# National Orbital Debris R&D Plan

1. Limit debris generation by design
2. Track and characterize debris
3. Remediate or repurpose debris

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES
OFFICE OF SCIENCE AND TECHNOLOGY POLICY

# NATIONAL ORBITAL DEBRIS RESEARCH AND DEVELOPMENT PLAN

*A Report by the*
ORBITAL DEBRIS RESEARCH AND DEVELOPMENT
INTERAGENCY WORKING GROUP
SUBCOMMITTEE ON SPACE WEATHER, SECURITY, AND HAZARDS
COMMITTEE ON HOMELAND AND NATIONAL SECURITY
*of the*
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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The Orbital Debris Research and Development (ODRAD) Interagency Working Group (IWG) is organized under the Subcommittee for Space Weather, Security, and Hazards, which is part of the NSTC Committee on Homeland and National Security. ODRAD seeks to coordinate the activities of Executive departments and agencies to promote the sustainability of the space environment, as well as space domain safety and security, through coordinated research and development (R&D) activities to overcome scientific and technical challenges associated with orbital debris risk management.

## About this Document

This document was developed by the ODRAD IWG to address science and technology issues related to orbital debris as discussed by Space Policy Directive 3 and other policy and guidance documents. It presents a national plan of research and development in support of managing the risk posed by orbital debris. This document was reviewed by the Subcommittee on Space Weather, Security, and Hazards and the Committee on Homeland and National Security and was finalized and published by OSTP. This document will be reviewed and updated as appropriate.

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## Abbreviations and Acronyms

| | |
|---|---|
| **ADR** | active debris removal |
| **DHS** | Department of Homeland Security |
| **DOC** | Department of Commerce |
| **DoD** | Department of Defense |
| **DOE** | Department of Energy |
| **DOI** | Department of the Interior |
| **DOS** | Department of State |
| **DOT** | Department of Transportation |
| **FAA** | Federal Aviation Administration |
| **FCC** | Federal Communications Commission |
| **GSO** | geosynchronous orbit |
| **LEO** | low-Earth orbit |
| **LNT** | lethal nontrackable debris |
| **NASA** | National Aeronautics and Space Administration |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NSF** | National Science Foundation |
| **ODMSP** | Orbital Debris Mitigation Standard Practices |
| **OSTP** | Office of Science and Technology Policy |
| **R&D** | research and development |
| **SPD-3** | Space Policy Directive 3 |

## Introduction

Orbital debris—defined as any human-made space object orbiting Earth that no longer serves any useful purpose[1]—poses a significant and growing hazard for safe spaceflight operations. Debris ranges from the thousands of spent upper stages to millions of almost miniscule particles (paint specks, bits of satellite shielding, etc.) that span all orbits. Debris creation can result from normal launch and reentry operations, erosion of spacecraft surfaces, in-space collisions of objects (including debris), on-orbit explosions, and defunct spacecraft remaining in orbit after completion of their missions.

Orbital debris has been accumulating since the first space missions, and the debris population is expected to continue to grow as nations and the private sector continue to expand their use of space. Figure 1 shows the growth of trackable debris objects since the beginning of the space age. There are currently approximately 23,000 debris objects 10 centimeters in size (about the size of a softball) or larger that are cataloged and tracked for purposes of collision avoidance. However, there are estimated to be roughly 500,000 objects 1 centimeter in size or larger, and upwards of 100 million debris objects at least 1 millimeter in size.[2] Objects less than 5 centimeters in size are difficult to track individually even if they are in low Earth orbit (LEO); therefore, these population size estimates rely heavily on statistical sampling and modeling techniques.

