NASA

National Aeronautics and Space Administration

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NASA's Efforts to Mitigate the Risks Posed by Orbital Debris

January 27, 2021

Report No. IG-21-011

Office of Inspector General

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Results in Brief

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IG-21-011 (A-20-002-00)

Why We Performed This Audit

Orbital debris is defined as human-made objects in space that no longer serve a useful purpose, such as decommissioned satellites and parts of spacecraft. This debris—also known as "space junk"—lingers above the Earth's atmosphere for years until it decays, deorbits, explodes, or collides with another object thus creating more debris. The amount of orbital debris has increased exponentially over the last 60 years due to (1) accumulating and increasing amounts of satellites and other objects launched into space by public, civil, and private entities from around the globe and (2) intentional and accidental spacecraft explosions and collisions.

Millions of pieces of orbital debris exist in low Earth orbit (LEO)—at least 26,000 the size of a softball or larger that could destroy a satellite on impact; over 500,000 the size of a marble big enough to cause damage to spacecraft or satellites; and over 100 million the size of a grain of salt that could puncture a spacesuit. Moreover, the growing volume of orbital debris threatens the loss of important space-based applications used in daily life, such as weather forecasting, telecommunications, and global positioning systems that are dependent on a stable space environment. At NASA, the Orbital Debris Program Office (ODPO), funded by the Office of Safety and Mission Assurance, has taken the national and international lead in conducting measurements of the debris environment and in developing the technical consensus for adopting mitigation measures.

In this audit, we evaluated NASA's efforts to mitigate the risks posed by orbital debris as well as the Agency's coordination and communication efforts with international and commercial organizations to address the issue. To complete this work, we interviewed representatives from NASA, the U.S. Department of Defense (DOD), and the commercial sector; reviewed federal laws, regulations, policies, and reports related to orbital debris; and assessed a sample of Orbital Debris Assessment Reports (ODAR), End of Mission Plans (EOMP), and supporting documentation to ensure they met NASA requirements.

What We Found

Given the rapid increase of space activity worldwide and the current state of orbital debris in LEO, international space agencies and the scientific community agree that mitigation-only activities focused solely on prevention are not sufficient to stabilize the orbital debris environment. Rather, to effectively address the orbital debris issue, global mitigation and strategic remediation efforts are necessary. Multiple studies have found that the growth of debris in LEO can be slowed by ensuring that at least 90 percent of all spacecraft are removed from orbit within 25 years of the end of their mission, and at least five defunct spacecraft (that will not deorbit on their own) are actively removed from orbit every year.

NASA's consistent position is that preventing future debris will have greater impact on mitigating orbital debris risks than pursuing development of costly remediation technologies. Although NASA's compliance rate for end-of-mission disposal within 25 years stands at approximately 96 percent over the last decade, the global compliance rate has only averaged between 20 to 30 percent—much lower than the 90 percent required to slow the rate at which debris is generated in LEO. Despite presidential and congressional directives to NASA over the past decade to develop active debris removal technologies, the Agency has made little to no progress on such efforts. Moreover, debris removal technologies from international agencies and commercial entities are in the early stages of development and testing.

We found that NASA models of the orbital debris environment lack sufficient data, putting the Agency at risk of under- or over-protecting spacecraft from debris. For objects larger than 3 mm, ODPO's data is limited by the decreasing amount of time available on the three radars it uses to detect and statistically estimate debris due to funding, inoperable equipment, and competing priorities from multiple users. ODPO has also been unsuccessful in securing a source of measurement data on debris 3 mm and smaller in the 400 to 1,000 km range of LEO with failed missions and others canceled due to a lack of funding, a shortcoming particularly concerning because millimeter-sized orbital debris represents the highest penetration risk to most missions operating in LEO. In addition, NASA does not have the ability to track debris smaller than 10 cm in the range of LEO where the International Space Station resides and plans to rely on DOD's Space Fence to track such debris. However, this ground-based radar system has not yet reached full operational capability, leaving the Station's critical elements vulnerable to damage from this size debris.

Finally, NASA evaluates ODARs and EOMPs to ensure programs and projects are complying with Agency orbital debris requirements, such as limiting the generation of debris and disposing of spacecraft safely. While the Agency has made improvements to this evaluation process, we found that ODARs and EOMPs were not consistently submitted to the Office of Safety and Mission Assurance in a timely manner (with some submitted nearly a year late), and the process used to route the reports for approval was laborious. Delays in providing the documentation for review could result in a missed opportunity for alternative or low-cost fixes to address mitigation issues.

WHAT WE RECOMMENDED

To better protect spacecraft, maintain the space environment, and address a top Agency risk to obtain direct measurements of millimeter-sized debris, we recommended NASA's Administrator: (1) lead national and international collaborative efforts to mitigate orbital debris including activities to encourage active debris removal and the timely end-of-mission disposal of spacecraft; (2) collaborate with Congress, other federal agencies, and partners from the private and public sectors to adopt national and international guidelines on active debris removal and strategies for increasing global compliance rates for timely removal of spacecraft at the end of a mission; (3) invest in methods and technologies for removing defunct spacecraft; and (4) prioritize obtaining direct measurements needed to fill the 3 mm and smaller sized debris gap at the 600 to 1,000 km altitude in LEO. In addition, we recommended NASA's Chief of Safety and Mission Assurance: (5) explore alternative orbital debris radar assets to fill the data gaps caused by the increased costs of utilizing existing radars and the loss of legacy assets; (6) explore commercial alternatives to obtaining information on debris smaller than 10 cm until Space Fence becomes fully operational; and (7) coordinate with Mission Directorate officials to develop and document a formal signature process that clarifies needs and expectations and supports the timely delivery of ODARs and EOMPs prior to key decision point reviews.

We provided a draft of this report to NASA management, who concurred with Recommendations 5 and 7; partially concurred with Recommendations 1, 2, 3, and 4; and non-concurred with Recommendation 6. We consider management's comments responsive to Recommendations 5 and 7; therefore, those recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions. However, for the remaining recommendations we found the Agency to be unresponsive and therefore those recommendations will remain unresolved pending further discussions with the Agency. Overall, we found management's responses to these five recommendations lacking in initiative and urgency to lead and collaborate with partners to encourage active debris removal, invest and evaluate methods and technologies for removing defunct spacecraft, prioritize obtaining direct measurements of millimeter-sized debris, and explore alternatives to obtaining information on smaller but potentially dangerous orbital debris.

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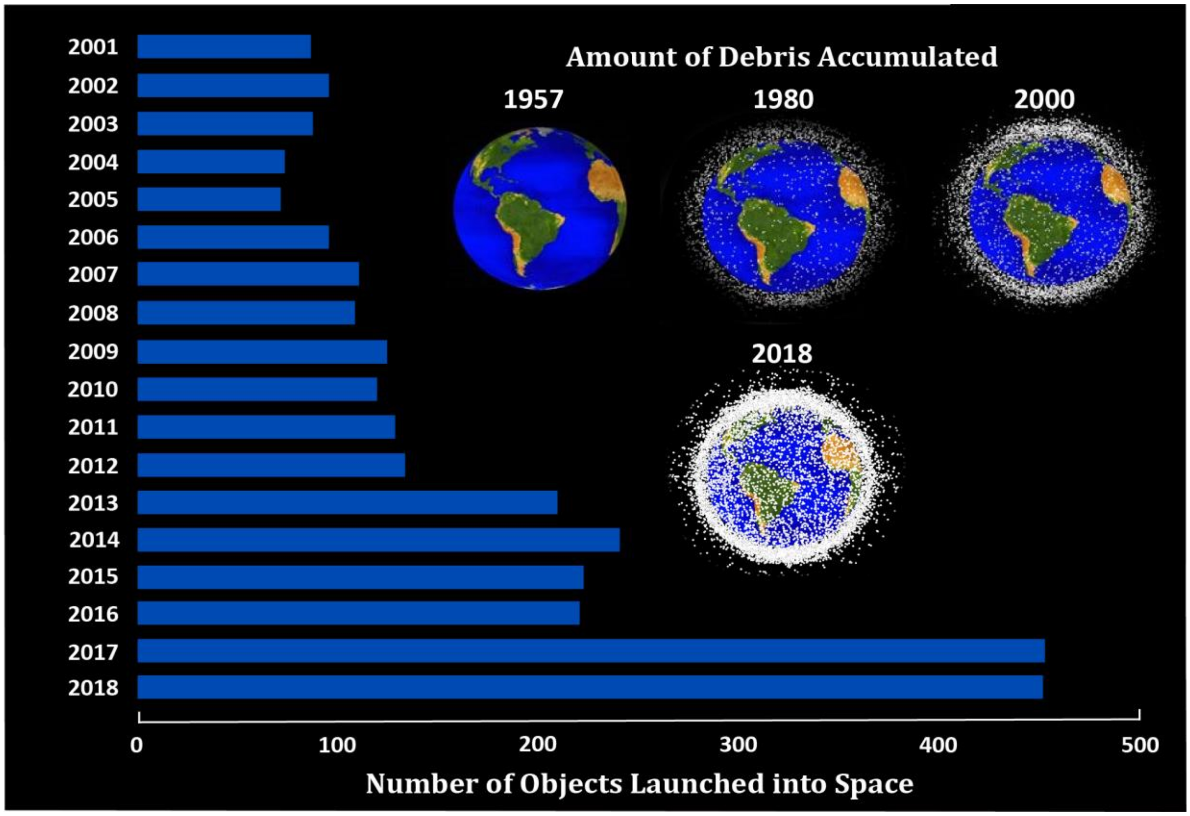
Acronyms

cm	centimeter
DARPA	Defense Advanced Research Projects Agency
DOD	U.S. Department of Defense
EOMP	End of Mission Plan
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FY	fiscal year
HAX	Haystack Auxiliary Radar
HUSIR	Haystack Ultrawideband Satellite Imaging Radar
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
km	kilometer
LEO	low Earth orbit
MAVEN	Mars Atmosphere and Volatile Evolution
mm	millimeter
NOAA	National Oceanic and Atmospheric Administration
NPR	NASA Procedural Requirements
ODAR	Orbital Debris Assessment Report
ODMSP	Orbital Debris Mitigation Standard Practices
ODPO	Orbital Debris Program Office
OIG	Office of Inspector General
OSAM-1	On-orbit Servicing, Assembly, and Manufacturing 1
OSIRIS-REx	Origins Spectral Interpretation Resource Identification Security—Regolith Explorer
OSMA	Office of Safety and Mission Assurance

INTRODUCTION

Orbital debris, or space junk, is defined as human-made objects in space that are no longer serving a useful purpose, such as decommissioned satellites or upper stages of launch vehicles jettisoned during a rocket launch. This debris lingers above the Earth's atmosphere for years until it decays, deorbits, explodes, or collides with another object thus creating more debris. As shown in Figure 1, the amount of orbital debris has increased exponentially over the last 60 years due to (1) accumulating and increasing amounts of objects such as satellites launched by public, civil, and private entities from across the globe and (2) intentional and accidental spacecraft explosions and collisions.[1] For example, in 2007 China conducted an anti-satellite test that used a missile to destroy an old weather satellite, turning a single large piece of debris (the defunct satellite) into more than 3,000 smaller pieces. Additionally, in 2009 a defunct Russian satellite inadvertently collided with and destroyed a functioning U.S. Iridium commercial satellite, generating more than 2,000 pieces of debris.

Figure 1: Number of Objects Launched into Space Compared to Estimated Amount of Debris Accumulated Over Time



Source: NASA Office of Inspector General (OIG) presentation of United Nations Office for Outer Space Affairs data and Orbital Debris Program Office information.

Note: Objects launched into space include satellites, rocket bodies, and launch vehicles.

[1] A spacecraft is an object designed to travel to and operate in space. In this report, the term spacecraft is used to encompass satellites, telescopes, rocket bodies, and rocket upper stages.

Millions of pieces of orbital debris exist today—at least 26,000 of which are the size of a softball or larger that could destroy a satellite on impact; over 500,000 of these are the size of a marble big enough to cause damage; and over 100 million are the size of a grain of salt that could puncture a spacesuit—amplifying the risk of catastrophic collisions to spacecraft and crew. Moreover, the growing volume of orbital debris threatens the loss of important space-based applications used in daily life, such as weather forecasting, telecommunications, and global positioning systems that are dependent on a stable space environment. Orbital debris is a global concern with stakeholders across public, civil, and private sectors who have adopted an array of guidelines, standards, and policies to limit the generation of future debris. However, global compliance with these guidelines, standards, and policies remains low, and global remediation activities designed to remove existing debris from space are limited and largely in the planning phases of development. At NASA, the Orbital Debris Program Office (ODPO) has taken the national and international lead in conducting measurements of the orbital debris environment and in developing the technical consensus for adopting mitigation measures to protect the users of space.

We evaluated NASA's efforts to mitigate the risks posed by orbital debris—human-made objects in space that are no longer serving a purpose—as well as the Agency's coordination and communication efforts with international and commercial organizations to address the issue. See Appendix A for details of the audit's scope and methodology.

Background

Human influence in space has boomed in the last 20 years, vastly increasing the number of objects launched into orbit. For example, in 2018 Space Exploration Technologies Corporation (SpaceX) received approval from the Federal Communications Commission (FCC) to launch up to 12,000 communication satellites. In October 2019, the company requested permission to launch an additional 30,000 satellites.[2] Further, the development of smaller satellites known as CubeSats has decreased the cost of access to space and made it possible for nonprofits, startups, and even amateur enthusiasts and students to launch objects into orbit.[3] However, as more spacecraft are launched the likelihood of satellite collisions creating orbital debris also increases. In addition, countries that accidentally or intentionally destroy satellites compound the debris problem. For example, in March 2019 India conducted an anti-satellite test using a missile to destroy its own satellite, creating a cloud of debris that NASA and other satellite operators said posed a risk to the International Space Station (ISS or Station) and other active assets. Furthermore, non-operational spacecraft pose a threat to the space environment as evidenced in October 2020 when a defunct Soviet satellite narrowly missed a discarded Chinese rocket booster—a collision that could have produced thousands of pieces of orbital debris. The increase in launches and debris raises concerns about the likelihood of a "Kessler syndrome"

[2] The FCC, on behalf of SpaceX, requested permission from the International Telecommunication Union to launch both sets of satellites. This organization is the United Nations agency for information and communication technologies. The agency allocates global radio spectrum and satellite orbits, develops the technical standards that ensure networks and technologies seamlessly interconnect, and strives to improve access to information and communication technologies to underserved communities worldwide.

