Addressing the challenges of space traffic and space debris management

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Overview

Space traffic management and debris are among the most serious issues of the modern space age with human space activities in Earth orbit increasing at a previously unknown pace. Space Traffic Management (STM) encompasses technical and regulatory actions aimed at promoting safe entry into outer space, in-orbit activities, and return from space to Earth without physical and radio-frequency interference (1). The growing congestion of orbital space around Earth has posed significant concerns for safety, economics, and the environment that should be urgently addressed.

Space traffic and debris management are complicated with technical, financial, and policy implications. They involve difficulties in tracking and clearing debris, especially small fragments, high technology development costs for removal, and the need for more international cooperation (2). Complexity is added by the increasing number of space-faring nations and private entities venturing into space, each adding to orbital debris and raising the risk of collision.

The consequences of ineffective space traffic management would be catastrophic, particularly with regard to the Kessler syndrome* (3, 5). This phenomenon threatens not only current space activities but also future access to space and the benefits derived from space-based technologies. The European Space Agency, along with other space agencies, has already begun imposing stricter regulations on space missions and developing new technology to remove debris (4), but the challenge requires ongoing international cooperation and creative solutions.

The international response to these challenges has evolved through various initiatives and structures, but the lack of an international common response to space traffic management is one of the principal challenges (7). With more space activities, with a predicted high rise in space activities and satellite launches, it is urgent that there be effective and proper mechanisms for space debris removal and space traffic since it becomes extremely necessary to make space usage sustainable in the future (8).

Definitions of Important Terms

Space Traffic Management (STM)

An end-to-end structure for managing and controlling space activity to provide safety of operations within Earth's orbit. STM consists of tracking space objects, launching and maneuver planning coordination, and defining procedures for collision avoidance and is the dominant system for sustaining order in space operations.

Active Debris Removal (ADR)

The processes and technologies for removing debris objects from orbit physically which pose a danger to operational space vehicles. The ADR systems include various methodologies such as robots, nets, harpoons, and lasers, which is among the simplest mechanisms to address the space debris menace.

Space Situational Awareness (SSA)

The general know-how and perception of the space environment, encompassing the location and movement of natural and artificial objects in orbit. SSA systems employ ground sensors and space sensors to track objects, predict potential collisions, and provide critical information to space traffic management.

Kessler Syndrome

Theoretical scenario under which objects in Earth orbit are so dense that collisions induce cascades of collisions. As proposed in 1978 by NASA specialist Donald Kessler, such a situation would make available portions of orbits unusable for many generations.

End-of-Life Protocols

Pre-established processes and procedures for disposing of satellites and spacecraft safely upon the termination of their lifespan. Such protocols would either necessitate bringing the spacecraft into a graveyard orbit or a controlled reentry into the Earth's atmosphere, ensuring sustainable space operations.

Graveyard Orbit

An assigned orbit high above working satellite orbits where spent satellites are removed at the end of their working life. The disposal orbit, by another name, avoids satellite jamming with working satellites and reduces the danger of collision in densely populated regions of orbit.

Space Infrastructure Servicing

Technologies and systems employed for servicing, maintaining, or enhancing satellites and other space infrastructure orbiting the earth. This includes refueling capabilities, hardware maintenance, and space debris removal capabilities, which play a critical role in sustainable space operations.

Orbital Debris Remover

Space vehicles or systems that are designed particularly to capture and remove space trash from orbit. These systems may employ new technology like electromagnetic tethers or adhesive mechanisms for capturing and de-orbiting debris objects securely.

Long-term Debris Traffic Management (LDTM)

A long-term approach towards space debris management emphasizing sustainable practices and long-term solutions. LDTM includes preventive and active measures for new debris production reduction and debris removal.

Just-in-Time Collision Avoidance (JCA)

An emergency response system that enables spacecraft to make real-time maneuvers to avoid potential collisions with other objects in orbit. JCA systems rely on advanced tracking and prediction capabilities to identify and respond to collision threats in real-time.

Timeline of Key Events

1978: Donald Kessler proposes the Kessler Syndrome theory

Donald J. Kessler and Burton G. Cour-Palais of NASA scientists published their now famous paper "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," detailing what would eventually be termed as the Kessler Syndrome. According to their postulate, collisions among growing numbers of objects orbiting Earth at low Earth orbits would spawn a cascade leading to a continuous cycle of production of debris. As of 2009, Kessler discovered that modeling showed the debris environment was already destabilizing and particles from impending collisions were dropping into it faster than the atmospheric drag was erasing them (9).

April 5-7, 1993: First European Conference on Space Debris

The pioneering conference was hosted by the European Space Agency in Darmstadt, Germany, bringing together more than 250 experts from 17 countries to discuss the growing issue of space debris. Co-sponsored by a number of national space agencies including ASI, BNSC, CNES, and DARA, the conference addressed technical as well as legal aspects of space debris. The conference was one of the first major international efforts to address space debris through collective scientific and policy discussion, with experts debating means to control and regulate debris through a special round table discussion (10).

