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Response of The MITRE Corporation to the NSTC Request for Comment on the Orbital Debris Research and Development Implementation Plan

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Introduction

The MITRE Corporation is a not-for-profit company that works in the public interest to tackle difficult problems that challenge the safety, stability, security, and well-being of our nation through the operation of multiple Federally funded research and development centers (FFRDCs) and labs, and participation in public-private partnerships. Working across Federal, state, and local governments—as well as industry and academia—gives MITRE a unique vantage point. MITRE works in the public interest to discover new possibilities, create unexpected opportunities, and lead by pioneering together for public good to bring innovative ideas into existence in areas such as artificial intelligence, intuitive data science, quantum information science, health informatics, policy and economic expertise, trustworthy autonomy, cyber threat sharing, and cyber resilience.

MITRE provides FFRDC support to a broad swath of the federal government's space-related agencies, including the Department of Defense (all service branches), the Intelligence Community, Department of Commerce (Office of Space Commerce and National Oceanographic and Atmospheric Administration), and the Federal Aviation Administration, all of whom are impacted differently by the challenges of orbital debris. Because of this experience, we are uniquely positioned to recommend solutions that take advantage of whole-of-government options to make substantial improvements on orbital debris.

While we recognize that this request for information is focused on the technical aspects of orbital debris, we would be remiss to omit mentioning that some of the major obstacles to overcoming orbital debris are regulatory in nature, as there is a lack of international agreement on fundamental issues such as demanding debris minimization, directing collision risk minimization maneuvers, and removing defunct space objects (with known or unknown owners). The direction that the international community takes in the future on these matters will play a large role in determining the optimal research and development path.

Overarching Recommendations

MITRE recommends that the National Science and Technology Council (NSTC) prioritize space debris research and development (R&D) into three distinct areas, beginning with the most achievable in terms of time to implement and the opportunity to have the most immediate positive effect.

- Limit, with the goal of eliminating, creation of new debris by improved spacecraft and launch vehicle designs. This approach starts on the ground. Examples include, but are not limited to, (a) R&D into spacecraft that are "designed for demise," (b) designs and operational procedures to ensure that launch vehicle components are removed from orbit as quickly as possible, (c) "cleaner" launch vehicles that do not shed solid propellant chunks or components and parts, and (d) elimination of mission debris that cannot be restrained.
- Improve the ability to accurately track and characterize debris objects. This R&D area focuses on refinements in current space situational awareness (SSA) systems and algorithms for close approach predictions that reduce positional errors and accommodate new spacecraft propulsion systems that make current techniques increasingly obsolete.

R&D should be applied for expansion of currently "non-traditional" SSA systems such as laser ranging, passive radio frequency monitoring, and spacecraft tracking aids. Another R&D focus topic is to determine where the SSA systems should be located on Earth to provide continuous tracking of space objects throughout their entire orbits.

- Create an R&D strategy to develop concepts and systems to perform active removal of debris currently populating critical orbital regimes and which pose the greatest hazards to safe human and robotic space missions. While these objects have been identified, much work is needed to determine how to remove them.[1] MITRE believes that active debris removal is the most challenging R&D area from cost, schedule, technology, policy, and international consensus perspectives.

Questions Posed in the RFI

(1) The extent to which progress in the R&D topical areas identified in the Orbital Debris R&D Plan will address the orbital debris challenges. What, if any, R&D areas are missing?

MITRE considers that all current R&D topic areas in the orbital debris plan remain necessary, broadly agrees with the groupings, and in particular agrees with the apparent prioritization of the three R&D elements. Within each element, MITRE does see opportunities for NSTC to strengthen, either in breadth or depth, the R&D topics for greater effect.

For ***Element I: Limit Debris Generation By Design***, MITRE recommends that the R&D Plan be expanded to include the full spectrum of potential debris limiting design features, particularly design features that will be active during the operational lifetime of the spacecraft. Specifically, R&D is needed for technologies that can be incorporated into the satellites themselves to make collision, and thus debris creation, less likely. MITRE has observed that the present commercial launch licensing and review process treats payload designs as though they are unable to be improved in any way. The consequence of this philosophy is that the entire global commons of space is handicapped by the continued launch of low reliability, hard-to-track, or poorly understood commercial and foreign spacecraft into an increasingly congested operating environment. This philosophy has also crept into the R&D Plan and should be removed.

