as Its Commercial Partner for Satellite Servicing Program," SpaceNews, March 4, 2020, https://spacenews.com/darpa-picks-northrop-grumman-as-its-commercial-partner-for-satellite-servicing-program/.

[229] "In-Space Robotic Servicing Program Moves Forward with New Commercial Partner," DARPA, March 4, 2020, https://www.darpa.mil/news-events/2020-03-04.

[230] "Parts Come Together This Year for DARPA's Robotic In-Space Mechanic," DARPA, July 17, 2020, https://www.darpa.mil/news-events/2020-07-17.

[231] Sandra Erwin, "Maxar's Exit from DARPA Satellite Servicing Program a Cautionary Tale," SpaceNews, January 30, 2019, https://spacenews.com/maxars-exit-from-darpa-satellite-servicing-program-a-cautionary-tale/.

[232] Erwin; DARPA, "Parts Come Together This Year for DARPA's Robotic In-Space Mechanic."

[233] DARPA.

[234] DARPA.

The RSGS can be viewed as a foundational program for the development of a domestic ADR capability for two reasons. The first is the proven rendezvous and docking capabilities of the MEV technologies within the RSGS spacecraft. The RSGS mission plans to add a remote inspection capability, where the spacecraft circles the target satellite in an inspection process to establish the safest method to dock and service the satellite.[235] These capabilities will be necessary for remediation missions as well. Whether the target is to be serviced or remediated, the mission spacecraft needs to be able to dock safely with the target in a manner that does not produce any damage or fragmentation. Second, Northrop Grumman will manage the initial RSGS launch.[236] This handling represents a public–private partnership in which the commercial sector is operating the spacecraft using technologies developed by both parties. Furthermore. DARPA intends to turn these servicing technologies over to the private sector once the systems are proven to be operational.[237] Turning these capabilities over to the private sector is intended to establish national leadership in the OOS industry.[238] The OOS capabilities developed in this program can then be utilized to service both government and commercial satellites in GEO, with government satellites being serviced for an established fixed-cost.[239] This model of operation aligns with partnership efforts in NASA, with both government and private operators cooperating on the development of technologies, and then handing off these capabilities to the private sector to operate to establish global leadership in the commercial sector.

The successful docking of MEV-1 and IS-901 demonstrate that docking with and moving derelict satellites is possible with existing technology. Additionally, it has proven that private-sector ambition and innovation can find solutions to a complex problem. Using components and technologies from previously successful spacecraft, Northrop Grumman and SpaceLogistics generated a completely new system that has a wide range of

[235] DARPA.

[236] DARPA, “In-Space Robotic Servicing Program Moves Forward with New Commercial Partner.”

[237] DARPA, “Parts Come Together This Year for DARPA’s Robotic In-Space Mechanic.”

[238] DARPA.

[239] DARPA.

applications.[240] Northrop Grumman and Intelsat are negotiating for additional MEV missions to extend the life of more satellites, which shows that a potential market for commercial OOS exists.[241] The technological breakthroughs the MEV achieved have also jumpstarted the RSGS program, which is now on track to develop a diverse OOS capability in GEO for both government and commercial satellites. This initiative will only strengthen the United States' position of leadership in OOS following the MEV's successes. The technologies developed and the experience gained in these programs will provide an excellent foundation upon which a domestic ADR program can be built.

2. NASA's OSAM-1

NASA's Goddard Spaceflight Center is developing a spacecraft (OSAM-1) for the On-Orbit Servicing, Assembly, and Manufacturing (OSAM) program.[242] Similar to the RSGS, this program's intent is to establish OOS capabilities. However, the OSAM program will be conducting operations in LEO as opposed to GEO. NASA approved this mission's budget and schedule in May 2020; no launch date has been set as of November 2020.[243] The OSAM-1 mission was previously known as the RESTORE-L mission; however, the addition of new mission objectives resulted in a name change.[244] NASA is the owner and operator of the OSAM-1 spacecraft being built by SSL for a demonstration mission to refuel the Landsat-7 satellite.[245] This mission has a level of complexity not found in MEV operations. Upon docking with the target, the OSAM-1 will refuel the target instead of staying attached and providing station-keeping services. These functions will be carried

240 Henry, "Northrop Grumman's MEV-1 Servicer Docks with Intelsat Satellite."

241 "Intelsat 901 Satellite Returns to Service Using Northrop Grumman's Mission Extension Vehicle," Northrop Grumman Newsroom, April 17, 2020, https://news.northropgrumman.com/news/releases/intelsat-901-satellite-returns-to-service-using-northrop-grummans-mission-extension-vehicle.

242 "NASA's Exploration & In-Space Services," NExIS, May 29, 2020, https://nexis.gsfc.nasa.gov/.

243 "Mission Update: OSAM-1 Successfully Passes Key Decision Point-C," NExIS, May 29, 2020, https://nexis.gsfc.nasa.gov/.

244 "OSAM-1 (Formerly Restore-L) Continues to Make Progress, Fuel Tank Installed," *Maxar Technologies* (blog), April 23, 2020, https://blog.maxar.com/space-infrastructure/2020/osam-1-formerly-restore-l-continues-to-make-progress-fuel-tank-installed.

245 Benjamin Reed, "Designing for On-Orbit Servicing Capability" (presentation, Availability and Maintainability Improvement Initiative Working Group, Greenbelt, MD, October 11, 2019), 14, https://ntrs.nasa.gov/citations/20190031787.

out with three robotic arms that will perform such tasks as removing fuel filler caps and attaching fuel lines.[246] The ability to perform these types of precise operations will allow follow-on spacecraft to refuel a wide range of satellites, not just ones of a specific design.

The OSAM-1 differs from the MEV spacecraft in that it can refuel or repair the target and then moves on. The OSAM-1 spacecraft is more closely aligned with the DARPA/Northrop Grumman RSGS vehicle because it intends to provide a variety of servicing options for satellites in orbit. Both spacecraft will require the ability to rendezvous and dock with a target, along with the ability to perform autonomous dexterous functions using robotic components to perform the servicing actions. These goals align with that of the RSGS; the primary difference is the orbital altitudes in which the spacecraft operate.

The OSAM-1 will be carrying the Space Infrastructure Dexterous Robot (SPIDER), which will assemble a 9-ft. antenna and manufacture a composite beam in a demonstration of on-orbit manufacturing and construction.[247] The addition of this module facilitated the name change to OSAM-1. The ability to manufacture and assemble on-orbit will allow specific tools or parts needed for servicing missions to be created. In other words, future spacecraft will not have to carry specific spare parts or tools but will have the capability of manufacturing the needed equipment after being tasked. The follow-on mission in the OSAM program, OSAM-2, will manufacture and assemble a solar array to provide power for the spacecraft.[248] The manufacturing and assembly systems developed in the OSAM program will be shared with the Artemis program, NASA's human deep-space exploration mission to the moon and Mars.[249]

The OSAM-1 is the first step in a series of technology demonstrations to develop robotic systems capable of servicing, repairing, assembling, and manufacturing outside of

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[246] NExIS, "NASA's Exploration & In-Space Services."

