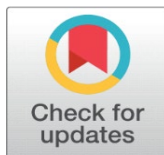
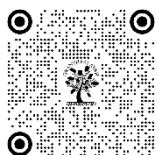


ORBITAL DEBRIS MITIGATION: PERSPECTIVE FROM ENVIRONMENTAL LAW

Huma Parveen ¹, Dr. Rajesh Kumar Verma ²

¹ PhD Scholar, School of Legal Studies, Babu Banarasi Das University, Lucknow, Uttar Pradesh

² Associate Professor, School of Legal Studies, Babu Banarasi Das University, Lucknow, Uttar Pradesh



ABSTRACT

Orbital debris from spacecraft, has been circling Earth for over 50 years. Humans have launched objects into space, and most of them fall back to Earth daily. These debris either land or burn up in the atmosphere. Most return to Earth end up in water, which makes up 70 percent of Earth's surface. However, many of these objects remain in orbit around Earth.

Space debris poses a significant threat to outer space activities, ranging from tiny paint flakes to intact, nonfunctional spacecraft and rocket bodies. The increasing amount of debris increases the risk of collision with operational satellites, highlighting the need for sustainable solutions.

The evolution of the space object environment is causing an uncontrolled population growth due to increasing collisions, primarily among debris. To preserve the space environment for future generations, it is crucial to address the debris problem. International space law, including Article IX of the Outer Space Treaty, obligates states to avoid harmful contamination of outer space. These norms are more effective when considering sustainable development principles and intra- and inter-generational justice. As debris pollution increases, questions of liability and responsibility become more relevant. The Liability Convention provides a remedy for victims of damage caused by space debris, with absolute liability for damage on Earth's surface. International responsibility law also allows states to be held accountable for environmental pollution events, including a duty to active debris removal.

While international law is effective in addressing the debris problem, growing use and dangers necessitate the status quo of a complete site visitors control regime for outer space. This would strengthen the rule of law in outer space and ensure the sustainability of space utilization.

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Keywords: Orbital Debris, Environmental Law, Legal Consequences, Effective Solution

1. INTRODUCTION

Satellites are vital in various fields such as space science, Earth observation, meteorology, climate research, telecommunication, navigation, and human space exploration. They provide a distinctive viewpoint, a valuable resource for scientific data collection, and numerous essential applications and services, thereby enhancing research and exploitation possibilities. Over the past few decades, the rise in space activities has led to the emergence of a new and unexpected hazard: space debris.

Space debris, or space junk^[1], refers to any human-made object in orbit that is no longer useful and is a result of no longer in service space vehicles. These objects can range in size from old spacecraft and rocket stages to micro-debris like paint flecks. Around 25,000 space debris objects are currently tracked and cataloged, but when considering minuscule pieces like lens covers, peeling insulation, and fragments from "breakup events," the number rises to millions. The velocity of orbit can significantly impact the health and operation of currently healthy space systems due to the

presence of debris in the space environment. The increasing debris from radiation and increased activity poses a growing threat to sustainable access to space.

Space debris comprises a diverse range of objects, ranging from tiny paint flecks to massive metal chunks. Out of 34,260 objects tracked in orbit, 25% are working satellites, while the rest are junk, including broken satellites and discarded rocket stages. Around 130 million pieces of debris, measuring between 1 mm and 1 cm, are likely too small to be tracked. The speed at which these objects travel over 25,000 kilometers per hour can cause even the smallest debris to cause significant damage. Debris accumulates on the orbital "highway", making it increasingly challenging for functional satellites to avoid collisions.^[2]

2. HISTORY OF SPACE RACE ERA

The space race was a 20th-century conflict between the Soviet Union (USSR) and the United States (US). Both pursued the domination of space flight technologies. The competition for artificial satellites began on August 2, 1955, when the Soviet Union responded to the US's announcement of similar intentions.^[3] The space race originated from the nuclear arms race between Germany and the United States after World War II, aided by German missile technology and scientists. The technological profit required for such power were deemed necessary for national security and political superiority. The space race led to significant advancements in artificial satellite launch, lunar probes, and human space voyages in low Earth orbit and lunar missions. The space race between the US and USSR, lasting twenty years, was a significant period in history with significant advancements in science, space exploration, and technology.