[3] A CubeSat is a type of miniature satellite used for research typically the size of a Rubik's cube (10 cm x 10 cm x 10 cm) and weighing less than 3 pounds.

event—a cascading series of orbital collisions that could curtail human access to space for hundreds of years.[4]

As of January 2020, the amount of debris orbiting the Earth exceeded 8,000 metric tons, which is equivalent to the weight of approximately 727 school buses. This debris is composed of parts of old satellites, such as bolts or paint chips, as well as entire defunct satellites and rocket bodies. The debris is for the most part located in low Earth orbit (LEO), defined as the region from Earth's edge to 2,000 kilometers (km) altitude, or about 1,200 miles above the ground.[5] Most NASA satellites and the ISS orbit Earth in the 400 to 1,000 km range of LEO. While the debris varies in size and shape, it all is considered a threat to human space flight and robotic missions as shown in Table 1. Orbital debris circles the Earth at speeds of about 7 to 8 km per second (approximately 17,500 miles per hour). However, the average speed at which one object impacts another in space is approximately 10 km per second—more than 10 times faster than a bullet. At these speeds, even millimeter-sized debris pose a threat. In fact, the highest mission-ending threats to robotic spacecraft are not from large debris, but rather impacts from millimeter- to centimeter-sized (mm to cm) objects because such debris is too small to be detected and operators are unable to change course or move spacecraft to avoid it.

Table 1: Size, Amount, and Potential Risk of Orbital Debris

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

Source: NASA OIG depiction of ODPO data.

[4] The Kessler syndrome, proposed by NASA scientist Donald J. Kessler in 1978, is a theoretical scenario in which the density of objects in low Earth orbit due to space pollution is high enough that collisions between objects could cause a cascade in which each collision generates additional space debris that increases the likelihood of even further collisions.

[5] Orbital regimes include LEO—the region from Earth to 2,000 km altitude; medium Earth orbit—an altitude between 2,000 to 35,000 km; and geosynchronous Earth orbit—about 36,000 km altitude. NASA, https://www.orbitaldebris.jsc.nasa.gov/photo-gallery.html, and the Center for Strategic and International Studies, https://aerospace.csis.org/aerospace101/popular-orbits-101/ (last accessed October 9, 2020).

The higher the altitude, the longer the orbital debris will typically remain in the Earth's orbit. Debris in orbits below 600 km normally fall back to Earth within 25 years, either burning up in the atmosphere or landing on the Earth's surface (mostly commonly in bodies of water). At altitudes of 800 km and above, the time that debris can remain in orbit is often measured in centuries. Debris can leave the orbital environment in two ways: (1) by deorbiting (getting dragged into the atmosphere by friction over time or getting "driven" into the atmosphere by spacecraft owners and operators) or (2) by getting propelled out of the Earth's orbit. If not deorbited in a timely manner, debris can decay (breakup or fragment due to prolonged radiation exposure), explode (independently because of onboard propellants and batteries), or collide with another object, all of which generates more debris.

Efforts to address the risks posed by orbital debris fall mainly into two categories: mitigation and remediation. Mitigation refers to attempts to prevent future debris generation through the design, operation, and post-mission disposal of spacecraft to ensure they do not explode or collide with other objects. Remediation refers to active removal of debris, including defunct spacecraft, before it explodes, collides, or fragments in orbit.

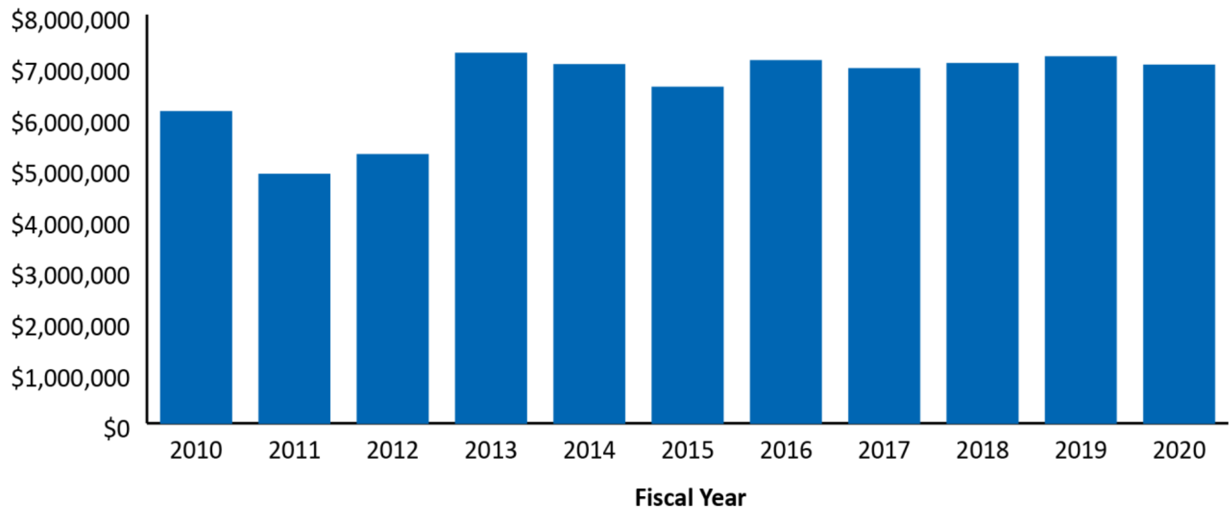
NASA's Efforts to Address Orbital Debris

NASA's approach to addressing the risks from orbital debris includes four separate but interrelated efforts: (1) characterizing the orbital debris environment; (2) protecting missions, spacecraft, and crews; (3) limiting and preventing the generation of orbital debris; and (4) coordinating and communicating with federal agencies, commercial entities, and international stakeholders.

These efforts are conducted and coordinated by multiple organizations within the Agency; however, primary responsibility for assisting NASA in understanding the orbital debris environment and the risks to both spacecraft and the environment resides with ODPO at Johnson Space Center. Established in 1979, ODPO is the only organization in the U.S. government conducting a full range of research on orbital debris issues and is considered the worldwide leader in orbital debris characterization including measuring, modeling, and describing the distinct nature of debris; assessing and mitigating risk; and developing policy. ODPO's primary roles and responsibilities include conducting research to develop, maintain, and update tools in orbital debris risk assessments; supporting missions with technical assessments and evaluations; assisting federal, commercial, and international entities with risk assessments and mitigation efforts; and contributing to the determination, adoption, and use of international orbital debris guidelines.

The Office of Safety and Mission Assurance (OSMA) at NASA Headquarters funds ODPO and as shown in Figure 2, consistent with prior years, the budget for fiscal year (FY) 2020 is approximately $7 million. Currently, the office employs 7 civil servants and approximately 20 full- and part-time contractor employees.

Figure 2: Orbital Debris Program Office Budget History, FYs 2010 through 2020



Source: NASA OIG presentation of OSMA budget data.

Characterizing the Orbital Debris Environment

The U.S. Department of Defense (DOD) and ODPO collaborate to determine the amount of debris orbiting Earth, dividing responsibilities by the size of debris. DOD monitors, catalogs, and tracks debris 10 cm and larger in LEO through the U.S. Space Surveillance Network—a collection of over 30 ground-based radars and optical telescopes located worldwide, plus 6 satellites in orbit.[6] Monitoring objects in space means that DOD can, at any given time, obtain a real-time view of objects in a particular part of LEO. Tracking and cataloging involves identifying the specific objects being monitored and predicting where they will be over the next 24 to 72 hours.

For its part, ODPO uses ground-based radars, optical telescopes, and examination of returned spacecraft to sample and statistically estimate the amount of debris in LEO smaller than 10 cm because such debris is too small for DOD or NASA to track. NASA relies on three ground-based radars to estimate debris smaller than 10 cm (see Figure 3). These radars statistically sample the debris population by "staring" at selected portions of the sky and detecting debris flying through the field-of-view. Two of the radars—Haystack Ultrawideband Satellite Imaging Radar (HUSIR) and Haystack Auxiliary Radar (HAX)—are operated by the Massachusetts Institute of Technology's Lincoln Laboratory at their Space Surveillance Complex in Westford, Massachusetts. HUSIR has been collecting orbital debris data for ODPO since 1990 and HAX since 1994 under an agreement with DOD. The third radar—Goldstone Radar (Goldstone)—is a part of the Goldstone Deep Space Communications Complex located in California's Mojave Desert. Operated by the Jet Propulsion Laboratory, the Goldstone complex consists of eight operational antennas, two of which have been collecting orbital debris data for ODPO since 1990.[7]

[6] DOD also tracks debris 1 meter and larger in geosynchronous Earth orbit.

[7] The Goldstone Deep Space Communications Complex, one of three complexes around the world that comprise what is known as the Deep Space Network, provides the ability to communicate with spacecraft not only in orbit around the Earth, but also in the farthest reaches of our solar system.

Figure 3: HUSIR, HAX, and Goldstone Radars

The image to the left includes the Haystack Ultrawideband Satellite Imaging Radar (HUSIR), which is the larger dome covered antenna, and the Haystack Auxiliary Radar (HAX), which is the smaller dome covered antenna. The image to the right is of the Goldstone Radar Complex.

Source: Massachusetts Institute of Technology Lincoln Laboratory (left image) and NASA/Jet Propulsion Laboratory (right image).

In addition to these radars, ODPO uses telescopes to obtain optical measurements that compliment radar measurements by yielding a more comprehensive description of individual debris pieces and the space environment. Finally, returned spacecraft surfaces, such as those from NASA's Space Shuttle that operated from 1981 through 2011, provide OPDO insight into micrometer-sized particles in the orbital debris environment.

ODPO uses statistical estimates of debris that are detected but cannot be tracked (smaller than 10 cm) and DOD's data on tracked debris to create models of the orbital debris environment. The models include data on the amount, location, and type of debris in the environment and are used by most NASA programs and many spacecraft designers and operators worldwide to assess the risks of debris colliding with their spacecraft. ODPO periodically updates its engineering models to more accurately reflect the current debris environment, including the addition of data on intentional and accidental explosions that increase the amount of debris as well as information on the material types and density of individual debris. Updates to the engineering models have been released three times—in 2002, 2013, and 2019—since the first model was released in 1996. According to ODPO, the next update is expected in about 5 years and will incorporate the element of debris shape into the models, which will allow NASA to better predict impact damage and risks to spacecraft that could be caused by debris of differing shapes. In addition to the engineering models, ODPO has a more forward-looking model it uses to predict the future debris environment.[8]

Protecting Missions, Spacecraft, and Crews

Spacecraft are subject to orbital debris impact damage, which has the potential to degrade performance, shorten the mission, or result in catastrophic loss of the vehicle or crew. To protect

[8] The Leo-to-Geo Environment Debris Model is a three-dimensional evolutionary model for the study of the long-term debris environment. The main function of the model is to provide an understanding of how the orbital debris environment—including all sizes of detected and tracked debris—will evolve in the future.

spacecraft, NASA has a dedicated team that conducts hypervelocity impact tests to assess the risk presented by orbital debris by simulating its impact on spacecraft shielding, components, and materials and develops new materials and shielding to provide better protection. The data gathered from these tests provides the link between the environment defined by ODPO's models and the risk presented by that environment to operating spacecraft. Based on the research and results of the tests, ODPO quantifies the risk and makes recommendations to program and project management teams that make decisions regarding the design and operational procedures to reduce risk to their projects.

Once spacecraft are operational, NASA has additional processes in place to help them avoid accidental collisions with orbital debris. The Conjunction Assessment Risk Analysis group at Goddard Space Flight Center, along with DOD, provides conjunction assessment services—the real-time process of assessing risk posed by close approaches—for NASA's uncrewed spacecraft and robotic missions as well as for spacecraft owned and operated by commercial and international entities.[9] Additionally, the Trajectory Operations Officer at Johnson Space Center provides collision avoidance services for crewed spacecraft such as the ISS. If the collision avoidance programs identify a high risk of collision with NASA assets, they inform spacecraft operators who then determine whether a change in course or movement to avoid the debris or object (referred to as maneuvering) is necessary.

The ISS is the most heavily protected spacecraft with shields or barriers installed on the U.S. modules to protect it from damage by orbital debris as large as 1 cm. To avoid debris larger than 10 cm, NASA has had the ISS conduct approximately 27 collision avoidance maneuvers since 1999, the most recent of which was in September 2020 when a piece of debris was expected to pass within 1 mile of the Station. This was the third time in 2020 that the Station had to maneuver to avoid debris—a significant change given the last year it was required to conduct such a maneuver to avoid debris was in 2015. NASA also has contingency plans and evacuation procedures for crew in case maneuvering to avoid debris is not possible or if the ISS is irreparably damaged by debris.

Limiting and Preventing the Generation of Orbital Debris

To date, NASA's efforts related to orbital debris have focused on preventing and limiting its generation. NASA has stated that controlling the growth of orbital debris is a high priority for the Agency, the United States, and major spacefaring nations to enable safe space flight for future generations. Mitigation measures can take the form of curtailing or preventing the creation of new debris; designing satellites to withstand impacts by small debris; and implementing operational procedures such as using different orbital regimes with less debris, adopting specific spacecraft altitudes, and operators maneuvering on-orbit assets to avoid collisions.

The United States Government Orbital Debris Mitigation Standard Practices (ODMSP), based on guidelines developed by NASA, were established in 2001 to limit the generation of new debris through the following objectives: control of debris released during normal operations, minimizing debris generated by accidental explosions, selection of safe flight profile and operational configuration to minimize accidental collisions, and post-mission disposal of space structures. Revised in 2019, the

[9] DOD is responsible for performing conjunction assessments for all designated NASA space assets in accordance with an established schedule (3 times daily every 8 hours totaling 24 hours a day, 7 days a week for human space flight vehicles and 3 times daily totaling 20 hours a day, 7 days a week for robotic vehicles). DOD notifies NASA (Johnson Space Center for human space flight and Goddard Space Flight Center for robotic missions) of the potential for collision between an operational spacecraft and a cataloged debris object that meets established criteria.

updated version included improvements to the original objectives as well as clarification and additional standard practices for certain classes of space operations.[10] Table 2 summarizes the objectives and respective implementation measures outlined in the ODMSP.

