Orbital Debris 101

This NSS guide is a simplified, non-exhaustive introduction to the issue of orbital debris and its management.

BACKGROUND INFORMATION

Why is the space sector important?

Orbital debris jeopardizes the safety of spacecraft and crew, the functioning of space systems, and the viability of human activity in Earth's orbit. Satellites are crucial to everyday life. Important space-based applications within the Space Sector include:

- Weather forecasting
- Climate change research
- Resource monitoring to support agriculture, forestry, and fishing
- Navigational systems, such as the Global Positioning System (GPS)
- Scientific understanding of our universe, such as through astronomy and physics (e.g. James Webb Space Telescope)
- Telecommunications, such as 5G connectivity, streaming, internet, cellphone, television, radio, etc.
- Network resiliency and redundancy to support fiber networks and to provide emergency services during disasters
    - An example is when SES Satellites provided equipment to Tonga in the aftermath of a volcanic eruption that damaged a submarine fiber cable cutting off telecom services to the island. Satellite connectivity was used here, as it is used often, in the aftermath of earthquakes, hurricanes, and other disasters, to restore service and support emergency first-responder efforts.
- Future progress: space mining of asteroids for valuable and rare metals in large quantities; in-space servicing, assembly, and manufacturing (e.g. 3D printing organs); space transportation; lunar industrialization; and mars colonization.

The Space Sector and its assets, systems, and networks are critical infrastructure. The destruction of the Space Sector would have a debilitating effect on national security, economic stability, and quality of life. The U.S., however, recognizes the Communications Sector but not the Space Sector as critical. Telecommunication satellites makes up over 60% of all Earth satellites. In addition, the U.S. has more than half of the total amount of satellites orbiting Earth. It is thus at the greatest risk of incurring financial and operational losses from spacecraft collisions with orbital debris. Its over 3,000 satellites are either owned by the U.S. Government or operated by a commercial or civil entity from the U.S. The management of Earth's orbital environment is crucial for the continued use and development of space infrastructure.

What are some of Earth's orbital regions and why are they relevant?

There are four general types of satellite orbits around Earth. They are Low-Earth Orbit (LEO), Medium-Earth Orbit (MEO), Highly Elliptical Orbit (HEO), and Geosynchronous-Earth Orbit (GEO). LEO extends from the Karman line, at about 100 km, to 2,000 km above Earth's surface. This is where the majority of orbital debris and most satellite are located. Many LEO satellites are used for telecommunications and remote sensing. LEO satellites are typically smaller, have shorter life spans, and form larger constellations than satellites in GEO. SpaceX's Starlink constellation, the International Space Station, and the Hubble Space Telescope all orbit in this zone. MEO is the region between LEO and GEO. Many MEO satellites are used for navigation systems. GEO is exactly at the altitude of 35,786 km. However, the GEO zone extends form 35,586 km to 35,986 km. Many GEO satellites are used for telecommunications and Earth observation.

How long orbital debris takes to fall back down to Earth depends on its altitude, as well as its geometry and mass. Here are some of the relevant timelines:

- Below 600 km debris usually falls back down to Earth in less than 25 years.
- At around 800 km it usually falls back down in less than 150 years.
- At around 1,200 km it usually falls back down in less than 2,000 years.
- Above 35,000 km (around the GEO zone) it usually takes over 60,000 years.
- Finally, at some point the altitude will be too high for debris to be significantly impacted by the atmosphere and Earth's gravitational forces, so the debris will stay in orbit indefinitely.

How is orbital debris created?

Orbital debris is defined as any human-made space objects orbiting the Earth that no longer serve any useful purpose. Most of the largest orbital debris objects are rocket upper stages and old, derelict satellites. Spacecraft can decay (and thus fragment) due to prolonged radiation exposure. They can explode due to onboard propellants and unstable batteries and collide with other satellites, spacecraft, or objects. For the latter, an extreme example is the recent Russian direct-ascent, anti-satellite missile test. Russia destroyed its old Cosmos 1408 satellites in November 2021, creating thousands of pieces of additional orbital debris. There have been 16 destructive anti-satellite (ASAT) tests to date, mostly by Russia, but also conducted by the U.S., China, and India.