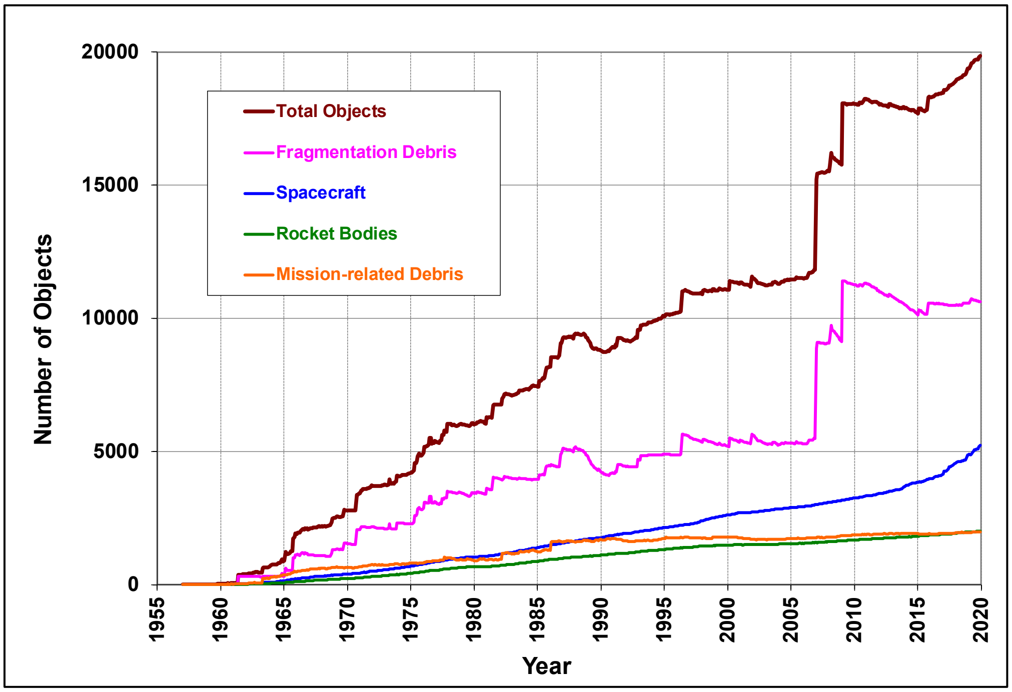

**Figure 1. Growth of orbital debris objects over time by object type**

While orbital debris is present throughout the space environment surrounding the planet, it is concentrated around the most widely used orbits. The highest concentration of cataloged objects is located in LEO—defined as the region below approximately 2,000 kilometers in altitude. The LEO region

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[1] Space Policy Directive – 3 (SPD-3), National Space Traffic Management Policy, 83 FR 28969 (June 18, 2018).

[2] Liou, J.-C. 2020. "Risks from Orbital Debris and Space Situational Awareness." IAA Conference on Space Situational Awareness, January 14, 2020. Washington, D.C. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20200000450.pdf

also contains the highest estimated mass of debris, at about 3,000 metric tons.[3] Collectively, there are over 8,000 metric tons of orbital debris from LEO to geosynchronous orbit (GSO), which is around 35,800 kilometers in altitude.[2]

With average impact speeds of 10 kilometers per second in LEO, orbital debris is hazardous to space assets and astronauts. A collision between an active satellite and a larger debris object (10 centimeters or greater) will most likely result in catastrophic destruction of the satellite. Collisions with much smaller objects (millimeter-sized debris) can impair meeting mission objectives, reduce mission lifetime or, depending on where the satellite is struck, cause the mission to fail. For example, collisions with smaller objects and solar panels can shorten lifetimes by reducing the ability to charge on-board batteries, while collisions with fuel tanks or communication electronics can instantly disable mission-critical functions. This type of relatively small debris is often termed "lethal non-trackable debris" (LNT) due to the potentially severe consequences of collision and the inability to track them. LNT represents the largest quantity[4] of orbital debris of concern and poses significant risk. Beyond the immediate damage that some collisions can cause, all collisions—whether between active or inactive objects—produce additional debris that increases the overall debris hazard and can potentially result in a cascading process known as the Kessler Syndrome.[5] Deliberate actions, including scientific experiments and tests of anti-satellite weapons (ASATs),[6] have also significantly increased orbital debris.

The risk orbital debris presents must be properly managed to ensure the safety and success of both ongoing and future space missions. The importance of debris risk management is underscored by collisions that have occurred in past years. These range from "small" impacts resulting in, e.g., damaged solar arrays, electronic assemblies, and space shuttle windshields, to catastrophic impacts of full-sized satellites. As the use of space increases, the risk of "mission-fatal" debris impact will also increase.

In the United States, multiple agencies are involved in orbital debris risk management. The Department of Defense (DoD) collects debris data, tracks debris, and notifies operators of possible collisions. The National Aeronautics and Space Administration (NASA) uses radars, telescopes, and *in situ* measurements to statistically sample debris too small to be tracked but still large enough to threaten human spaceflight and robotic missions. NASA also led the development of the U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP), which are directly applicable to U.S. Government operators and also apply to non-U.S. Government operators to the extent that they are incorporated into applicable regulations.[7] The Federal Aviation Administration (FAA), the National Oceanic and Atmospheric Administration (NOAA),[8] and the Federal Communications Commission (FCC) all have

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[3] Liou, J.–C. 2017. "USA Space Debris Environment, Operations, and Research Updates." United Nations Committee on the Peaceful Uses of Outer Space, 54th Session of the Scientific and Technical Subcommittee, January 30, 2017, Vienna.

[4] "3 Debris Population Distribution." National Research Council. 1995. *Orbital Debris: A Technical Assessment.* Washington, DC: The National Academies Press. Doi: 10.17226/4725.