[247] NExIS.

[248] Jennifer Harbaugh, "OSAM-2," National Aeronautics and Space Administration, October 23, 2019, http://www.nasa.gov/mission_pages/tdm/osam-2.html.

[249] Harbaugh.

Earth.[250] This first mission will demonstrate capabilities that will allow satellites to maintain functionality beyond their designed lifespan, and possibly create fewer derelict satellites in orbit. The flexibility to service a wide variety of client satellites through autonomous robotics will increase the market value of these systems, an important factor since NASA intends to turn over these technologies to commercial operators in an effort to boost the domestic servicing industry.[251] This goal aligns with DARPA's with regard to commercial participation; both programs intend to hand over the technologies to the private sector to maintain commercial leadership in the field.

When the United States begins any remediation efforts, it can draw on the capabilities of the MEV, RSGS, and OSAM program for valuable data regarding rendezvous and docking. NASA's Goddard Spaceflight Center, home to the OSAM program and the Hubble Space Telescope, would be an ideal location to manage such an effort given the experience this center has in complex spacecraft development. OOS technology has reached a level of maturity in the MEV that has enabled commercial operations to begin and future missions to be negotiated. The MEV's success has resulted in the RSGS partnership with DARPA to develop an OOS spacecraft for servicing government and commercial satellites in GEO that will be operated by a commercial partner. This arrangement is very similar the one NASA created during COTS. The OSS capabilities developed by NASA in the OSAM program are also intended to be handed over to the commercial sector to execute OOS missions. Both DARPA and NASA recognize the commercial sector is better suited to handle these missions after development; it frees up government agencies to pursue other goals while allowing the commercial sector to grow and lead in the OOS marketplace. The knowledge and experience gained in the pursuit of OOS capabilities are a solid foundation upon which a future remediation program can be built.

[250] "On-Orbit Servicing, Assembly, and Manufacturing," On-orbit Servicing, Assembly, and Manufacturing, accessed October 17, 2020, https://nexis.gsfc.nasa.gov/osam.

[251] NExIS, "NASA's Exploration & In-Space Services."

C. FOREIGN DEVELOPMENTS IN REMEDIATION

While no operational remediation missions exist, other nations have made progress in developing the capabilities needed for a remediation program. These foreign efforts are being conducted in both the public and private sectors, and partnerships are being established between the two to create operational remediation programs. Just as important, these efforts represent a head start for foreign competitors in a potential marketplace for remediation services. With the threat debris poses and the need for remediation missions established, the United States cannot allow leadership in this field to fall to a foreign party. Given the critical role satellites play in U.S. homeland security and the economy as a whole, a domestic remediation program must be developed to protect government and commercial satellites. Furthermore. the economic benefit of a robust commercial space sector has been established with the data from COTS; the job growth and taxation of domestic launch services has more than paid for the investment of government funds. To keep the domestic space industry competitive globally, remediation efforts must begin to establish U.S. leadership in the new remediation services market. While the programs highlighted in this section are being developed for remediation missions, the evidence will show the gap between the United States and its foreign competitors is not large. However, unless action is taken quickly to establish a domestic remediation program, the United States will quickly fall behind in developing these capabilities.

1. Demonstration Missions

Foreign efforts in the field of ADR include demonstration missions, in which spacecraft in orbit have conducted experiments to develop the capabilities needed to remediate space debris. The demonstration mission of the RemoveDEBRIS spacecraft is one such effort, which was released into orbit from the ISS in June 2018.[252] The RemoveDEBRIS program was a consortium of 10 partners led by the Surrey Space Center

[252] Guglielmo S. Aglietti et al., "The Active Space Debris Removal Mission RemoveDebris. Part 2: In Orbit Operations," *Acta Astronautica* 168 (March 2020): 314, https://doi.org/10.1016/j.actaastro.2019.09.001.

in the United Kingdom and funded by the European Union.[253] Other notable partners in this group include several subsidiaries of Airbus and the Ariane Group, major players in the European aerospace industry.[254] This program shows a joint effort between both public and private actors to gather data that will benefit both. The purpose of the mission was to perform demonstrations of different technologies that might be used to remediate debris and gather data on the strengths and challenges of each technology. The techniques demonstrated in this program include the use of a vision-based navigation (VBN) system, a harpoon, a net, and a drag sail, all of which could be used for future remediation efforts.[255]

The demonstration of the VBN system was successful in its identification of both strengths and limitations of the technology. The data provided will be of particular value to future efforts in the field. The VBN systems used onboard cameras and flash imaging light detection and ranging (LiDAR), to track a target successfully to rendezvous with it. The results of the demonstration matched expectations for the camera system, while the LiDAR achieved mixed results.[256] The LiDAR deviated from expected results when significant backlight occurred behind the target.[257] The identification of this flaw will help future researchers enhance the technology. A second successful experiment was the use of a harpoon fired by cold gas generators on a target at a range of 1.5 m.[258] On-board cameras showed the harpoon hit the target dead center and imbedded itself into the target.[259] A

[253] Jason Forshaw et al., "The Active Space Debris Removal Mission RemoveDebris. Part 1: From Concept to Launch," *Acta Astronautica* 168 (March 2020): 296, https://doi.org/10.1016/j.actaastro.2019.09.002; Charity Weeden et al., *Development of Global Policy for Active Debris Removal Services* (Tokyo: Astroscale, 2019), 5, https://astroscale.com/wp-content/uploads/2020/02/Reg-V-Development-of-Global-Policy-for-Active-Debris-Removal-Services-v2.0.pdf.

[254] Guglielmo S. Aglietti, "RemoveDEBRIS Mission: 2nd Briefing to UN COPUOS," in *UN—COPUOS Scientific and Technical Subcommittee* (Vienna, Austria: United Nations Office for Outer Space Affairs, 2019), 4, https://www.unoosa.org/documents/pdf/copuos/stsc/2019/tech-32E.pdf.

[255] Forshaw et al., "The Active Space Debris Removal Mission RemoveDebris, Part 1," 296.

[256] Eric Marchand et al., "RemoveDebris Vision-Based Navigation Preliminary Results," in *IAC 2019—70th International Astronautical Congress* (Washington, DC: International Aeronautical Congress, 2019), 8, https://hal.inria.fr/hal-02315122.

[257] Marchand et al., 8.

[258] Aglietti et al., "The Active Space Debris Removal Mission RemoveDebris, Part 2," 318.