Satellite designs can be improved, and R&D is needed to develop the technologies necessary to create the improvements. For example, R&D is needed to develop satellite-to-satellite communication techniques and standards that enable autonomous collision deconfliction maneuvers between constellations with different owner/operators, significantly reducing the risk of two nearby constellations having a collision. R&D could also produce miniaturized onboard GPS transponders, ephemeris sharing transponders, or ultra-lightweight radar reflectors, reducing tracking errors and making collision prediction more accurate and actionable, especially in the time between detaching from the launch vehicle and obtaining full tracking custody, which currently can take days. Also, focusing on the spacecraft's operational phase, R&D should be used to develop miniature onboard event monitors, which could detect close approaches and

[1] McKnight, D. et. al. Identifying the 50 statistically-most-concerning derelict objects in LEO. 2021. Acta Astronautica Volume 181, pages 282–291.

provide miss distance (or collision) information back to owner/operators and space traffic coordinators. Armed with this feedback data, owner/operators could make better decisions, and space traffic coordinators could employ machine learning methods to improve orbital models, atmospheric models, and ultimately collision predictions. None of these topics are addressed in the current R&D Plan.

Another key component of limiting debris generation by design is devoting R&D efforts to improve end-of-life technologies and methods. While this is identified in the existing R&D Plan, more is still needed, especially for missions that end earlier than expected. To facilitate future removal, R&D is needed into standardized end-of-mission removal technologies, including standardized docking connections, standardized grappling connections, and standardized autonomous de-orbiting technologies, thus creating a full suite of debris minimization options. Once a full suite of options is available, it is feasible to ensure that at least one option is included on future spacecraft, preventing future payloads from becoming unmitigable debris.

For ***Element II: Track and Characterize Debris***, MITRE considers this element to be essential to improving not only the orbital debris problem, but also to providing assured and continued access to space. At MITRE, we believe that Space Domain Awareness (SDA) means having continuous eyes-on-space, but today we do not, and we recommend NSTC expand the scope of the R&D Plan to include the additional technologies that will be necessary to achieve SDA.

Today, between the Department of Defense's (DoD) Space Surveillance Network sensors, civil sensors, and commercial sensors, we know where the bigger (>10 cm) space objects are and where they are going. But most of what is in orbit (as pointed out in the current R&D Plan) are objects <10 cm that we cannot reliably track. Sensors that can see small/far-away space objects generally are more "exquisite" and, therefore, extremely expensive. Because of our incomplete monitoring, it is not currently possible to do simple things like accurately count the number of objects in Earth's orbit or observe how close objects actually came during an approach. This foundational information is needed to train the artificial intelligence and machine learning models needed to improve the conjunction risk assessment process, reduce false positives, and draw increased attention to the situations with actual collision risk.

This is a solvable problem, and an ideal target for R&D funding. Specifically, the focus in this element should be targeted to reduce the manufacturing, operating, and maintenance costs of the sensors needed to provide continuous space surveillance. Along with the cheaper sensors, R&D should develop improved workflows to automate the process from tracking to collision prediction, to owner/operator notification. With enough data, it may be possible to increase the information provided to owner/operators, including recommended maneuvers, and automatically tell SDA sensors where to look for the maneuvering object next, maintaining full tracking custody. This would be a tremendous improvement from our observations of the current space tracking and conjunction-notification process.

Our most ambitious recommendation in this element is that the debris tracking and characterization R&D effort be expanded to also identify the material composition of tracked debris. One example is photopolarimetry; it identifies the surface material of the principal light-scattering component of an artificial satellite.[2] As active debris removal (ADR) technologies mature, it will be important to understand which debris can be removed by which

[2] Tapia, S; Beavers, W; and Cho, J. Photopolarimetric Observations of Satellites. 1990. SPIE Vol. 1317 Polarimetry: Radar, Infrared, Visible, Ultraviolet, and X-Ray, pages 252–262

technology, which is why we recommend NSTC include R&D on non-traditional attributes of space debris that may become useful in the future. For example, it may be useful to know if a piece of debris is magnetic (e.g., for ADR using magnets) or the melting point of the material (e.g., for ADR using lasers to ablate the surface). For ADR to make a significant contribution to solving orbital debris challenges, this information will be necessary, and the current capabilities are severely limited.