Table 2: Summary of United States Government 2019 ODMSP Objectives

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

Source: NASA OIG presentation of ODMSP.

Note: Satellite constellations are a group of artificial satellites working together as a system. Unlike a single satellite, a constellation can provide global or near-global coverage.

NASA implements the ODMSP through policy requirements and publications on limiting orbital debris.[11] These requirements are intended to control the generation of debris and mitigate its growth by minimizing the amount of debris released during normal operations, limiting the potential for debris generated by accidental explosions and the potential for breakup or loss of disposal capabilities due to on-orbit collisions, limiting the number and duration of decommissioned space objects remaining in orbit, and minimizing the likelihood of collisions with other space objects.

[10] United States Government Orbital Debris Mitigation Standard Practices (November 2019) can be viewed at https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf (last accessed October 9, 2020).

[11] NASA Procedural Requirements (NPR) 8715.6B, *NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments* (February 16, 2017); NASA Technical Standard 8719.14B, *Process for Limiting Orbital Debris* (April 25, 2019); and NASA Handbook 8719.14, *Handbook for Limiting Orbital Debris* (July 30, 2008).

To meet these objectives, NASA project managers are required to complete an Orbital Debris Assessment Report (ODAR) during key points of their project's life cycle including the Preliminary and Critical Design Reviews and prior to launch.[12] Additionally, project managers are required to complete an End of Mission Plan (EOMP), which details the spacecraft's post-mission disposal plans, and update this plan as needed, including if a decision is made to extend the mission. If a project does not or is not able to meet one of the requirements, the Chief of OSMA may approve a waiver if the additional risk to the public and space environment is deemed acceptable given the importance of the mission, and if the design and operational measures have been applied to the extent reasonably practical.[13] In FYs 2018 and 2019, NASA issued eight waivers for missions that did not meet mitigation requirements.[14]

Coordinating and Communicating with Federal Agencies, Commercial Entities, and International Stakeholders

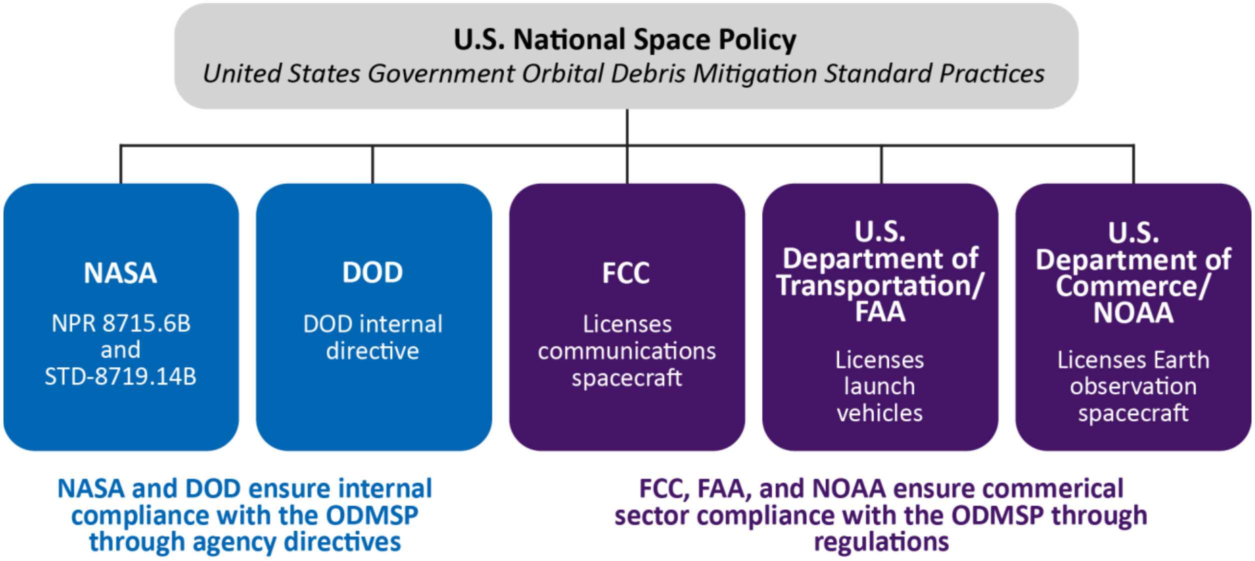
NASA has played a major role in developing guidelines and in coordinating and communicating with various entities to share orbital debris measurement expertise, support and encourage the adoption and implementation of orbital debris mitigation guidelines, and provide consultation about orbital debris risk assessment and mitigation. Many federal and commercial entities in the United States rely on NASA's models and DOD's tracking information to implement the ODMSP. As shown in Figure 4, five federal entities have significant roles in orbital debris mitigation: NASA, DOD, FCC, the Federal Aviation Administration (FAA), and the National Oceanic and Atmospheric Administration (NOAA). NASA and DOD—two agencies that develop and launch spacecraft—implement the ODMSP through internal policies. Regulatory entities such as the FAA, FCC, and NOAA hold commercial entities accountable by implementing the ODMSP through regulations they issue.

[12] The Preliminary Design Review is used to evaluate the completeness and consistency of the planning, technical, cost, and schedule baselines developed during the Formulation Phase; assess compliance of the preliminary design with applicable requirements; and determine if the project is sufficiently mature to move from Formulation to the Implementation Phase. The Critical Design Review is used to demonstrate the design is sufficiently mature to proceed to full-scale fabrication, assembly, integration, and testing, and that the technical effort is on track to meet performance requirements within identified cost and schedule constraints.

[13] If relief from the requirements results in a violation of the ODMSP, the Chief of OSMA may obtain the Administrator's consent to adjudicate the request. On behalf of the Administrator, the Associate Administrator for International and Interagency Relations notifies the U.S. Secretary of State of any non-compliance with the ODMSP, as required by the June 2010 National Space Policy.

[14] The Transiting Exoplanet Survey Satellite—a survey mission launched in 2018 to focus on the discovery of exoplanets—has one waiver because the mission was unable to deplete all on-board sources of energy. The Ionospheric Connection Explorer Mission, also launched in 2018, is studying the dynamic zone where Earth weather and space weather meet and has two waivers due to (1) risk of human casualty when the spacecraft reenters the Earth's atmosphere and (2) inability to deplete on-board sources of energy. The Geostationary Operational Environmental Satellite-S, launched in 2018 as part of a collaborative effort between the National Oceanic and Atmospheric Administration and NASA to provide faster, more accurate, and more detailed observations for weather forecasting, has one waiver because its launch vehicle exceeds the allowable probability of explosion. The Interior Exploration using Seismic Investigations, Geodesy and Heat Transport mission—launched in 2018 to study the interior structure of Mars—received one waiver because its launch vehicle exceeds the allowable probability of explosion. The Parker Solar Probe mission—launched in 2018 to travel through the Sun's atmosphere and provide the closest-ever observations of a star—received one waiver because its launch vehicle exceeds the allowable probability of explosion. Finally, the Green Propellant Infusion Mission launched in 2019 is helping NASA develop a green alternative to conventional chemical propulsion systems for next-generation spacecraft and has two waivers due to (1) risk of human casualty when the spacecraft reenters the Earth's atmosphere and (2) inability to deplete on-board sources of energy.

Figure 4: Implementation of the United States Government Orbital Debris Mitigation Standard Practices



Source: NASA OIG depiction of ODPO information.

National Space Policy. NASA works closely with DOD, FAA, FCC, and NOAA on improving commercial industry mission and launch licensing processes that include mitigating orbital debris, improving orbital debris tracking and measurement, and updating government-wide mitigation practices. While NASA also works closely with other agencies on issues related to orbital debris mitigation, evolving national space policies have provided agencies with differing levels of responsibility for space traffic management and orbital debris mitigation. Space traffic management is the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment. These activities are primarily concerned with coordination among spacecraft owners and ensuring operational spacecraft do not collide. DOD has historically provided services to NASA and other entities alerting them about potential collisions between operational spacecraft. However, the growth in the commercial space sector has necessitated a regulatory overhaul. For instance, Space Policy Directive-2 directed the U.S. Department of Commerce (Commerce) to create an entity with primary responsibility for administering the Department's regulation of commercial space flight activities, while Space Policy Directive-3 required Commerce to assume responsibility for cataloging objects larger than 10 cm for commercial sector use and taking over conjunction assessment services from DOD, a transition expected to take place by September 2021.[15] Space Policy Directive-3 also required NASA to lead an interagency working group to update the ODMSP, a task completed in 2019.

International Policy. The United States plays a leading role in international forums to encourage foreign nations and international organizations to adopt voluntary policies and best practices aimed at minimizing debris, exchanging information on debris research, and identifying improved debris

[15] President Trump, Space Policy Directive-2, *Streamlining Regulations on Commercial Use of Space* (May 24, 2018) and Space Policy Directive-3, *National Space Traffic Management Policy* (June 18, 2018).

mitigation practices.[16] Specifically, ODPO has taken the lead in developing the technical consensus for adopting orbital debris mitigation measures. In addition, NASA represents the United States in international forums related to orbital debris, such as the United Nations Committee on the Peaceful Uses of Outer Space and the Inter-Agency Space Debris Coordination Committee, both of which have published voluntary orbital debris mitigation guidelines.[17] NASA is a founding member of the Inter-Agency Space Debris Coordination Committee—a 13-member international governmental forum for the worldwide coordination of activities related to debris. The Committee has adopted the voluntary orbital debris mitigation guidelines consistent with the United States Government ODMSP and collaborates on orbital debris-related issues such as encouraging efforts to limit the growth of orbital debris.[18] In addition to participating on the Inter-Agency Space Debris Coordination Committee, countries and organizations including China, the European Space Agency, France, Japan, and Russia have followed NASA in developing their own orbital debris mitigation guidelines.

As a result of NASA's efforts, the Agency's orbital debris mitigation programs and models are now widely used by the providers and users of both government and commercial spacecraft, nationally and internationally.

Remediation—Actively Removing Existing Orbital Debris

Another important aspect in addressing the risks posed by orbital debris is the remediation—or removal—of existing debris. The June 2010 National Space Policy of the United States of America directs NASA and DOD to "Pursue research and development of technologies and techniques…to mitigate and remove on-orbit debris…"[19] Additionally, Space Policy Directive-3 states that "The United States should pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes. This effort should not detract from continuing to advance international protocols for debris mitigation associated with current programs." Currently, no U.S. government entity has been assigned, received funding, or actively undertaken the task of removing existing orbital debris.

Multiple active debris removal studies and concepts have been proposed, but cost-effective methods for removing large debris (such as defunct spacecraft) are not yet available. For example, between 2009 and 2011 the Defense Advanced Research Projects Agency (DARPA) conducted a study that evaluated

[16] DOD has space situational awareness data sharing agreements and memoranda of understanding with 13 countries (Australia, Belgium, Canada, France, Germany, Israel, Italy, Japan, Norway, South Korea, Spain, the United Arab Emirates, and the United Kingdom); two intergovernmental organizations (European Space Agency and European Organization for the Exploitation of Meteorological Satellites); and more than 60 commercial satellite owners, operators, and launchers.

[17] Established in 1959, the Committee on the Peaceful Uses of Outer Space deals with international cooperation in the peaceful uses of outer space, monitors and discusses developments related to the exploration and use of outer space as well as the technical advancements in space exploration, geopolitical changes, and the evolving use of space science and technology for sustainable development.

[18] Members of the Inter-Agency Space Debris Coordination Committee include: Agenzia Spaziale Italiana, Centre National d'Etudes Spatiales, Canadian Space Agency, China National Space Administration, European Space Agency, German Aerospace Center, Indian Space Research Organisation, Japan Aerospace Exploration Agency, Korea Aerospace Research Institute, NASA, State Space Agency of Ukraine, State Space Corporation ROSCOSMOS, and the United Kingdom Space Agency.

[19] President Obama, *National Space Policy of the United States of America* (June 28, 2010).

the necessity and feasibility of actively removing debris to decrease the overall population of debris.[20] DARPA, with support from NASA's ODPO, gathered information on potential active debris removal concepts and technologies from the aerospace community through roundtables, requests for information, and an international conference. The study found that "Compliance with existing international debris mitigation guidelines coupled with the pre-emptive removal of the sources of future medium debris [i.e., large debris such as defunct spacecraft] is by far the most cost-effective strategy." [21] After reviewing the proposed concepts, DARPA found that removing large objects would generally entail advanced rendezvous operations to first grab or attach to the debris, and complicated techniques to subsequently move the debris to less congested orbits or to burn up in the Earth's atmosphere—activities that will likely be expensive. Proposals for capturing large objects included nets, harpoons, and lassos, and suggestions for moving or relocating debris included using thrust or electromagnetic energy. At the time of the DARPA study, these concepts were in the early stages of research and development.

More recently, commercial and foreign entities have made progress in developing technologies needed to perform active debris removal. For example, the DARPA study identified advanced rendezvous operations as a necessary technology for performing active debris removal, and in February 2020, Northrop Grumman's Mission Extension Vehicle-1 performed advanced rendezvous operations when it successfully docked with a commercial communication satellite that was running low on fuel.[22] Without such intervention, operators would have lost the ability to control the satellite. Mission Extension Vehicle-1 took over maneuvering and navigation for the communication satellite, which will now be able to function for an additional 5 years, before the extension vehicle maneuvers the satellite to an orbit clear of other active satellites. Further, RemoveDEBRIS, a $20 million project led by the Surrey Space Centre at the University of Surrey in Guildford, England, and co-funded by the European Commission, successfully demonstrated four novel orbital debris removal technologies since its launch in 2018.[23] The four technologies the project demonstrated were: (1) deploying a net in space to capture a specified target, (2) tracking a specified target in orbit, (3) harpooning (firing a spear-like projectile) at a specified target in space, and (4) deploying a large drag sail that will shorten the time it takes for an object to deorbit before burning up in the Earth's atmosphere.

In addition to the technologies described above, the European Space Agency and Japan Aerospace Exploration Agency (JAXA) have recently funded missions for removal of both small and large debris. The European Space Agency's debris removal mission known as ClearSpace-1, slated to launch in 2025, consists of a four-armed robot that intends to latch onto debris and descend back to Earth where both machine and debris will burn up in the atmosphere. The initial mission will target a piece of large debris—an upper stage left over from a 2013 launch. In November 2020, the European Space Agency

[20] Wade Pulliam, PhD, DARPA, *Catcher's Mitt Final Report* (2011). DARPA is the technology research and development division of DOD.

