
SPACE DEBRIS POLLUTING THE ORBIT: LEGAL ACCOUNTABILITY AND ENVIRONMENTAL CONSEQUENCES IN OUTER SPACE

Nirupama R.L., LL.M., Kerala Law Academy, Trivandrum

ABSTRACT

Space debris has emerged as the most significant hazard to human operations in outer space today, endangering not only spacecraft systems but also the lives of astronauts aboard missions. This growing cloud of orbital waste includes defunct satellites, spent rocket stages, and fragments from accidental or deliberate collisions. This study examines the sources of space debris, the risks it poses to active space missions, and its impact on the fragile outer space environment. The environmental consequences of space debris are profound and long-lasting. Unlike terrestrial pollution, orbital debris cannot naturally decay or be easily cleaned; instead, it persists for decades or even centuries, threatening a catastrophic chain reaction known as the Kessler Syndrome. Such a scenario could render vital orbital zones unusable and jeopardize satellite-based services critical for communication, weather forecasting, navigation, and Earth observation. The urgency of this topic lies in the rapid commercialization and militarization of space, where increasing launches by private and public actors are outpacing the development of effective regulatory safeguards. Existing international legal frameworks, most notably the Outer Space Treaty (1967) and the Liability Convention (1972) offer only broad principles, lacking binding enforcement mechanisms or clarity on accountability. This paper includes an in-depth examination of the legal gaps, environmental consequences, and human impacts of space debris. Without enforceable global cooperation and reform, the orbit may soon transform from a pathway of innovation into a zone of irreversible hazard for humanity.

Keywords: Debris, Space debris, Space environment, Orbital waste, Legal policy.

INTRODUCTION

The Soviet Union launched the first space vehicle less than thirty-five years ago. Since then, the exploration and use of space have proliferated dramatically. Activities in space have generated millions of pounds of debris, most of it remaining in Earth orbit. This debris threatens the Earth's biosphere. "Debris" is defined from the common English usage "debriser" which means to break down. In common English usage, "debris" means scattered fragments, wreckage or drifted accumulation. Space debris, also known as space junk, refers to defunct, human-made objects in space, primarily in Earth's orbit, that no longer serve any useful purpose. Started off our rendezvous with space by launching of SPUTNIK I in the year 1957 which depicted to the world that USSR 'could boldly go where no one dare to go' and claims technicalities through which it can launch satellites into orbit, can explore universe, a new life and could probably use outer – space to launch inter- continental ballistic missiles. The launch of SPUTNIK I made human beings think beyond their imagination and uplifted their inquisitiveness. The Inter-Agency Space Debris coordination Committee's (IADC)¹ Space Debris Mitigation Guidelines and the subsequent UN Space Debris Mitigation Guidelines came up with the first internationally accepted definition of space debris, i.e. *"all man-made objects, including fragments and elements, in Earth orbit or re-entering the atmosphere, that are non-functional."* Consequently, debris includes 'things' of all sizes that are the product of human activity and not of natural origin. These 'things' either never were functional or eventually became non- functional. Outer space is getting crowded with litter. For almost fifty years, countries have been sending rockets into space, around Earth and beyond. Old satellites, used rockets, and debris from explosions or collisions are now polluting space. This debris can be tiny fragments less than a millimetre wide or large objects like whole spacecraft several meters long. It includes working and broken satellites, rocket parts, pieces from exploded rockets, and fragments from crashes. Since the late 1980s, scientists and legal experts have been urging countries and the international community to act against the effects of space debris. Recent estimates show that 43% of space debris comes from China, 27.5% from the US, and 25.5% from Russia.²

¹Inter-Agency Space Debris Coordination Committee (IADC), Space Debris: An International Perspective. https://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf#:~:text=Foreword.%20The%20Inter%2DAgency%20Space%20Debris%20Coordination%20Committee,activities%20and%20to%20identify%20debris%20mitigation%20options.

² United Nations Office for Outer Space Affairs, Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space https://www.unoosa.org/pdf/publications/st_space_49E.pdf

Travelling at speeds exceeding 22,000 km per hour, even the smallest fragment of debris can inflict catastrophic damage. Collisions may result in anything from minor impairment to the complete destruction of operational spacecraft. Beyond physical harm, debris interferes with radio frequencies and disrupts essential satellite communications, navigation, and Earth-observation services. Larger debris, capable of surviving atmospheric re-entry, poses an additional hazard by falling back to Earth and impacting land or oceans. Since the late 1980s, scientists, policymakers, and legal experts have consistently urged the international community to confront the growing menace of orbital pollution. The issue of space debris now stands at the intersection of environmental protection, technological expansion, and international legal responsibility.³

Every fragment orbiting Earth is a reminder that even in the void, our actions have consequences. We often forget that space, vast and silent, is not some distant elsewhere; it is part of our shared home, and like every corner of that home, it deserves to be kept clean. The idea of “environment” traditionally embraces water, air, and land, and the intricate relationships that bind them to human beings, animals, plants, microorganisms, and property. Yet our attention remains curiously earth-bound. We worry about toxic substances and pollutants that harm life on this planet, but seldom pause to consider the quiet damage we are inflicting beyond our atmosphere. Modern science and technology have given us remarkable gifts, rockets that touch the heavens, satellites that watch over our world, missions that seek answers in the cosmic dark. But the irony is sharp, once these magnificent machines complete their purpose, we simply abandon them. We celebrate their launches, yet forget their afterlives. Over time, these lifeless objects decay into fragments, drifting as debris, cluttering the very space we boldly explore. ⁴And still, no global authority truly shoulders responsibility for this growing constellation of junk. The environmental footprint we leave in space is as real as any pollution on Earth, but it receives far less concern. In this landscape of neglect, the so-called “25-year rule” stands as one of the few guiding lights. Formulated by the Inter-Agency Space Debris Coordination Committee (IADC), first released in 2002 and revised in 2007, the IADC Space Debris Mitigation Guidelines urge organisations operating in low-Earth orbit to ensure that their spacecraft or launch hardware will naturally de-orbit or re-enter the Earth’s atmosphere

³ Id

⁴ NASA Headquarters Library, Space Debris, NASA (last visited Nov. 10, 2025), <https://www.nasa.gov/headquarters/library/find/bibliographies/space-debris/>

within 25 years of mission completion⁵. The goal is simple, prevent long-term accumulation of orbital debris. Echoing this concern, the United Nations has also advised all spacefaring companies to withdraw their satellites from orbit within the same 25-year window. It is a gentle nudge toward cosmic responsibility a reminder that stewardship does not end at the edge of the atmosphere.⁶