For *Element III: Remediate or Repurpose Debris*, MITRE has significant technical concerns that the R&D priorities omit mitigation for the single greatest risk of ADR: inadvertently creating additional debris. MITRE advises NSTC that the time to learn that an ADR technology was inadequate to accomplish its intended mission is during simulation, not after a failed ADR operation that renders an orbit unusable. ADR accidents could create debris due to collision, excessive rotation, or other unforeseen interactions between the debris and the ADR device. For example, grappler satellites have a fair chance of failing and destroying both spacecraft, causing more debris. This is because the debris objects may not be small enough for a given ADR device to tug or "still" (non-rotating) enough to gain control of, or "graspable" (a stable location to grab the object) enough to capture. R&D should be used to better model and characterize the capabilities and risks of specific ADR technologies, to develop performance-based capability standards so that ADR missions can proceed with a high level of confidence that the mission will reduce debris, rather than creating more, or worse yet—rendering a priceless orbit unusable.

(2) Among the topic areas listed in the R&D Plan, what are the highest priority R&D areas (up to five) for making progress in addressing the challenges posed by orbital debris to the space environment?

As noted above, MITRE identified three priority areas that align with the three topic areas listed in the R&D Plan. Below are listed details about those areas we believe will make the biggest impacts towards meaningful improvements in the space debris environment. Investment decisions need to be guided by risk and cost-benefit analysis to understand how effective the results of various R&D alternatives might be in mitigating the risk of collision. Many research paths—even if successful—will have little effect on the ever-increasing orbital pollution encircling the Earth or our ability to predict or counter resultant impacts, so precious research funding needs directed at those avenues that look to provide the best chances of having a positive effect. Our vision for the correct funding avenue prioritization from the current R&D Plan is provided below.

First, limit debris generation by design. Development of specific design standards and best practices can limit or even eliminate creation of new debris; this is the most effective way to slow the growth of the debris population. Reducing the creation of new debris during launch and deployment of new spacecraft is the primary factor in reducing the growth of the on-orbit debris population. This is directly analogous to mitigating pollution, where the most effective step is to first minimize the creation of new pollution.

This is especially important for space, because the vast majority of debris that could result in critical (mission-ending) or catastrophic (additional debris-creating) impacts are simply too small and too numerous to "sweep up" or otherwise clear from the sky. Figure 1 (produced in June 2013, so the numbers have increased, but the relative distribution is still considered roughly correct) shows that the total number of objects and distribution in relative sizes make cleaning up the current environment virtually impossible. While any impact at orbital crossing speeds can be significant (see the picture of damage to a space shuttle window from a paint fleck), the most severe impacts and potential for creating cascading debris come from higher mass or denser debris (see picture of 1 cm projectile hitting aluminum block). The debris that currently exists will persist; the most appropriate focus now is to prevent the number of objects from growing.