The 1957 launch of Sputnik II^[4] led to the creation of human-made orbital debris, including the rocket stage and satellite itself, and underscored the necessity for space surveillance of these objects. The United States Air Force developed Project Space Track to track foreign and domestic artificial space objects. The United States pursued understanding of this new frontier due to a combination of academic curiosity and the need for intelligence gathering. A network of early warning radars was established to monitor the skies for potential incoming nuclear missiles. The military utilized this surveillance system to differentiate between non-threatening orbital objects and sub-orbital ballistic weapons. A catalog was created based on collected data, offering insights into satellites' predicted routes over radar sites.

The 1960s saw increased space activity, including launches, anti-satellite testing, and old spacecraft explosions, which further contributed to the creation of orbital debris. The initiative to continue tracking spacecraft that reached and remained in orbit has begun. Projects like NORAD, now the North American Aerospace Defense Command's Space Object Catalog^[5], aimed to enhance the foundation established by Project Space Track. On June 29, 1961, the database's records nearly tripled due to the explosion of a Thor-Ablestar rocket upper stage.^[6] The incident marked the first satellite breakup, resulting in over 200 cataloged fragments. Over time, the number of cataloged space debris items and pieces too small to trace has continued to increase.

3. REASONS OF ORBITAL DEBRIS

Defunct satellites

Satellites have a short lifespan and, once their batteries are depleted or they malfunction, they are left stranded in space. Initially, the space race assumed that abandoned objects would eventually fall to Earth and burn up upon re-entry. However, this may not occur at higher orbits.

Missing equipment

During space walks, astronauts may drop tools or other objects. In 2008, astronaut Heidemarie Stefanyshyn-Piper dropped a box of tools. The object disintegrated nearly a year later, after orbiting Earth over 4,000 times.

Rocket stages

Certain rocket stages are jettisoned in low orbits and descend back to Earth shortly following launch. Higher objects, sometimes containing fuel remnants, drift in space and may explode, resulting in thousands of fragments.

4. ELABORATIVE REASONS OF ORBITAL DEBRIS

Breakups have historically been the primary contributors to the fragmentary space debris population, with ASAT tests being among the largest single events. Explosive breakups or ASAT tests can result in millions of lethal but nontrackable particles.

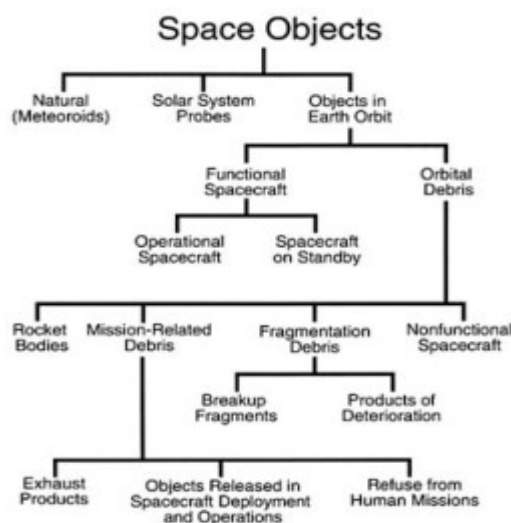
For reference, The 1986 Ariane 1^[7] breakup resulted in the creation of nearly 500 trackable pieces, while the 1996 Pegasus/HAPS breakup produced over 750 trackable fragments^[8]. Models suggest that there are tens to hundreds of non-trackable fragments for every trackable fragment, increasing in quantity as fragment size decreases. In the late 2000s, a rapid series of debris events raised concerns among U.S.

government leaders about the potential risks to spacecraft. The 2007 Chinese FY-1C ASAT test^[9] and 2009 Iridium 33 satellite collision with the Russian Cosmos 2251 satellite significantly increased debris, highlighting the need for improved collision prevention and debris cleanup efforts.^[10] Aerospace established the Debris Analysis Response Team (DART) in response to the 2007 Chinese ASAT test.^[11]

The team, with expertise in trajectory reconstruction algorithms and hypervelocity collision modeling, offers a comprehensive operational risk analysis for active satellites in debris fields. The Aerospace Debris Environment Projection Tool (ADEPT)^[12] is utilized for long-term analysis to predict the impact of future population and operations practices and policies. Recent years have seen a significant enhancement in the ability to track debris and manage new mass launches of low Earth orbit (LEO) constellations.