[21] The DARPA study found that any system for active debris removal would generally include four stages during an encounter with debris: 1) detection, 2) interception or rendezvous, 3) interaction, and 4) disposal. Once the target object was detected, any debris removal system would need to then interact with the debris by intercepting it, rendezvousing with it, or via an energy pulse or beam, imparting a force on the debris. The interaction would be used to relocate the debris for disposal (either to a safe, unused orbit) or to deorbit the debris back into the Earth's atmosphere (to burn up). A few other means of disposal were proposed, such as completely vaporizing the debris, breaking it up into sub-millimeter particles, or reusing it in some manner.

[22] The Mission Extension Vehicle-1 spacecraft was developed by Northrop Grumman with technical assistance from NASA through a no-funds exchanged partnership called Collaborations for Commercial Space Capabilities.

[23] The European Commission is the European Union's politically independent executive arm that proposes new laws, manages policies, and allocates funding.

announced a $102 million contract for this mission citing the remainder of the mission's cost would be raised through commercial investors. JAXA's debris removal mission is designed to launch in two phases, an "approach and observe" phase in 2022 to 2023 and a follow-up "observe, approach, capture, and retrieve" phase in 2026. The intent is to collect a discarded large upper stage of a Japanese rocket selected for removal by JAXA. In addition, JAXA is working on a project to demonstrate the first ever "debris prevention" device in 2021 that involves an electromagnetic tether mounted to a miniaturized satellite prior to launch, which at the end of the mission will extend into space, interact with the Earth's magnetic field, and cause the satellite to slow, lowering its orbit within a short period of time resulting in the satellite falling into the Earth's atmosphere where it will burn up.

Artist's Rendering of European Space Agency's Debris Remover

Planned to launch in 2025, ClearSpace-1 is the European Space Agency's mission to remove debris from orbit. ClearSpace-1 will use its four robotic arms to capture the debris; in this depction, it is capturing part of an upper stage left over from a 2013 launch.

Source: European Space Agency.

NASA's Mitigation-Only Efforts Insufficient to Stabilize the Debris Environment

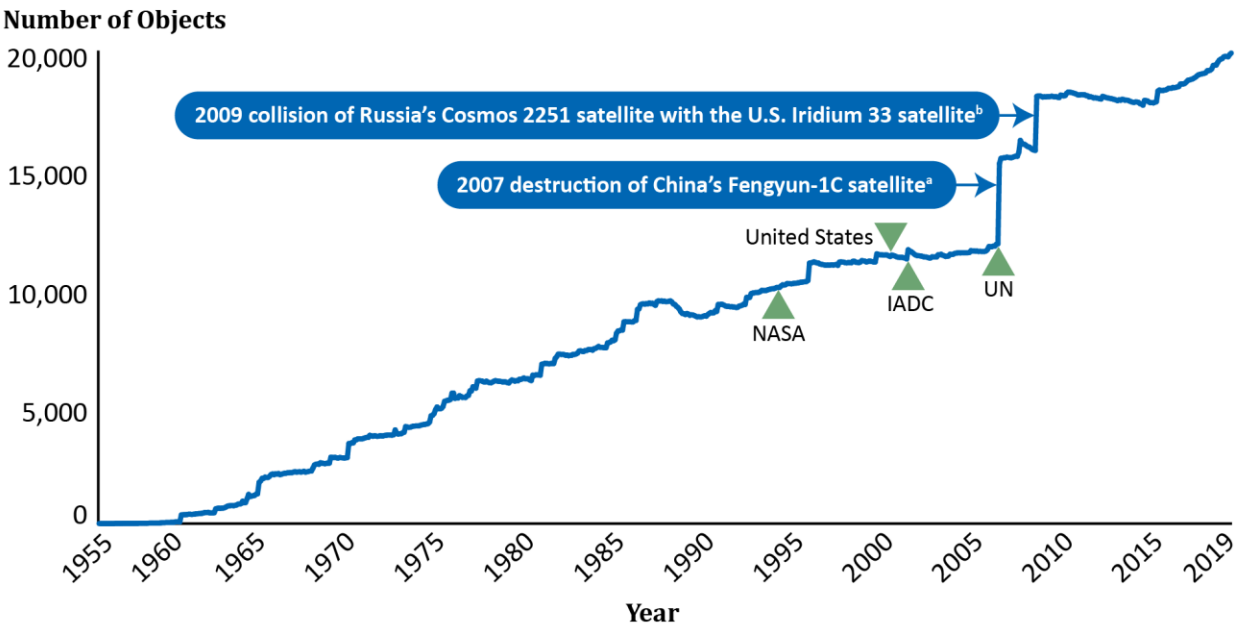
The rapid increase of space activity has accelerated the creation of orbital debris, threatening the safety of spacecraft and crew, and along with it the sustainability of the space environment in low Earth orbit (LEO). Given the current state of debris in LEO where the majority of assets belong to U.S. entities, NASA's mitigation-only activities—focused solely on prevention—are not sufficient for stabilizing the orbital debris environment. To effectively address the orbital debris issue, global mitigation and strategic remediation efforts are necessary. NASA's policy has long reflected its position that preventing future debris will have greater impact on mitigating risks than cleaning up existing orbital debris, despite multiple studies concluding that preventing future debris is not enough to stabilize the orbital debris environment. Furthermore, although there have been multiple presidential and congressional directives to NASA over the past decade to develop active debris removal technologies, the Agency has made little to no progress. While debris removal technologies and missions are being tested by commercial entities and international agencies, the technologies are still in the early stages of development. Leaving defunct spacecraft in orbit increases the likelihood of collisions and the creation of more debris, resulting in a continuous cycle of increasing costs to spacecraft owners and operators as well as safety risks to crews, spacecraft, and space flight missions. Finally, although international compliance with mitigation measures is widely accepted as necessary, international space agencies and the scientific community agree that mitigation alone is no longer sufficient in preventing the continual growth of orbital debris. Consequently, NASA and the international community need to also focus on remediation of existing debris.

Orbital Debris Environment Has Reached the Tipping Point

Ten years ago, the number of spacefaring entities was relatively small, limited mainly to government space agencies with budgets capable of supporting the development of complex technology, spacecraft, and launch vehicles. However, the advent of the commercial launch industry and miniaturized satellites have significantly decreased the costs of owning and launching spacecraft over the last 10 years, enabling more countries and even commercial entities to develop, own, and launch space-based assets. For example, the cost of a trip to LEO on NASA's now-retired Space Shuttle was about $25,000 per pound; the cost of that same trip today with commercial companies costs as little as $1,250 per pound. Currently, more than 500 entities—including small government agencies, nonprofits, students, and commercial companies—have assets in space. This rapid increase of space activity has simultaneously accelerated the creation of orbital debris.

Multiple studies by NASA and other space agencies have found that orbital debris has already reached critical mass, and collisional cascading will eventually happen even if no more objects are launched into orbit. According to NASA, by 2005 the amount and mass of debris in LEO had grown to the point that even if no additional objects were launched into orbit, collisions would continue to occur, compounding the instability of the debris environment and increasing operational risk to spacecraft by 2055 unless measures were taken to curb the growth of the debris population. However, the amount of orbital debris has not decreased, or even stabilized, since 2006. Instead, the largest increases of new spacecraft and debris generation have occurred in LEO since 2006. As shown in Figure 5, the massive amount of orbital debris created by the 2007 Chinese anti-satellite test and 2009 U.S. Iridium collision negated any possible progress made by the adoption of voluntary debris mitigation guidelines (marked by the green triangles).

Figure 5: Growth of the Population of Cataloged Objects in Orbit



Source: NASA OIG presentation of ODPO information.

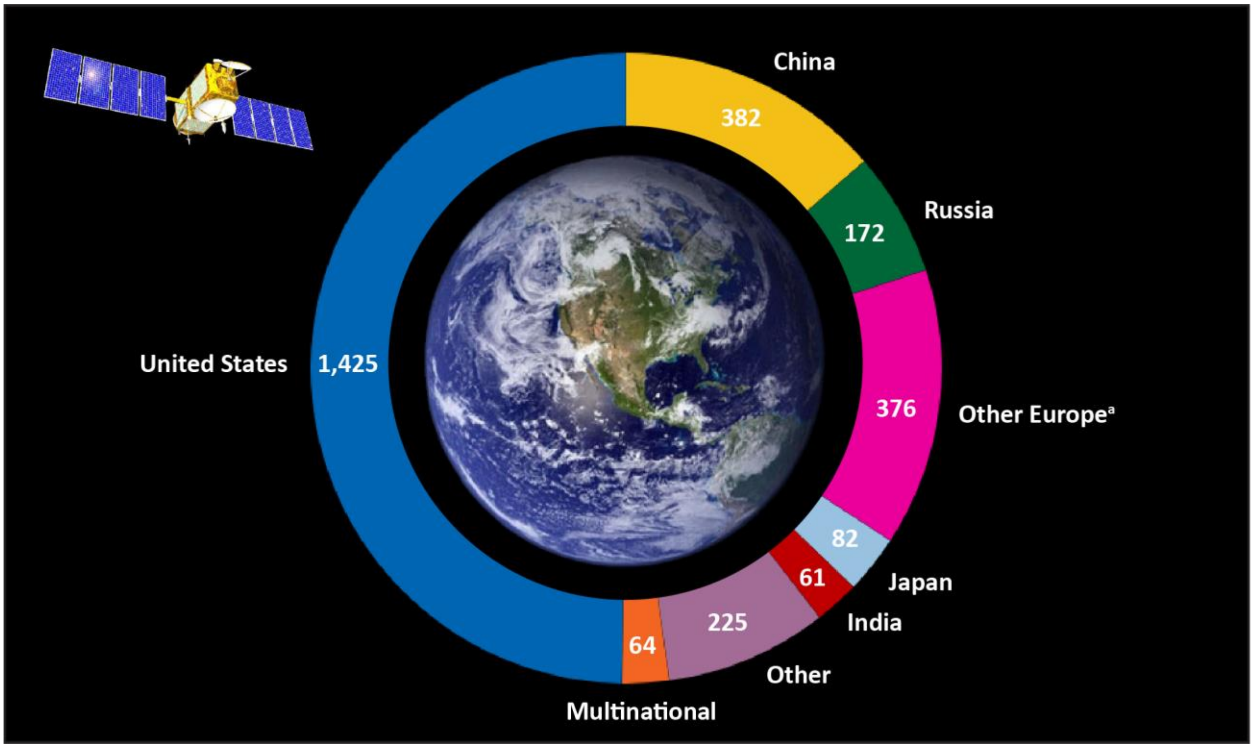
Note: IADC is Inter-Agency Space Debris Coordination Committee and UN is United Nations.

[a] In 2007, China conducted an anti-satellite test in which it launched a land-based missile to destroy Fengyun-1C, a decommissioned weather satellite. The destruction of this defunct satellite generated more than 3,000 pieces of debris.
[b] In 2009, Russia's defunct Cosmos 2251 satellite collided with and destroyed the functioning U.S. Iridium 33 commercial satellite, generating more than 2,000 pieces of debris. The U.S. Iridium satellite cost an estimated $15 million.

The United States Faces the Greatest Risk in an Unstable Orbital Debris Environment

As shown in Figure 6, the United States operates about half of all spacecraft in LEO—over three times more than any other entity—and is therefore at the greatest risk of incurring financial and operational losses from spacecraft collisions with other spacecraft or debris. The U.S. government developed the original ODMSP in 2001 based on the voluntary orbital debris mitigation guidelines first developed by NASA in 1995. However, even if all spacecraft operators in the United States follow these mitigation guidelines, U.S. spacecraft will still be vulnerable to impact from debris generated by foreign entities. Further compounding the challenge is the lack of international regulations to hold spacefaring entities accountable for conducting safe, responsible, and sustainable space operations, such as those that consider orbital debris mitigation. In lieu of an international regulatory framework for orbital debris mitigation, the United States encourages spacefaring entities across the globe to adopt the ODMSP.

Figure 6: Number of Satellites in Operation by Country (as of August 2020)



Source: NASA OIG presentation of Union of Concerned Scientists information.

[a] Other Europe includes the European Space Agency, the United Kingdom, and other countries in Europe excluding Russia.

For example, at the February 2020 United Nations Committee on the Peaceful Uses of Outer Space meeting in Vienna, Austria, the United States urged all spacefaring nations, emerging space nations, international organizations, and non-government organizations to implement orbital debris mitigation guidelines to limit the generation of debris.[24] However, adopting voluntary guidelines does not ensure compliance, as demonstrated when China and India—both signatories of the Inter-Agency Debris Coordination Committee—conducted their anti-satellite tests in 2007 and 2019, respectively, resulting in the creation of additional orbital debris. At a September 2020 congressional committee hearing, NASA's Administrator commented, "...there has been a lot of activity from our international friends who don't necessarily follow the guidelines. While countries sign on to the guidelines, it does not necessarily mean they fully adhere to the guidelines."[25] Although it is important for NASA to continue to support efforts to encourage spacefaring entities to adopt orbital debris mitigation guidelines, it is equally

[24] In June 2019, all 92 member countries signed onto the United Nations Committee on the Peaceful Uses of Outer Space's Guidelines for the Long-Term Sustainability of Outer Space Activities. The voluntary guidelines encourage the member states to adopt requirements that promote the long-term sustainability of outer space—including those related to orbital debris mitigation—into their respective national regulatory mechanisms.

[25] NASA Missions and Programs: Update and Future Plans. Before the Committee on Commerce, Science, and Transportation, House of Representatives, 116th Congress (September 30, 2020) (statement of NASA Administrator Jim Bridenstine).

important that the Agency act on the multiple presidential and congressional directives to pursue active debris removal technologies, and on its own studies and those conducted by the Inter-Agency Space Debris Coordination Committee over the last 10 years—after the rapid increase in the amount of debris in LEO—that conclude that mitigation alone will not be sufficient to stabilize the orbital debris environment.[26]

NASA Focused on Mitigation and Not on Removing Its Own Defunct Spacecraft from Orbit

Multiple studies, including those by ODPO in 2005 and 2008, have found that the growth of debris in LEO can be slowed by ensuring that at least 90 percent of all spacecraft are removed from orbit within 25 years of the end of their mission, and that at least five defunct spacecraft (that will not deorbit on their own) are actively removed from orbit every year.[27] Furthermore, if less than 90 percent of spacecraft are removed from LEO within 25 years of the end of their missions, a greater number of objects will need to be actively removed from LEO to stabilize and preserve the future space environment. However, despite requirements to engage in research and development technologies to remove debris (per the 2010 National Space Policy) and to pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in Earth's orbit (per Space Policy Directive-3), NASA is not conducting active debris removal.