[5] Kessler, D.J., Cour-Palais, B.G. 1978. "Collision frequency of artificial satellites: The creation of a debris belt." JGR 83 (A6), 2637–2646.

[6] Kelso, T. S. 2007. "Analysis of the 2007 Chinese ASAT Test and the Impact of its Debris on the Space Environment." AMOS Conference. September 19, 2007, Maui, HI.

[7] U.S. Government Orbital Debris Mitigation Standard Practices, available at https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf.

[8] NOAA defers to the FCC orbital debris requirements as almost all commercial remote sensing systems have an FCC license and are therefore subject to the FCC rules.

policies or regulations that are intended to limit the creation or accumulation of debris. Finally, Space Policy Directive 3 (SPD-3) established national policy around orbital debris.[9] SPD-3 directs updates to existing orbital debris mitigation guidelines and practices to enable more efficient and effective compliance and to establish standards that can be adopted internationally. SPD-3 also requires efforts to improve understanding of the debris environment by advancing state-of-the-art science and technology that supports space situational awareness.

While some challenges related to orbital debris may require legal, regulatory, or policy solutions, many of the challenges will require research and development activities. Multiple U.S. departments and agencies fund and conduct orbital debris R&D, and greater coordination across these agencies' activities can help advance a common national vision for orbital debris risk management.

This report presents a national plan of R&D activities to support three essential elements of orbital debris risk management, and within these three core elements, it prioritizes fourteen topical areas for further R&D:

**1. Limit debris generation by design.** Deliberate spacecraft design choices can limit the generation of new debris.

*R&D priorities for element 1:*

- Reduce debris during launch
- Improve resilience of spacecraft surfaces
- Improve shielding and impact resistance
- Develop designs that will reduce or limit fragmentation processes
- Improve maneuverability capabilities
- Incorporate end-of-mission approaches to minimize debris into spacecraft and mission design

**2. Track and characterize debris.** Debris tracking and characterization are critical to enabling effective mitigation measures and safe spaceflight operations.

*R&D priorities for element 2:*

- Characterize orbital debris and the space environment
- Develop technologies to improve orbital debris tracking and characterization
- Reduce uncertainties of debris data in orbit propagation and prediction
- Improve data processing, sharing, and filtering of debris catalogs
- Transition research on debris tracking and characterization into operational capabilities

**3. Remediate or repurpose debris.** Remediation activities, also called active debris removal, could in the long-term substantially reduce the risk of debris impact in key orbital regimes. Repurposing may also contribute to reducing risk and removing debris.

*R&D priorities for element 3:*

- Develop remediation and repurposing technologies and techniques for large-debris objects
- Develop remediation technologies and techniques for small-debris objects
- Develop models for risk and cost-benefit analyses

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[9] https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/

In the sections below, each topical research area includes a description of R&D that will help advance the three approaches to orbital debris risk management, and each R&D subcategory includes a recommendation—provided in brackets at the end of each topical area description—regarding which agencies should consider supporting (i.e., conducting and/or funding) R&D in the given area. Departments and agencies should prioritize among these topical research areas through regular budgeting and planning processes, informed by continuing interagency discussion and coordination. Continued coordination between private industry, academia, and international partners will provide additional resources and will help close critical gaps in the data, knowledge, and capabilities needed to meet the challenges of orbital debris risk management.

## Element I: Limit Debris Generation by Design

Limiting the creation of new debris may be the most cost-effective approach to managing orbital debris risk. Reducing new debris limits the chance of collision (and with it the chance of additional collision-generated debris) and lowers the extent of on-orbit mitigation required to maintain mission risk below an acceptable limit for safe operation. It also reduces the potential future need for and cost of debris remediation. Deliberate design choices can limit debris generation. This includes choices related to the reliability of critical spacecraft subsystems such as power and propulsion, preventing explosions and selection of spacecraft materials, shielding, enhanced capabilities such as maneuverability and end-of-mission safe modes, mission parameters, and mission design.

Several broad spacecraft and mission design challenges impact the goal of limiting debris generation:

- Satellites can break up and generate debris during operation. Some of these are older satellites launched when debris considerations received less emphasis, but events involving newer satellites continue despite design improvements. Fragmentation debris objects dominate the tracked debris population.
- Satellite owners/operators lack common orbital debris-related standards or best practices for satellite and mission design—including protection against mission-ending impacts by small orbital debris—and standards that would support active-mission collision avoidance and decision-making.
- Many satellite owners/operators do not design for or meet guidelines for deorbiting at end of life, which may be due in part to the high cost of available approaches.
- Many satellite owners/operators do not develop or employ capabilities for post-mission collision avoidance.
- Components of launch vehicle upper stages and payload deployment devices continue to contribute to orbital debris growth. Many launch vehicle operators do not develop approaches for orbital debris prevention.