There are currently over 5,000 satellites orbiting Earth. Most of these satellites are used for telecommunications and weigh over 100kg. Still, 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. This increases the crowding of the LEO environment and the further generation of orbital debris. The greatest factor to satellite growth has been the ongoing development of mega-constellations. Oneweb, Planet, SpaceX (i.e. Starlink), and Amazon (i.e. Kuiper Systems) all have expanding mega-constellations. To put it into perspective, there were less than 100 objects launched per year in 2004 and 2005, and by 2017 and 2018 there were more than 400 objects launched per year. Now SpaceX owns the largest number of satellites of any company or country. It has launched hundreds of satellites in this year alone. The U.S., through its government ownership or the operation by a U.S.-based entity, (e.g. SpaceX's Starlink), has by far the most satellites of any country in space, numbering in the thousands. It's followed by China, the UK, and Russia, whose satellites number in the hundreds. The American, Chinese, and Russian militaries each own over 100 satellites.

<u>What are some of the types of debris and what amounts do they exist in?</u>

The types and amounts of orbital debris influence the stability of the orbital environment and the risk to satellites, spacecraft, and crew. Millions of pieces of orbital debris exist in LEO. Their movements are uncontrolled and thus difficult to predict.

1. There are at least 26,000 debris objects 10 cm or larger, which means they are at least the size of a softball. Each of these would destroy a satellite on impact. They can be detected, tracked, and catalogued from ground-based tools.
2. There are over 500,000 debris objects around 1 cm, which are about the size of a marble and are big enough to cause damage to spacecraft and satellites. They create a mission-ending threat due to the potential penetration of thermal protective systems, critical infrastructure (e.g. fuel tanks), and cabins. They typically can't be tracked but can be detected by ground-based tools.
3. There are over 100 million debris objects 1 mm or smaller, which are about the size of a grain of salt. They can erode surfaces, crack windows, and penetrate spacesuits. They cannot be tracked and typically can't be detected by ground-based tools. However, space-based tools, such as the Space Debris Sensor attached to the International Space Station, can detect debris objects smaller than 1 mm.

Unfortunately, the highest mission-ending threats to robotic spacecraft are not from large debris, but rather impacts from mm- to cm-sized objects. These types of debris are too small to be detected and operators are unable to change course or move spacecraft to avoid them. NASA posits that due to the high risks of damage and high collisional probability, debris ranging from 1 to 2 cm is the most dangerous. 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. Orbital debris circles the Earth at speeds of about 17,500 miles per hour and space objects are likely to collide at more than 10 times faster than a bullet. At these speeds, even mm-sized debris poses a significant threat.

<u>What is the Kessler Syndrome and why is it important?</u>

The Kessler Syndrome is a theoretical scenario in which the density of objects in LEO due to space pollution is so high that collisions between objects cause a cascade. In such a case, each collision generates additional orbital debris that increases the likelihood of even further collisions. This collisional cascading could eventually curtail human access to space for hundreds of years. Such a positive feedback loop increases costs to spacecraft owners and operators. It increases the safety risks to crews, spacecraft, and space flight missions. Orbital debris has already reached critical mass. Thus, collisional cascading will eventually happen even if no more objects are launched into orbit. Multiple studies by the National Aeronautics and Space Administration (NASA) and other space agencies have concluded that the growth of debris in LEO can be sufficiently slowed. This would require at least 90 percent of all spacecraft to be removed from orbit within 25 years of their operational life. It would also require at least five derelict spacecraft (without post-mission disposal), which means they now qualify as "debris," to be actively removed from orbit every year. However, the global compliance rate for the post-mission disposal measures has only averaged between 20 to 30 percent in LEO.

ORBITAL DEBRIS MANAGEMENT

What is orbital debris management?

Orbital debris management is about understanding, managing, and reducing the risks posed by orbital debris. It involves stabilizing current debris generation and striving for long-term sustainability in our orbital environment. The NSS believes that creating a sustainable orbital environment requires a comprehensive approach that effectively uses Space Situation Awareness (SSA), Space Traffic Management (STM) (i.e. norms of responsible behavior), Mitigation, Remediation, and On-Orbit Recycling.

What is SSA?

SSA involves mapping Earth's orbital environment by characterizing orbital debris. This includes detecting, tracking, and cataloging all debris and spacecraft. This is crucial for satellite maneuvering, space operations and mission design, and collision avoidance. Other elements include developing ground-based and on-orbit debris tracking technology; improving data processing, sharing, and filtering of debris catalogs; and combining commercial and government SSA data.