The Earth's space has never been empty, as particles of various sizes continuously passed through near-Earth space before the 1957 launch of Sputnik. The risk of spacecraft colliding with naturally occurring meteoroids is minimal, with simple shielding techniques protecting against most small particles, and the likelihood of serious damage is extremely low. Since the beginning of space flight, the collision hazard in Earth orbit has steadily increased due to the growing number of artificial objects orbiting Earth. Since 1957, over 4,500 spacecraft have been launched, with nearly 2,200 remaining in orbit. 450 are functional, while the rest are considered debris, unable to perform missions. Since 1957, over 4,500 spacecraft have been launched, with nearly 2,200 remaining in orbit. 450 are functional, while the rest are considered debris, unable to perform missions. The spacecraft orbits Earth alongside spent rocket bodies, mission-related debris, fragmentation debris, and nonfunctional spacecraft.

Figure 1 illustrates the diverse array of objects in space, including various types of debris.



The artificial orbital debris is evident to pose a potential threat to functional spacecraft. Colliding objects in orbits near Earth typically have a relative velocity of over 10 km/s. Spacecraft at high speeds can be severely damaged or even

fatally damaged by collisions with objects as small as a centimeter in diameter. Large debris particles, a millimeter or less in diameter, can cause damage to optics, degrade surface coatings, or even crack windows.

There are no confirmed incidents of severe damage or destruction caused by collision with orbital debris, but several spacecraft malfunctions and breakups may have been caused by debris impacts. Smaller debris particles have damaged windows and surfaces of spacecraft like the U.S. Space Shuttle, Salyut^[13], Mir,^[14] Solar Maximum Mission spacecraft (Solar Max)^[15], and Long Duration Exposure Facility (LDEF)^[16]. Low-grade damage is likely widespread in low Earth orbit (LEO), but often goes undetected due to the lack of spacecraft return for examination. Since the late 1970s, modeling techniques predict that the hazard from orbital debris is expected to increase over time unless deliberate actions are taken to minimize the creation of new debris. The predicted increased hazard will necessitate spacecraft designers and operators to implement countermeasures against debris threats or risk losing spacecraft capability due to impacts. The design of large, long-evolving, and potentially damaging debris-prone LEO spacecraft, such as the International Space Station, has been significantly influenced by projected future increases in debris hazard.

The hazard of orbital debris has experienced a significant increase in the past decade. The events such as rocket upper stage breakups and Shuttle window replacements due to small particle impacts raised awareness of space debris issues and the need to consider debris considerations in Space Station Freedom design.

The report by various organizations, including the Aeronautics and Astronautics (AIAA)^[17], the European Space Agency (ESA)^[18], the U.S. Civilian Interagency Group on Space^[19], the International Academy of Astronautics (IAA)^[20], and The Japan Society for Aeronautical and Space Sciences (JSASS)^[21], aimed to better define the problem and provide suggestions for its mitigation. Over the past few years, there has been a significant increase in understanding about orbital debris. New data on debris population has been gathered from various sources, including LDEF, the European Retrievable Carrier (EURECA)^[22], Mir, and Haystack radar^[23], which collected data on small debris impacts in space and medium-sized debris previously undetectable. The new data has enhanced the models used to estimate the current characteristics and predict the growth of the overall debris population. Despite extensive research, there is still a significant amount of information available about orbital debris.

The main reason for the limited knowledge on debris is the difficulty in studying small, fast-moving, often dark objects orbiting Earth, and the limited data collected due to non-debris-related investigations covering limited debris size and altitude ranges and time frames. The understanding of debris populations is limited due to gaps in estimates, such as the significant population of LEO debris with diameters ranging from 1 mm to 10 cm, the fact that breakups in geosynchronous Earth orbit occur only because telescopes were looking at spacecraft, the surprising discovery of small debris in elliptical orbits from LDEF data, and the lack of meaningful measurements of debris smaller than 1 mm at altitudes higher than 600 km.

Despite extensive work in defining the current and future debris environment, data collection and analyses have improved our understanding of the overall magnitude of the orbital debris problem. The space community is recognizing the significant issue of debris and is recognizing the need for immediate action to safeguard the future of space. The current challenge lies in implementing the necessary actions to address the issues arising from orbital debris. The problem at hand is complex and will not be resolved easily. To effectively manage orbital debris, ongoing measurement and modeling efforts are needed, along with the creation of tools to assist spacecraft designers in protecting against existing debris hazards and widespread implementation of measures to minimize debris creation.

60 years of space activity

Over 60 years of space activities, over 6050 launches have produced 56450 tracked objects in orbit. About 28160 remain in space, regularly tracked by the US Space Surveillance Network. The catalogue covers objects larger than 5-10 cm in low-Earth orbit and 30 cm to 1 m at geostationary altitudes. Only about 4000 are intact, operational satellites today. The vast quantity of space hardware weighing over 9300 tonnes is a significant amount.