TYPES OF SPACE DEBRIS

1. Defunct Satellites.

These are satellites that have stopped working but still orbit the Earth. They include both old satellites from decades ago and newer ones that failed or finished their missions. There are over **3,000** of these dead satellites circling our planet, adding to space junk.⁷ **Iridium - Kosmos Collision (2009)** is an example for this. Iridium 33 **was an American commercial communications satellite launched by a Russian Proton rocket. It was an operational communications satellite launched on September 14, 1997.** On 10 February 2009, the **Iridium 33** collided with the defunct Russian military satellite **Kosmos-2251** over Siberia. Kosmos-2251 had been inactive since 1995 but was left in low Earth orbit without deorbiting. Iridium 33 was still fully operational. The two smashed into each other at 42,000 km/h (26,000 mph). The collision produced **over 2,000 trackable debris pieces** and tens of thousands of smaller fragments. Many of these fragments are still orbiting today, increasing the risk of further collisions.⁸

In January 2007, China conducted an anti-satellite (ASAT) missile test in which it deliberately destroyed its own defunct weather satellite, Fengyun-1C. The satellite, which was orbiting in a sun-synchronous polar orbit at approximately 865 kilometres above the Earth, was struck with such force that it shattered into more than 3,000 pieces of trackable debris, making it the single largest debris-generating incident in the history of space activities. Because this destruction occurred at a high orbital altitude, the resulting fragments are expected to remain

⁵ Nat'l Research Council, Comm. on Space Shuttle Meteoroid/Debris Risk Mgmt., Protecting the Space Shuttle from Meteoroids and Orbital Debris (Nat'l Acad. Press 1997), <https://doi.org/10.17226/5958>

⁶ Sylvie Durrieu & Ross F. Nelson, Earth Observation from Space -The Issue of Environmental Sustainability, 4 Space Pol'y 238, 238-50 (2013), <https://ntrs.nasa.gov/citations/20140011102>

⁷ The Aerospace Corporation, Space Debris 101, Aerospace, <https://aerospace.org/article/space-debris-101> (last visited Nov. 1, 2025).

⁸ United Nations Office for Outer Space Affairs, Consequences of the collision of Iridium 33 and cosmos 2251, ST/SPACE/TECH-27 (2009), <https://www.unoosa.org/pdf/pres/copuos2009/tech-27.pdf>

in space for several decades before naturally decaying, and they continue to pose significant collision risks to functioning spacecraft, including vital assets such as the International Space Station.

2. Spent rocket stages.

The upper stages of rockets used to launch satellites into space, often left in orbit after their mission is complete.⁹ The Long March 4B rocket is the China Aerospace Science and Technology Corporation (CASC) is a Chinese launch vehicle, commonly used to launch various satellites, especially those for Earth observation and weather forecasting, into low Earth and sun-synchronous orbits. It is used for a wide range of scientific and commercial applications, including environmental monitoring, disaster prevention, climate change research, and testing new satellite technologies for constellations. After successfully delivering its payload, the rocket's upper stage, the final segment that carries the satellite into its precise orbit often remains in space as "spent rocket stage" debris. In November 2022, one such spent upper stage from a Long March 4B¹⁰ rocket re-entered Earth's atmosphere in an uncontrolled manner. Unlike controlled re-entries where debris is directed to fall safely over unpopulated areas (usually oceans), this upper stage fell unpredictably over populated regions of India and Myanmar. Fortunately, there were no reported injuries or damage, but this incident heightened international concerns regarding the dangers posed by uncontrolled re-entries of spent rocket stages. Such events remind the global community of the need for stricter guidelines and better technologies to ensure safe disposal of space debris, especially for large rocket components that can survive atmospheric re-entry and reach the surface. The Long March 4B upper stage is indeed a spent rocket stage, a leftover segment of a rocket no longer in use, which remains a hazard if not properly managed after its mission is complete.¹¹

Another explosion was, on 22 August 1991, a U.S. Delta II rocket¹² upper stage that had remained in orbit since the late 1980s exploded due to the gradual buildup of pressure in its unvented fuel and pressurised tanks. Because these tanks had not been emptied or safely vented after the mission, years of exposure to extreme temperature fluctuations in space eventually

⁹ Id

¹⁰ Tiago Brito, C.C. Celestino & R. Vilhena de Moraes, A Brief Scenario About the "Space Pollution" Around the Earth, 465 J. Phys. Conf. Ser. 012020 (2013).

¹¹ Id

¹² European Space Agency, Debris Landed in Texas, ESA, https://www.esa.int/ESA_Multimedia/Images/2015/12/Debris_landed_in_Texas (last visited Nov. 16, 2025).

caused them to rupture. The resulting explosion generated roughly 2,000 pieces of trackable debris, in addition to numerous smaller fragments that could not be detected by monitoring systems, thereby substantially increasing the collision risk for operational spacecraft travelling through low Earth orbit.

3. Mission-Related Objects.

Mission-related debris (MRD)¹³ refers to artificial objects left in space from spacecraft operations, such as discarded tools, rocket stages, and paint flecks. Things like tools, screws, or cables that astronauts or spacecraft release accidentally or on purpose during missions. Ejected bolts, nuts, and screws, dropped tools or equipment, discarded lens caps and other mission-specific items, trash from astronauts like clothing or other personal items, fragments from wear and tear or collisions, paint flakes from spacecraft surfaces etc. In November 2008, astronaut Heidemarie Stefanyshyn-Piper experienced a moment that quietly reminded the world how fragile work in space can be. During a routine spacewalk outside the International Space Station, a tool bag slipped from her grasp and drifted away into the vastness of orbit. Inside were grease guns and other essential supplies ordinary tools on Earth, yet suddenly transformed into a wandering object circling the planet. For months, the bag became an unusual, almost poetic piece of space debris, bright enough to be spotted from Earth, before finally re-entering the atmosphere and burning up in August 2009. The incident remains one of the most memorable examples of unintentional “space littering,” where even a simple human error contributes to the growing cloud of debris surrounding our planet.¹⁴

4. Paint Flecks.¹⁵

Paint flecks in space may sound harmless, but they’re surprisingly dangerous. These tiny chips peel off spacecraft when they’re exposed to intense sunlight, freezing darkness, and constant temperature changes. Once they break away, they race through orbit at incredible speed sometimes faster than a bullet. Even though they’re no bigger than a grain of sand, a single

¹³ Mark Matney, Measuring Small Debris - What You Can't See Can Hurt You, Paper presented at the VKI Lee Series, Space Debris Reentry and Mitigation, Brussels, Belgium, Sept. 12–14, 2016, NASA Tech. Report JSC-CN-37432-1, 20160011226, <https://ntrs.nasa.gov/citations/20160011226>

¹⁴ NASA, Astronaut Loses Tool Bag During Spacewalk, NASA (Nov. 2008), <https://www.nasa.gov/feature/astronaut-loses-tool-bag-during-spacewalk>

¹⁵ Ned Dymoke, This Is the Damage a Tiny Speck of Space Debris Can Do at 15,000 mph, Freethink (July 3, 2022), <https://www.freethink.com/space/space-debris-15000mph> (last visited Nov. 16, 2025).