[259] Aglietti et al., 319.

harpoon could be used in future remediation missions to capture debris targets and reel them into the remediating spacecraft as opposed to having the remediating spacecraft rendezvous with the target directly.

The demonstration on the use of a net to capture a debris target was a partial success. The plan for the experiment was to fire the 5 m.-wide net at the target from a range of 7 m.[260] Upon deployment, the net only opened to a radius of 4 m., and the range to target was 11 m. The net did impact and enclose the target; however, the longer-than-anticipated distance between spacecraft and target prevented the onboard cameras from confirming full-enclosure of the target.[261] A net could be used in a similar manner as the harpoon for future remediation efforts; a target could be captured by a net and then moved by a remediating spacecraft. The drag sail experiment failed to achieve any of the desired results. When the system was activated and the process to deploy the sail initiated, the deployment motors for the sail mechanisms failed.[262] With the sail deployed, the cross-sectional area of the spacecraft would increase dramatically by creating drag and slowing the spacecraft down to reenter the atmosphere.[263] However, the RemoveDEBRIS spacecraft was deployed in an orbit that would allow for natural orbital decay within 25 years. The unsuccessful net demonstration still resulted in useful data; lessons learned during the design of the drag sail experiment were incorporated into another mission, InflateSail, which resulted in a successful deorbiting of the cubesat from 500 km in just three months' time.[264] RemoveDEBRIS was an important step in developing remediation technologies due to conducting experiments in-orbit versus a lab setting. The results of these experiments can be built upon for future efforts. Furthermore. this program demonstrated partnership between the private and public sectors in working toward the goal of remediating debris.

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[260] Forshaw et al., "The Active Space Debris Removal Mission RemoveDebris, Part 1," 299.

[261] Aglietti et al., "The Active Space Debris Removal Mission RemoveDebris, Part 2," 314.

[262] Aglietti et al., 320.

[263] Aglietti et al., 319.

[264] Aglietti et al., 321.

While RemoveDEBRIS provided data on the use of varied methods to remediate debris, using the VBN system to track a target was one of the mission's most successful components. This system will provide future remediation spacecraft the ability to rendezvous, inspect, and capture debris targets safely. The United States has already put this capability into commercial operation with the MEVs. The ability to rendezvous and dock in GEO would not have been possible without these technologies. However, the lessons learned from the other experiments of RemoveDEBRIS provide a foundation for future European efforts in remediation. Indeed, the lessons learned in constructing the unsuccessful drag-sail experiment resulted in a successful deployment of the technology in a later experiment. These initial efforts in development provide the RemoveDEBRIS partners with a head start in these technologies.

Astroscale is a multinational company and is the world's first company devoted to remediating space debris.[265] In 2020, the company intends to launch a technology demonstrator spacecraft called the End of Life Services by Astroscale demonstration (ELSA-d).[266] ELSA-d will demonstrate technologies for rendezvous and docking with cooperative and uncooperative targets using a proprietary docking system, and will also perform a search and inspection function.[267] Additionally, ELSA-d's flight plan includes a rendezvous and docking maneuver with a target tumbling in all three axis to test the technologies needed to dock with a cooperative debris target tumbling in a similar manner.[268] Like the RemoveDEBRIS mission, ELSA-d will not be removing any existing debris, but will be deploying its own targets for demonstrations. ELSA-d differs from RemoveDEBRIS in the type of technologies to be demonstrated. The searching of a debris

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265 "Tackling Constellation Debris with Japan's Astroscale," *Satellite Today* March 19, 2019, ProQuest.

266 "SSTL Ships Target Satellite to Tokyo for Astroscale's ELSA-d Mission," *Astroscale* (blog), November 7, 2019, https://astroscale.com/sstl-ships-target-satellite-to-tokyo-for-astroscales-elsa-d-mission/.

267 Chris Blackerby et al., "The ELSA-d End-of-Life Debris Removal Mission: Preparing for Launch," in *70th International Astronautical Congress* (Washington, DC: International Astronautical Federation, 2019), 1, 3, https://astroscale.com/wp-content/uploads/2019/10/ELSA-IV-Conference-IAC-2019-v1.1.pdf.

268 Blackerby et al., 3.

target and the docking with an uncooperative target are new experiments, and if successful, will be key technologies needed for future remediation efforts. Future remediation spacecraft will have to search for targets using onboard sensors, and many debris targets are tumbling; ELSA-d will provide important data of how to overcome these challenges for future efforts.

Another significant factor of ELSA-d is that it is solely a commercial effort.[269] Astroscale CEO Nobu Okada created the company due to the growing threat of space debris and the lack of progress in addressing the threat from the United Nations or other regulatory agencies.[270] Okada intends to establish Astroscale as a leader in remediation technologies and drive the development of this new market.[271] Astroscale has grown due to investments from the private sector; the company has received over $102 million from outside investors that believe in the commercial viability of remediation missions. The company also received a $4.5 million grant from the Innovation Tokyo Project to develop commercial plans to remediate space debris.[272]

Astroscale is demonstrating a level of ambition seen with SpaceLogistics/Northrop Grumman with the MEV. Both companies have identified a potential future market in space operations and have invested accordingly to be a leader in these fields. Both spacecraft will rely on the ability to rendezvous and dock with their targets; the only difference is one spacecraft will prolong the life of its target, while the other will dispose of its target. The MEV has already docked in GEO and is in operation, while ELSA-d still has not launched. This comparison is further evidence that the technology gap between the United States and other nations is not insurmountable.

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269 Mercedes Ruehl, "Space Debris Pays Dividends for Disposal Sector: Aerospace & Defence. Funding Boost Steadily Rising Volume of Junk Hands Vital Role to Businesses Such as Japan's Astroscale," *Financial Times*, April 11, 2019, sec. Companies and Markets.

270 *Satellite Today*, "Tackling Constellation Debris with Japan's Astroscale."

271 *Satellite Today*.

272 Caleb Henry, "Astroscale Wins First Half of JAXA Debris-Removal Mission," SpaceNews, February 12, 2020, https://spacenews.com/astroscale-wins-first-half-of-jaxa-debris-removal-mission/.

2. Public–Private Partnerships in Remediation Programs

The progress made in foreign remediation efforts is not limited to demonstration missions. Currently, two partnerships between foreign space agencies and the private sector are planning missions to remove debris objects from space. These partnerships are similar because both are targeting single debris objects, and the public sector is financing both efforts.[273] The existence of these programs provides evidence that foreign space agencies believe the threat of debris has risen to the level where remediation is necessary. If these programs prove viable, the United States will fall behind in the development of remediation capabilities unless action is taken to keep pace. The agencies involved, the Japan Aerospace Exploration Agency (JAXA), and the ESA, have entrusted the private sector to develop the technologies to begin remediation efforts.