The Agency's position is that orbital debris is a global issue and therefore encouraging all countries and spacecraft operators to follow the ODMSP guidelines—such as preventing explosions and ensuring post-mission disposal within 25 years—will have greater impact on mitigating the risks of orbital debris than pursuing the development of costly remediation technologies. NASA's compliance rate for end-of-mission disposal (ensuring the spacecraft is at a low enough orbit at the end of its mission that it is pulled into the Earth's atmosphere) within 25 years stands at approximately 96 percent over the last decade. However, the global compliance rate has only averaged between 20 to 30 percent—much lower than the 90 percent required to slow the rate at which debris is generated in LEO. In 2013, the Inter-Agency Space Debris Coordination Committee compared the findings from six independent simulations (including ODPO's) of the future debris environment and found them consistent with ODPO's earlier projection of the growth of debris in LEO.[28] The study also concluded that the orbital debris population in LEO is unstable and that active debris removal must be considered to stabilize the orbital debris environment over the long term. As shown in Figure 7, even if global spacefaring entities achieve a 90 percent compliance rate with post-mission disposal (notated by the yellow line), it will not be sufficient to slow the growth of orbital debris without the active debris removal of at least five defunct spacecraft a year, beginning in the year 2020.

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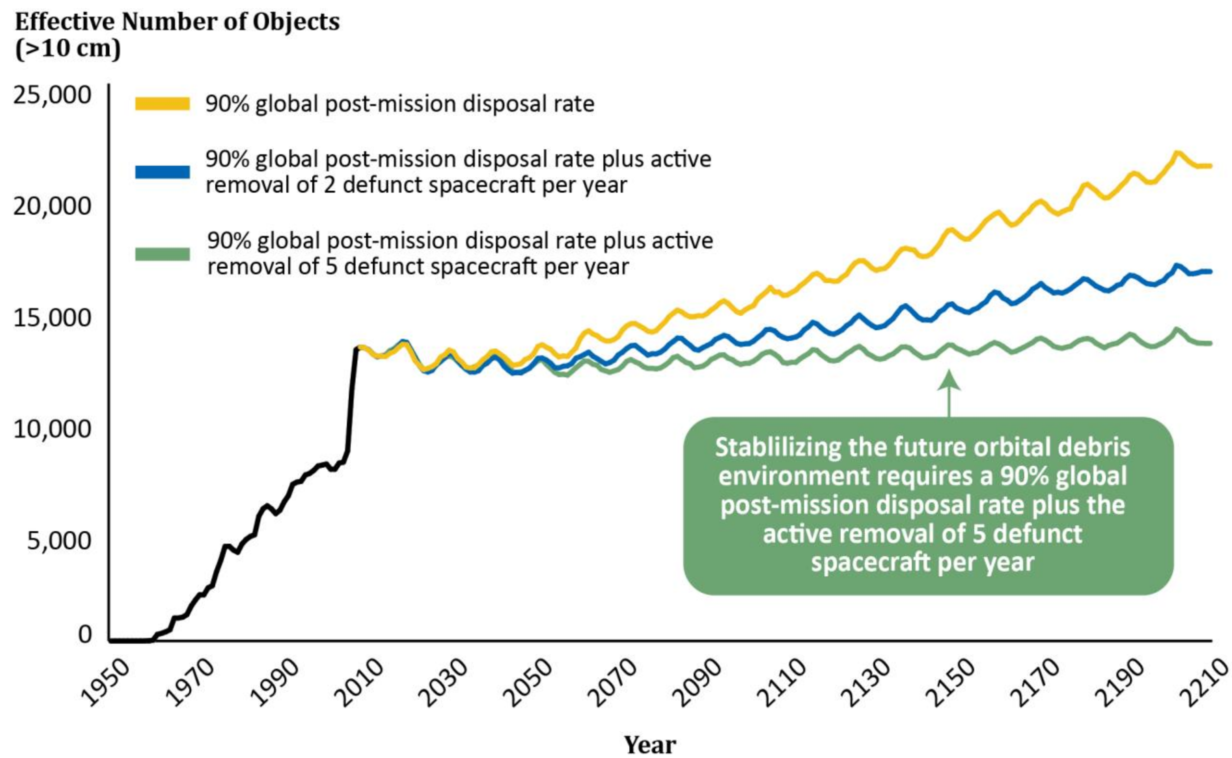
[26] Inter-Agency Space Debris Coordination Committee, *Stability of the Future LEO Environment—An IADC Comparison Study* (2013).

[27] J.-C. Liou and N.L Johnson, "A LEO Satellite Post-Mission Disposal Study Using LEGEND," *Acta Astronautica*, 57, 324-329 (2005); J.-C. Liou and N.L. Johnson, "Risks in Space from Orbiting Debris," *Science*, 311, 340-341 (2006); J.-C. Liou, N.L. Johnson, and N.M. Hill, "Stabilizing the Future LEO Debris Environment with Active Debris Removal," *Orbital Debris Quarterly Newsletter,* 12:4, 4-7 (October 2008); *Catcher's Mitt Final Report*; and *Stability of the Future LEO Environment—An IADC Comparison Study*.

[28] *Stability of the Future LEO Environment –An IADC Comparison Study*.

Figure 7: Estimated Impacts of Successful Post-Mission Disposal and Active Debris Removal Activities on LEO's Orbital Debris Environment



Source: NASA OIG depiction of ODPO information.

Although the decrease of operational risk to functioning spacecraft will be realized immediately after the removal of large defunct spacecraft (especially those orbiting nearby), the greater benefits of active debris removal on the overall debris population in LEO will be realized over time. Furthermore, according to a NASA study conducted in 2018, without global post-mission disposal, the debris population in LEO will increase rapidly over time, resulting in an approximately 330 percent increase in the next 200 years.[29] However, the increase drops to 110 percent over the same time period with a 90 percent rate of global post-mission disposal. To stabilize the orbital debris environment in LEO, it is vital for all spacefaring entities to achieve the 90 percent global compliance rate with the 25-year rule, while also removing from orbit a total of at least five defunct spacecraft a year.

According to ODPO, the majority of defunct spacecraft in LEO are foreign owned, and thus cannot be removed by NASA due to legal and liability issues. While we agree that the removal of foreign-owned debris is complex and outside the purview of NASA, focusing on removing the Agency's own defunct spacecraft reduces both present and future operational risk to NASA's spacecraft and helps to preserve the orbital debris environment over the long term. Furthermore, agencies such as NASA, DOD, and the signatories of the Inter-Agency Space Debris Coordination Committee that have launched spacecraft into orbit for decades are best positioned to develop and implement active debris removal technology.

[29] J.-C. Liou, M. Matney, A. Vavrin, A. Manis, and D. Gates, "NASA ODPO's Large Constellation Study," *Orbital Debris Quarterly Newsletter* 22:3, 4-7 (September 2018). In order to determine the effect of large constellations on the environment, the study first projected the launch cycle (2008 to 2015) into the future—with the assumption that no large constellations were deployed. The results of that baseline scenario are reported above. When large constellations were added to the no post-mission disposal scenario, the amount of debris nearly doubled.

Such agencies are likely to have numerous large, defunct spacecraft in orbit that are increasing the risk to their operational spacecraft and should be removed to lower the risk to current and future spacecraft operating in LEO. For example, NASA could consider efforts to remove spacecraft following completion of their missions, including the ones noted below, that it launched prior to the implementation of the ODMSP, as these are less likely to be compliant with mitigation requirements such as the 25-year rule.

- The Quick Scatterometer Earth satellite, launched in 1999 and decommissioned in 2018.[30] Orbiting in LEO at about 800 km, the approximately 2,000-pound spacecraft is expected to remain in orbit for 90 years, increasing the chances that it may collide with another object in orbit. In addition, the battery cannot be disconnected and will continue to charge while in orbit, increasing the likelihood of an explosion.
- The Terra spacecraft, a 10,000 pound satellite observatory that has been operating in the 700 km orbit of LEO since 1999 and is scheduled to be decommissioned in 2026.[31] Terra will not be able to deorbit within 25 years, its batteries cannot be disconnected, and the propellant system cannot be depressurized, increasing the possibility for a debris-generating explosive event. Furthermore, Terra is expected to be in orbit for 50 years after the end of its mission, also increasing the likelihood of collision with other objects in orbit.

According to Agency officials, NASA has no viable, cost-effective option for active debris removal and no plans to establish an operational role in such efforts. However, NASA could leverage existing partnerships and recent technology advances in satellite servicing and small debris removal techniques to develop active debris removal technology for large objects, such as defunct spacecraft, that increase the operational risk to NASA's robotic spacecraft in the 600 to 1,000 km altitude of LEO. By taking no action and leaving defunct spacecraft in orbit, NASA will add to the increasing costs of tracking, monitoring, and modeling orbital debris; performing maneuvers to avoid collisions; and increasing shielding and protection for spacecraft.

Further exacerbating the difficulty in conducting an accurate cost-benefit analysis is that NASA does not track the costs associated with mitigating orbital debris risks, including shielding, tracking, and collision avoidance. These costs increase with risk, and in an increasingly congested space environment, costs associated with failing to remove defunct spacecraft may ultimately outweigh the costs of conducting active debris removal. For example, both NASA and DOD officials tasked with identifying potential collisions between spacecraft, performing conjunction assessments (the real-time process of assessing risk posed by close approaches), and working with spacecraft owners and operators to conduct collision avoidance maneuvers noted that the rapid growth in the number and variety of both spacecraft and spacecraft owners has created an increasingly challenging, complex, and costly environment for conjunction assessment and collision avoidance. Specifically, both agencies have experienced an increase in the surveillance workload, necessitating a dedicated team for monitoring satellite constellations and preventing collisions in space. The active removal of defunct spacecraft—especially those that present a high risk to the entities operating in LEO—is necessary to stabilize the current orbital debris environment, create safe space for functioning spacecraft, and preserve the future space environment over the long term.

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[30] The Quick Scatterometer mission was managed by the Jet Propulsion Laboratory for NASA's Science Mission Directorate.

[31] The Terra mission is managed by the Goddard Space Flight Center for NASA's Science Mission Directorate. A flagship Earth observing satellite, Terra provides global data on the state of the atmosphere, land, and oceans.

NASA has been directed by the President and Congress multiple times over the past 10 years to develop active debris removal technology; however, the Agency has not requested or received funding to support these efforts. For example, the 2010 National Space Policy and NASA Authorization Act directed NASA and DOD to pursue research and development of technologies for mitigating and removing on-orbit debris. In the Authorization Act, Congress recognized the need for a national and international effort to develop a coordinated approach for preventing, negating, and removing orbital debris, and directed the White House Office of Science and Technology Policy to submit an overall strategy for addressing the challenges associated with mitigating and removing on-orbit debris.[32]

In response to the directive to develop an interagency strategy, NASA led an effort to develop the U.S. government's collaborative framework for active debris removal. The framework was presented to NASA leadership and the Office of Science and Technology Policy in 2014. However, no action was taken to share (beyond the Office of Science and Technology Policy), adopt, or implement the framework. According to NASA officials, this was due to both internal and external factors including a lack of dedicated funding, differing priorities of the then-Administrator, and national security concerns such as rogue actors potentially using active debris removal technologies to harm operating spacecraft. Additionally, in a 2014 memorandum NASA's Associate Administrator directed the Agency to conduct only low-effort, basic technology development activities related to active debris removal and advised the Office of the Chief Technologist would coordinate and prioritize such activities contingent on the availability of resources.[33] According to officials from the Space Technology Mission Directorate, the rationale for this memorandum was that no viable technology for active debris removal existed at the time, therefore the Agency should focus on initial-stage activities, such as generating ideas and advancing new promising concepts for potential future solutions for the issue. The memorandum acknowledged that NASA responsibilities for remediation had not been documented or codified, and that any NASA work related to active debris removal should only be specific to technology development, not developing operational systems. According to the memorandum, the Agency had no plans to establish an operational role in active debris removal.

Under the NASA Transition Authorization Act of 2017, Congress again directed NASA and the Office of Science and Technology Policy to address the reporting requirements in the 2010 Authorization Act by submitting reports to Congress on the status of international and interagency efforts to develop a coordinated approach to removing on-orbit debris. The Transition Act also contained a new requirement for NASA to collaborate with other relevant agencies to solicit and review active debris removal concepts.[34] In response, the Office of Science and Technology Policy reported to Congress in August 2017 that an ad hoc interagency working group reviewed existing orbital debris mitigation measures and concluded that the measures were working sufficiently to slow the accumulation of orbital debris in the space environment. The report also stated that although the group discussed policy, legal, and international conditions that would allow for active debris removal, it did not develop a specific strategy. NASA officials explained that the Agency's position at that time was to focus on obtaining a 90 percent global compliance rate with the 25-year rule. Finally, in 2018, Space Policy Directive-3 again stated that the United States should pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes, but this effort should not detract from continuing efforts to advance orbital debris mitigation. In response to Space Policy

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[32] National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267 (2010).

[33] Robert M. Lightfoot, NASA Associate Administrator, *Orbital Debris Remediation—Agency Guidelines for Technology Development* (June 19, 2014).

[34] National Aeronautics and Space Administration Transition Authorization Act of 2017, Pub. L. No. 115-10 (2017).

Directive-3, NASA officials pointed to the Agency's continued efforts on debris mitigation. They also advised that developing an active debris removal system would be a costly and complex endeavor that NASA would not be interested in taking on, especially absent additional funding.