paint flake moving that fast can scratch a satellite, damage sensitive equipment, or even pose a risk to astronauts. They're small, silent troublemakers in an already crowded sky. The two most famous space telescopes are the Hubble Space Telescope and the James Webb Space Telescope (JWST). The Hubble Space Telescope is a large, powerful telescope launched into low Earth orbit in 1990. It has provided some of the most stunning and detailed images of our universe, revolutionizing astronomy. Because it orbits Earth at about 540 kilometers altitude, The Hubble has suffered gradual paint chipping over decades of exposure to harsh space conditions. Extreme heat, cold, and radiation in space can cause spacecraft surfaces to crack, peel, or shed tiny particles. Paint flecks from thermal cycling and micrometeoroid impacts have contributed to small debris particles orbiting Earth, adding to the already crowded debris field. According to ESA's 2025 estimates, Earth's orbit is now cluttered with roughly 36,000 pieces of debris larger than 10 centimetres, objects big enough to be easily tracked. Beyond that, there are nearly one million fragments between 1 and 10 centimetres, each capable of damaging or destroying a spacecraft. And hidden in the vastness of orbit are more than 130 million tiny particles smaller than 1 centimetre, too small to track but fast enough to tear through sensitive equipment. Together, they form an invisible minefield circling our planet.¹⁶

Laboratory impact tests conducted by aerospace research facilities have demonstrated how destructive even tiny fragments of space debris can be. In one such test, a particle no larger than a pencil eraser weighing barely half an ounce was fired at high velocity using a light-gas gun. The result was a crater nearly five inches deep in a block of solid aluminium. This experiment highlights the immense kinetic energy carried by even the smallest objects in orbit.

The International Space Station, with its vast structure comparable to the size of a football field, is particularly vulnerable to such impacts. To avoid collisions, it periodically performs orbital manoeuvres. Despite these precautions, the station has suffered damage from debris as small as paint chips, requiring time-consuming repairs by the crew.

5. Military Anti-Satellite (ASAT) Test.

Several countries have conducted tests to demonstrate their ability to destroy satellites in space, known as anti-satellite (ASAT) tests. These tests involve firing missiles or weapons at their own defunct satellites to prove military capabilities. However, such destruction creates large

¹⁶ Id

clouds of debris that scatter across orbital paths¹⁷. Mission Shakti was India's first successful anti-satellite (ASAT) missile test. It was conducted on March 27, 2019, by the Defence Research and Development Organisation (DRDO). It is designed to knock out an opponent's satellites and weaken their ability to operate in a conflict. By targeting space-based systems used for communication, surveillance, navigation, and early-warning signals, ASATs can disrupt everything from intelligence gathering to troop movements and even the guidance of modern weapons. In essence, they give a state the power to blind or silence an adversary in space. At the same time, the very existence of ASAT capabilities acts as a form of deterrence, signalling that any threat to a nation's own satellites will be met with equal or greater force. The test missile destroyed one of India's own satellites orbiting at about 300 kilometers above Earth. This showed India's ability to target satellites in low Earth orbit. The test was planned to reduce space debris risks. It targeted a low orbit where debris would quickly fall back and burn up in the atmosphere within weeks to months. This avoided long-lasting debris clouds seen in other tests. Despite this, the test created a temporary cloud of fast-moving debris fragments. Unfortunately, NASA Administrator Jim Bridenstine criticised this mission. He expressed concern that the test created over 400 pieces of orbital debris. These increased the risk of collisions with other satellites and the International Space Station. Space agencies tracked the debris closely to reduce dangers. Mission Shakti raised global concerns about weaponizing space. It highlighted the need to balance defence capabilities with protecting the long-term safety of space activities. In a recent article, scholars argue for a kinetic ASAT test ban (especially at high altitudes), particularly between the U.S. and China. Such a ban would reduce the debris risk without undermining broader space security dynamics.¹⁸

LOCATION OF ORBITAL DEBRIS

1. Low Earth Orbit (LEO) (The Most Crowded)

Low Earth Orbit, which stretches up to 2,000 kilometres above the Earth's surface, is the busiest and most congested region in the orbital environment. This zone hosts a wide range of satellites essential to daily life, Earth-observation systems, remote-sensing instruments, communication satellites, and, most notably, the International Space Station. Because LEO is

¹⁷ Anti-Satellite Weapon, WIKIPEDIA, https://en.wikipedia.org/wiki/Anti-satellite_weapon (last visited Nov. 10, 2025).

¹⁸ Vajiram & Ravi, Anti-Satellite Missile Test (ASAT) – Mission Shakti, Vajiram & Ravi (Oct. 15, 2025), <https://vajiramandravi.com/upsc-exam/anti-satellite-missile-test/> (last visited Nov. 10, 2025).

so heavily used, it has also become the region with the highest concentration of space debris. The fragments travelling here move at extraordinary speeds of nearly 28,000 kilometres per hour, turning even a paint chip into a dangerous projectile. In a sense, LEO has become the cosmic equivalent of a bustling city street crowded, constantly active, and vulnerable to accidents if not properly managed.

2. Medium Earth Orbit (MEO)

Medium Earth Orbit lies much farther out, at around 20,000 kilometres above the Earth. It is the operational home of major navigation constellations, including the United States' GPS, Europe's Galileo, China's BeiDou, and Russia's GLONASS. Although MEO is less crowded than LEO, debris in this region poses its own unique challenges. The atmosphere at this altitude is far too thin to exert meaningful drag, which means that any object or fragment of an object can remain in orbit for decades or even centuries. As a result, MEO resembles a quiet, high-altitude highway of fewer vehicles, but those that stray or break apart tend to linger for generations, complicating long-term navigation safety.¹⁹

3. Geostationary Orbit (GEO)

Geostationary Orbit is located approximately 35,786 kilometres above the Earth's equator. Satellites placed here rotate at the same speed as the Earth itself, allowing them to remain fixed over one geographical point, a feature that makes GEO indispensable for weather forecasting, disaster communication, television broadcasting, and strategic military operations. Unlike lower orbits, atmospheric drag is virtually absent in GEO, meaning that any debris created here can persist for centuries. Over time, such objects drift out of their assigned slots, often being nudged into so-called "graveyard orbits" just beyond GEO. This region is the quiet outer balcony of the Earth's orbital architecture steady, reliable, and vital yet increasingly threatened by long-lasting fragments that have nowhere else to go.²⁰

STATE RESPONSIBILITY- LEGAL ACCOUNTABILITY AND GAPS.

Under international customary law, outer space is considered *res extra commercium*, meaning

¹⁹ NASA Orbital Debris Program Office & NASA Academy of Program/Project & Engineering Leadership, *Orbital Debris Management & Risk Mitigation* (2012), https://www.nasa.gov/wp-content/uploads/2018/12/692076main_orbital_debris_management_and_risk_mitigation.pdf

²⁰ Id

it is not subject to national appropriation, whereas celestial bodies have sometimes been treated as *res nullius*, potentially subject to sovereignty. However, the Outer Space Treaty clarifies that both outer space and celestial bodies are *res extra commercium*, affirming their status as areas free from national ownership. Article I of the Treaty²¹ further provides that outer space, including the Moon and other celestial bodies, shall be freely accessible for exploration and use by all states on the basis of equality and in accordance with international law. It ensures freedom of scientific investigation and guarantees that all areas of celestial bodies remain open to all states without discrimination. Article III obliges state parties to conduct their space activities in accordance with international law, including the United Nations Charter, with the purpose of maintaining international peace and security while promoting cooperation and understanding among nations.