Building off ELSA-d's research, Astroscale is developing a follow-on project in a partnership with JAXA. The company was selected to develop a spacecraft capable of inspecting a rocket body in orbit for a future removal mission (CRD2).[274] JAXA categorizes the target as non-cooperative; therefore, this mission will be able to refine the techniques used in the ELSA-d mission during the non-cooperative capture.[275] These two operations starkly differ in that ELSA-d's target will have a docking plate to utilize while docking with the target, whereas the rocket body being remediated during CRD2 will not have such a feature and will be significantly more massive.[276] Astroscale has until March 2023 to complete an inspection mission during which time the target will be assessed and data gathered to develop a remediation plan. Astroscale will have until March 2026, to complete the removal of the target.[277] Astroscale is looking for potential commercial

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[273] Caleb Henry, "Swiss Startup ClearSpace Wins ESA Contract to Deorbit Vega Rocket Debris," SpaceNews, December 9, 2019, https://spacenews.com/swiss-startup-clearspace-wins-esa-contract-to-deorbit-vega-rocket-debris/; Henry, "Astroscale Wins First Half of JAXA Debris-Removal Mission."

[274] Henry, "Astroscale Wins First Half of JAXA Debris-Removal Mission."

[275] "JAXA Concludes Partnership-Type Contract for Phase I of Its Commercial Removal of Debris Demonstration (CRD2)," Japan Aerospace Exploration Agency, March 23, 2020, https://global.jaxa.jp/press/2020/03/20200323-1_e.html.

[276] Japan Aerospace Exploration Agency.

[277] Henry, "Astroscale Wins First Half of JAXA Debris-Removal Mission."

partners for the mission, and the expectation is that JAXA will provide most of the financing.[278]

In an effort similar to NASA's partnership with SpaceX and Orbital Science during COTS, JAXA is not providing design specifics to Astroscale for the remediation spacecraft. For this reason, the effort to remove this rocket body is divided into two segments. This inspection mission will allow Astroscale to refine its on-orbit inspection capabilities further, as well as to develop a solution tailored to the target.[279] JAXA is allowing Astroscale to use its expertise to devise the best solution instead of directing the company on how to proceed.

ClearSpace-1 is a partnership between the European Space Agency and commercial partner ClearSpace to remove a debris object in orbit since 2013.[280] This program is a component of ESA's Active Debris Removal/In-Orbit Servicing (ADRIOS) project, intended to develop the technologies needed to service satellites and remove debris objects.[281] Swiss startup ClearSpace, comprised of personnel from across Europe, was competitively selected as the recipient of the contract targeting a 2025 launch.[282] ClearSpace is forming a consortium of partners to build the spacecraft for the mission, while the company plans to be the sole designer.[283] The ESA will supply the components for the navigation and guidance systems, a vision-based AI systems, and robotic arms for capturing the target.[284] The ESA signed a contract with ClearSpace for €86 million

278 Henry.

279 Japan Aerospace Exploration Agency, "Concludes Partnership-Type Contract for Phase I."

280 "ESA Commissions World's First Space Debris Removal," ESA, December 9, 2019, https://www.esa.int/Safety_Security/Clean_Space/ESA_commissions_world_s_first_space_debris_removal

281 "Space for the Environment: Space19+ Proposals," ESA, November 22, 2019, https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Space_for_the_environment_Space19_proposals.

282 Matt Williams, "An Upcoming ESA Mission Is Going to Remove One Piece of Space Junk from Orbit," Phys., December 13, 2019, https://phys.org/news/2019-12-upcoming-esa-mission-piece-space.html.

283 Henry, "Swiss Startup ClearSpace Wins ESA Contract"; Williams.

284 Andrew Parsonson, "ESA Signs Contract for First Space Debris Removal Mission," SpaceNews, December 2, 2020, https://spacenews.com/clearspace-contract-signed/.

(approximately $104 million USD) to pay for the mission.[285] In addition to the funding from the ESA, ClearSpace has raised €24 million from commercial investors to finance the mission.[286]

A Vespa payload adaptor from a 2013 ESA Vega rocket launch is the target for ClearSpace-1.[287] The agency describes the significance in choosing this target, "With a mass of 100 kg, the Vespa is close in size to a small satellite, while its relatively simple shape and sturdy construction make it a suitable first goal, before progressing to larger, more challenging captures by follow-up missions—eventually including multi-object capture."[288] The ESA describes the mission profile, "the ClearSpace-1 'chaser' will be launched into a lower 500-km orbit for commissioning and critical tests before being raised to the target orbit for rendezvous and capture using a quartet of robotic arms under ESA supervision. The combined chaser plus Vespa will then be deorbited to burn up in the atmosphere."[289] The use of robotic arms is very different from the other missions previously discussed. This method might be used on debris targets of various sizes and shapes, which could enable the capture of rocket bodies or other objects with unusual dimensions.

ClearSpace-1's and JAXA's CRD2 significance to future remediation efforts is considerable. These missions are not intended to perform small-scale technology demonstrations for research purposes; their objectives are the removal of debris targets resembling the massive derelicts posing significant risk in LEO. A successful removal of the Japanese rocket body and Vespa payload adapter will be a significant step forward for future remediation missions and give credibility to the overall remediation effort. If these programs are successful, it will also further validate public–private partnerships as a viable model for future efforts. The funding structure of these programs differs from the COTS model, the public partner primarily funds these efforts while COTS was co-financed.

285 Parsonson.

286 Parsonson.

287 ESA, "ESA Commissions World's First Space Debris Removal."

288 ESA.

289 ESA.

However, both these partnerships allow the private sector partner to design the technologies needed to complete the mission. They can leverage the strengths of their organizations to find the best solution. CRD2 and ClearSpace-1 show both public and private sector motivation to address the debris threat overseas; the United States must follow suit.

CRD2 and ClearSpace-1 show clear initiative on the part of JAXA and the ESA. These agencies recognize the threat of orbital debris and are reacting accordingly. However, the technologies to remediate debris in these programs are not high on NASA's TRL scale. This scale, in which 1 represents the lowest level of readiness, and 9 represents an operational system, shows much work must still be completed before these spacecrafts are ready for operations.[290] ClearSpace acknowledges the use of robotic arms to capture the Vespa payload adapter is innovative, but is unproven and has a low TRL.[291] Astroscale has not conducted its ELSA-d demonstration mission, nor its inspection flight of the target rocket body within the CRD program; therefore, the systems it is developing are far from operational as well. The United States possesses a TRL-9 capability in rendezvous and docking with the MEV, with the same systems being used in the RSGS spacecraft. Having established this capability means that any future effort on the part of the United States will have an advantage in this area of remediation systems. Additionally, the use of public–private partnerships, with RSGS domestically and the JAXA-ESA efforts internationally, further validate this model of project management for a domestic remediation program.