October 11-13, 1999: IADC develops first Space Debris Mitigation Guidelines

At the 17th meeting of the Inter-Agency Space Debris Coordination Committee in Darmstadt, Germany, Working Group 4 developed the initial set of consensus international space debris mitigation guidelines. It was these consensus guidelines, adopted in October 2002, that dealt with the total environmental contribution of space missions with the focus on the restriction of released debris during nominal operations, reduction of on-orbit break-ups, post-mission disposal, and on-orbit collision avoidance. Even though non-binding, the guidelines inspired organizations to utilize them when determining mission requirements and later became the foundation for UN-endorsed guidelines (11).

February 10, 2009: First accidental hypervelocity collision between satellites

The first intentional hypervelocity collision of two intact satellites occurred when Iridium 33, an operational U.S. communications satellite, struck Cosmos 2251, an inactive Russian communications satellite at an altitude of approximately 800 kilometers over Siberia. This effect produced almost 2,000 pieces of debris with diameters of at least ten centimeters and tens of thousands of pieces less than ten centimeters in diameter. Much of this debris remained in orbit for decades, possibly colliding with other objects in Low Earth Orbit and demonstrating the real-world applications of the Kessler Syndrome hypothesis (12).

June 18, 2018: U.S. establishes first National Space Traffic Management Policy

Space Policy Directive-3 was signed into law by President Trump, marking the establishment of the first-ever National Space Traffic Management Policy in the third session of the National Space Council. The policy provided direction and instruction to ensure the United States was a leader in providing a secure and safe environment as commercial and civil space traffic increased. According to this directive, the Department of Commerce was to render space safety information and services to the public, whereas the Department of Defense would be in charge of keeping the authoritative catalog of space objects (13).

March 2-3, 2022: 8th Annual Space Traffic Management Conference

The Space Security, Safety, and Sustainability Program of The University of Texas at Austin's Strauss Center and Cockrell School of Engineering, in partnership with the International Academy of Astronautics and Privateer, hosted the 8th annual Space Traffic Management conference. Titled "Anthropogenic Environmental Impact and Assessment of Space Traffic on Space Operations and Implications for Climate Change Monitoring," the conference witnessed experts from all over the world coming together to present and discuss various aspects of space traffic management (14).

2022-2023: ESA adopts "Zero Debris approach"

The European Space Agency developed and executed its Zero Debris strategy, whereby it aimed to completely remove the generation of debris in beneficial orbits by 2030. A part of this effort was a Concurrent Design Facility study conducted during September and October 2022 to revise ESA's Space Debris Mitigation Standard. The strategy was institutionalized by means of the Zero Debris Charter, which contained ambitious, quantifiable objectives to improve space safety and sustainability through policy and technology development (15).

Position of Key Nations and Organisations

Japan:

Japan is becoming a pioneer to develop fresh space trash regulation technology. Japan startup Orbital Lasers, separated from satellite firm SKY Perfect JSAT, is crafting lasers that inhibit rotation of space litter by burning miniature surface sections (20). Japan is working with India on debris removal technology and plans to put its laser system in space by 2027. This is part of broader Japan-India space collaboration, including their joint Lunar Polar Exploration mission scheduled for 2026 (20).

United States:

The United States has been firmly standing in leading space traffic management by giving the first ever National Space Traffic Management Policy in 2018. The US administration feels it is necessary to "address threats to space assets; champion space traffic management to support the growing space economy; and incorporate commercial perspectives into civilian and national security space policy" (16). In 2025, the US also encourages making space a top national priority, reviving American global leadership, and shaping current international regimes to improve space traffic management. The US also realizes that it must involve China in space traffic management issues without losing deterrence capability (16).

China:

China has committed to strengthening its space debris monitoring system such that it can ensure the safe and stable functioning of Chinese space activities. According to its 2021 white paper, China is set to "strengthen space traffic control and improve its space debris monitoring system, related database and early warning services" (17). The country has already established practices such as upper stage passivation for carrier rockets and active deorbiting of spacecraft near the end of their life. China is also developing a near-Earth object defense system and an integrated space-ground space climate monitoring system.

India:

India has pledged its intent to have debris-free space missions by all Indian space actors, both government and non-governmental, by 2030. The pledge, made in April 2024, calls upon all other state space actors to do the same for the long-term sustainability of outer space (19). Roll-out of India's Debris Free Space Missions (DFSM) initiative will be from early 2025 with an initial emphasis on mission planning and spacecraft, and launch vehicle design. India is also working together with Japan in the latest trash clearing technology, like satellite laser facilities (20).