These treaty principles have been reinforced through subsequent international instruments. For instance, the Annex of Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting recognizes that all states have equal rights to conduct satellite broadcasting activities and benefit from their results. Similarly, the Principles Relating to Remote Sensing of the Earth from Outer Space emphasize that remote sensing must serve the interests of all countries, with particular consideration for developing nations. GA Resolution 1721 on international cooperation in the peaceful use of outer space confirms that, consistent with international law, outer space and celestial bodies are not subject to national appropriation and remain open to all. Moreover, non-functional satellites remaining in orbit violate obligations under Article 35 of the International Telecommunication Union Convention and Article 29 of the World Administrative Radio Conference, both of which prohibit interference in radio frequencies, a situation directly threatened by defunct satellites. Article IX of the Outer Space Treaty further identifies space debris as a form of pollution in outer space. Collectively, these principles underscore the essential duty of states to conduct space activities with due care, ensuring that debris generation does not impede free access to space. To continue lawful use of outer space, states must actively mitigate debris and clean up the hazards they create, thereby upholding the foundational principles of the Outer Space Treaty

²¹ Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, UNOOSA, Outer Space Treaty, <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>

and related international agreements.²²

- **The Outer Space Treaty (1967)**

The Outer Space Treaty (OST) is the constitution of outer space. It proclaims that:

- a) States are internationally responsible for all national space activities, whether carried out by government agencies or private companies (Art. VI).
- b) States are internationally liable for damage caused by their space objects (Art. VII).

The Outer Space Treaty stands as the foundational charter of human activity beyond Earth, articulating a moral and legal architecture for the heavens. At its heart is the principle of state responsibility when a nation launches or authorizes an object into space, it carries with that object the authority and the consequent obligations of the state.²³ This obligation was deliberately written broadly so that, whether a rocket is launched by a government agency or by a private company operating under a government licence, the launching state remains answerable on the international stage for the conduct and consequences of that mission. In practice, this doctrine of responsibility was intended to create a chain of accountability that would discourage reckless behaviour and ensure victims of space-related harm have a diplomatic avenue for redress. Yet, the Treaty's high moral tone is not matched by a practical enforcement mechanism. The 1967 text imposes duties without creating an international body that can compel compliance, adjudicate disputes rapidly, or impose sanctions. It assumes that states will exercise supervision over their national actors in good faith, but it offers little practical recourse when states either lack the capacity or the political will to regulate fast-moving commercial enterprises. Moreover, the Outer Space Treaty lack of strong enforcement mechanisms for the treaty and deliberately avoids technical definitions; it does not define "space debris," "abandoned object," or the precise moment when a functioning object becomes "non-functional." That vagueness leaves tolerances for differing state interpretations and

²² J.C. Liou, Highlights of Recent Research Activities at the NASA Orbital Debris Program Office (paper presented at the 7th Eur. Conf. on Space Debris, Darmstadt, Ger., Apr. 18–21, 2017) (NASA Rep. No. JSC-CN-3199, NTRS Doc. No. 20170003872, May 2017).

²³ Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, UNOOSA, Outer Space Treaty, <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>

weakens the Treaty's deterrent value: responsibility is declared, but the scope of what must be prevented, mitigated, or removed remains undefined.²⁴

- **The Liability Convention (1972)**

The key provisions of this convention are: -

- a) Liability for damage: The Convention holds a "launching State" absolutely liable for damage caused by its space object on the surface of the Earth or to aircraft. Damage from space debris is considered covered, even if it originates from defunct objects or their fragments.
- b) Fault-based liability: For damage occurring in outer space, liability is based on "fault," meaning a state must be proven to be at fault for the damage to incur responsibility.
- c) Joint liability: If multiple states are involved in jointly launching a space object, they are jointly and severally liable for any damage caused.

The Liability convention builds on the Treaty by translating responsibility into compensatory obligations. Under the Convention, a launching state faces absolute liability for damage on the surface of the Earth or to aircraft in flight resulting from its space objects, and fault-based liability for damage occurring elsewhere in space. This principle of strict liability for terrestrial harm reflects the drafters' desire to protect people and property on Earth from the unintended consequences of space activity. In real-world application, however, the Liability Convention reveals striking limitations. The Convention is reactive rather than preventive liability is triggered only after demonstrable damage has been caused. For billions of dollars of near-misses, for years of increased collision risk, or for the slow, cumulative choking of orbital lanes with small, untraceable fragments, there is no compensatory trigger. The famous Kosmos-954 incident where radioactive debris rained over Canadian territory, producing a diplomatic claim and a negotiated settlement exemplifies that the Convention can work where damage is visible, traceable, and politically straightforward.²⁵ But most orbital debris does not manifest as a dramatic, single event. When two objects graze or a small fragment damages a solar array,

²⁴ Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, U.S. Dep't of State, <https://2009-2017.state.gov/t/isn/5181.htm>

²⁵ Convention on International Liability for Damage Caused by Space Objects, UNOOSA, Liability Convention, <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html>

tracing the causal chain, proving fault, and establishing which state's object created the fragment are technically and politically fraught exercises. The Convention therefore functions well only in a narrow class of dramatic cases, leaving a vast grey zone of hazard and risk where no liability is assigned and no corrective legal incentive exists.

- **UN Space Debris Mitigation Guidelines (2007)**

Recognising the technical and cooperative nature of the threat, the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS) ²⁶ issued Space Debris Mitigation Guidelines in 2007. These guidelines distilled decades of engineering practice and recommended that states and operators design missions to minimise debris generation, passivate spent stages to prevent explosions, limit mission-related objects, and plan for end-of-life disposal through controlled re-entry or transfer to graveyard orbits. They reflect a pragmatic ethos, many aspects of debris risk can be mitigated through best practice, transparency, and shared standards. Yet the character of the guidelines as advisory rather than binding law is their core weakness. States may endorse them rhetorically but implement them unevenly. Where national regulatory regimes are weak, commercial pressure favors rapid deployment and cost minimisation over the additional engineering and operational expenses of robust passivation, deorbit capability, or redundant shielding. Moreover, the guidelines focus primarily on preventing new debris rather than cleaning up the enormous volume of existing fragments. The result is layered, while new missions may be marginally cleaner, the legacy of decades of launches, explosions, and collisions continues to circulate as an unmanaged hazard.