The catalogued objects comprise 24% of satellites, with less than a third operational, and 11% spent upper stages and mission-related objects like launch adapters and lens covers. Since 1961, over 560 in-orbit fragmentation events have been documented. The majority of current events involve explosions of spacecraft and upper stages, with only seven collision-related events associated. Future collisions are expected to become the primary source of space debris.

Explosions of satellites and rocket bodies

The fragmentation events are believed to have resulted in a population of objects larger than 1 cm, approximately 900000. The sporadic flux from naturally occurring meteoroids may outpace that from human-made debris objects of 0.1-1 mm in size. In orbit explosions are primarily caused by residual fuel in tanks or fuel lines, or other energy sources, that remain on board after a rocket stage or satellite is discarded in Earth orbit. The harsh space environment can lead to mechanical issues, such as leaks or fuel component mixing, which can trigger self-ignition over time. The explosion can cause the object to be destroyed and its mass to be spread across multiple fragments with varying masses and velocities. In recent times, satellite interceptions by surface-launched missiles have been a significant factor in the recent past. In January 2007, the Chinese FengYun-1C engagement significantly increased the trackable space object population by 25%.^[24]

Over 2460 solid rocket-motor firings have been the primary non-fragmentation debris source, releasing micrometre-sized dust and mm- to cm-sized slag particles of aluminium oxide. The ejection of reactor cores from Buk reactors was a significant factor following the end of Russian radar ocean reconnaissance satellites operations in the 1980s. In 16 ejection events, numerous droplets of reactor coolant liquid (a low-melting sodium potassium alloy) were released into space. The 1960s Missile Defense Alarm System (MIDAS missions)^[25] involved a historic radio communication experiment involving the release of thin copper wires. Extreme ultraviolet radiation, atomic oxygen, and micro particles erode the surfaces of space objects due to the impact of atomic oxygen and micro particles. The process results in the significant loss of surface coatings and the detachment of paint flakes ranging from micrometer to mm in size. ESA's 1 m-diameter telescope at Teide Observatory in Tenerife, Spain^[26], has detected a population of objects with high area-to-mass ratios. The origin and nature of these objects are not fully understood, but they are generally believed to have been created in the GEO region from thermal covering material of disposed satellites. On 10 February 2009, the first-ever accidental in-orbit collision between two satellites occurred at an altitude of 776 km above Siberia. The American communication satellite Iridium-33 and the Russian military satellite Kosmos2251 collided at a speed of 11.7 km/s. Both were destroyed, resulting in over 2300 trackable fragments, some of which have decayed and reentered the atmosphere, where they have burned up.^[27]

Distribution of catalogued objects in space - global view

Satellites launched into the Late Earth Orbit (LEO) are continuously exposed to aerodynamic forces from the Earth's upper atmosphere. The satellite's resistance, varying in altitude, decelerates over time, allowing it to reenter the atmosphere after weeks, years, or centuries. At altitudes above 800 km, air drag becomes less effective, resulting in objects remaining in orbit for many decades. Natural cleansing mechanisms, such as air drag and luni-solar gravitational attraction, counteract debris generation from normal launch operations and breakups at different altitudes. The balancing effects result in a spatial density of space debris objects that is dependent on altitude and latitude. Maximum debris concentrations occur at altitudes of 800-1000 km and near 1400 km, while spatial densities in GEO and navigation satellite constellation orbits are smaller by two to three orders of magnitude.

The number of debris objects in space is expected to increase due to current launch rates of 110 and future break-ups at historic rates of 10-11 per year. The increasing debris count will progressively increase the probability of catastrophic collisions, with doubling the number of objects increasing the collision risk by approximately four times. As the debris population increases, more collisions are expected to occur. In a 'business-as-usual' scenario, collisions will eventually overtake the dominant explosions within a few decades. Collision fragments will eventually collide with each other until the entire population is reduced to subcritical sizes. The 'Kessler syndrome'^[28], a self-sustaining process crucial for the LEO region, requires timely international mitigation and remediation measures to prevent its occurrence.

Consequences of space debris

Since 1961, the ESA reports over 560 fragmentation incidents, primarily due to rocket stage fuel explosions. Seven direct collisions have occurred, with the most severe destroying an inactive Russian satellite, Kosmos 2251, and the operational satellite, Iridium 33. The most significant threat lies in the small fragments. Micrometeorites, such as paint flakes and antifreeze droplets, can cause damage to solar panels on active satellites.