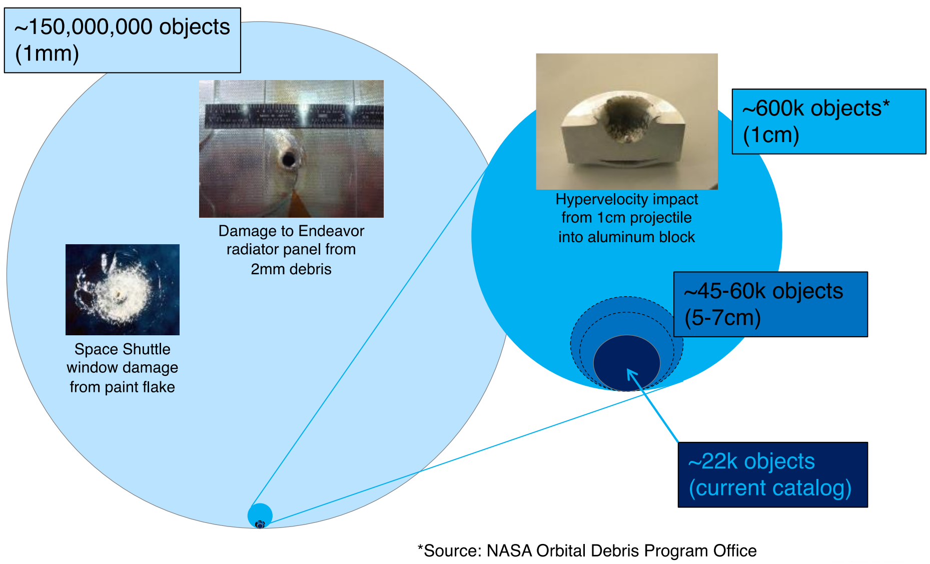

Figure 1. Space Debris Population and Collision Risk

The top R&D priorities to limit debris creation by design are:

- Methods and technology to reduce debris during launch. This includes launch vehicle components that remain orbital after orbit insertion. Mission debris must be restrained, and design standards for "clean" launch vehicles and upper stages researched and implemented.
- For spacecraft, R&D should lead to design standards and best practices to:
  - Improve resilience of spacecraft surfaces;
  - Improve shielding and impact resistance;
  - Develop designs that will reduce or limit fragmentation processes;
  - Improve maneuverability capabilities; and,
  - Incorporate end-of-mission approaches to minimize debris into spacecraft and mission design.

Second, better track and characterize debris. Small debris must be tracked to determine probabilities of collision and characterized to assess the consequences of a possible impact; and without improved sensing and tracking capabilities, the latent risk of the small object population shown in Figure 1 will remain. The premier debris-tracking sensor for Low Earth Orbit, the United States Space Force's (USSF) new Space Fence, has reliable tracking for objects down to about 5 cm in diameter although it can detect objects down to 2–3 cm in diameter.[3] However, no second Space Fence has been procured, so follow-ups on detections can be difficult, and we are nowhere close to true SDA. Current technologies for tracking debris require use of very high-power radar like the Space Fence (over $1B per copy), and/or very sensitive optics, and are still incapable of tracking most orbital debris. To better track and characterize debris, the top R&D priority should be developing more accurate and persistent tracking and characterization systems that are capable of:

- Characterizing <1 cm orbital debris and the space environment;
- Improving orbital debris tracking and characterization;
- Reducing uncertainties of debris data in orbit propagation and prediction;
- Improving data processing, sharing, and filtering of debris catalogs; and,
- Transitioning research on debris tracking and characterization into operational capabilities.

Lastly, prioritize efforts to remediate or repurpose debris. Theoretically, remediation activities like ADR could, in the long term, substantially reduce the risk of debris impact in key orbital regimes. Repurposing may also eventually contribute to reducing risk and removing debris from key orbital regimes. MITRE notes that ADR is the most technically demanding of debris mitigation R&D areas and is also impeded by numerous policy and treaty issues. Likewise, repurposing debris is unproven and poses both technical and legal challenges. To the extent that this R&D avenue is funded, MITRE recommends the following priority topics be addressed in order, to better assess whether ADR or repurposing might be able to play a substantive role in future orbital debris reduction:

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

(3) What near-term actions can be taken by the Federal government to make progress towards high priority R&D areas? How would these specific actions address the orbital debris challenges in the near term?

MITRE believes that the most important near-term actions for the Federal government to take are the R&D recommendations listed in our response to Question (2) and the partnership and collaboration recommendations listed in our response to Question (5). Federal government leadership is needed on these high priority topics to demonstrate a committed focus to resolving the problem and to communicate a common vision of how the future space-debris creation, tracking, and removal environment should look. Most immediately, the Federal government should take action on the technology, policy, and R&D efforts to minimize or eliminate the

[3] Space Fence.2021. Lockheed Martin, https://www.lockheedmartin.com/en-us/products/space-fence.html. Last Accessed December 22, 2021.

creation of orbital debris by future space launches and spacecraft operations. In parallel, action should be taken to perform the R&D necessary to develop the next generation of high-sensitivity, high-reliability, low-cost sensors that will eventually enable full SDA.