[290] Mai, "Technology Readiness Level."

[291] ClearSpace, *SOR Executive Summary Report*, CS-ESA-SOR-TD-005 (Ecublens, Switzerland: ClearSpace, 2020), 9, https://nebula.esa.int/sites/default/files/neb_study/2508/C4000128786ExS.pdf.

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V. A PATH FORWARD

This thesis has detailed the threat that space debris poses to U.S. satellites in orbit and the conditions that allowed that threat to grow. Furthermore. it examines barriers to implementing a debris remediation program. The recent growth in competition and capability in the commercial space sector now demonstrates the ability to overcome the barriers to remediation efforts, along with providing evidence that the United States possesses the talent and experience to develop the needed technologies. This chapter provides a path forward for a new public–private partnership to begin the development of remediation capabilities through the actions of Congress, the National Space Council, NASA, and international agreements. The remediation program components are all within reach; the nation must only make the decision to start.

A. CONGRESSIONAL ACTION

Bold action from Congress must provide the funding and framework for an ADR program to be built on, including legislation that will create enforceable regulations intended to eliminate debris-generating activities. National space policies and directives led to the creation of mitigation standards that eventually became commonplace internationally; yet, a lack of any enforcement mechanism to hold offending parties accountable has produced an untenable situation in orbit. A Clean Space Act passed by Congress should include funding for developing a domestic ADR capability. Both public and private research shows that ADR missions are necessary to stabilize congested orbits; compliance with current mitigation standards will not remove dangerous objects already in orbit. Building off the language in SPD-3, which directed the creation of a debris removal capability, Congress must budget for the needed systems to carry out ADR missions. The ESA has signed an €86 million (approximately $104 million USD) contract with ClearSpace to remediate the Vespa payload adapter in 2025; this figure can provide a starting point in terms of development cost, depending on the scale of the program to be initiated.[292] A budget of this size may be sufficient to begin the development of a remediation system to perform a demo mission in

[292] Parsonson, "ESA Signs Contract for First Space Debris Removal Mission."

orbit to validate the technology. Such success may lead to follow-on programs and larger budgets. If the National Space Council (NSpC) and NASA believe a larger scale effort is required earlier, additional funding may be needed. Considering satellite-based technologies drive $5 trillion in annual revenues domestically and are critical to national defense and homeland security capabilities, an initial investment of $100 million–$200 million for a remediation capability represents a wise decision.

A precedent for such congressional action can be found in the 1972 Clean Water Act (CWA); legislation passed to prevent municipal and industrial actions that led to the contamination of water resources.[293] Additionally, the new statutes should contain language that will indemnify the U.S. government of liability for any damage caused by commercially owned objects in orbit in violation of these statutes launched after implementation. The intention of a legislative act, such as the Clean Water Act, is to force industrial or municipal parties' compliance to a regulatory standard when that standard may not align with these parties' primary objectives. Claudia Copeland calls this type of legislation a "technology-forcing statute," due to the pressure it applies on regulated individuals or organizations to innovate to achieve compliance with established standards. This type of action from Congress can create an enforcement capability for executive branch departments to generate compliance with already established orbital debris mitigation standards. Both public and private launch and satellite providers would be forced to implement new technologies to comply with the new law. Regulatory pressure, like competitive pressure, would result in technical innovation on the part of both launch providers and satellite operators.

Regulatory changes that will force the U.S. space industry to develop new technologies, therefore increasing costs and reducing profit, will be met with resistance. A real-world example of such resistance occurred in April 2020, when the Federal Communications Commission (FCC) proposed regulatory changes that would reduce the risk of debris-generating events.[294] The proposed FCC rule change would have required satellite

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293 Claudia Copeland, *Clean Water Act: A Summary of the Law,* CRS Report No. RL30030, (Washington, DC: Congressional Research Service, 2016), 2, https://aquadoc.typepad.com/files/crs_cwa_18oct2016.pdf.

294 Alyssa K. King, *FCC Draft Rule Seeks to Limit Space Debris*, CRS Insight IN11342 (Washington, DC: Congressional Research Service, 2020), 1, https://fas.org/sgp/crs/space/IN11342.pdf.

operators to provide detailed probability assessments on the likelihood of collision and the successful post-mission disposal of satellites, require all satellites orbiting above 250 miles (ISS altitude) to have collision-avoidance maneuvering capability, provide detailed flight plans to the Air Force to ensure accurate tracking, indemnify the U.S. government for costs associated with any international liability claims, and post bonds to ensure post-mission disposal of satellites.[295]

Several companies, space industry trade groups, and the White House Science Committee vocalized their objections to the new FCC rules and argued that these changes would result in hardship for smaller satellite operators.[296] In particular, the Commercial Spaceflight Federation (CSF) argued that such changes would result in increased costs due to a required redesign of existing satellites and risk derailing U.S. leadership in the nascent global small-satellite market.[297] The NSpC, which the FCC is part of, agreed to delay the implementation of the FCC rule changes to preserve U.S. leadership in the global space industry.[298] This hesitancy to adapt to new regulations is identified as a common theme by Gerard and Lave; the lobbying by the CSF aligns with this research.[299]

However, the implementation of the Clean Air Act of 1970 faced similar resistance from the automotive industry, and that legislation was passed with "overwhelming congressional support."[300] Furthermore. as much as the automobile industry lobbied against the legislation, the new law led to the installation of catalytic converters on 80 percent of new cars manufactured in 1975 and more than a 50-percent reduction in hydrocarbons along with

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295 King, 1–2.

296 Caleb Henry, "FCC Urged to Delay Vote on New Space Debris Regulations," SpaceNews, April 17, 2020, https://spacenews.com/fcc-urged-to-delay-vote-on-new-space-debris-regulations/.

297 Eric W. Stallmer, C*SF Letter to Chairman Pai on Orbital Debris NPRM* (Washington, DC: Commercial Spaceflight Federation, 2020), 3, https://ecfsapi.fcc.gov/file/104161265605622/CSF%20Letter%20to%20Charman%20Pai%20on%20Orbital%20Debris%20NPRM.pdf.

298 Jeff Foust, "National Space Council in Discussions on FCC Orbital Debris Policies," SpaceNews, May 7, 2020, https://spacenews.com/national-space-council-in-discussions-on-fcc-orbital-debris-policies/.

299 David Gerard and Lester B. Lave, "Implementing Technology-Forcing Policies: The 1970 Clean Air Act Amendments and the Introduction of Advanced Automotive Emissions Controls in the United States," *Technological Forecasting and Social Change* 72, no. 7 (September 2005): 764, https://doi.org/10.1016/j.techfore.2004.08.003.