Solid fuel remnants, which are highly flammable and float in space, are another dangerous debris. Explosions of these devices can cause significant damage and release pollutants into the atmosphere. Russian satellites may contain

nuclear batteries containing radioactive material, which could pose a risk of contamination upon their return to Earth. The heat of reentry destroys most of the space debris before it reaches Earth. Larger fragments have occasionally reached the surface and caused significant damage.

In 2009, a collision between a defunct and active communications satellite resulted in thousands of debris pieces still orbiting Earth today.^[29] The debris can potentially harm other objects, including the International Space Station, which conducts annual maneuvers to prevent such impacts. The European Sentinel-2 satellite recorded over 8,000 alerts between 2015 and 2017^[30], demonstrating the ability of satellites to alert of potential collisions. Collision avoidance between active satellites can be challenging due to the need for efficient communication and swift agreement-making by agencies. For reference, In 2019, a European Space Agency satellite performed an emergency maneuver to avoid colliding with a communications satellite after an agreement with the operator was not reached.^[31]

By 2030, over 100,000 new spacecraft could be launched, surpassing the current 8,000. The increasing number of satellites in the orbit leads to a higher risk of collisions. The collision of debris generates millions of pieces, which can then collide with other debris or satellites, resulting in even more shrapnel. The collisions will eventually lead to a chain reaction, causing our orbit to become dense with shrapnel, rendering it unusable. The destruction of existing space infrastructure could render future space activities potentially impossible.

As space becomes the final frontier, with countries and companies competing, it is crucial to consider our desired future. The current trajectory of Earth's orbits poses a risk to society's future opportunities. To mitigate this, stricter regulation of space launches, responsible disposal of satellites and spacecraft, and investment in orbital debris tracking technologies are crucial. The global community's collective effort to treat Earth's orbits as a valuable common good can help ensure our future in space before it's too late.

The ISRO had to delay the launch of Singapore's DS-SAR satellite onboard the PSLV-C56 mission by one minute to prevent space debris collision.^[32] The ISRO was required to perform 23 collision avoidance manoeuvres (CAM) in 2023 to protect its satellites from potential harm from space debris.^[33]

In August 2023, a large object discovered on western Australia's shores was confirmed to be debris from an ISRO rocket, likely from one of its Polar Satellite Launch Vehicles.^[34]

In February 2024, the Russian spy satellite Cosmos 2221 and The National Aeronautics and Space Administration (NASA)'s TIMED craft were observed approaching uncomfortably close by 10 meters.^[35]

In April 2024, China's Shenzhou-17 crew successfully repaired damaged solar wings of its core module through two spacewalks during its first extravehicular maintenance mission.^[36]

In February 2024, ISRO's 2007-launched Cartosat-2 Earth-observation satellite was lowered for controlled atmospheric reentry over the Indian Ocean^[37], with all major parts predicted to vaporize during the event. Scientists are discovering that more objects survive the journey to the surface than previously thought, potentially contradicting the previous belief.

In April 2024, debris from a used battery pallet thrown overboard from the International Space Station, predicted to burn up completely, hit a Florida home, causing widespread destruction.^[38]

The unpredictable path of objects from space poses a risk of their "uncontrolled re-entry" into the stratosphere.

In March 2024, Germany issued an alert about an ISS battery pack following a "natural" trajectory.^[39] The battery pack's predicted trajectory, which included multiple flights over the country before entering the atmosphere, was unexpected as it spanned from Latin America to northeastern Africa, the Middle East to South and Southeast Asia, and Australia to most of Europe.

Solutions to space debris

The main challenge is avoiding space waste, especially with the increasing circulation of small satellites for high-speed internet access worldwide. Many satellites and the International Space Station have Whipple Shields, an outer shell that shields the debris's walls from collisions, ensuring safety in orbital debris.

The strategies used to avoid this problem include:

ORBITAL CHANGES: Modern satellites are often launched into elliptical orbits with perigees within Earth's atmosphere, leading to eventual breakdown.

SELF DESTRUCTION: The process involves programming a satellite to exit its orbit at the end of its useful life and be eliminated when it comes into contact with the atmosphere.

PASSIVISATION: The process involves the depletion of the vehicle's internal energy at the end of its useful life. The risk of explosions decreases as the chassis remains in orbit, and the same applies to the rocket stages.