Debris smaller than 10 cm is usually not tracked or directly monitored in real-time. Instead debris in small portions of the sky are recorded and "sampled." Statistical models are then used to estimate the amount and location of this small-sized debris. Debris models include data on the amount, location, and type of debris in the orbital environment. Material types, shapes, and density are being added to these models to better map the orbital environment. The Department of Defense (DOD) and NASA's Orbital Debris Program Office (ODPO) track debris using the U.S. Space Surveillance Network of over 30 ground-based radars and optical telescopes, and more than 6 satellites. Currently, the Space Fence Radar System and the Haystack Ultrawideband Satellite Imaging Radar (HUSIR) are two of the most advanced and powerful ground-based radars. Direct measurement data for debris, especially space-based tools like vision-based sensors, is important for the safe and efficient operation of satellites and rockets.

What is STM?

STM involves norms and rules of responsible behavior that reduce uncertainty and conflict in space activity, minimize collisional risk between spacecraft, and enable safe and efficient space operations. It is important to note that STM and mitigation have significant overlap. At the international level, STM consists entirely of voluntary guidelines, standards, and best practices. Still, organizations such as the International Telecommunications Union (ITU) and the UN's Office of Outer Space Affairs have more tangible, substantial soft power. Through the planning and coordination of space activities, the first priority of STM is ensuring that operational spacecraft do not collide. This includes right-of-way rules, such as requiring commercial satellites to maneuver out of the way of military satellites if there is a high chance of collision. Commercial LEO operators can anticipate receiving between 300 - 5,000 3-km conjunction warning messages per week and 35 – 560 1-km maneuver warning messages per week. These right-of-way rules, however, are not codified at the national level and are solely made up of industry practices.

In addition, STM may also include bans on destructive ASAT tests or satellite standardization requirements. For the latter, this includes satellite design rules for demisability, maneuverability, and tracking. Satellites may be required to do the following: use propulsion capabilities at certain altitudes; carry unique telemetry trackers or other markers, such as broadcast beacons or visual fiducials; or even install capture interfaces, such as docking plates. These rules would likely be codified by government agencies, such as the Federal Communications Commission (FCC).

What is Mitigation?

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. Mitigation through spacecraft design includes improving material resiliency and shielding. Engineers design spacecraft to withstand impacts by small debris, maintain performance throughout the mission while reducing fragmentation from solar radiation, and protect spacecraft and crews through shielding (e.g. whipple shields, reinforced cabins, etc.). One example is NASA's use of 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 in size. Moreover, engineers can increase the quality and reliability of propellants and batteries to prevent accidental explosions.

Within mission design, mitigation involves reducing debris during launch and improving the maneuverability capabilities and collisional avoidance processes. The maneuvering and collision avoidance aspects of mission design rely heavily on the STM pillar. Mitigation may also include elements of in-space servicing, assembly, and manufacturing. For example, SpaceLogistic's Mission Extension Vehicles and Nanorack's Mission Extension Kit provide in-space servicing that extend the operational life of spacecraft and satellites. They can conduct in-situ repairs, fueling, or propulsion attachments. They can help satellites obtain additional power, communication, and navigation capabilities.

Finally, and most importantly, mitigation involves Post-Mission Disposal (PMD). First, operators can "graveyard" spacecraft to unused, higher disposal orbits. This is usually used in GEO. Second, operators can "deorbit" spacecraft into the atmosphere to burn up. But very large debris doesn't fully burn up and instead falls back to Earth's surface. Ideally spacecraft material that makes it through the atmosphere during reentry falls to targeted locations like Point Nemo in the Pacific Ocean. Point Nemo is a space cemetery containing old satellites, rocket parts, and even space stations. Deorbiting is usually used in LEO.

What is Remediation?

Remediation refers mainly to the Active Debris Removal (ADR) of debris, including derelict spacecraft, before they explode, collide, or fragment in orbit. ADR is different than PMD because the former refers to the removal of debris rather than "functional" spacecraft at the end of their operational life. 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. ADR uses the PMD techniques discussed above, which are graveyarding and deorbiting. Currently, global remediation activities designed to remove existing debris from space are limited and largely in the planning phases of development. Remediation may include relevant models for risk and cost-benefit analysis. Further, remediation involves elements of in-space servicing, assembly, and manufacturing when it targets debris. One example is reviving the functionality of derelict satellites characterized as debris. Another example is repurposing derelict rocket upper stages that have turned into debris into orbital outposts for future refueling or manufacturing.