300 Gerard and Lave, 766.

a one-third reduction in carbon monoxide.[301] Research by Gerard and Lave suggests the Clean Air Act was successful in reducing emissions from newly manufactured automobiles because Congress set specific standards and did not delegate this responsibility to a regulatory agency.[302] Additionally, the implementation of specific performance standards versus technology standards may have contributed to the successful reduction in emissions.[303]

The economic and national threat that a loss of satellite capabilities presents necessitates Congress looking past lobbying from industry and passing a comprehensive Clean Space Act to give the executive branch the mandate to enforce compliance with debris mitigation standards. This new space marketplace would result in investments through not only a mandate, but also competition, since launch providers and satellite operators would be in a race against each other to gain an edge within the new regulatory environment. While satellite manufacturers may face the economic burden of implementing collision-avoidance systems or carrying additional fuel for end-of-life disposal, this legislative step is needed to trigger the industry to evolve into a sector that is sustainable for future operations.

B. NATIONAL SPACE COUNCIL

The NSpC, whose members include secretaries or administrators of NASA, the Department of Defense, Department of Transportation, Department of Commerce, and many other departments and agencies, steers space policy decisions affecting both commercial and public space programs. The U.S. Vice President chairs this council. With regard to the creation of a remediation program based on a public–private partnership model, the NSpC should establish NASA as the lead agency in coordinating this effort, based on the agency's past success using this framework. However, successes in the field of OOS and the knowledge gained thereof in the private sector and in partnership with the Department of Defense (DARPA specifically) should be leveraged as well. The NSpC should make every effort to incorporate technical data or personnel from related programs to stand up any ADR program. Again, these efforts must be focused on establishing a remediation capability, not specific

[301] Gerard and Lave, 766, 771.

[302] Gerard and Lave, 776.

[303] Gerard and Lave, 776.

technologies, in pursuit of ADR systems. This focus will allow for agility and innovation on the part of participating private sector partners and not limit their research and development to a narrow set of technological goals.

The NSpC must prioritize what debris targets should be remediated first and make their disposal a priority for any initial ADR effort. The massive and long-lived debris objects between 775 and 1,500 km in orbital altitude need to be the primary focus of these early missions. Research shows the amount of fragmentation generated and the longevity of that fragmentation present a threat greater than the risk of collisions in the lower altitudes of LEO. Once ADR missions begin the removal of these massive U.S.-owned objects in the higher regions of LEO, the NSpC can pursue a low-LEO capability and possibly leverage the breakthroughs already developed during initial ADR operations. While establishing a viable domestic remediation capability is the primary goal, the NSPC and the Department of State need to establish plans for cooperating with other nations to remove foreign-owned debris.

With a Congressional mandate requiring compliance to federal statutes pertaining to debris generating activities and post-mission disposal, the NSpC will be tasked with implementing the processes and procedures to gain compliance. It is imperative that any action taken by NSpC agencies should be in pursuit of compliance with performance standards in lieu of technology standards. This action falls in line with the research from Gerard and Lave, along with NASA reporting that shows the challenges pursuing specific designs presented to the Constellation program.[304]

The FAA and the FCC will play the largest role in the execution of new federal policy, with the former licensing launch activities and the latter licensing satellites in orbit. Both agencies should approach the execution of these policies with caution and in cooperation with the commercial sector to allow for compliance without stunting the growth of the evolving commercial sector. This approach may involve a grace period to develop the necessary capabilities to comply with the standards, a practice found in both the Clean Water Act and

[304] Gerard and Lave, 776; Jennifer L. Rhatigan, *Constellation Program: Lessons Learned*, vol. 1 (Washington, DC: National Aeronautics and Space Administration, 2011), 15, https://history.nasa.gov/SP-6127.pdf.

the Clean Air Act.[305] Building off a concept proposed by Joseph N. Pelton, the FAA could collect payment from launch providers upon licensing a launch to be deposited into an account in which remediation efforts could be funded.[306] Pelton elaborates that to encourage compliance with debris mitigation standards further, portions of these payments could be refunded to launch providers if it could be established that the launch did not generate any debris.[307] Furthermore. additional refunds should be administered to satellite operators who comply with mitigation standards and perform end-of-life maneuvers to deorbit satellites.

If launch providers of satellite operators do not comply with mitigation standards, the statutes passed by Congress gives these agencies the authority to assess fines. If an ADR capability proves viable, fines may be assessed to satellite operators who fail to remove their satellites within the required time window that results in a fee assessed periodically (month or annually). This method may put enough financial pressure on offending operators to pay for a removal mission instead of paying a one-time fee and leaving their hardware in orbit. Additionally, these regulations will force other satellite operators to invest in the necessary hardware to perform end-of-life maneuvers. The money spent by the auto industry to comply with the Clean Air Act is evidence that this type of pressure is effective in forcing industry to invest in new technology.

Additionally, the NSpC may examine a program of tax initiatives or grants for satellites providers to leverage to establish a maneuvering and deorbit capability to comply with standards. This method falls in line with the synergistic relationship the public and private space sectors have established over the past two decades. Federal assistance in developing commercial capabilities has proven successful at NASA in both large-scale programs, such as COTS, but also in initiatives that benefit smaller projects, such as the Small Business Innovation Research (SBIR) and the Small Business Technology Transfer (STTR)

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[305] Copeland, *Clean Water Act*, 2; Gerard and Lave, 767.

[306] Joseph N. Pelton, *New Solutions for the Space Debris Problem*, (New York: Springer International Publishing, 2015), 47.

[307] Pelton, 47.

programs.[308] Providing assistance to satellite operators or manufacturers that might not have the capabilities to comply with more stringent standards could allow them to keep their business domestically and not purchase services from foreign firms in an effort to circumvent the new statutes. This approach potentially addresses some of the concerns brought forth by the CSF that fears a mandate may drive business overseas in an effort to reduce costs. Furthermore, this type of program falls in line with previous national space policies that encouraged the growth of the commercial space sector.

For any initiatives the NSpC creates to gain compliance with a Clean Space Act, a periodic review of its effectiveness is imperative to ensure that these measures result in compliance with congressional statutes. However, these reviews need to ensure compliance in a manner with the least possible impact to private sector growth. These periodic evaluations should review the efficacy of fines as a method of compliance, in addition to the effectiveness of any initiative that uses bonds or deposits to fund remediation efforts. If remediation missions are no longer required due to increased compliance, Pelton suggests a sunset clause could be established to refund any deposited funds to contributing parties in the event those funds were no longer needed.[309] The creation of such a provision would demonstrate transparency on the part of the FAA and FCC (or any other agency charged with managing said fund) and illustrates that it is not simply an additional tax to be spent on efforts outside of the ADR mission.