REUSE: Space X, an aerospace company owned by Elon Musk, uses intact rockets to return to Earth.

LASER: The process involves using a powerful laser to vaporize the surface of fragments, causing them to fall.

5. ROLE OF INTERNATIONAL AGENCIES IN MITIGATING ORBITAL DEBRIS

The **European Space Agency (ESA)** has consistently been a key player in the implementation of space debris mitigation measures.

In 2011, ESA completed the end-of-mission operations for its European Remote Sensing (ERS-2) satellite, which had been in operation for over 16 years^[40]. The operations significantly reduced the remaining orbital lifetime from over 200 years to below 15 years, consuming all residual fuel. On February 21, 2024, ERS-2 successfully entered the atmosphere, significantly reducing the risks of collision and accidental break-up^[41]. In 2013, ESA's Planck and Herschel satellites were injected into orbits around the Sun after their missions to prevent collision threats or reentry hazard, located at the second Lagrange point.^[42] In 2015, ESA's Integral spacecraft and a satellite in its Cluster-2 mission underwent significant orbit-change manoeuvres.^[43] The maneuvers ensured the safe reentry of Integral and all four Cluster spacecraft into Earth's atmosphere over the next decade, avoiding long-term interference with protected low-Earth and Geostationary orbits. In 2023, ESA successfully performed the first assisted reentry of its Aeolus mission^[44]. Aeolus was designed for debris mitigation purposes and was not intended to be controlled as it entered Earth's atmosphere. ESA operators performed the first assisted reentry of its kind, aiming the satellite towards the ocean, reducing the risk of fragments causing harm if they reach Earth's surface.

The European Space Agency (ESA) has adopted the "Zero Debris approach" as per Agenda 2025, aiming to significantly reduce debris production in Earth and lunar orbits by 2030 for all future missions and activities.^[45] The European Space Agency (ESA) implemented its new Space Debris Mitigation guidelines and Policy in November 2023. The guidelines outline stricter requirements for ESA missions to minimize additional debris and ensure a net-neutral contribution to space debris.^[46]

6. ESA MISSION REQUIREMENTS FOR SPACE DEBRIS MANAGEMENT

- **Guarantee successful disposal:** ESA missions should ensure safe disposal of space objects through atmospheric reentry or reorbiting with a probability of success higher than 90%. Missions should include interfaces for easy removal from orbit.
- **Improve orbital clearance:** The maximum time spent in protected low-Earth orbits at end of life has been reduced from 25 years to five.
- **Avoid in-orbit collisions:** Improved collision avoidance strategies, automation, space traffic coordination, and new communication protocols are needed to reduce collision risks.
- **Avoid internal break-ups:** Improved satellite health monitoring and robust passivation techniques are needed to prevent satellites from breaking up.
- **Prevent intentional release of space debris:** Measures to minimize the impact of space objects on optical and infrared astronomy and radio astronomy are needed.
- **Guarantee dark and quiet skies:** Measures to minimize the impact of space objects on optical and infrared astronomy and radio astronomy are needed.
- **Protect other orbits:** Adapted Zero Debris recommendations should be formulated and applied beyond low-Earth orbit and Geostationary orbit.

7. NASA

NASA and its partners may have more cost-effective methods to address the increasing issue of orbital debris than previously thought. NASA's Office of Technology, Policy, and Strategy (OTPS) has released a

report in 2023 providing new insights into measuring risks from orbital debris^[47]. NASA's OTPS leads Charity Weeden, highlighted the benefits of Earth's orbit's growth, including faster terrestrial communications and a better understanding of our changing climate. NASA is enhancing our understanding of the environment through an economic lens, as outlined in its Space Sustainability Strategy. The report, "Cost and Benefit Analysis of Mitigating, Tracking, and Remediating Orbital Debris," is the second phase of OTPS' work to address technical and economic uncertainties related to orbital debris.^[48] The 2023 OTPS Phase 1 report offers policymakers initial insights into cost-benefit analyses for remediation measures for orbital debris, including moving, removing, or reusing objects. The report has enhanced the accuracy of estimating the risks posed to spacecraft by orbital debris. The new estimates encompass a wide range of debris sizes, from the largest in space to millimeter-sized fragments. The report broadens the OTPS teams' focus to include measures to prevent the creation of new debris and to monitor existing debris.