State responsibility as a legal doctrine strikes at the centre of contemporary difficulty because of the gap between legal accountability on paper and political, technical, and economic realities on the ground. States remain the international actors with legal personality and, therefore, the ones they can be held to account. But the dramatic rise of private actors in space – commercial constellation operators, start-ups, and university payloads complicates this vertical relationship. Governments must supervise and license these actors, but licensing regimes, export controls, and oversight mechanisms vary widely. ²⁷ In some jurisdictions oversight is robust, with strict licensing conditions and continued operational monitoring; in others, nascent

²⁶ Committee on the Peaceful Uses of Outer Space, UNOOSA, <https://www.unoosa.org/oosa/en/ourwork/copuos/index.html>

²⁷ Space Law Treaties and Principles, UNOOSA, <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties.html>

commercial sectors outpace regulatory capacity. When a private firm's satellite fragments, the law points inevitably to the launching state, but obtaining effective redress or ensuring corrective measures depends on national regulatory processes, political negotiations, and the technical ability to identify the responsible object. This mismatch undermines the normative promise of state responsibility by placing most of the burden of enforcement back on domestic systems that may be under-resourced or influenced by economic and strategic priorities favouring launch activity.

Jurisdictional and ownership rules add a further and peculiar obstacle to active remediation, under existing law, states retain jurisdiction and control over their space objects, often indefinitely. That means that even abandoned or derelict satellites remain sovereign property, and any attempt by another actor to capture, tow, or dismantle such debris could be treated as an unauthorized interference with state property or as an act of aggression. Practically, this legal protection renders many plausible orbital-cleanup operations politically untenable. Imagine a large fragment on a collision course with a nation's satellite, the safest technical remedy could be to capture and redirect the fragment, but doing so without the owner state's consent could spark a diplomatic protest, a demand for compensation, or even in the worst case an accusation of hostile intent. Without a shared approval system or a quick way to settle disputes, the duty to respect each nation's sovereignty in space ends up locking the world into the same dangerous debris conditions we already have.²⁸

NATIONAL LAWS AND POLICIES.

Space Policy Directive-3 (SPD-3), issued in 2018, is the U.S. national policy for Space Traffic Management (STM) and Space Situational Awareness (SSA). Space Policy Directive-3, sets out a policy framework aimed at improving the safety, stability, and sustainability of the space environment by strengthening space traffic management and debris mitigation practices. The Directive recognises that increasing congestion in Earth orbits creates risks to government and commercial space operations and therefore calls for coordinated action across civil, commercial, and national security sectors. To implement this policy, U.S. agencies led by the Department of Commerce for civil space traffic services and the Department of Defence for national security concerns are directed to improve space situational awareness, develop

²⁸ Committee on the Peaceful Uses of Outer Space, UNOOSA, <https://www.unoosa.org/oosa/en/ourwork/copuos/index.html>

standards and best practices for collision avoidance, and implement measures for timely sharing of conjunction data among operators.²⁹ The Directive emphasises modernization of tracking and data-sharing capabilities so that operators can make informed decisions to reduce collision risks, and it encourages the development of technical and operational guidelines for end-of-mission disposal, passivation (de-energising residual systems), and other debris-mitigation steps. Although Space Policy Directive-3 provides a strong policy signal and has catalysed regulatory and commercial activity in the United States, it is largely an executive policy framework rather than a comprehensive statute; as a result, its practical effect depends on implementing rules, interagency coordination, and voluntary compliance by commercial actors. Enforcement therefore relies on a combination of federal licensing conditions, contractual requirements, incentives, and coordination with international partners rather than on a single, uniform enforcement mechanism.

The European Space Agency's "Zero Debris by 2030" objective,³⁰ announced in 2022, represents an institutional commitment to ensuring that ESA missions do not leave long-lived debris in orbit and that mission design, operations, and end-of-life handling adhere to the highest sustainability standards. Under this initiative, ESA requires that satellites and launcher stages associated with its programmes be designed so that any remaining on-orbit hardware will either re-enter and burn up safely in the Earth's atmosphere within an acceptable timeframe or be actively transferred to a designated graveyard orbit where they no longer interfere with operational services. ESA's approach combines technical requirements such as passivation to prevent explosions, design for controlled re-entry where feasible, and removal or relocation to graveyard orbits with programmatic measures including procurement rules, mission reviews, and contractor obligations. The initiative also fosters research and development in active debris removal technologies, improved space traffic management, and better tracking and cataloguing of small debris. Because ESA represents a consortium of member states and primarily operates through programmatic directives, its "Zero Debris by 2030" goal is implemented through agency procurement, mission approval processes, and technical standards rather than by direct legislative power; therefore, the initiative's success depends on consistent enforcement by

²⁹Space Policy Directive-3, National Space Traffic Management Policy, 83 Fed. Reg. 28,969 (June 21, 2018). https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/?utm_

³⁰ The Zero Debris Charter, European Space Agency, https://www.esa.int/Space_Safety/Clean_Space/The_Zero_Debris_Charter

ESA, cooperation by national space agencies in Europe, and compliance by commercial partners engaged in ESA projects.

India's Debris-Free Space Missions initiative, is a significant policy announced by the Indian Space Research Organisation (ISRO) with the goal of achieving zero space debris from all Indian space actors (governmental and private) by 2030. India's Debris-Free Space Missions (DFSM) initiative, reflects a national policy commitment to sustainable space operations across governmental and non-governmental actors. The initiative requires that Indian mission planners and space operators incorporate debris mitigation into mission design from inception, including measures such as controlled re-entry or disposal to graveyard orbits, passivation of residual energy sources, and end-of-life deorbit planning for satellites and upper stages. The DFSM initiative³¹ aims to apply across the full spectrum of Indian space actors, meaning that state agencies, public sector undertakings, and private companies participating in the Indian space ecosystem are expected to follow common standards and reporting practices. Implementation mechanisms typically include licensing conditions administered by India's space regulatory authority, technical guidelines for mission approval, and monitoring obligations to demonstrate compliance. As with other national initiatives, challenges remain in translating aspirational targets into uniformly enforceable rules; effective implementation will require clear regulatory instruments, transparent reporting and verification, capacity building for tracking and collision avoidance, and incentives or penalties to ensure adherence by private operators.

All three initiatives share the same fundamental recognition that is. preventing and mitigating orbital debris requires a mix of technical standards, operational discipline, and institutional oversight. Each relies heavily on mission design best practices such as passivation, planned de-orbiting or transfer to graveyard orbits, and improved space situational awareness through tracking and data sharing. However, many rules and targets are policy statements or agency requirements rather than criminal statutes, which means enforcement is often soft and distributed through licensing or procurement rather than through punitive measures. Secondly the global coordination remains weak, space is inherently international, and unilateral national measures cannot fully prevent debris generation without broad multinational compliance. Third, the rapid rise of commercial small-satellite constellations challenges traditional

³¹ India's Intent on Debris-Free Space Missions, Indian Space Research Organisation, https://www.isro.gov.in/Debris_Free_Space_Missions.html

licensing and tracking regimes, creating regulatory mismatches between legacy frameworks and contemporary operational realities. Finally, practical implementation depends on adequate tracking capability, timely data sharing, and technical capacity for active debris removal all areas where investment and international cooperation remain incomplete.

ENVIRONMENTAL CONSEQUENCES.

1. Atmospheric Impact.³²

Whenever rockets launch or fragments of space debris re-enter Earth's atmosphere, they release aluminum oxide and other combustion by-products into the upper atmospheric layers. These microscopic particles wreak disproportionate harm. As they disperse into the stratosphere and mesosphere, they interact chemically with ozone molecules, destabilizing them and contributing to the thinning of the ozone layer.