While NASA has not developed a cost-effective method for active debris removal, the Agency has funded technology development efforts that promote timely post-mission disposal of small spacecraft in LEO, as well as early stage studies of concepts for active debris removal in line with the Associate Administrator's 2014 memorandum. Such efforts are in their infancy. Specifically, NASA's Space Technology Mission Directorate has developed technology to demonstrate passive (uncontrolled) deorbiting of small spacecraft, such as CubeSats, using NASA's Exo-Brake Parachute that increases the spacecraft's drag once the braking device, which resembles a parachute, is deployed from the spacecraft. Additionally, through the NASA Innovative Advanced Concepts Program, the Space Technology Mission Directorate has issued grants for basic concept development efforts of potential low technology active debris removal methods.[35] For example, NASA awarded a $100,000 grant to Tethers Unlimited, Inc. in 2014 for research into a system that involves a CubeSat-sized spacecraft capturing a large piece of debris using a tether that could then deorbit the object. In another example, The Aerospace Corporation received a $500,000 grant in 2017 for research into developing a 3 foot by 3 foot spacecraft similar to a piece of wrapping paper that could be deployed to collect orbiting space debris by wrapping itself around the item and deorbiting it to burn up in the Earth's atmosphere.[36] According to Space Technology Mission Directorate officials, while both concepts are promising, NASA has chosen not to provide either company follow-on awards to further develop their projects.

Although NASA has not developed an active debris removal system, the Agency has been working on robotic refueling technologies that could provide additional fuel to extend missions and relocate or deorbit satellites. NASA has flown Robotic Refueling Mission technology demonstrations aboard the ISS from 2011 through 2019. Moreover, NASA's On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission—a technology demonstration spacecraft currently scheduled for launch in 2025—includes satellite servicing technologies that enable on-orbit satellite life extension.[37] Specifically, OSAM-1 is designed to rendezvous with, grasp, refuel, and relocate the Landsat 7 satellite to extend its life.[38] If successful, the technology can give satellite operators new ways to manage their fleets more efficiently, derive more value from initial investments, and provide the additional fuel needed to deorbit satellites or move them to a less congested orbit.

[35] The NASA Innovative Advanced Concepts Program seeks innovations from diverse and non-traditional sources to study innovative, technically credible, advanced concepts that could one day "change the possible" in aerospace. The Program awards grants in phases: Phase I explores the viability of the technology during a 9-month period, Phase II develops concepts for up to 2 years and prepares a roadmap for development, and Phase III continues development for an additional 2 years and strategically transitions the concept to NASA and/or other government or commercial partners.

[36] Tethers Unlimited, Inc. was a Phase I award and The Aerospace Corporation was a Phase II award.

[37] Formerly known as Restore-L, NASA originally planned to launch the satellite servicing demonstration mission in November 2020; however, in May 2020 the OSAM-1 mission was baselined with a $1.78 billion cost and launch readiness date in 2025. The mission also includes the SPace Infrastructure DExterous Robot that intends to demonstrate robotic assembly of a functional communications antenna and in-space manufacturing capabilities.

[38] NASA launched Landsat 7 in April 1999. Operated by the U.S. Geological Survey, the satellite continues the legacy of providing images of the Earth's surface that began with the launch of Landsat 1 in 1972.

Lack of Data on Hazardous Debris Limits NASA's Ability to Properly Protect Spacecraft

NASA models of the orbital debris environment lack sufficient data, putting the Agency at risk of under- or over-protecting spacecraft from debris. Data is limited by the decreasing amount of time made available to the Agency on the three ground-based radars it uses to detect and statistically estimate debris larger than 3 mm. NASA also does not have the data needed to predict the risk orbital debris 3 mm and smaller present to its spacecraft operating at altitudes in the 400 to 1,000 km range because of a failed mission and lack of funding.[39] This is particularly concerning as millimeter-sized orbital debris represents the highest penetration risk to most missions operating in LEO. In addition, NASA does not have the ability to track debris smaller than 10 cm in the range of LEO where the ISS resides. Without adequate time to estimate the debris environment or obtain direct measurement data, NASA's modeling tools—used by programs and projects to make decisions about shielding, trajectory, and altitude—likely are not providing an accurate depiction of the debris environment.

Time on Ground-Based Radars Limited for Obtaining Sampling Data on Orbital Debris

NASA obtains measurements from three ground-based radars and must extrapolate that data through its modeling tools in an attempt to depict the orbital debris environment. However, time available on these radars are limited due to funding, inoperable equipment, and competing priorities from multiple users.

ODPO obtains its orbital debris statistical measurements in LEO from three radars: HUSIR, HAX, and Goldstone. HUSIR and HAX are operated by the Massachusetts Institute of Technology's Lincoln Laboratory and utilized by both NASA and DOD. HUSIR is the highest-resolution space-object-imaging radar in the world, enabling it to statistically sample the debris population in its field-of-view and provide data about the size, shape, orientation, and motion of objects orbiting Earth. HUSIR measures debris from 2 cm to as small as 5 mm. ODPO also collects data from the HAX radar located next to the main HUSIR antenna. Although HAX is less sensitive than HUSIR, it operates at a different wavelength and has a wider field-of-view that can measure debris from 2 to 10 cm. ODPO annually purchases a total of approximately 1,000 hours on HUSIR and HAX. Upgrades to HUSIR have resulted in cost increases being passed on to users, reducing the amount of time ODPO was able to purchase to 500 hours. According to ODPO officials, maintaining at least 500 hours on HUSIR is adequate to sample the debris environment, but additional time on the radar increases the quality of the data and makes the modeling more accurate. Additionally, HAX was out of commission from September 2018 through January 2020 which forced ODPO to rely exclusively on HUSIR.

39 The failed mission was intended to operate in the 400 km range of LEO, the location where the ISS resides.

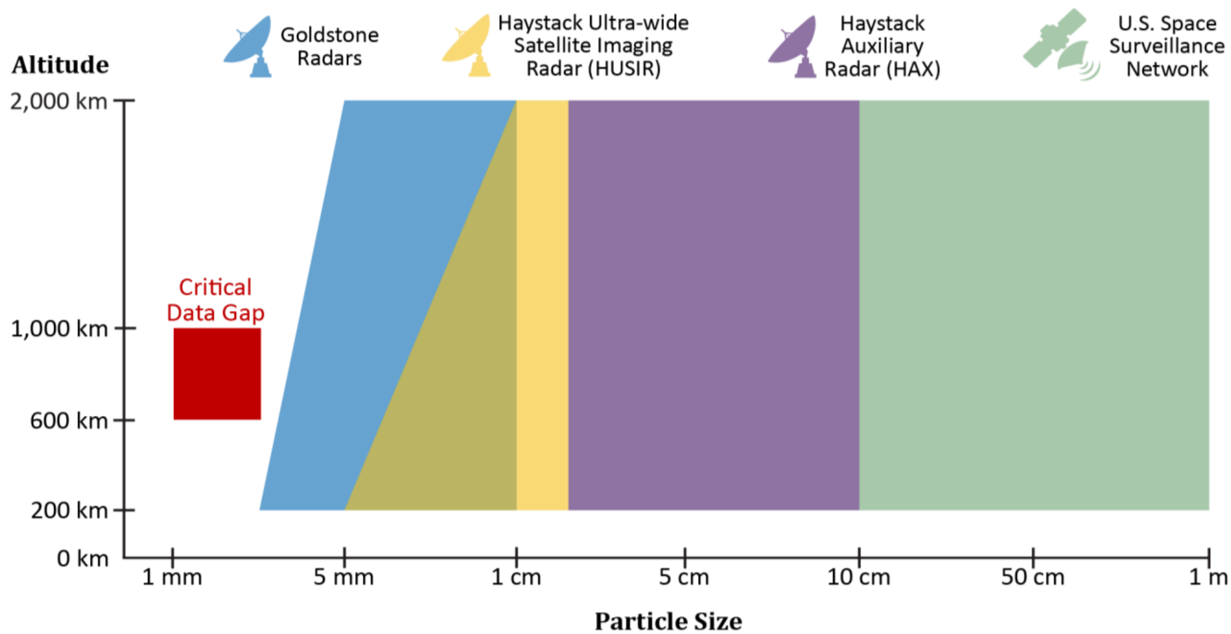
The third radar utilized by ODPO is Goldstone, operated by the Jet Propulsion Laboratory and capable of detecting debris from 3 to 5 mm, making it a critical tool in the characterization of the sub-centimeter-sized debris population. ODPO's time on the Goldstone radar has also decreased substantially over the last 5 years, from 120 hours in 2014 to just 4 hours in 2019, partly because one of the antennas was permanently decommissioned. While an alternate antenna has been identified, multiple programs are vying for time on the radar. For instance, both the Mars Atmosphere and Volatile Evolution (MAVEN) and Origins Spectral Interpretation Resource Identification Security—Regolith Explorer (OSIRIS-REx) missions use the Goldstone radar.[40] As of September 2020, ODPO received 12 hours on Goldstone and expects additional hours for the remainder of the calendar year although officials are uncertain of the exact number.

NASA Has Failed to Secure Space-Based Resources for Collecting Direct Measurement Data on Most Hazardous Debris

NASA cannot measure orbital debris below 3 mm in the most congested region of LEO—the 600 to 1,000 km range—using ground-based radars or telescopes. As shown in Figure 8, these particles are too small and too far away to be detected by ground-based radars such as HUSIR, HAX, and Goldstone, or through the U.S. Space Surveillance Network. According to ODPO, direct measurement data—obtained by space-based tools—is needed to support the development of cost-effective protective measures for safe operation of future missions. Debris this small (the size of a fleck of paint or grain of salt) is extremely dangerous and can cause catastrophic damage to spacecraft due to the high rate of speed the debris travel. On average, a piece of debris this size travels at speeds of 17,500 miles per hour (almost seven times faster than a bullet) and are large enough to be a serious safety concern for the over 400 missions currently operating in this part of LEO. Millimeter-sized debris can damage solar panels and communication arrays. During the Space Shuttle Program, for example, several Shuttle windows had to be replaced because of damage caused by material this size. Further, such debris can cause significant or catastrophic damage if it hits vulnerable parts of a satellite such as the fuel tank.

[40] MAVEN launched in 2013 to study the Martian atmosphere, and OSIRIS-REx launched in 2016 to bring back to Earth a small sample of the asteroid Bennu for study.

Figure 8: Data Gap in Low Earth Orbit



Source: NASA OIG presentation of ODPO data.

Note: Boundaries are notational.

NASA has identified this gap in measurement data as a top Agency risk through its enterprise risk management process.[41] In 2010, NASA's Chief of the Office of Safety and Mission Assurance (OSMA) asked the National Academies (formerly the National Research Council) to evaluate Agency programs responsible for addressing meteoroids and orbital debris. The National Academies identified the need for in-situ measurements and recommended that NASA obtain the capability to make space-based observations of debris in order to more accurately model the orbital debris environment.[42] Further, internal reports from NASA's Engineering and Safety Center recommended that ODPO obtain this type of space-based data in 2015 and again as recently as 2020.[43] Finally, the 2020 NASA Authorization Act, approved by the House of Representative's Subcommittee on Space and Aeronautics in January 2020, requires NASA to identify and report on options to address any risks and gaps with millimeter-sized debris.[44]

NASA has largely been unsuccessful in securing a source of measurement data on debris 3 mm and smaller in the mid-LEO orbit range—including the 400 km range (ISS altitude) where crew safety is a priority and the 600 to 1,000 km range where NASA's robotic missions are located—due to one mission failing and another being canceled multiple times because of a lack of funding. Specifically, in 2018 ODPO sponsored the Space Debris Sensor mission deployed on the ISS to characterize the millimeter-

[41] Enterprise risk management is a management approach that allows organizations to assess threats and opportunities that could affect the achievement of its goals.

[42] National Research Council, *Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs* (2011).

[43] NASA Engineering and Safety Center Technical Assessment Report, *Joint Polar Satellite System Micrometeoroid and Orbital Debris Assessment* (July 2015) and *Review of Orbital Debris Engineering Model Version 3.1* (February 20, 2020).

[44] National Aeronautics and Space Administration Authorization Act of 2020, H.R. 5666, 116th Congress (2020).

sized orbital debris environment. However, after 25 days a software anomaly caused the sensor to fail and the mission ended. Additionally, in 2019 ODPO was directed as part of the Agency's FY 2022 budget planning process to sponsor a second mission that involved sending a sensor into the 600 km and above range of LEO for 3 years beginning in 2023 to measure and collect data at an estimated cost of $49 million. However, the mission was canceled in January 2020 due to a lack of funding. More recently in April 2020, NASA's Associate Administrator directed the Science Mission Directorate to work with ODPO to submit an updated proposal for a mission to gather orbital debris data in LEO's 600 to 1,000 km range. Initially, the proposal was intended to be submitted to the Office of Management and Budget as part of NASA's overguide request—the process for requesting additional funding for Agency activities—but in September 2020 Agency management decided not to submit any such Science Mission Directorate overguide requests.[45] Currently, OSMA and Science Mission Directorate personnel are evaluating options for obtaining this direct measurement data. However, even if a mission is approved, it would likely be 2 to 3 years before a sensor or satellite is launched and able to start gathering data. Without direct measurement data on millimeter-sized debris in the 600 to 1,000 km range of LEO, NASA missions will continue to rely on incomplete data to make decisions regarding risk and spacecraft protection.

NASA Lacks Direct Measurement Data on Debris near the International Space Station

Orbital debris has been identified as a major safety risk for the ISS with respect to loss of mission and crew. NASA employs shields to protect the U.S modules on the ISS, which have proven effective against impacts by small orbital debris up to about 1 cm. According to NASA officials, installing additional shielding to the ISS would be cost prohibitive. Collision risk against objects 10 cm and larger are mitigated by real-time conjunction assessments that determine the risks posed by close approaches of debris and collision avoidance maneuvers when necessary. Therefore, the biggest threat to the U.S. modules is debris between 1 and 10 cm. Since the orbital debris population follows a power-law size distribution, meaning there is a higher number of small debris than large debris, the risk to these modules is driven by orbital debris in the 1 to 2 cm range.

NASA does not monitor nor is there currently an operational capability to track orbital debris smaller than 10 cm in the 400 km range of LEO where the ISS resides. Instead, the Agency obtains statistical measurements from its ground-based radars and estimates the mass of this debris. The primary option to mitigate risks from debris that cannot be monitored or tracked is through physical protective measures such as shielding. While DOD tracks and monitors debris 10 cm and larger through its U.S. Space Surveillance Network, the U.S. modules of the ISS remain vulnerable to impact from debris in the 2 to 9 cm range—sizeable enough to puncture critical elements including the Station's hull.