Lastly, a third type of both PMD and ADR is on-orbit recycling. On-orbit recycling is in its technological infancy and relies on the development of an extensive in-space infrastructure. Traditionally, on-orbit recycling has been viewed only as a minor and theoretical component of remediation. But the NSS believes that operationalizing on-orbit recycling is critical to the long-term sustainability and stability of Earth's orbital environment. Here, on-orbit recycling will be treated as a separate and fifth pillar of effective debris management. NSS envisions a space industry and orbital environment shaped by a culture of on-orbit recycling that mirrors the automobile industry where about 95% of today's cars are recycled.

So what is On-Orbit Recycling?

On-orbit recycling involves the in-situ recycling of satellites and debris to manufacture new spacecraft systems and modules, and eventually entire satellites. An example of an existing capability is Astroscale, Nano Racks, CisLunar Industries, and Neumann Space working together to turn debris into metal rods and then into ion thrusters capable of electric propulsion.

Although spacecraft designs are not currently recycle-friendly, many of their parts can be reused. Spacecraft metals, such as steel and aluminum, are recyclable. There are also many other reusable components, such as cameras, navigation sensors, radiation measurement systems, spectrometers, communication arrays, solar panels, and copper wiring. In GEO, over half of the graveyarded commercial satellites are sent to disposal orbits solely because they ran out of fuel. Derelict spacecraft that have not fragmented may thus have systems that are functioning nominally. For example, about two-thirds of the undamaged GEO solar panels may still be capable of generating significant power. In LEO, solar panels degrade surprisingly little over time. The solar arrays on the International Space Station decrease in efficiency at only about 0.15% to 0.45% per year.

Recycling would rely upon on-orbit manufacturing, which allows for larger, lighter, and more complex deployable systems. For example, the space industry could build more advanced parabolic booms and reflectors, solar arrays, antennas, drag and solar sails, and radiators. These systems would not be limited by launch mass, volume, and geometric extension. Satellite systems could also have less mass and structural strength because they would avoid the stresses of high gravity and of the vibrational and thermal launch environments. Satellite deployment and manufacturing would be faster and more adaptable. Spacecraft, such as satellites in mega-constellations, could have shorter lifespans that quickly respond to markets needs and advancing technology. Modular components that are manufactured on-orbit from debris could be used immediately to upgrade and reconfigure the design and function of space systems. On-orbit recycling will require cheap, but fast continuous maneuvering between orbits. In-space transportation will be necessary to collect debris, recycle reusable materials, assemble and manufacture new spacecraft, and then inject the spacecraft into their desired orbits.

The critical and desired in-situ technologies for recycling operations includes: fine-control propulsion; advanced guidance, navigation, and control; advanced automation; artificial intelligence and machine learning; visual fiducials; computer vision, such as vision-based navigation sensors; advanced robotic arms; intra-spacecraft mobility; standard interfaces for power and data; modular payloads; cutting tools; space welding; verification and validation processes; additive manufacturing; multi-material manufacturing; industrial processing; materials separation; and docking and capture tools.

<u>What are some of the relevant U.S. Government entities and what are their notable policies?</u>

FCC

Regulates the U.S. telecommunications industry, including satellite operations and radiofrequency spectrum allocation.

National Oceanic and Atmospheric Administration (NOAA), Department of Commerce (DOC)

Helps regulate and coordinate remote sensing and Earth observation activities of satellites.

Office of Space Commerce (OSC), NOAA, DOC

Leads space commerce policy activities and is starting to take over civil and commercial SSA and STM responsibility from the DOD.

Office of Commercial Space Transportation (AST), Federal Aviation Administration (FAA), Department of Transportation (DOT)

Regulates the U.S. commercial space transportation industry, including commercial-crew spacecraft launch and reentry.

ODPO, NASA

Conducts measurements of the orbital environment and develops technical consensus for adopting best practices, standards, and guidelines for orbital debris management. NASA conducts significant space operations.

National Telecommunications and Information Administration (NTIA)

Assists in the regulation of telecommunications for U.S. government entities and advises the President on corresponding policy issues.

DOD

Collects data on and tracks space objects and notifies spacecraft operators of possible collisions. Catalogues debris populations. The DOD conducts significant space operations.

Joint Space Operations Center's 18th and 20th Space Control Squadrons, Space Force

Collects data on and tracks space objects and notifies spacecraft operators of possible collisions. Catalogues debris populations.