(4) What R&D activities would be most valuable in the long-term or would be the most transformative to addressing orbital debris challenges?

It has taken decades for the orbital debris situation to reach this point, and a long-term perspective and action plan will be necessary to fully solve the problem. The orbital debris proliferation history can be compared to terrestrial environmental pollution on Earth. While there is general consensus among responsible countries about technologies needed to reduce new pollutants, a massive effort exists to begin to mitigate pollutants created over hundreds of years. MITRE considers that the maximum value and impact outcomes that need R&D effort are:

- Developing a system, including sensors, data storage, communication channels, and algorithms that enable U.S., and then global, space-traffic coordination;
- Improving the tracking of space objects using a diverse set of sensors to improve tracking on all space objects down to the millimeter size range in orbits of 370 km and higher;
- Developing cost-effective, technically feasible, and reliable methods for ADR;
- Implementing a consensus-based ADR priority list that takes into account severity of the hazard, cost, and technical feasibility of removing each unique debris object; and,
- Developing an orbital allocation scheme that maximizes opportunities for commercial and government space missions while minimizing the potential for undesirable interference between neighboring space systems, including electro-magnetic interference and collision risk.

(5) What are the opportunities to partner with entities outside the Federal government, nationally and internationally? What are the viable and potentially innovative mechanisms to partner most effectively?

Ongoing Collaboration Activities

The current orbital-debris partnerships can benefit from improved communication and integration across activities. Since 1993, international collaboration on orbital debris research has existed via the Inter-Agency Space Debris Coordination Committee (IADC). The four original members were the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), Japan, and Russia. Today, the IADC consists of at least 13 participants, including the space agencies of France, Italy, Germany, the United Kingdom, India, Canada, and China. The space debris–mitigation guidelines established by the IADC in 2002 became the foundation of the guidelines adopted by the United Nations (UN) Committee on the Peaceful Uses of Outer Space; these guidelines were endorsed by the UN General Assembly in 2007.[4]

[4] Liou, J. – C. NASA Orbital Debris Program Office Overview. 2019. The ReDSHIFT Final Conference; Florence, Italy, 13–14 March 2019.

NASA and ESA both actively engage in the measurement and modeling of orbital debris. Both agencies rely on the satellite Conjunction Data Message provided by the 18 Space Control Squadron (18 SPCS) of the U.S. Space Force. Furthermore, both agencies benefit from the two-line orbital elements that the 18 SPCS publishes on space-track.org. In addition to their own sensors, NASA relies on the pair of Haystack radars owned and operated by MIT Lincoln Laboratory; both radars are contributing sensors to the U.S. Space Surveillance Network (SSN). The European Union is developing its own Space Surveillance & Tracking System.[5] At minimum, it collects observations on the larger objects of the orbital debris populations (e.g., rocket bodies, and decommissioned and malfunctioned spacecraft).

The U.S. Space Force's Pivot Space Domain Awareness (SDA) program brings together three FFRDCs operated by the Aerospace Corporation, MIT Lincoln Laboratory, and MITRE. One of the lines of effort of Pivot SDA is the reduction of the *noise floor* of the U.S. SSN. The noise floor pertains to the smallest resident space objects (in general, the weakest radar targets and the faintest optical targets) tracked by the U.S. SSN with sufficient regularity to maintain a current set of orbital elements. Common ground exists between the observations of these noise floor objects and the orbital debris measurements collected by NASA and ESA. Another effort of the U.S. Space Force is the Advanced Tracking and Launch Analysis System (ATLAS). An objective of both Pivot SDA and ATLAS is the augmentation of the U.S. SSN with non-U.S. Government sensors. Candidate sensors include the radars of Leo Labs; the Rincon passive RF network; the global telescope networks operated, individually, by ExoAnalytic Solutions and Numerica Corporation; the EU Space Surveillance & Tracking System; as well as optical telescopes under development by the Australian government. L3 Harris Technologies and Omitron Corporation are also key players in the Pivot SDA and ATLAS programs. Thus, these two U.S. Space Force programs provide potential mechanisms for national and international collaboration in the measurement and modeling of orbital debris; they provide a means for transitioning into operational capabilities the improvements derived from the research into the tracking and characterization of orbital debris. MITRE recommends that the NSTC actively facilitate these opportunities in its Orbital Debris R&D Plan.