The ozone layer, a delicate veil shielding life from ultraviolet radiation, is easily unsettled by such intrusions. When the protective layer becomes thinner, UV-B exposure increases, elevating skin cancer risks, damaging plant life, harming marine ecosystems, and interfering with delicate ecological cycles. In essence, every rocket plume and every burning shard of satellite leaves a fingerprint upon the skies.

The more frequently satellites are launched and deorbited, the more these particles accumulate. Scientists warn that sustained increases in alumina concentration may mimic, on a smaller scale, the harmful atmospheric disruptions caused previously by chlorofluorocarbons (CFCs). Thus, although space exploration represents human ambition, its atmospheric footprint demands caution, mitigation, and responsible innovation.

2. Kessler Syndrome.

Kessler syndrome is a hypothetical scenario where the density of objects in Earth's orbit becomes so high that a cascade of collisions is triggered, creating an exponential amount of space debris. This chain reaction could render Earth's orbit unusable for satellites and spacecraft for generations, potentially disrupting technologies like GPS, weather monitoring, and communication. While theoretical, the increasing amount of space junk raises concerns

³² Sylvie Durrieu & Ross F. Nelson, *Earth Observation from Space – The Issue of Environmental Sustainability*, 29 *Space Policy* (2013), <https://doi.org/10.1016/j.spacepol.2013.07.003>

that this scenario is becoming more probable, especially with the growth of satellite constellations.³³

Among the most feared scenarios in space operations is the Kessler Syndrome, a chain reaction of orbital collisions described by NASA scientist Donald Kessler. According to this model, when two pieces of orbiting debris collide, they do not simply break apart they shatter into thousands of smaller fragments traveling at speeds up to 28,000 km per hour. Each fragment then becomes a new projectile capable of striking other satellites or debris, triggering further fragmentation. This process, once started, can accelerate uncontrollably.

The consequences would be severe. A dense cloud of debris in Earth's low-orbit environment would threaten the satellites that modern life depends on GPS systems, weather forecasting networks, communication infrastructure, banking transactions, military surveillance, and emergency navigation tools. Even the International Space Station and future crewed missions would face amplified risks.³⁴

3. Ground Risks

While the vast majority of re-entering debris burns harmlessly in the atmosphere, large or dense fragments such as fuel tanks, pressure vessels, or heat-resistant alloys may survive re-entry. When these remnants fall, they may land in populated regions, causing property damage or, in rare cases, posing a threat to human safety. There have been several documented incidents of debris falling near villages, crashing into fields, or landing close to homes. Although no major casualties have occurred so far, the expanding number of satellites ensures that such events may become more frequent. The proliferation of mega-constellations thousands of satellites launched by private companies has increased the statistical probability of debris-related ground impacts. Moreover, pieces that contain toxic fuel residues or hazardous materials can contaminate soil or water. Nations with limited monitoring systems may face additional burdens, as falling debris may go unnoticed or unreported, leading to environmental and health risks.

³³ D.J. Kessler & S.Y. Su, *Orbital Debris* (paper presented at the NASA Johnson Space Center Workshop, Houston, Tex., July 27–29, 1982) (NASA CP-2360, S-532, NAS 1:55:2360, 1985) (NTRS Doc. No. 19850012878).

³⁴ *Id*

4. Space Sustainability³⁵

The challenge of space sustainability arises from the finite and increasingly congested nature of Earth's orbital environment. As the number of satellites grows driven by commercial, scientific, governmental, and military activities the available orbital pathways become progressively restricted. This congestion is exacerbated by the persistence of long-lived debris, inactive satellites, and millimeter-scale fragments that cannot be tracked with present technological capabilities.

High debris density hampers the safe and efficient operation of satellites. Essential services such as global communications, navigation, remote sensing, and climate monitoring all depend on stable orbital access. As orbits become more crowded, satellites require more frequent collision-avoidance maneuvers, leading to increased fuel consumption, operational complexity, and mission costs. Scientific missions, including astronomical observatories and Earth-monitoring platforms, also face heightened risks of interruption or degradation. Additionally, future missions may encounter prohibitive insurance costs or launch constraints if orbital paths remain compromised.

Therefore, space sustainability is not merely an environmental concern but a strategic necessity for the continuation of space-based services. Achieving it requires the adoption of stringent debris-mitigation standards, the development of technologies for active debris removal, enhanced international regulations governing satellite life cycles, and comprehensive space-traffic management systems. Without such measures, future generations may inherit an orbital environment so congested and hazardous that the continued use of space for peaceful, scientific, and commercial purposes becomes severely limited.³⁶

DEBRIS MANAGEMENT APPROACHES.

The rapid expansion of human activity in outer space has made the effective management of orbital debris an indispensable responsibility for all spacefaring nations and institutions. As satellite constellations multiply and launch frequencies increase, the need for systematic

³⁵ Sylvie Durrieu & Ross F. Nelson, *Earth Observation from Space – The Issue of Environmental Sustainability*, 29 *Space Policy* (2013), <https://doi.org/10.1016/j.spacepol.2013.07.003>

³⁶ Written Contribution: Space Sustainability Rating (SSR), Workshop of the Working Group on the Long-Term Sustainability of Outer Space Activities, 61st Sess., Sci. & Tech. Subsidiary Comm., U.N. Office for Outer Space Affairs (Feb. 6, 2024), https://www.unoosa.org/documents/pdf/copuos/stsc/2024/WG_LTS_Workshop/Written_Contribution_SSR.pdf

approaches to debris control becomes urgent. Debris management rests on three principal pillars:

- a) Mitigation strategies,
- b) Active removal technologies, and
- c) Advanced tracking and early-warning systems.

Each plays a distinct role in preserving the safety, sustainability, and long-term viability of Earth's orbital environment.

a) Mitigation Strategies.³⁷

Mitigation strategies constitute the first line of defence against the growing debris population. Their primary objective is to prevent the creation of new debris rather than merely reacting to existing hazards. These strategies are embedded within the design, launch, and operational phases of space missions and are now standard practice among responsible space actors. A central component of mitigation is the concept of "Design for Demise." This design philosophy ensures that when a satellite or upper-stage rocket re-enters Earth's atmosphere at the end of its mission, it disintegrates completely due to atmospheric heating. By engineering components from materials with lower melting points or modified structural shapes, mission planners significantly reduce the risk of debris fragments reaching the ground. This method also limits the volume of long-lived debris that could remain in low Earth orbit.