National Orbital Debris Implementation Plan (2022) by the National Science and Technology Council

Space Traffic Management: Assessment of the Feasibility, Expected Effectiveness, and Funding Implications of a Transfer of Space Traffic Management Functions (2020) by the National Academy of Public Administration

Orbital Debris Mitigation Standard Practices (2019) by NASA's Orbital Debris Program Office (ODPO)

Space Policy Directive-3, National Space Traffic Management Policy (2018) by the Executive Office of the President

<u>What are some of the relevant international space entities and what are their notable policies?</u>

Inter-Agency Space Debris Coordination Committee (IADC)

The internationally recognized authority for the worldwide technical coordination of activities related to orbital debris. It consists of thirteen government space agencies, including those from Russia, China, Japan, the United States, and Europe. The IADC has released mitigation guidelines, which were updated in 2020.

Committee on the Peaceful Uses of Outer Space (COPUOS), Office of Outer Space Affairs (OOSA), United Nations (UN)

Another key player in global space collaboration that leads efforts to address the legal and scientific issues within space operations. COPUOS adopted the Guidelines for the Long-Term Sustainability of Outer Space Activities in 2019.

International Telecommunications Union (ITU)

The specialized UN agency that coordinates GEO satellite operations at the international level. The ITU facilitates cooperation between national telecommunication regimes, organizing worldwide spectrum sharing and orbital slotting for GEO satellites. Its Recommendation ITU-R S.1003.2 provides guidance on basic mitigation and remediation standards for GEO satellite activity.

Space Debris Mitigation Guidelines (2020) by the IADC

Space Debris Mitigation Guidelines (2010) by the UN's COPUOS

Guidelines for the Long-term Sustainability of Outer Space Activities (2019) by the UN's COPUOS

Reducing space threats through norms, rules and principles of responsible behaviours (2021) by the UN General Assembly

REFERENCES (*passim*) & FURTHER RESOURCES

Amrith Mariappan, *Theoretical studies on space debris recycling and energy conversion system in the International Space Station*, Engineering Reports (2020)

Asha Balakrishnan, *U.S. Policies Relevant to Orbital Debris*, Institute of Defense Analyses (2020)

Benjamin A. Corban, *Global Trends in On Orbit Servicing, Assembly and Manufacturing (OSAM)*, Institute of Defense Analyses (2020)

Caroline Arbaugh, *Gravitating Toward Sensible Resolutions: The PCA Optional Rules for the Arbitration of Disputes Relating to Outer Space Activity*, 42 Ga. J. Int'l & Comp. L. 825 (2014)

Carson Bullock and Robert T. Johanson, *A sustainable geostationary space environment requires new norms of behavior*, MIT Science Policy Review (2020)

Carson Bullock and Robert T. Johanson, *Policies for incentivizing orbital debris assessment and remediation*, MIT Science Policy Review (2021)

Department of Transportation, *Report on Processing and Releasing Safety-Related Space Situational Awareness Data*, Public Law 114-90 (2016)

Dewesoft, *Every Satellite Orbiting Earth and Who Owns Them* (2021)

ESA, *ESA is looking into futuristic in-orbit services recycling satellites,* OMAR: On-orbit Manufacturing Assembly and Recycling (2019)

Frank Koch, *A Business Case for Space Debris Executive Summary*, Orbit Recycling (2021)

Jeremy Turner, *How Can Humans Thrive an d Service Satellites in a Geostationary Orbit*, The University of Nottingham (2018)

Minoo Rathnasabapathy et al., *Space Sustainability Rating: Designing a Composite Indicator to Incentivize Satellite Operators to Pursue Long-Term Sustainability of the Space Environment,* 71st International Astronautical Congress – The CyberSpace Edition (2020)

National Aeronautics and Space Administration, *NASA's Efforts to Mitigate the Risks Posed by Orbital Debris*, IG-21-011, 14-17 (2021)

National Research Council, *Orbital Debris: A Technical Assessment* (1995)

National Space Society, *An SPD-3 and NAPA Informed Model for a Safe and Sustainable Space Economy: Six Recommendations* (2020)

National Space Society, *Orbital Debris: Overcoming Challenges* (2017)

National Space Society, *Space Debris Removal, Salvage, and Use: Maritime Lessons,* NSS Position Papers (2019)

Nicholas L. Johnson, *Saving Space: The Multilateral Approach to Orbital Debris*, 15 Geo. J. Int'l. Aff. 130, 130-138 (2014)

Shenyan Chen, *The Space Debris Problem*, 35 Asian Persp. 537, 537-58 (December 2011)