NASA intends to rely on DOD's Space Fence, which achieved initial operating capability in March 2020, for tracking debris of this size. Located on Kwajalein Island in the Republic of the Marshall Islands, Space Fence is a ground-based radar system designed to track, monitor, and characterize satellites and small debris in LEO. As of September 2020, Space Fence has detected approximately 5,000 new unique objects; however, because it is just one radar based in a single location its functionality is limited. In

[45] The Office of Management and Budget provides agency-specific programmatic and budgetary guidance, including decisions on budget proposals that exceed initial requests (typically called overguide requests), that generally require additional justification and evidence that the overguide activities cannot be accommodated within the agency's budget.

order to reach full operational capability, a second radar is needed and while ODPO officials explained that DOD intends to build the second radar in Australia, as of September 2020 the project has not been approved and the time frame for completion is unknown.

Additional monitoring and tracking capabilities for debris in the 2 to 9 cm range may become available from commercial entities through custom-built radars as early as 2021.[46] However, until commercial options or the Space Fence becomes fully operational NASA will continue to rely on statistical estimates of the debris that pose the greatest risk to the ISS.

[46] One commercial entity developing this capability is LeoLabs, a provider of low Earth orbit mapping and space situational awareness services designed to track orbital debris, prevent collisions in LEO, and deliver accurate tracking and curated orbit data.

NASA Needs to Improve the Approval Processes for Orbital Debris Assessment Reports and End of Mission Plans

NASA assesses program and project compliance with Agency orbital debris mitigation requirements through OSMA's evaluation and concurrence with mission Orbital Debris Assessment Reports (ODAR) and End of Mission Plans (EOMP). While NASA has made improvements to the evaluation process, we found that ODARs and EOMPs were not consistently submitted to OSMA in a timely manner, with some submitted nearly a year late.

The ODAR outlines how a spacecraft and launch vehicle will comply with orbital debris mitigation requirements such as limiting the probability of an accidental explosion. The EOMP is developed during the later stages of a mission and ensures that the risk to the public and other active spacecraft is minimized during decommissioning and that proper disposal of all operational space objects will occur. Projects are required to submit ODARs and EOMPs to OSMA at key decision points of the project's life cycle including the Preliminary Design Review, Critical Design Review, and Safety and Mission Success Review.[47] Projects are required to update EOMPs when a spacecraft or event occurs that significantly reduces the likelihood of a planned disposal or at least once every 2 years. According to NASA requirements, OSMA, with technical support from ODPO, must review and concur within 14 days of receiving the ODAR document.[48] Additionally, an updated EOMP must be submitted at least 30 days prior to a decision on the mission extension.

Over the past 5 years, OSMA officials have used a database to better track the ODARs and EOMPs and have improved the approval process by being more aware of projects' upcoming key decision points and working with program officials to ensure the reports are submitted to OSMA for timely approval. Additionally, the officials identify overdue ODARs and EOMPS during briefings to Agency management. However, we found that timeliness issues remain as well as confusion about the approval process. Specifically, we found 4 out of 23 ODARs and EOMPs we reviewed from FYs 2018 to 2019 were not submitted to OSMA timely, sometimes up to a year after the project completed the documents, greatly

[47] A key decision point is defined as the point in time when the Decision Authority—the responsible official who provides approval—makes a decision on the readiness of the project to progress to the next life-cycle phase. Key decision points serve as checkpoints or gates through which projects must pass during their development. The Preliminary Design Review and Critical Design Review are held approximately a month prior to the Decision Authority granting or denying permission to proceed. The Safety and Mission Success Review is held approximately 1 month to 2 weeks prior to flights or launches of NASA human and robotic missions, and test flights and demonstrations of commercially developed launch vehicles and spacecraft. The outcome is a documented recommendation from NASA's Technical Authorities to the responsible mission director concerning residual risk and the advisability of proceeding.

[48] NPR 8715.6B defines responsibilities and requirements to ensure that NASA and its partners, providers, and contractors consider the preservation of the near-Earth space environment and the space environment beyond Earth's orbit and mitigation of the risk to human life and space missions due to orbital debris and meteoroids. These requirements include the ODAR and EOMP.

exceeding the expected delivery dates for ODARs and EOMPs as required by policy.[49] Further, as of January 2020 OSMA officials were working with an additional four missions on overdue ODARs.[50]

OSMA and ODPO officials explained that at times they have limited time to review ODARs and EOMPs because they receive the reports too close to the key decision point review. In some instances, OSMA officials said they had no choice but to waive a requirement in an ODAR or EOMP because they were not given adequate time to review the documentation and provide options for meeting the requirements. For example, in 2017 the Science Mission Directorate approved an extension of the Van Allen Probes mission yet did not submit the updated EOMP to OSMA until almost a year later.[51] The extension triggered an additional orbital debris mitigation non-compliance with a requirement to remove, disconnect, and dump all energy sources to lower the impact explosions and collisions have on the orbital debris environment. Originally, the mission planned to reserve sufficient fuel in order to lower the spacecraft to an orbit that would enable reentry within 5 months and in which the spacecraft could be reoriented so that its solar arrays would be away from the Sun preventing recharging of the batteries. However, the subsequent mission extension led to insufficient fuel to lower the spacecraft's orbit per the original plan and disconnect the solar array from the battery. Instead, the batteries will continue to recharge which could eventually result in an explosion and creation of additional orbital debris.

We also found that the process used to route ODARs and EOMPs to OSMA laborious. Specifically, Science Mission Directorate officials we spoke with found the concurrence and signature process cumbersome and confusing in terms of which personnel are required to sign and concur with the reports, noting that it has taken over a year in some instances to obtain all required signatures. For example, the Soil Moisture Active Passive EOMP was prepared by project management at the Jet Propulsion Laboratory in March 2018 yet was not provided to OSMA for evaluation until September 2019.[52]

Per requirements for a Preliminary Design and Mission Critical Design ODAR, the Mission Directorate Associate Administrator is only required to be notified and does not have to concur with the document prior to it being sent to OSMA. However, depending on the project or mission, internal processes and requirements implemented by mission and project personnel add to the time the project takes to submit the documents. For example, although OSMA requires a project manager's signature and notification to the Mission Directorate Associate Administrator at a key decision point, such as a Preliminary Design Review, project managers have at times instead interpreted that notification as a concurrence and requested the Mission Directorate Associate Administrator's signature. Depending on

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[49] OSMA officials reviewed 43 ODARs and EOMPs in FY 2018 and 27 in FY 2019.

[50] All four missions are scheduled for FY 2022 launches. The Double Asteroid Redirection Test mission is a planetary defense-driven test of technologies for preventing an impact of Earth by a hazardous asteroid. The Geostationary Operational Environmental Satellite-T mission will provide advanced imagery and atmospheric measurements of Earth's weather, oceans, and environment; real-time mapping of total lightning activity; and improved monitoring of solar activity and space weather. The Joint Polar Satellite System-2 will provide operational continuity of satellite-based observations of atmospheric, terrestrial, and oceanic conditions for both weather forecasting and long-term climate and environmental data. Landsat 9—a partnership between NASA and the U.S. Geological Survey—will continue the Landsat program's critical role in monitoring, understanding, and managing the land resources needed to sustain human life.

[51] Launched in 2012, two Van Allen Probes spacecraft collect data in the Van Allen Radiation Belts that surround Earth with the goal of helping to predict space weather before it impacts the Earth.

[52] Launched in 2015, the Soil Moisture Active Passive mission is an orbiting observatory that measures the amount of water in the surface soil on Earth.

which Center designed the project, at times this also triggered an internal requirement for the Center Director to review and sign the documents prior to sending it to the Mission Directorate Associate Administrator adding more time to the approval process.

Unnecessarily adding additional approvals to the review process results in delayed submission to OSMA, inhibiting OSMA's ability to review and the mission's ability to obtain approval of mitigation plans in a timely manner. OSMA's review of ODARs and EOMPs is the process the Agency uses to ensure it is limiting the generation of debris and disposing of spacecraft safely. At times, ODPO can provide alternatives to programs and projects such as shielding for a satellite to help ensure mitigation standards are met. A delay in providing the documentation for review could result in a missed opportunity for a low-cost "fix" to address a mitigation issue while also avoiding the need for a waiver to an issue that ultimately could result in the creation of additional orbital debris.

CONCLUSION

Since its first mention in the Presidential Directive on National Space Policy in 1988, the danger of steadily increasing amounts of orbital debris in LEO has gained greater public recognition.[53] Through NASA's leadership and collaboration efforts, significant progress has been made over the last 30 years in the development and implementation of national orbital debris mitigation guidelines, coordination with international partners to adopt debris mitigation safeguards, and the characterization and modeling of the overall orbital debris environment.

While NASA cannot address the issue of reducing orbital debris on its own, the Agency can make an important impact through its continued leadership in responsible mitigation measures, coupled with a new commitment to develop cost-effective active debris removal technologies. However, to date the Agency has made only limited progress in this area due to funding issues and a lack of prioritization from Agency leadership.

Enhancing efforts to characterize the debris environment such as obtaining data on millimeter-sized debris and obtaining additional time on critical ground-based radar assets will result in a more complete picture of the amount of debris that exists so spacecraft owners and operators can better protect the spacecraft and satellites accordingly. Additionally, as this lack of data has been identified as a top Agency risk, prioritizing obtaining this data is imperative.

Protecting the expanding space environment is critical since the services billions of people rely on daily such as weather forecasting, telecommunications, and global positioning systems require a stable space environment.

[53] President Reagan, *Presidential Directive on National Space Policy* (February 11, 1988).

Recommendations, Management's Response, and Our Evaluation

To better protect spacecraft, maintain the space environment, and address a top Agency risk to obtain direct measurements of millimeter-sized debris, we recommended NASA's Administrator:

1. Lead national and international collaborative efforts to mitigate orbital debris including activities to encourage active debris removal and the timely end-of-mission disposal of spacecraft.
2. Collaborate with Congress, other federal agencies, and partners from the private and public sectors to adopt national and international guidelines on active debris removal and strategies for increasing global compliance rates for timely removal of spacecraft at the end of a mission.
3. Invest in methods and technologies for removing defunct spacecraft. As part of this effort, conduct a study evaluating the technical merit and cost to investing in active debris removal systems and technologies.
4. Prioritize obtaining direct measurements needed to fill the 3 mm and smaller sized debris gap at the 600 to 1,000 km altitude in LEO.

In addition, we recommended NASA's Chief of Safety and Mission Assurance:

5. Explore alternative orbital debris radar assets to fill the data gaps caused by the increased costs of utilizing existing radars and the loss of legacy assets.
6. Explore commercial alternatives to obtaining information on debris smaller than 10 cm until Space Fence becomes fully operational.
7. Coordinate with Mission Directorate officials to develop and document a formal signature process that clarifies needs and expectations and supports the timely delivery of ODARs and EOMPs prior to key decision point reviews.

We provided a draft of this report to NASA management, who concurred with Recommendations 5 and 7; partially concurred with Recommendations 1, 2, 3, and 4; and non-concurred with Recommendation 6. We consider management's comments responsive to Recommendations 5 and 7; therefore, those recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions. However, we found the Agency's response to Recommendations 1, 2, 3, 4, and 6 unresponsive and those recommendations will remain unresolved pending further discussions with the Agency.

For Recommendations 1 and 2, the Agency partially concurred, stating NASA has received no direction from the Administration to lead national and international collaborative efforts to encourage active debris removal. In addition, the management response noted that NASA has led interagency efforts to update the 2019 U.S. Government Orbital Debris Mitigation Standard Practices "to promote efficient and effective space safety practices" for domestic and international operators. However, as stated in the report, NASA has been directed by the President and Congress multiple times over the past 10 years to develop active debris removal technology. At the same time, Congress has stated in authorizing legislation that a national and international effort is needed to develop a coordinated approach towards the prevention, negation, and removal of orbital debris and that NASA should collaborate with other relevant agencies to solicit and review concepts and options for removing debris. We believe this prior congressional direction, coupled with the imminent danger posed to U.S. space assets, provides sufficient basis for the Agency to work with Congress, federal agencies, international partners, and other stakeholders to address the risks posed by orbital debris. Further, because NASA considers itself "the international lead in conducting measurements of the orbital environment and in developing the technical consensus," we believe it is best positioned to lead national and international efforts to encourage debris mitigation and removal activities. As such, we find the Agency's partial concurrence to Recommendations 1 and 2 questionable given their lack of proposed actions moving forward in response to our findings.

In response to Recommendation 3, the Agency also partially concurred and stated that the Space Technology Mission Directorate already invests in methods and technologies for removing orbital debris by focusing on early-stage efforts. In addition, the management response stated that the Space Technology Mission Directorate conducted a study "in the 2014 timeframe" to evaluate the technical viability of concepts for active debris removal, but concluded that since then there have been "no major technological breakthroughs that would warrant another study at this time." We disagree. As highlighted in our report, the European Space Agency and JAXA have spearheaded several new developments for debris removal. Considering these active debris removal efforts, we find management's response significantly lacking. Furthermore, since 2014 the number of objects launched into space has increased dramatically, increasing the likelihood of collisions between active NASA spacecraft and orbital debris, a situation that to us increases the imperative to develop removal technologies.

NASA also partially concurred with Recommendation 4 and noted that obtaining direct measurement of 3 mm and smaller sized debris is a high priority for OSMA. The Science Mission Directorate plans to form an interagency "tiger team" to conceptualize a research and analysis program and mission concept to improve space situational awareness, tracking, and collision avoidance coordination and collaboration. While that effort may prove beneficial to NASA's long-term efforts, we fail to see how this effort would prioritize obtaining direct measurement of 3 mm and smaller sized debris in the critical 600 to 1,000 km altitude of LEO, the focus of our recommendation.

Finally, the Agency non-concurred with Recommendation 6 and stated that exploring commercial alternatives to obtaining information on debris smaller than 10 cm until DOD's Space Fence becomes fully operational will add an unreasonable cost-burden to OSMA for a task assigned to DOD. While we understand that implementing commercial alternatives could be costly, such a response is merely guesswork without carefully exploring the alternatives. In addition, relying solely on the as-yet limited functionality of Space Fence does not relieve NASA of the responsibility to ensure the safety of the ISS, which is currently vulnerable to debris in the 1 to 10 cm range. Therefore, we recommend the Agency explore commercial alternatives to obtaining information on debris smaller than 10 cm to make an informed decision regarding protection of the ISS and its other space assets.

Management's comments are reproduced in Appendix B. Technical comments provided by management have been incorporated as appropriate.