Mitigation strategies also include strict adherence to post-mission disposal guidelines, such as the widely referenced "25-year rule," which requires spacecraft in low Earth orbit to re-enter or move to a disposal orbit within 25 years after the end of operations. Operators are further encouraged to passivate their spacecraft, meaning they must remove residual fuel, disconnect batteries, and vent pressurised systems to avoid explosions that could generate new debris clouds. Collectively, these deliberate design and operational measures slow the growth of orbital debris and reinforce global norms of responsible conduct in space.³⁸

³⁷ Sustainable Debris Management, UN Env'tl. Programme, <https://www.unep.org/topics/waste/sustainable-debris-management>

³⁸ Mitigating Space Debris Generation, European Space Agency, https://www.esa.int/Space_Safety/Space_Debris/Mitigating_space_debris_generation

b) Removal Technologies.³⁹

Mitigation alone is insufficient to address the vast reservoir of debris already circulating Earth. Consequently, space agencies and private organizations have begun investing in active debris removal (ADR) technologies. Active Debris Removal (ADR) is the process of using dedicated satellites or other means to remove existing space debris, such as defunct satellites and rocket bodies, from orbit. This is a crucial strategy to prevent the growth of orbital debris, which is caused by collisions and can lead to a chain reaction known as the Kessler Syndrome, making space unsustainable. ADR missions use technology like robotic arms or propulsive kits to capture and safely de-orbit debris. These technologies aim to physically capture, redirect, or eliminate large pieces of debris whose continued presence represents significant collision risks. Missions take different forms, with some focusing on the removal of large debris using dedicated spacecraft known as Orbital Transfer Vehicles, which capture and guide defunct satellites toward safe de-orbit. Other concepts aim at addressing smaller pieces of debris, though much of current attention remains on removing the larger, more threatening objects. Various capture methods are employed, including robotic arms capable of grasping “uncooperative” objects that lack docking fixtures, as well as propulsive kits that can be attached to debris to manoeuvre it into a disposal orbit. Once captured, the debris is steered into a trajectory that ensures its eventual atmospheric re-entry, where it will safely burn up. One notable initiative is the European Space Agency’s ClearSpace-1 mission⁴⁰, which employs robotic arms capable of grasping non-cooperative objects in orbit. This mission symbolises a major advance in space servicing and debris capture, as non-functional satellites cannot manoeuvre themselves and require external intervention for removal.

Similarly, JAXA’s RemoveDEBRIS programme demonstrates experimental methods including nets and harpoons. These tools are designed to immobilise debris targets and pull them into controlled re-entry paths. The use of such devices shows promise in reducing the population of medium-to-large debris fragments, which pose the greatest collision threats. Japan’s space agency, JAXA, has emerged as a global frontrunner in developing practical technologies for active debris removal, primarily through its Commercial Removal of Debris Demonstration

³⁹ Active Debris Removal, European Space Agency,
https://www.esa.int/Space_Safety/Space_Debris/Active_debris_removal

⁴⁰ ESA Commissions World’s First Space Debris Removal Mission, European Space Agency,
https://www.esa.int/Space_Safety/Clean_Space/ESA_commissions_world_s_first_space_debris_removal

(CRD2) programme.⁴¹ This initiative aims to confront the growing danger posed by large, derelict rocket bodies and other uncooperative debris that threaten long-term orbital safety. In the first phase of the programme, JAXA works with the Japanese company Astroscale to demonstrate the ability to safely approach, inspect, and track massive debris objects using advanced navigation and proximity-operations technologies. This observational phase acts as the technical foundation for future removal attempts, proving that close-range manoeuvring around unstable, tumbling debris is possible.

The second phase of CRD2 focuses on achieving what no nation has yet accomplished, the physical capture and controlled de-orbit of a real, existing piece of large space debris. JAXA's approach relies on innovative methods such as magnetic capture systems, robotic arm technologies, and precision guidance sensors, all designed to secure debris that was never built for docking or removal. By pioneering these capabilities, JAXA strengthens international efforts to reduce long-term fragmentation risk and sets the stage for a new commercial market dedicated to safe orbital clean-up. Its work underscores Japan's commitment to responsible space stewardship and demonstrates that active debris removal is both technically achievable and essential for a sustainable future in space.⁴²

Furthermore, NASA is exploring orbital debris recycling technologies, a pioneering approach that seeks to convert defunct satellites into usable materials or components for future missions. By transforming orbital waste into a resource, NASA aims not only to remove dangerous objects but also to establish a more circular and sustainable orbital economy. NASA is actively addressing the growing problem of space debris through a multifaceted approach that includes tracking, debris mitigation, and research into active removal technologies. Among its initiatives are projects such as the Active Debris Removal Vehicle (ADRV) and the SpaDE program, which focus on developing technologies capable of safely capturing and removing large, non-functional objects, including defunct satellites and spent rocket bodies, from orbit. In addition to active removal, NASA studies methods for minimizing the creation of new debris through improved spacecraft design and operational practices. Effectively managing space debris is a complex challenge that requires not only technological innovation but also regulatory

⁴¹ Mekhi Dhesi, Introduction to Astroscale (UN/IAF 31st Workshop on Space Technology for Socio-Economic Benefits, Milan, Oct. 12, 2024), UNOOSA, https://www.unoosa.org/documents/pdf/psa/activities/2024/UN-IAF/Presentation/SatAM/P3-4_Dhesi.pdf

⁴² About CRD2 (Commercial Removal of Debris Demonstration), JAXA, <https://www.kenkai.jaxa.jp/eng/crd2/about/>

frameworks and international cooperation to ensure the long-term sustainability of the orbital environment and safe space traffic management. Active removal represents the most technologically ambitious and diplomatically complex limb of debris management. Its development indicates a rising global recognition that passive strategies alone cannot guarantee the long-term stability of the orbital environment.⁴³

c) Tracking and Early Warning Systems.

Accurate tracking and early warning capabilities form the informational backbone of debris management. These systems monitor thousands of objects across multiple orbital regimes, allowing agencies to predict potential collisions and implement evasive manoeuvres when necessary.

India's ISRO operates the NETRA project,⁴⁴ a dedicated surveillance and tracking system designed to enhance national space situational awareness. NETRA uses ground-based telescopes and radars to detect and catalogue orbital objects, ensuring that Indian satellites receive timely warnings of conjunction risks. According to the 2024 Indian Space Situational Assessment Report (ISSAR), ISRO executed 10 CAMs in 2024 to protect its satellites from potential collisions with space debris. ISRO Chairman S. Somanath has stated that India targets debris-free space missions by 2030. This includes designing spacecraft and rocket stages to deorbit themselves or be safely disposed of once their mission ends. The United States Space Command maintains one of the most extensive global catalogues of space objects, tracking debris down to sizes as small as a few centimetres. Its data and alerts are used by space operators worldwide, making it a critical node in international space safety. The European Union's Space Situational Awareness (SSA) programme also plays a vital role by coordinating surveillance assets across Europe and distributing alerts to satellite operators. By integrating radar systems, optical telescopes, and analytical models, the EU's SSA programme strengthens Europe's capacity to prevent collisions and respond quickly to orbital threats.

These early-warning systems not only reduce the likelihood of debris-related accidents but also support more sophisticated forms of space traffic management, which will become

⁴³ J.C. Liou, Active Debris Removal – A Grand Engineering Challenge for the Twenty-First Century (paper presented at the 21st AAS/AIAA Space Flight Mechanics Meeting, New Orleans, La., Feb. 13–17, 2011) (AAS Rep. No. AAS-11-254, NASA Rep. No. JSC-CN-23012, NTRS Doc. No. 20110011986).