C. NASA AND COMMERCIAL PARTNERS

NASA needs to utilize a public–private partnership model as a foundation for any ADR efforts. A partnership model based on NASA's COTS program should be developed once specific capabilities are identified. NASA should release a request for proposals to the commercial space industry in a process similar the COTS program. SpaceLogisitics/Northrop Grumman stands as a strong candidate for this type of partnership as DARPA is leveraging the success of the MEV for the RSGS spacecraft. NASA has an opportunity to do the same

[308] "NASA SBIR & STTR Program Homepage," SBIR, accessed March 30, 2021, https://sbir.nasa.gov/.

[309] Pelton, *New Solutions for the Space Debris Problem*, 46.

but it should focus on remediation. However, seeking multiple proposals from industry and utilizing the experience and talent of the whole sector may result in multiple viable options. By reviewing multiple proposals, NASA has an opportunity to spread research and development funding with more than one partner, depending on the level of appropriated funds. It is in the agency's best interest to keep its options open and review multiple proposals and leverage the innovation in the private sector that it helped evolve.

The proposals submitted by industry need to be comprehensive and include the details of the technologies needed to develop the proposed system, a management plan on how the company will run the program, and how the commercial end of development funding will be provided. In providing a complete picture of the program, NASA can make better determinations of viability. Program management needs to avoid the "technology first" mindset that has been identified as a factor in program delays and cost overruns.[310] Commercial partners should be selected based on the strength of all aspects of their proposals. This method served NASA well during COTS and should be utilized again. Once selections have been made, both sides of the partnership should develop a schedule with agreed upon milestones to review progress and distribute funding. This method will hold both parties accountable and allow all parties involved better situational awareness of the entire program. Once development is complete, the responsibility of remediation missions will fall to the commercial partners utilizing fixed-priced contracts for services in a marketplace where NASA is one of many customers paying for ADR services. Such a marketplace represents the embryonic stage of a new line of services that will be available to satellite operators. Iridium Communications stated it would pay for remediation services for 30 of its inoperable satellites currently in LEO, which demonstrated the beginning of a customer base for commercial ADR services.[311]

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[310] Paul K. Martin, *NASA Cost and Schedule Overruns: Acquisitions and Program Management Challenges* (Washington, DC: NASA Office of Inspector General, 2018), 2, https://oig.nasa.gov/docs/CT-18-002.pdf.

[311] Caleb Henry, "Iridium Would Pay to Deorbit Its 30 Defunct Satellites—for the Right Price," SpaceNews, December 30, 2019, https://spacenews.com/iridium-would-pay-to-deorbit-its-30-defunct-satellites-for-the-right-price/.

The structure of the program should include a program office located at Goddard Spaceflight Center in Greenbelt, Maryland. Goddard is the logical location for the program office, given that most of the NASA expertise needed for this effort will be located at this center. This NASA center is currently working on the OSAM program; the knowledge and experience related to the OOS technologies of this program can be applied to the ADR mission. Programs of note that involve complex autonomous or robotic systems include the Curiosity (Mars Science Laboratory) rover and the OSIRIS-REx spacecraft; the latter briefly landed on an asteroid passing near Earth in October 2020 and collected a sample to bring back.[312] The NASA Jet Propulsion Lab in Pasadena, California, employs personnel with additional experience and expertise in related projects. Robotic missions developed at this facility include the Spirit, Opportunity, Pathfinder, and Sojourner Mars rovers. In addition, the planned Europa Lander mission is looking for life on one of Jupiter's icy moons.[313] Both NASA and any commercial partners can utilize the expertise found at research facilities within these centers as a model of shared learning, which the literature on public private partnerships highlights as a contributor to success.[314]

Between inoperable satellites and derelict rocket bodies, the United States owns 41 objects (21 rocket bodies and 20 payloads) between the orbital altitudes of 650 and 1,500 km, which should be the initial target list for the program.[315] These orbits contain both massive debris objects and a high density of debris that necessitate ADR operations. The mass of the objects in these orbits would result in large amounts of fragments generated during a collision, and the density of the debris population increases the likelihood of a collision.

To maximize the innovation, talents, and technical strengths of potential commercial partners, exact design specifications for remediation spacecraft must be avoided to circumvent

[312] Rob Garner, "Goddard Missions—Present," National Aeronautics and Space Administration, October 6, 2015, http://www.nasa.gov/content/goddard-missions-present; Jeff Foust, "OSIRIS-REx Safely Stores Asteroid Sample," SpaceNews, October 30, 2020, https://dev.spacenews.com/osiris-rex-safely-stores-asteroid-sample/.

[313] "Missions," NASA Jet Propulsion Laboratory—California Institute of Technology, accessed December 3, 2020, https://www.jpl.nasa.gov/missions/.

[314] Berry et al., *The Effectiveness of Partnership Working in a Crime and Disorder Context*, 22.

[315] Darren McKnight, Rohit Arora, and Rachel Witner, "Intact Derelict Deposition Study," 3, 6.

the identified design challenges of the Constellation program as discussed Chapter II. These lessons were applied during COTS with positive results. The commercial partners designed and delivered spacecraft capable of cargo deliveries to the ISS without specific design requests from NASA. Considering the success of this decision in COTS, this remediation program should follow suit and not specify remediation methods.

D. INTERNATIONAL ACTIONS

While the threat of space debris is global, the United States must lead in efforts to combat it. Several nations own the debris currently residing in orbit, and many nations would feel the effect in any reduction of services due to a collision event. While no global response has addressed this issue, Megan Ansdell proposes that an international response is not ideal for remediation but should be led by one country. As Ansdell notes, "This [U.S. leadership] would accelerate technology development and demonstration, which would, in turn, build up trust and hasten international participation in space debris removal."[316] The United States has a chance to lead the global effort in remediation; it does not have to concede this role to Japan or the European Union. Furthermore. the 2020 National Space Policy calls for the United States to take the lead in the development of innovative space technologies. This policy calls on the federal government to "preserve and expand United States leadership in the development of innovative space technologies, services, and operations. Work with likeminded international and private partners, to prevent the transfer of sensitive space capabilities to those who threaten the interests of the United States, its allies, and its supporting industrial base."[317] This policy demonstrates that leadership in a field, such as debris remediation, represents a national imperative.