Russia:

Russia possesses a significant space surveillance capability through its Main Center for Situation Reconnaissance in Space, capable of tracking over 5,000 space objects with a catalog accuracy of 1-2 km. While Russia is planning to launch its first special-purpose satellite to monitor space debris in 2027 as part of its new "Milky Way" automated early warning system, the country has also engaged in controversial events, such as the November 2021 direct-ascent anti-satellite missile test that created over 1,500 pieces of trackable debris and sparked international outcry (31).

Japan Aerospace Exploration Agency (JAXA):

JAXA itself became a global leader in space debris management through its large-scale research activities and debris removal activities by itself, using its Space Debris Mitigation Guidelines as an international standard since 1996 (32). The agency's Commercial Removal of Debris Demonstration program, which was launched in partnership with companies like Astroscale and GITAI Japan, recorded a huge milestone in February 2023 when JAXA successfully tested robotic space debris removal technology in a controlled zero-gravity environment (33).

European Union (EU) and the European Space Agency (ESA):

The European Space Agency has adopted a "Zero Debris approach," aiming to significantly reduce debris creation in Earth and lunar orbits by 2030 for all future ESA missions (21). In November 2023, ESA accepted new Space Debris Mitigation guidelines with tighter requirements, e.g., safe disposal with more than a 90% chance of success and reducing the longest period in protected low-Earth orbits from 25 to five years (21,25). ESA has also facilitated the establishment of the Zero Debris Charter, an international initiative to which any space agency can subscribe as a pledge towards a Zero Debris future (25). The EU is drafting the EU Space Law to be adopted in 2027, which will introduce end-to-end rules for space traffic management like "mandatory anti-collision systems, satellite disposal procedures, and debris management requirements" (18). The EU has asked all the COPUOS Member States to "avoid, to the maximum extent possible, the generation of space debris in order to ensure the safe, secure, stable, and sustainable use of outer space" (24).

National Aeronautics and Space Administration (NASA):

NASA has been working on space debris studies and mitigation for decades, focusing on improving tracking systems, prevention measures, and active debris removal technologies (22). The agency is seeking low-impact, low-mass, and energy-efficient recycling technologies to reduce waste on future missions. NASA also encourages satellite operators to design spacecraft with deorbiting features so that they can disintegrate harmlessly in Earth's atmosphere once their mission is complete (22).

Past Actions and Suggested Solutions

Addressing space debris consists of short-term removal and long-term prevention activities. Active Debris Removal (ADR) technologies are very promising, with ESA's ClearSpace-1 mission in 2025 to demonstrate the capture of a Vega Secondary Payload Adapter that was launched into orbit in 2013 (36). This pioneering mission will test robotic capture systems with four robotic arms, opening the door to a commercial debris removal market. Other innovative technologies are net capture systems, harpoon technology, and vision-based navigation systems, which have been tested successfully through projects like RemoveDEBRIS (34). More companies, including Paladin Space, are developing reusable debris removers like "Triton" that can collect multiple debris fragments in a single mission. Laser-based removal systems, which nudge smaller debris into reentry paths, are also being developed by Orbital Lasers (39).

A comprehensive approach to space traffic control requires strong policy frameworks and international cooperation. The European Union has developed the EU Space Surveillance and Tracking system, which now protects more than 520 spacecraft using more than 40 sensors contributing to its network (41). ESA has adopted a "Zero Debris strategy" that will significantly reduce debris generation by 2030, reducing the maximum lifetime in protected low-Earth orbits from 25 years to just 5 years (40). The strategy requires more stringent safety disposal requirements with a success probability of more than 90% and spacecraft design with interfaces that make removal easier in case of self-disposal failure. According to the European Space Policy Institute, there are three core tasks of efficient Space Traffic Management: Space Traffic Monitoring (detection and tracking), Space Traffic Regulation (technical and regulatory measures), and Space Traffic Coordination (information exchange and coordinated operations) (38). With around 300,000 more satellites scheduled to be launched in the coming decade, there is an increased need to ensure a harmonized global framework for space traffic management to make space access sustainable (41).

Going forward, a comprehensive global solution must integrate technological innovation, policy standardization, and economic incentives. Future space traffic management systems can combine AI-powered collision prediction algorithms with automated collision avoidance protocols, perhaps even a "space traffic control" system similar to air traffic control. International agreements can establish orbital "right of way" rules and satellite launch corridors to minimize the dangers of collisions. Market-based mechanisms such as orbital use fees, debris removal bonds, and insurance requirements can create market incentives for responsible behavior. In addition, developing countries can be helped with technology transfer programs as well as exclusive orbital access zones to ensure equitable participation in space governance while ensuring sustainability standards. A space sustainability global fund, administered through organisations such as but not limited to UNOOSA, could finance debris removal missions and the creation of new mitigation technologies, with contributions to funding levied based on nations' levels of space activity and historical debris generation.

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