Aspects of these challenges can be addressed through R&D investments to improve the design and operation of spacecraft and launch vehicles. Agencies should focus on six R&D topical areas related to limiting debris generation by design:

**1.1 Reduce debris during launch.** Recent launches of small satellites such as cubesats and constellation payloads often include detached deployment devices of various sizes that do not have propulsion. These devices fasten payloads, maintain separation between payloads, or expel payloads and are released at the same altitude as the constellations; they are therefore potential sources of debris. In addition, some vehicles release liquids, which coalesce into spherical drops of orbital debris during safing operations at the end of launch operations. Even propellant particles can become a source of debris. Agencies should investigate development of improved payload separation and deployment mechanisms that could mitigate excess debris generation during launch. For existing mitigation technologies, such as pyrotechnic devices or pressurized gas separation techniques that reduce debris generated during system separations or deployments, relevant agencies should support R&D to reduce the cost of implementation, increase their effectiveness, and determine barriers to wider use. Agencies should also support R&D to refine alternative technologies and identify unique and novel deployment approaches that would further mitigate debris generation. To mitigate propellant as a source of debris, agencies should support chemistry-based research to remove or stoichiometrically reduce any compounds that could produce solid exhaust particles or slag. Finally, agencies should target propulsion technology R&D to help predict and reduce the amount of slag and free-floating particles during and after launch. [DoD, DOT, NASA]

1.2 **Improve resilience of spacecraft surfaces.** Satellite surfaces degrade over time, and in the process create millimeter- and smaller-sized debris, due to impacts by micrometeoroids and orbital debris and effects from charged particle and ultraviolet radiation, atomic oxygen, and thermal cycling. These effects are most severe in LEO. Long-term exposure to the space environment may also alter spacecraft material properties to make them more susceptible to producing debris from impacts. These degradation sources of debris are an important contributor to the overall orbital debris environment. [DoD, NASA]

1.3 **Improve shielding and impact resistance.** Spacecraft protection techniques have advanced only incrementally since the development of the protection and shielding for the International Space Station. Directing R&D of both new protection techniques and new shielding methodologies should support actionable development and implementation of cost-effective protective measures for the safe operations of future space missions. This R&D should focus on the following three areas. The first R&D area is to develop new multifunctional shields, for example, meeting thermal and orbital debris protection requirements in a single multifunctional approach based on hypervelocity impact analyses and testing of new shielding materials and configurations (e.g., nanostructures and self-healing materials). Research into improving low-cost, effective, multipurpose orbital debris impact protection for satellites is important to mitigating the risk of damage and additional debris creation from impacts. Research into deflection strategies coupled with autonomous detection and avoidance capabilities could enable attitude adjustments to minimize debris impact. The second R&D area is to determine failure criteria for shielded, carbon-composite overwrapped pressure vessels based on hypervelocity impact tests and analyses. This should include determination of ballistic limits for common shield materials and configurations to meet impact protection requirements and accurately quantify spacecraft risk. The third R&D area is the development of ballistic and penetration equations relating spacecraft vulnerability to debris size, mass, material density, shape, velocity, and impact angle based on hypervelocity impact simulations supported by tests. [DoD, NASA]

1.4 **Develop designs that will reduce or limit fragmentation processes.** Given that fragmentation debris accounts for the majority of the tracked debris population, and most of the fragmentation debris was generated from accidental explosions associated with launch vehicle upper stages and spacecraft, there is a critical need to better understand the nature of on-orbit fragmentation, including anomalies, and use this information to prevent similar events in the future. Agencies should support R&D into the causes of accidental explosions as the first step to address the problem. Agencies should encourage satellite owners and operators to share fragmentation and anomaly data with the space community to enable R&D to learn and gain important insights into the nature of such events. Agencies should also support R&D to improve the design, fabrication, testing, and operations of subsystems, such as propulsion, batteries, and pressurized components with a documented history of on-orbit fragmentation, to limit accidental explosions during deployment and operations of launch vehicle upper stages and spacecraft in the future. [DoD, NASA]

1.5 **Improve maneuverability capabilities.** Satellites with maneuvering capabilities use propellant to avoid collisions as well as to deorbit. Improved maneuverability is a key component for autonomous collision avoidance. Development of better propellant estimation techniques and improved propellant sensor technologies are important for optimizing fuel usage and properly budgeting fuel for maneuvers while maintaining reserves for post-mission disposal. Low-cost, fuel-efficient maneuverability capabilities are also becoming more feasible. Agencies should support research into further increasing fuel efficiency and reducing costs of small-scale propulsion systems to reduce the operational risk of many small satellites, particularly when combined with improved positioning knowledge. Agencies should also support R&D in autonomous collision avoidance. [DOC, DoD, NASA]