The United States can establish a leadership role by working with a state that has a history of cooperation with the United States, Russia. The research shows that while the United States owns debris residing in at-risk orbits, Russia owns a much higher percentage. Russia owns 137 massive derelict objects in the at-risk region of LEO, which far outnumbers

316 Ansdell, "Active Space Debris Removal," 18.

317 White House, *National Space Policy*, 6.

the 41 U.S. objects.[318] Removal of foreign-owned objects will be necessary to mitigate the risk of collision in these orbits. No U.S. remediation program can remove these debris objects without either permission from the owning-state or an update to existing international treaties. While the United States and Russia may publicly disagree on many topics, space operations have been an area of cooperation for years. The joining of an American Apollo spacecraft and a Soviet Soyuz in orbit during 1975 changed the nature of the space race between the two nations.[319] The ISS is the greatest example of cooperation between the two states. The cooperation in the ISS has been the result of the United States treating the Russians as equals in space as opposed to rivals and has taken an approach of working toward common goals to foster better relations.[320] The threat of space debris affects all spacecraft in orbit; debris remediation can be a further example of working toward a common and mutually beneficial goal. Future research should examine potential diplomatic resolutions that will allow for U.S.-Russian cooperation for the remediation of hazardous Russian debris and provide a framework to be applied for joint operations with other states as well. Further momentum will be gained if the United States and Russia can come to agreement concerning the removal of massive Russian debris in the higher regions of LEO.

Beyond U.S.-Russian cooperation to remove specific debris objects, international treaties and agreements must be amended or updated to address the realities of the debris issue. This action becomes especially necessary if the ESA, JAXA, and NASA field ADR programs. The United Nation's Committee on the Peaceful Uses of Outer Space (UNCOPUOS) should address the issues of ownership of derelict objects, clarify ownership of objects when multiple states are involved in a launch, and update liability for damages given the growth of the commercial space sector. All the previous issues were highlighted as significant challenges in the literature reviewed for this thesis. Specifically, updates to Article

[318] Darren McKnight, Rohit Arora, and Rachel Witner, "Intact Derelict Deposition Study," 3, 6.

[319] Anatoly Antonov, "With the Apollo-Soyuz Handshake in Space, the Cold War Thawed a Little," *Air & Space Magazine*, July 15, 2020, https://www.airspacemag.com/space/apollo-soyuz-cold-war-thawed-little-180975321/.

[320] Caleb Costa, "Space: The Last Frontier of Russian-American Cooperation," *Southern California International Review* 10, no. 1 (2020): 52.

VIII of the Outer Space Treaty, along with the 1972 Liability Convention and the 1974 Registration Convention, may resolve the issues highlighted previously.

The United Nations has successfully created international agreements regarding the protection of the environment and natural resources, with the 1972 London Convention being a standout example. This agreement, formally titled the "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter," provides a mechanism requiring ratifying states to create statutes and regulations to protect the planet's water resources from dumping.[321] This convention provides definitions on what activities constitutes dumping. It also created authorities to enforce these standards and ensured flagged vessels were equipped and able to comply with these standards.[322]

The UNCOPUOS should pursue the creation of an international convention to prevent future pollution of the orbital environment using the 1972 London Convention as a precedent. This convention must contain specific definitions on what actions constitute dumping in orbit, require signatory states to create an authority to enforce standards, and update the liability of states regarding the collision of commercially owned payloads. The committee should examine existing orbital debris mitigation standards along with current research on the debris environment to ensure that any standards created are sufficient to cope with the increased volume of satellite traffic due to the growth of the commercial satellite and launch industry. If the United States is successful in the creation of its own Clean Space Act domestically, this act will place the state in a position to act as a global leader in this new initiative. The United States at the forefront of such an effort will not only align with domestic space policy calling for the nation to lead in international space efforts, but also ensure that U.S. interests are protected as much as possible in any such agreement.

E. CONCLUSION

This thesis provides evidence that a public–private partnership between NASA and the commercial space sector demonstrates the quickest and most cost-effective method to take

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[321] Convention on the Prevention of Marine Pollution of Wastes and Other Matter, *Treaty Series* 1046, no. I–15749 (1977): 138.

[322] Convention on the Prevention of Marine Pollution of Wastes and Other Matter, 140–42.

the necessary step to remediate space debris. To begin this effort, Congressional action is needed to provide funding and a legal basis for the program. Just as Congress created legislation to protect terrestrial resources, the threat of space debris merits similar action to protect U.S. assets in orbit. A Clean Space Act must be passed. Furthermore. this type of direct action will enable government agencies to regulate compliance to mitigation standards, the lack of which has resulted in the current untenable situation in LEO. Only through a Clean Space Act will the United States be able to begin ADR missions and reinforce the necessary behaviors from space operators to mitigate this threat.

The NSpC must work hand in hand with the commercial sector to bring operators into compliance with new regulations regarding debris mitigation and ADR requirements in a manner that does not financially cripple these companies. Federal regulators and the commercial sector have a history of finding common ground to protect the environment in a manner that is beneficial to both sides, with the Clean Air and Clean Water Acts being examples. Allowing grace periods to develop the necessary capabilities for compliance, providing grants or tax incentives to offset developmental costs, and encouraging the development of commercial ADR capabilities, the NSpC will increase the sustainability of domestic space operations and open up additional revenue streams for commercial operators.

After Congress and the NSpC build the necessary framework, NASA must utilize the proven public–private partnership model to develop a domestic ADR capability. The joint-funding approach pioneered in the COTS program, which resulted in shorter development schedules and lower costs, should be leveraged as well. In addition, NASA must avoid the pitfalls of the Constellation program and allow latitude and innovation from commercial partners to meet the requirements of the program. This model transformed SpaceX into a dominant force in the commercial sector and provided NASA, along with commercial customers, with reduced costs to orbit. A similar approach for ADR can ensure U.S. leadership in this new marketplace, while providing the most cost-effective solution for ADR customers.

A domestic ADR marketplace will be constrained until the United States takes the lead in pursuing an update to existing international agreements. Foreign ownership of debris objects and the challenges it presents threatens the safety of all satellites in orbit, and this matter cannot be adequately addressed until amendments are made to Article VIII of the Outer

Space Treaty. Furthermore. the United States must pursue new agreements on liability to adapt to the growth of the global commercial space sector. Gaining Russian cooperation is a key element to the success of any effort to update international agreements regarding debris remediation. Not only is Russia a large player in the UNCOPUOS, it is also the owner of a significant portion of the debris in critical LEO orbits. The United States must find a way to incentivize Russian cooperation in these efforts; otherwise, any ADR efforts will be unable to remove enough of the dangerous objects necessary to significantly reduce the risk of a catastrophic collision. Through the U.S. State Department, NASA, and the UNCOPUOS, the United States must find common ground with Russia in ADR efforts either through technology sharing or financial incentives.

The United States has the financial strength and the technical expertise needed to begin ADR development to safeguard critical U.S. assets and services. The nation has relied on space operators to adhere to mitigation standards in a voluntary manner. This method, both domestically and internationally, has led the debris population to reach a tipping point. Now is the time for the United States to take direct action to develop an ADR capability and lead an international effort not only to remove existing hazardous debris, but also to do so in a manner that will allow for further growth in the U.S. commercial space sector and allow the nation to maintain leadership in the space domain. The services and capabilities that U.S. satellites provide are too valuable to delay any further in addressing this clear and present threat to the nation's economy and security.

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