The new OTPS report directly estimates space debris risk, unlike previous studies that rely on risk proxies like debris number in orbit. The risk assessment measures the costs of spacecraft maneuvering to avoid debris, dealing with close approaches, and damage or loss due to debris impact. The study predicts the evolution of the orbital debris environment over a period of 30 years. The study evaluates the cost-effectiveness of over 10 actions to mitigate the risk from orbital debris, including shielding, tracking small debris, and remediating large debris. The team plans to evaluate the cost-effectiveness of various portfolios, which are combinations of various actions. The report revisits the conventional wisdom that the space community has traditionally considered as cost-effective strategies for promoting space sustainability. The report suggests that certain debris remediation methods may be equally valuable as debris mitigation. The report suggests that swiftly deorbiting defunct spacecraft is a cost-effective method for mitigating risk. The findings could offer fresh insights for NASA and the space community regarding the issue of orbital debris. OTPS plans to publicly release the research code used to conduct the study. The research team plans to continue exploring orbital debris and its various approaches, and will share their findings with stakeholders.

In 2023, NASA launched a competition to identify, characterize, track, and remediate small space debris in low Earth orbit, inviting global innovators to contribute innovative solutions to clean up space.^[49]

NASA Johnson Space Center engineers have developed an Active Debris Removal Vehicle (ADRV) capable of removing large orbital debris from low-Earth orbit.^[50] The ADRV will approach a debris object, assess its motion, determine its initial capture trajectory, match its rotation rates, execute a capture maneuver, and control and deorbit the object. This concept can help prevent catastrophic collisions with debris involving astronauts, their spacecraft, and other valuable space assets. The ADRV incorporates NASA's innovative technologies such as a new spacecraft control system, debris object characterization system, and capture and release system. NASA ADRV technologies can be utilized for satellite servicing and orbital adjustments. The Active Debris Removal Vehicle (ADRV) has been demonstrated in an operational environment and is now available for license, indicating its technology readiness level (TRL) 6.

The NASA Orbital Debris Program, established in 1979, is based at the Space Sciences Branch at the Johnson Space Center in Houston, Texas. The program aims to reduce orbital debris and develops equipment for tracking and removing debris already in space. NASA has developed a sustainability strategy that covers four domains: Earth, Earth orbit, cislunar space, and deep space.^[51]

8. JAPANESE EFFORTS

Astroscale's satellite successfully captured a close-up image of a 15-year-old space junk, marking the first time the company has successfully rendezvoused with such a large piece of debris. The object is a discarded rocket segment measuring 11m by 4m, weighing three tonnes. It reports that future missions by Astroscale-Japan will use robotic arms to actively remove debris.^[52]

9. INDIA'S APPROACH TOWARDS MITIGATING ORBITAL DEBRIS PROBLEM

ISRO achieved a milestone on March 21, 2024, when the PSLV Orbital Experimental Module-3 successfully re-entered Earth's atmosphere, leaving almost zero debris in orbit during the PSLV-C58/XPoSat mission.^[53] On January 1, 2024, the PSLV-C58 Mission successfully injected all satellites into their desired orbits, transforming the terminal stage into the POEM-3, a 3-axis stabilized platform. The stage was de-orbited from 650 km to 350 km, enabling early re-entry, and passivated to remove residual propellants to minimize accidental break-up risks. POEM-3 was equipped with nine experimental payloads for conducting technology demonstrations and scientific experiments on newly developed indigenous systems. Six payloads were delivered by NGEs via IN-SPACe, meeting their mission objectives within a month. The upper stage's orbital altitude is decaying due to natural forces, primarily atmospheric drag, with the module (NORAD ID 58695) expected to impact the North Pacific Ocean on March 21, 2024, at 14:04 UTC.

ISRO's POEM offers a cost-effective platform for short-duration space-borne experiments, enabling academia, startups, and NGEs to explore new payloads. Numerous startups, universities, and NGEs have utilized this unique opportunity to conduct space experiments, including electric thrusters, satellite dispensers, and star-tracking. POEM offers new features like total avionics in single-chain configuration, industrial-grade components, standard interfaces for electric power, telemetry & telecommand, and new in-orbit navigation algorithms using rate-gyro, sun sensor, and magnetometer. The experiments in POEM-3 were conducted with body rates stabilized to less than 0.5 deg/s, and innovative schemes like controlled dumping of residual propellant after the main mission were introduced to minimize passivation disturbances.