1.6 **Incorporate end-of-mission approaches to minimize debris into spacecraft and mission design.** Objects remaining in orbit after their operational mission may be passivated to reduce stored energy that could promote debris-producing fragmentation events. Components of intact debris objects (e.g., spacecraft and rocket bodies) that may retain stored energy include batteries and electrical power systems (EPS), propellant, pressure vessels, pyrotechnic devices, and angular momentum devices such as control moment gyros and reaction wheels. Advances in battery and EPS technologies could result in systems capable of safely discharging energy while preventing recharging, keeping the risk during the operational mission phase at a minimum. Designs to allow venting of energetic liquid and gaseous systems from pressurized components would also limit on-orbit component explosions, thus limiting a major source of debris creation. Where complete energy dissipation is not possible, agencies should develop test-backed thresholds for battery states of charge and pressurized system pressures to protect against debris-producing events. To help address the challenge of spacecraft becoming prematurely disabled or operationally impaired before implementing their end-of-mission plans, relevant agencies should support R&D to deliver low-size, -weight, -power, and -cost technologies that allow impaired spacecraft to recover sufficiently to either maneuver as planned to a safer orbit, deploy features that would increase decay rate for deorbit, or implement venting and other safe mode procedures to reduce the risk of further debris generation. Agencies should support R&D to improve accelerated but controlled maneuvers for de-orbiting and transition to graveyard orbits to reduce delivery vehicle debris in key orbital regimes. Agencies should also support further work in methods for pre- and post-attachment. [DOC, DoD, DOI, DOT, NASA]

## Element II: Track and Characterize Debris

Capabilities for space object tracking and characterization underpin effective orbital debris risk management. Accurate tracking and characterization of debris—small and large, both collectively and of individual objects—is vital to protecting spacecraft and enabling collision avoidance. The challenge of orbital debris risk management is compounded by the fact that less than 1 percent of potentially lethal debris objects are large enough to be detected and tracked via existing capabilities. For millimeter-sized debris objects in this category, accurate characterization depends upon direct measurement data as well as verified and validated modeling capabilities.

Accurate modeling must be based on measurement data and account for atmospheric characteristics and various orbital perturbations of the space environment. Atmospheric drag, which has greater effects on smaller debris and debris in lower orbits, changes with atmosphere layer density and charge fluctuations. Space weather events impact debris behavior by perturbing the magnetic field around the planet and by injecting dense charged particles that can become trapped for some time.

Astrodynamics models account for the perturbations caused by atmospheric drag, space weather, and gravitational effects to predict object trajectories. Improvements in theory, modeling, measurements, and other capabilities in all these areas would help in the development of new and improved orbital debris conjunction event management and debris mitigation techniques and technologies, and such improvements could help inform better design choices and remediation methods.

Tracking and characterizing debris are key to understanding debris generation processes, protection of key spacecraft components, avoiding debris, and otherwise mitigating its effects on orbit. Challenges to improving the accuracy, resolution, and robustness of tracking and characterization include the following:

- There are insufficient data on the existing debris population. Less than 1 percent of the debris objects that could cause mission-ending damage are currently tracked.
- Debris is insufficiently characterized for accurate and reliable risk assessments. An object’s size, shape, mass, and velocity all affect how much and what kind of damage occurs upon impact.
- The uncertainties are high in tracking objects and propagating orbits. The uncertainty tends to grow with time due to the compounding effects of atmospheric drag, space weather, and other nongravitational perturbations that may be difficult to predict.
- There is difficulty in integrating heterogeneous data in real time. Many different types of systems are used for object tracking, with different uncertainties, data formats, and possible proprietary restrictions.

Aspects of these challenges can be addressed through R&D investments. Agencies should focus on five R&D topical areas related to mitigating debris effects on orbit:

**2.1 Characterize orbital debris and the space environment.** Using R&D to better characterize the orbital debris population, the space environment in relevant orbital regimes, and interactions between the debris population and the space environment is fundamental to mitigating risk from orbital debris. Agencies should continue top-to-bottom reviews of assumptions in current debris population models for all national agencies, as well as consult with other nations and the Inter-Agency Space Debris Coordination Committee. Efforts to characterize debris populations should focus in particular on millimeter-scale debris, since this drives mission-ending risk to most operational spacecraft, and measurement data on them are lacking. Agencies should support the use of ground- and space-based sensors to improve the detection and characterization of LNT debris, including their flux, size, mass, material density, and orbit distributions. Agencies should also support the use of laboratory experiments to better characterize the physical properties of small debris, such as shape and material density distributions. Efforts to characterize the space environment should include studies of atmospheric properties and rarefied gas flows to provide better models for orbital debris environment definition and prediction. Such studies could enable forecasting of natural effects on the orbital debris population and on space systems. Efforts to better characterize interactions between debris and the space environment should include an in-depth review of orbital fragmentation events and their short- and long-term effects on satellite operations and collision avoidance. Agencies should also support R&D to identify and characterize the sources of small debris, especially LNT debris. Similarly, agencies should support R&D to better understand effects of space weather on debris (e.g., improved atmospheric drag prediction capabilities through better prediction of space weather indices, advances in data assimilative modeling of the upper atmosphere, improved solar radiation pressure modeling, and change from classic plasma to dusty plasma environment) through analysis of environmental conditions relevant to space systems. [DOC, DoD, DOI, DOS, DOT, NASA]