Recommendations for Future Collaboration Activities

Orbital debris is a global problem that impacts every spacefaring nation, and complete resolution will require global cooperation between governments and commercial entities. Internationally, obtaining buy-in from all spacefaring nations is crucial, as unilateral actions by a single nation cause detrimental effects that impact all, as exemplified by the November 2021 Russian anti-satellite missile test and other irresponsible debris-producing events.[6] Ultimately, space needs to progress towards either a *maritime-type model*, where individual operators are responsible for and capable of monitoring their operating environment and preventing adverse events, or an *aviation-type model* where governments monitor the operating environment and have the authority to direct action that prevents adverse events. MITRE recommends that optimal

[5] Hermoso, J. M., et al.. System Approach to Analyze the Performance of the EU Space Surveillance & Tracking System. 2021. 2021 Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS), www.amostech.com.

[6] 2021 Statement by the North Atlantic Council on the recent anti-satellite missile test conducted by the Russian Federation. 2021. North Atlantic Treaty Organization, https://www.nato.int/cps/en/natohq/news_188780.htm. Last Accessed December 22, 2021.

objectives for future collaboration consider both international and national collaboration opportunities.

International Collaboration

MITRE recommends leveraging the best practices of the World Meteorological Organization (WMO) Space Programme within the international partnership efforts of Orbital Debris R&D strategy. Within the WMO, there are working groups focusing on policy, capacity building, real-time and archived data distribution, and training. An example of one such group is the Coordination Group on Meteorological Satellites (CGMS),[7] which was formed in 1972 by the meteorological agencies of the United States and Japan, and the forerunner to today's European Space Agency. Today, CGMS consists of 16 member agencies (including Russian and Chinese meteorological satellite agencies) and 6 observer agencies. Today, CGMS members, by consensus, have agreed upon satellite instrument design, common standards, a common data policy, and contingency operational agreements. Within the WMO, there are additional working groups focusing on policy, capacity building, real-time and archived data distribution, and training. The proven WMO working group structure, consensus, and requirements-management approach could be applied to the domestic and international orbital debris challenge by developing:

- A common set of agreed-to technical and operational requirements,
- Common algorithm and data archiving standards,
- Disciplined exchange of information, and
- Informal consensus-based working groups that focus on specific areas.

Additionally, MITRE recognizes the need to take more structured international action on orbital debris, and specifically recommends:

- Engaging with the UN with the intent of generating standards for space norms of behavior that can one day lead to a treaty on space behavior and responsibility.
- Forming a world-wide body to provide best practices and administer incentivized space norms and operations across the planet, as is done with air traffic.

National Collaboration

To preserve the United States' global space leadership position, MITRE recommends using the full spectrum of national power to partner and collaborate within government and across industry. Within the government, the focus of partnerships should be on improved interagency cooperation and developing methods and programs to encourage commercial participation and adoption. The government partnerships should consider incentivizing commercial participation and compliance, perhaps by using a responsible operator rating, providing tax breaks, reducing insurance burdens, or otherwise tangibly rewarding companies who contribute to mitigating the orbital debris problem.

The specific objectives of national partnerships involving industry should be to form and/or empower a U.S. body that drafts and enforces space norms of behavior, including active space

[7]Coordination Group for Meteorological Satellites. 2021. The Coordination Group for Meteorological Satellites, https://www.cgms-info.org/index_.php. Last accessed December 22, 2021.

traffic coordination, potentially along the lines of what the Federal Aviation Administration (FAA) does today for aircraft in U.S. airspace. Currently, the Department of Commerce (DOC) has the space traffic coordination mission, but it has extremely limited expertise to do that mission. MITRE recommends that NSTC form a consortium organization sponsored by these USG organizations: DoD, Intelligence Community, FAA, DOC, NASA, National Oceanic and Atmospheric Administration, and Department of State, plus commercial industry representatives to begin working on space norms of behavior.