The Vikram Sarabhai Space Centre (VSSC) has been instrumental in conceptualizing and executing the POEM by enhancing the 4th stage of PSLV. PSLV-C58/XPoSat is the third mission in the series, with

POEMs being successfully scripted each time.^[54] The spacecraft operations team at ISTRAC successfully executed payload operations, with ISRO's System for Safe and Sustainable Spacecraft Operations Management (IS4OM) continuously monitoring and analyzing the orbital decay throughout. POEM-3 was tracked by ISTRAC ground stations, MOTR at Shriharikota, and other Centres like URSC, LPSC, and IISU until March 21, with support from other centers. ISRO is committed to delivering a cost-effective orbital experiment platform. ISRO, a responsible space agency, is working to mitigate the growing threat of space debris, particularly from multiple small satellite constellations, by developing advanced debris tracking systems, space-object deorbiting technologies, and responsible satellite deployment practices. This aims to safeguard orbital environments for current and future space endeavors.

ISRO actively participates in international fora, including the Inter-Agency Debris Coordination Committee (IADC), International Academy of Astronautics, International Astronautical Federation, International Organization for Standardization, and UN-COPUOS scientific and technical sub-committee, to discuss space debris issues, related studies, and the long-term sustainability of outer space activities.^[55]

10. LAWS GOVERNING SPACE CLEAN-UP

There are no international space laws in place to ensure the efficient and safe disposal of debris in space. The World Economic Forum's Space Industry Debris Mitigation Recommendations emphasize reducing space debris generation through satellite end-of-life operations, data sharing, and orbital traffic management for debris avoidance. These guidelines are non-binding and serve as guidelines.

Most space-faring countries sign the Convention on International Liability for Damage Caused by Space Objects, which primarily addresses damage caused by space objects to other space assets and also applies to damage caused by falling objects on Earth. The Convention imposes a liability on the launching country for compensation for any damage caused by its space object on Earth or during an air flight.

In October 2023, the US Federal Communications Commission (FCC) settled with Dish Network, marking the regulator's first penalty related to space debris. Dish Network has admitted to being liable for the improper disposal of the EchoStar-7 broadcast communications satellite.^[56]

The Convention's compensation provision has only been used once, in 1978, when Canada sought damages from the Soviet Union for a radioactive satellite falling into an uninhabited region in its northern territory. The Soviet Union agreed

to pay Canada \$3 million in compensation for the damages caused by the disintegration of the Soviet satellite Cosmos 954 in 1978, resolving all related issues between the two governments.^[57]

11. CONCLUSION

Orbital debris mitigation is a crucial and multifaceted issue affecting space operations. Preserving the space environment involves adopting active and passive debris mitigation technologies to sustain crucial satellite-dependent activities like communication and weather forecasting. We can tackle space debris challenges and protect our orbital environment for future generations through innovation, international cooperation, and best practices. Efforts to address space debris require a combined approach involving technology, international laws, and global collaboration due to increasing awareness of associated risks.

Some observers argue that the threat posed by orbital debris should be considered as a long-term environmental issue. Some believe the threat could potentially impact U.S. security interests by disrupting the consistent satellite support to military and intelligence organizations. The space flotsam and jetsam populace, especially in LEO, may have come to a tipping point, agreeing to the characterized issue. Catastrophic collisions are anticipated to proceed driving its development, with the risk of orbital flotsam and jetsam possibly exacerbated by coincidental or purposefulness debris-generating occasions. Worldwide compliance with moderation measures is considered pivotal, but specialists contend that these endeavors alone are inadequately. To safeguard U.S. national security interests in space and ensure the long-term sustainability of the space environment, more aggressive measures like active debris removal could be considered.

To make an financially reasonable way to space flotsam and jetsam evacuation, center on building a pyramid of understanding and noteworthy steps. Address issues on particular orbital layers, construct community watchfulness and legitimate clarity, and implement standardizing conventions and common culture. Guarantee partners acknowledge these standards and prioritize zones of most prominent danger. Contextualize benefits for partners and reaffirm standards with proceeded authorization. Build up a steady commercial center and build up standards to distinguish unused advertise openings. Measure the costs of developing negative externalities and advance relief conventions to play down concerns. Qualify the taken a toll with partner agreement, as remediation is costly and requires back. Characterize the esteem in expelling impediments and apportion duty, specialist, and financing to remediate concerns. Distinguish changes from expulsion and build up unused standards to anticipate them from returning. Ceaselessly overhaul all layers of the pyramid with changes to financial matters, innovations, and the environment. By grasping social contracts, human association, and building the pyramid of conservation, we will make a more secure environment in space for all mankind.

CONFLICT OF INTERESTS

None.

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