**2.2 Develop technologies to improve orbital debris tracking and characterization.** Improving orbital debris measurement capabilities, whether ground-based or *in situ*, is fundamental to assessing the viability and effectiveness of techniques for limiting the debris population. *In situ* capabilities are necessary to enable autonomous collision avoidance. Technologies relevant to this challenge include active or passive beacons for accurate three-dimensional tracking; algorithms for stability determination (e.g., tumbling rates and axes) that could enable safe docking with servicing or removal buses; and techniques to discriminate and characterize high area-to-mass-ratio objects from more massive debris. Development of new and improved ground and *in situ* sensor technologies to collect remote data on small debris is more difficult but very important to better understanding the debris environment and enabling autonomous collision avoidance. Candidate ground-based optical and radar technologies include advanced radar waveforms to improve waveform angle and timing coherence, which would reduce radar return spread and increase return signal-to-noise ratios, resulting in increased detection threshold, optical binocular ranging to improve track accuracy, and observing approaches and exploitation algorithms to better correlate weak signal objects to better define orbit trajectories for debris. Agencies should support R&D into *in situ* sensor technologies that, from space-based platforms either on dedicated spacecraft or as a secondary instrumentation payload, can record debris impacts and capture small debris information that will assist in generating and maintaining an accurate state vector (e.g., U.S. Naval Observatory Time, 3D position, velocity, and accelerations) over time, such as mass, size, shape, rotation about the objects center of mass, and absorptivity and reflectivity of object surface materials. Agencies should consider R&D into improved ground-based optical and radar sensors that would provide more data with higher accuracy for object tracking and characterization. [DOC, DoD, NASA]

**2.3 Reduce uncertainties of debris data in orbit propagation and prediction.** Improvements to supporting models could reduce the number of conjunction data messages and provide better information to support satellite owner and operator assessments of collision risk. Specifically, R&D in space environment characterization, as specified in Section 2.1, and integrating real-time science data and space environment prediction with propagation models could lead to reduced uncertainties in orbit propagation. Agencies should therefore consider an examination of orbital propagation accuracy that could be realized from improvements to supporting models to reduce uncertainty and improve close approach predictions. Agencies should also consider providing more frequent tracking as a mechanism for reducing propagation times, thereby minimizing the accrued errors. Given the challenges in identifying custody of uncorrelated tracks, agencies should pursue R&D into improving custody determination algorithms for trackable debris. In addition, agencies should consider R&D focused on both improved probability-of-collision calculations and covariance realism that could lead to more consistent estimates throughout the close approach engagement. [DOC, DoD, NASA]

**2.4 Improve data processing, sharing, and filtering of debris catalogs.** Addressing challenges associated with data handling in the debris catalog is important to maintaining its integrity and utility as additional space tracking capabilities are brought online, more objects are identified and tracked, and more users rely on its data. For example, cross-tagging (attributing observations of one object to another) degrades the orbit estimates of cross-tagged objects and increases database errors. Conjunction data messages are used to notify spacecraft owners and operators of future conjunctions, but these data messages largely have not been analyzed for biases, behavior patterns, risk trends, or growth projections. Agencies should conduct R&D into improving data storage, data correlation systems, and data fusion approaches. Agencies should also pursue R&D to develop an architecture for ingesting and incorporating the wide variety of available data sources. As data from additional sensors, including those provided by commercial companies, are integrated into the database, agencies must develop techniques to maintain data integrity. Agencies should also examine data quality and data mining. Agencies should conduct R&D into correcting cross-tagging to decrease database errors. Agencies should conduct R&D using artificial intelligence and machine learning to gain insight, increase opportunities to validate norms, and improve processes regarding conjunction assessment risks. Finally, agencies should support research into autonomous communications for *in situ* debris detection and autonomous collision avoidance capabilities. [DOC, DoD, DOI, DOS, DOT]