Major contributors to this report include Ray Tolomeo, Science and Aeronautics Research Director; Tekla Colón, Project Manager; Cynthia Collado; Mona Mann; Lauren Suls; and Terri Thompson.

If you have questions or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

Paul K. Martin
Inspector General

Appendix A: Scope and Methodology

We performed this audit from November 2019 through December 2020 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Our audit objective was to evaluate the Agency's efforts to mitigate the risks posed by human-made objects in space that are no longer serving a purpose, as well as NASA's coordination and communication efforts with international and commercial organizations to address orbital debris. We did not consider space traffic management in our review, as it is primarily concerned with the coordination of operational objects in space. To accomplish our objective, we performed the majority of our work with OSMA at Headquarters and ODPO at Johnson Space Center.

To gain an understanding of the Agency's efforts to mitigate the risks posed by orbital debris, we conducted numerous interviews across multiple levels of OSMA and ODPO including the Hypervelocity Impact Team. This included reviewing how NASA characterizes the orbital debris environment as well as the models and tools they utilize to statistically estimate the amount of debris in space. We met with supporting organizations including the Conjunction Assessment Risk Analysis Team at Goddard Space Flight Center and the Flight Operations Directorate and Trajectory Operations Officer at Johnson Space Center. To understand how orbital debris affects missions, programs, and projects we met with officials from the ISS Program, Orion Program, Commercial Crew Program, Science Mission Directorate, and Space Technology Mission Directorate. We reviewed reports and met with officials from the NASA Engineering and Safety Center who had conducted internal reviews of orbital debris issues. To understand the risks of orbital debris to crew, we spoke with two NASA astronauts during a presentation at NASA Headquarters.

To evaluate whether NASA programs and projects were complying with orbital debris mitigation requirements as well as whether OSMA and ODPO were conducting reviews of orbital debris data judgmentally, we selected a sample of 23 ODARS and EOMPS from FYs 2018 and 2019. We reviewed the ODARs, EOMPs, and supporting documentation to ensure they met requirements outlined in NASA policy for limiting orbital debris. We also reviewed documentation to support waiving mitigation requirements. Finally, we assessed whether OSMA and ODPO reviewed ODARs and EOMPs in a timely manner.

To gain an understanding of NASA's coordination and communication efforts, we met with officials from NASA's Office of International and Interagency Relations as well as DOD officials from the Space and Missile Systems Center and the U.S. Space Surveillance Network to obtain an understanding of their roles and responsibilities related to orbital debris. Finally, we met with officials from LeoLabs, a commercial startup company to learn about commercial options for orbital debris tracking and monitoring services.

Federal Laws, Regulations, Policies, and Guidance

We reviewed the following federal laws, regulations, policies, and guidance related to orbital debris:

- National Aeronautics and Space Administration Authorization Act of 2020, H.R. 5666, 116th Congress (2020)
- National Aeronautics and Space Administration Transition Authorization Act of 2017, Pub. L. No. 115-10 (2017)
- National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267 (2010)
- President Trump, Space Policy Directive-3, *National Space Traffic Management Policy* (June 18, 2018)
- President Trump, Space Policy Directive-2, *Streamlining Regulations on Commercial Use of Space* (May 24, 2018)
- President Obama, *National Space Policy of the United States of America* (June 28, 2010)
- United States Government Orbital Debris Mitigation Standard Practices (November 2019)
- Inter-Agency Space Debris Coordination Committee, IADC-02-01, Revision 1, *IADC Space Debris Mitigation Guidelines* (September 2007)
- United Nations Office for Outer Space Affairs, *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space* (2010)
- NASA Procedural Requirements 8715.6B, *NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments* (February 16, 2017)
- NASA Technical Standard 8719.14B, *Process for Limiting Orbital Debris* (April 25, 2019)
- NASA Handbook 8719.14, *Handbook for Limiting Orbital Debris* (July 30, 2008)

Assessment of Data Reliability

We did not use computer-processed data to perform this audit.

Review of Internal Controls

We reviewed and evaluated the internal controls associated with NASA's OPDO and its operations. The weaknesses identified are discussed in this report. Our recommendations, if implemented, should correct the identified weaknesses.

Prior Coverage

During the last 5 years, the NASA Office of Inspector General and Government Accountability Office have issued two reports of significant relevance to the subject of this report. The unrestricted reports can be accessed at https://oig.nasa.gov/docs/IG-18-021.pdf and https://www.gao.gov/assets/710/704121.pdf, respectively.

NASA Office of Inspector General

NASA's Management and Utilization of the International Space Station (IG-18-021, July 30, 2018)

Government Accountability Office

NASA Commercial Crew Program: Plan Needed to Ensure Uninterrupted Access to the International Space Station (GAO-18-476, July 2018)

Appendix B: Management's Comments

National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

January 21, 2021

Reply to Attn of: Office of Safety and Mission Assurance

TO: Assistant Inspector General for Audits

FROM: Chief, Office of Safety and Mission Assurance

SUBJECT: Agency Response to OIG Draft Report, "NASA's Efforts to Mitigate the Risks Posed by Orbital Debris" (A-20-002-00)

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Efforts to Mitigate the Risks Posed by Orbital Debris" (A-20-002-00), dated December 8, 2020.

In the draft report, the OIG makes seven recommendations addressed to NASA to protect spacecraft better, maintain the space environment, and manage a top Agency risk to obtain direct measurements of millimeter-sized debris. Specifically, the OIG recommends the following:

Recommendation 1: Lead national and international collaborative efforts to mitigate orbital debris, including activities to encourage active debris removal and the timely end-of-mission disposal of spacecraft.

Management's Response: Partial-Concur. NASA's role within the executive branch is established by a combination of direction from Congress in law and implementing policy direction from the Administration. At present, there is no Administration direction to NASA for leading national and international collaborative efforts to encourage active debris removal. The Agency does not have a legislative or mission requirement to lead such efforts. Consistent with guidance in Space Policy Directive 3 (SPD-3), the National Space Traffic Management Policy, NASA led the interagency effort to update the U.S. Government (USG) Orbital Debris Mitigation Standard Practices (ODMSP). The 2019 ODMSP update includes improvements to the original standard practices which are significant, meaningful, and achievable with quantified parameters and preferred options; as well as clarifications and additional traditional practices for certain classes of space operations, such as flying large constellations of space vehicles, rendezvous and proximity operations, satellite servicing, and operating small satellites. The new standard practices established in the update include the preferred disposal options for immediate removal of structures from the near-Earth space environment. By establishing guidelines for USG activities, the 2019 ODMSP provides a reference to promote efficient and effective space safety practices for other domestic and international operators.

Estimated Completion Date: Closed. On December 9, 2019, the National Space Council announced that the revised U.S. ODMSP was posted. The first update of the ODMSP since its publication in 2001.

Recommendation 2: Collaborate with Congress, other federal agencies, and partners from the private and public sectors to adopt national and international guidelines on active debris removal and strategies for increasing global compliance rates for timely removal of spacecraft at the end of a mission.

Management's Response: Partial-Concur. NASA collaboration with Congress and others is governed by Administration policy and direction. NASA collaborates with partner agencies within the executive branch as well as with other stakeholders concerning orbital debris issues. NASA reports to Congress on these efforts. Related to the NASA response to Recommendation 1 regarding the 2019 update of the USG ODMSP, the Agency engages in systematic efforts, led by the Department of State, to increase international support for adhering to guidelines to mitigate orbital debris, including timely disposal of spacecraft at the end of mission. Specifically, NASA continues to share the ODMSP broadly, including: in February 2020 - presentation on SPD-3, the National Space Traffic Management Policy, and the ODMSP at the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space; in February 2020 - NASA Orbital Debris Quarterly News highlighted the ODMSP; and in April 2020 - during a virtual session of the Inter-Agency Space Debris Coordination Committee (IADC), the international technical forum on debris, provided e-mail copies of the updated 2019 USG ODMSP which is located on the IADC Web site.

Estimated Completion Date: Closed. Update to USG ODMSP complete and international engagement initiated, which will be recurring.

Recommendation 3: Invest in methods and technologies for removing defunct spacecraft. As part of this effort, conduct a study evaluating the technical merit and cost of investing in active debris removal systems and technologies.

Management's Response: Partial-Concur. The Space Technology Mission Directorate (STMD) invests in methods and technologies for removing orbital debris by investing in early-stage efforts to develop approaches to address this matter. STMD conducted a study, in the 2014 timeframe, to assess the nature of the orbital debris problem and evaluate the technical viability of concepts for active debris removal. Since this study, there have been no major technological breakthroughs that would warrant another study at this time. STMD continues to invest in promising early-stage concepts and technologies that could alter the landscape for identifying technically and cost-effective, viable orbital debris removal approaches.

Estimated Completion Date: Closed.

Recommendation 4: Prioritize obtaining direct measurements needed to fill the 3 mm and smaller sized debris gap at the 600 to 1,000 km altitude in LEO.

Management's Response: Partial-Concur. NASA recognizes the importance and urgency of quantifying the risk to spacecraft from orbital debris, which drives mission-ending risk to operational spacecraft at key orbits around the Earth, including at the 600 – 1,000 km altitude in low-Earth Orbit (LEO).

A high priority for the Office of Safety and Mission Assurance (OSMA) is to address the 3 mm and smaller sized debris gap at the 600 – 1,000 km altitude in LEO. A supporting priority for the Science Mission Directorate (SMD) is the space environment's characterization, ultimately enabling forecasting of natural effects on space systems. These two priorities have synergy to better quantify mission-ending risk and improve future missions' safe operations. Ongoing efforts related to orbital debris include recent participation by OSMA and SMD in an Orbital Debris Research and Development Interagency Working Group, which produced a report describing a national plan of research and development activities in support of the management of risk associated with orbital debris. Furthermore, SMD recently engaged in the Tri-Agency Strategic Architecture Workshop (TSAW) with the National Oceanic and Atmospheric Administration and the U.S. Space Force to discuss collaboration opportunities to characterize space weather and the space environment which has impacts on orbital debris. Based on discussions at the TSAW and synergy around space situational awareness/tracking/collision avoidance coordination and collaboration, SMD will form an interagency tiger team to conceptualize a research and analysis program and mission concept. Authorization to begin mission formulation will be required before the pursuit of obtaining direct measurements.

Estimated Completion Date: A summary report from the tiger team to be produced no earlier than December 2021.

Recommendation 5: Explore alternative orbital debris radar assets to fill the data gaps caused by the increased costs of utilizing existing radars and the loss of legacy assets.

Management's Response: Concur. OSMA will explore alternative orbital debris radar assets to fill the data gaps caused by the increased costs of utilizing existing radars and the loss of legacy assets, i.e., the Haystack Auxiliary Radar, via a Request for Information (RFI). The RFI will explore the potential of commercial sources for this data.

Estimated Completion Date: December 31, 2022.

Recommendation 6: Explore commercial alternatives to obtaining information on debris smaller than 10 cm until Space Fence becomes fully operational.

Management's Response: Non-Concur. The Department of Defense (DoD) detects, tracks, and catalogs the largest objects in the near-Earth space environment and provides conjunction warnings to satellite owners and operators, including NASA, to avoid collisions with the tracked objects. DoD's Space Surveillance Network consists of ground-based radars and telescopes situated worldwide and space-based sensors. DoD can detect, track, and catalog objects approximately 10 cm and larger in LEO, the region below 2,000 km altitude.

To improve the limit for objects smaller than 10 cm (down to several centimeters), the DoD initiated the Space Fence project more than ten years ago. The first Space Fence is located at Kwajalein Atoll, and it achieved the Initial Operational Capability in March 2020. As of October 2020, the Kwajalein Space Fence had detected about 5,000 unique new objects, and the detection is expected to improve over time. DoD plans to share the Space Fence data with the community, including NASA, at no cost starting in early 2021. The Kwajalein Space Fence is a multi-billion-dollar sensor. The Space Fence system will not achieve Full Operational Capability until a second Space Fence is designed, built, and becomes operational. Currently, DoD has not proposed a plan to make the second Space Fence.

SPD-3 - the National Space Traffic Management Policy, Section 6, Roles and Responsibilities, reaffirms DoD's responsibility for cataloging space objects: "The Secretary of Defense shall maintain the authoritative catalog of space objects." The recommendation to explore commercial alternatives to obtaining information on debris smaller than 10 cm until Space Fence becomes fully operational would add unreasonable cost-burden to OSMA for a task that the Administration has assigned to DoD.

Estimated Completion Date: N/A.

Recommendation 7: Coordinate with Mission Directorate officials to develop and document a formal signature process that clarifies needs and expectations and supports the timely delivery of ODARs and EOMPs before critical decision point reviews.

Management's Response: Concur. OSMA will revise the NPR 8715.6 – "NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments" and other guidance to clarify Agency roles and responsibilities in the Orbital Debris Assessment Report (ODAR) and End of Mission Plan (EOMP) development and review (signature/approval) process to facilitate their timely evaluation and mission compliance with NASA's orbital debris mitigation requirements. OSMA will conduct outreach and training with the NASA Mission Directorates to improve the timely delivery of ODARs and EOMPs.

Estimated Completion Date: June 30, 2022.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Appendix C: Report Distribution

National Aeronautics and Space Administration

Acting Administrator
Chief of Staff
Chief, Safety and Mission Assurance
Associate Administrator for Human Exploration and Operations Mission Directorate
Associate Administrator for Science Mission Directorate
Associate Administrator for Space Technology Mission Directorate
Chief Scientist, Orbital Debris Program Office

Non-NASA Organizations and Individuals

Office of Management and Budget
　Deputy Associate Director, Energy and Space Programs Division

Office of Science and Technology Policy
　Director, Office of Science and Technology Policy

Government Accountability Office
　Director, Contracting and National Security Acquisitions

Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations
　Subcommittee on Commerce, Justice, Science, and Related Agencies

Senate Committee on Commerce, Science, and Transportation
　Subcommittee on Aviation and Space

Senate Committee on Homeland Security and Governmental Affairs

House Committee on Appropriations
　Subcommittee on Commerce, Justice, Science, and Related Agencies

House Committee on Oversight and Reform
　Subcommittee on Government Operations

House Committee on Science, Space, and Technology
　Subcommittee on Investigations and Oversight
　Subcommittee on Space and Aeronautics

(Assignment No. A-20-002-00)