**2.5 Transition research on debris tracking and characterization into operational capabilities.** Agencies should translate orbital debris R&D into improved operations for identifying, tracking, and predicting the location and behavior of debris. Agencies should consider linkages between research findings and advancements with operations as well as operational needs as the domain of orbital debris R&D progresses. Agencies should pursue R&D for better conjunction data, improved conjunction screening techniques, and improved conjunction risk assessment techniques. Agencies should conduct research to understand decision thresholds for collision avoidance maneuvers, characterize confidence levels needed for execution, and determine appropriate mitigation levels for various scenarios. Agencies should also collaborate with satellite owners and operators to properly map these processes and provide better coordination in flight operations. [DOC, DoD, DOS, NASA, DOT]

## Element III: Remediate or Repurpose Debris

Debris remediation, also called active debris removal (ADR), is the forced modification of a debris object trajectory by means external to the object, to include removal of an object entirely from space. This contrasts with the design approaches described in Element I, which includes capabilities of spacecraft to deorbit or move themselves to safer "graveyard" orbits at the end of their missions. Remediation methods remove objects that could generate debris in the future, thereby contributing an important element to overall orbital debris risk management. Consistent with SPD-3, the United States should pursue ADR as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes. However, this effort should not detract from continuing to advance international protocols for debris mitigation associated with current programs.

ADR has both long-term technical and international policy challenges and is likely more costly than alternative approaches. However, research into ADR along with broader research in remediation methods and technologies will provide better understanding of the costs and benefits of these approaches and will help inform future technology and policy decisions. ADR also presents economic, legal, and policy issues outside of the scope of this plan that will have to be addressed if it is to become a realistic option for mitigating risks posed by orbital debris.

Some researchers and commercial entities view pieces of large orbital debris as a potential resource. In their view, valuable space systems and industrially processed materials are distributed throughout the orbital environment, and the challenge is to find ways to use them. The cost of repurposing or salvaging these large debris objects may be more cost-effective than trying to de-orbit them.

Challenges associated with debris remediation and repurposing include the following:

- The market for debris removal and supporting R&D is small, largely due to the lack of defined responsibility for orbital debris removal or economic incentives to do so. The economic, scientific, and national defense losses associated with the future orbital debris environment are potentially large but highly uncertain, and they are an externality that the market has little incentive to address.
- ADR methods may inadvertently generate more debris or increase the probability of collision, raising questions of liability and, possibly, intent.
- It is difficult to scale ADR methods from one piece of debris to many, or from large debris to small debris. Proposed ADR technologies are somewhat specific to debris type, and removing one or two pieces of debris at a time may not be cost-effective nor improve the debris environment significantly.
- Some remediation methods may reduce the near-term risk of orbital debris without addressing the long-term sustainability of space.
- Cost and cost-benefit are not well characterized. Demonstrations of ADR are likely to be very costly compared to efforts to reduce the creation of new debris. Determining a balance between mitigation efforts and removal and remediation efforts is important.

Aspects of these challenges can be addressed through R&D investments. Agencies should focus on three R&D topical areas related to remediating and repurposing debris:

**3.1 Develop remediation and repurposing technologies and techniques for large debris objects.** Large debris objects, such as rocket bodies and nonfunctioning satellites, represent the highest percentage of overall orbital debris mass and could present the highest risks for the generation of additional debris through collisions and other processes. Limiting their long-term presence in the environment is therefore an important component of effective overall orbital debris risk management. Agencies should pursue research into concepts, techniques, and technologies required to remediate these objects. Agencies should further develop generalized capture technologies and techniques that improve the likelihood of success across the widest possible diversity of object types while simultaneously reducing the risk of inadvertently generating additional debris. Agencies should investigate methods and structures for increasing atmospheric drag for accelerated deorbit. Agencies should develop and conduct modeling tools, ground tests, and where necessary, full system prototype demonstration tests to prove both the performance capabilities and cost-efficacy of various approaches. Agencies should also support R&D into methods of repurposing or recycling orbital debris on-orbit. Subsystems from derelict objects could be salvaged and used in assembly of new spacecraft. In addition, recycled materials could be used as fuel or manufacturing feedstock. [DOC, DoD, NASA]

**3.2 Develop remediation technologies and techniques for small debris objects.** In the aggregate, small millimeter-sized debris poses the greatest mission-ending risk to most robotic spacecraft. ADR R&D should focus on millimeter-sized orbital debris to address near-term orbital debris impact risks in order to better protect future space missions. Since objects this small are not tracked individually and the population is estimated to be on the order of 100 million, agencies should evaluate large-scale removal approaches that may produce beneficial and meaningful outcomes. Key agency R&D activities should include identifying, evaluating, and developing feasible technologies and techniques capable of maintaining very large collection and removal areas or volumes. Agencies should consider R&D to examine contactless methods of moving or de-orbiting debris. [DOC, DoD, NASA]

**3.3 Develop models for risk and cost-benefit analyses.** Developing ADR as a long-term contributor to safe flight operations will require better quantification of the risk posed by orbital debris and the costs and benefits of potential approaches to remediation and repurposing. Agencies should support the development of improved models and analyses of the risks and economic impacts associated with orbital debris and remediation methods to help identify tradeoffs between remediation targets and methods. Additionally, such models could also help enable a better understanding of the costs of mitigating debris risks as detailed in Element I. Analyses of anticipated economic impact, including launch costs for replacement satellites, disruptions in operations, and mission losses associated with the current and future debris environment could help inform future decisions regarding remediation. Multiple models can be used to better assess collision risk levels to safety of flight. These models can include risk models utilizing the space object catalog and environment models including millimeter-sized debris populations with estimated mass, size, and trajectories. Coupled with the ability to roughly model the amount of small and large debris and its distribution across a range of potential collision scenarios, the models also allow for improved consequence assessments, such as the risk of follow-on collisions and impacts to other operational spacecraft. Such tools could be used in support of a comparative cost-benefit analysis of mitigation and remediation technologies. [DOC, DoD, NASA]

## Coordination and Partnerships to Advance Orbital Debris R&D

Agencies can increase efficiencies in the orbital debris R&D activities and help avoid duplication by coordinating within a collaborative framework. Table 1 summarizes the recommendations in this report regarding agencies that should consider supporting R&D in the specific topical areas and that should collaborate with other identified agencies where appropriate.

**Table 1. Alignment of R&D Topical Areas to Agency Missions**

| Research Area | | DOC | DoD | DOI | DOS | DOT | NASA |
|---|---|---|---|---|---|---|---|
| **1. Limit by design** | 1.1 Reduce debris during launch | | ✓ | | | ✓ | ✓ |
| | 1.2 Improve resilience of spacecraft surfaces | | ✓ | | | | ✓ |
| | 1.3 Improve shielding and impact resistance | | ✓ | | | | ✓ |
| | 1.4 Develop designs that will reduce or limit fragmentation process | | ✓ | | | | ✓ |
| | 1.5 Improve maneuverability capabilities | ✓ | ✓ | | | | ✓ |
| | 1.6 Incorporate end-of-mission approaches to minimize debris into spacecraft and mission design | ✓ | ✓ | ✓ | | ✓ | ✓ |
| **2. Track and characterize** | 2.1 Characterize orbital debris and the space environment | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 2.2 Develop technologies to improve orbital debris tracking and characterization | ✓ | ✓ | | | | ✓ |
| | 2.3 Reduce uncertainties of debris data in orbit propagation and prediction | ✓ | ✓ | | | | ✓ |
| | 2.4 Improve data processing, sharing, and filtering of debris catalog | ✓ | ✓ | ✓ | ✓ | ✓ | |
| | 2.5 Transition research on debris tracking and characterization into operational capabilities | ✓ | ✓ | | ✓ | ✓ | ✓ |
| **3. Remediate** | 3.1 Develop remediation technologies and techniques for large debris objects | ✓ | ✓ | | | | ✓ |
| | 3.2 Develop remediation technologies and techniques for small debris objects | ✓ | ✓ | | | | ✓ |
| | 3.3 Develop models for risk and cost-benefit analyses | ✓ | ✓ | | | | ✓ |

R&D conducted outside of the Federal Government—including by industry, academia, and international partners—can also contribute significantly to the R&D priorities identified in this report. The private sector has contributed throughout the space age as a valuable supplier and partner to the Federal Government. The Federal Government conducts fundamental research with academic research groups, and these are well aligned for continued collaboration. Universities and other academic institutions also train scientists and engineers who are critical to maintaining the workforce and sustaining future orbital debris research efforts. Finally, many foreign governments and international organizations are similarly concerned about maintaining the safety of spaceflight operations.[10,11] These entities represent additional potential partners for R&D collaborations and offer opportunities for leveraging additional capabilities and resources.

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[10] European Space Agency. 2020. ESA's Annual Space Environment Report. Darmstadt, Germany. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[11] United Nations Office for Outer Space Affairs. 2010. Space Debris Mitigations Guidelines of the Committee on the Peaceful Uses of Outer Space. Vienna. https://www.unoosa.org/res/oosadoc/data/documents/2010/stspace/stspace49_0_html/st_space_49E.pdf

## Conclusion

The National Orbital Debris R&D Plan provides a resource to help coordinate orbital debris R&D supported by the Federal Government, helps those involved in this work to seek and identify opportunities to advance orbital debris R&D priorities, and achieves a more effective orbital debris risk management posture by advancing the understanding and security of safe flight regimes. Implementing this plan will close critical gaps in the knowledge and capabilities needed to meet current and growing challenges of orbital debris risk management.