⁴⁴ ISRO SSA Control Centre Inaugurated by Dr. K. Sivan, Chairman, ISRO / Secretary, DOS, Indian Space Research Organisation, https://www.isro.gov.in/ISRO_EN/ISRO%20SSACControl%20Centre.html

indispensable as orbital activity continues to expand.

1. Astroscale: Advancing Autonomous Capture and Removal

Astroscale, headquartered in Japan with significant operations in the United Kingdom, stands at the forefront of active debris removal (ADR). The company's vision is rooted in the recognition that space sustainability depends on the capacity to service, capture, and safely deorbit defunct satellites and hazardous debris fragments. Its most notable demonstration, the ELSA-d (End-of-Life Services by Astroscale - demonstration) mission, has established a technological foundation for future large-scale debris removal efforts.⁴⁵

The ELSA-d mission involved two spacecraft, a servicer and a client satellite equipped with a docking plate. The mission tested several critical capabilities, including autonomous rendezvous, magnetic capture, and controlled deorbiting procedures. The servicer demonstrated its ability to track, approach, and magnetically attach to the client satellite under both controlled and simulated tumbling conditions, an essential requirement for capturing real debris objects that drift unpredictably in orbit.

Astroscale's innovation lies not only in its technical achievements but also in its commercial vision. The company aims to establish debris removal as a routine, financially viable service that satellite operators can contract at the end of a mission. This shift from theoretical clean-up concepts to market-ready technological services represents a major advancement in global debris governance. By proving that non-cooperative objects can be captured safely, Astroscale has strengthened the case for mandatory end-of-life disposal rules and public-private partnerships in debris mitigation.

2. ClearSpace: Robotic Precision in Orbital Cleanup

ClearSpace, a Swiss company, has gained international recognition through its collaboration with the European Space Agency (ESA) on the ambitious ClearSpace-1 mission, scheduled for launch in 2026. This mission seeks to demonstrate the world's first fully operational debris-removal service undertaken by a private company under a public contract. The ClearSpace-1 spacecraft is equipped with four robotic arms designed to capture a defunct ESA payload adapter known as the VESPA target. Unlike the cooperative docking mechanisms used in

⁴⁵ ELSA-d, Astroscale, <https://www.astroscale.com/en/missions/elsa-d>

earlier experiments, ClearSpace-1 must grapple with a non-functional object lacking any built-in capture aids. This requires an extraordinary level of precision in relative navigation, autonomous control, and force-feedback technology.⁴⁶

By physically removing a large piece of debris from orbit and guiding it into a controlled atmospheric re-entry, ClearSpace-1⁴⁷ will provide proof of concept for large-scale commercial debris removal missions. The partnership between ESA and ClearSpace marks a major policy shift, it demonstrates that public agencies are willing to contract private companies to execute complex space-safety tasks that were previously the exclusive domain of national space agencies. ClearSpace's work reflects a broader trend in the privatisation of critical space services and underscores the importance of nurturing a competitive commercial market for orbital cleanup. If successful, the mission will open the door to recurring service contracts, multi-object removal missions, and new norms of responsible behaviour in orbit.

3. Northrop Grumman: Extending Satellite Life to Prevent New Debris⁴⁸

While some companies focus on removing existing debris, Northrop Grumman, an American aerospace leader, has taken an innovative approach by addressing the root cause of debris creation. Its Mission Extension Vehicle (MEV) programme is designed to prolong the operational life of aging satellites, thereby delaying the need for replacement launches and reducing future debris generation. The MEV docks with client satellites using a combination of autonomous navigation and mechanical latching technology. Once docked, it provides attitude control, station-keeping functions, and propulsion support. This effectively transforms the MEV into a propulsion "tug" that assumes the satellite's manoeuvring responsibilities. Northrop Grumman has successfully executed this concept through missions such as MEV-1 and MEV-2, which restored full operational control to satellites nearing the end of their fuel supply. By revitalising satellites that would otherwise become derelict, the MEV reduces the number of inactive spacecraft drifting in orbit. Moreover, by postponing replacement launches, the programme diminishes launch-related emissions, prevents the addition of new objects into crowded orbital pathways, and aligns with the broader goal of long-term space sustainability.

⁴⁶ ClearSpace SA, ClearSpace, <https://clearspace.today/>

⁴⁷ ClearSpace-1 Mission, ClearSpace SA, <https://www.clearspace.today/missions/clearspace-1>

⁴⁸ Satellite Services in Space, Northrop Grumman, <https://www.northropgrumman.com/what-we-do/space/satellite-services-in-space>

THREATS IN OUTER SPACE AND THEIR IMPACT ON HUMAN LIFE.

Space debris poses one of the most pressing hazards to modern space activities, with consequences that extend from technical failures to global economic disruption. Even small fragments of debris traveling at extremely high velocities can severely damage satellites, which are essential for communication, navigation, weather forecasting, and financial transactions. An example occurred in 2009 when the Russian satellite Cosmos 2251 collided with the commercial Iridium satellite, creating thousands of additional fragments that continue to threaten other orbital assets. Beyond the satellites themselves, space debris represents a significant risk to human life in space. Astronauts aboard the International Space Station (ISS) are particularly vulnerable, as even tiny debris can penetrate shielding, requiring constant adjustments to the station's orbit to avoid collisions. These hazards are compounded by the potential onset of the Kessler Syndrome, a cascading chain reaction of collisions in which the debris generated from one impact increases the likelihood of further collisions, potentially rendering specific orbital regions unusable for decades or even centuries.⁴⁹

The presence of debris also drives up the cost and complexity of space missions. Operators must invest in heavier shielding for spacecraft, carry additional fuel to maneuver safely around debris fields, and pay higher insurance premiums to cover the elevated risk, making space operations more expensive and technically demanding. The implications of these risks are far-reaching. Damage to satellites can disrupt daily life by affecting GPS systems, telecommunications, aviation, and agricultural monitoring, while large-scale satellite loss has the potential to destabilize global financial systems and trade. From a national security perspective, military and emergency communications rely heavily on satellite networks, making debris a threat to defense and disaster-response capabilities. Moreover, the growing density of debris in commonly used orbital paths poses serious constraints on future space exploration, both for human missions and emerging commercial ventures. Finally, space debris is not only a technological and economic concern but also an environmental one: outer space is a shared domain, and the unchecked accumulation of debris risks permanently restricting humanity's ability to access and utilize this frontier responsibly. In sum, the hazards posed by space debris are multifaceted, affecting safety, economics, security, and the long-term

⁴⁹ Nat'l Research Council, Comm. on Space Debris, *Orbital Debris: A Technical Assessment* (Nat'l Acad. Press 1995), <https://doi.org/10.17226/4765>

sustainability of outer space, emphasizing the urgent need for mitigation and active removal strategies.

LANDMARK INCIDENTS.

Space debris, which includes defunct satellites, spent rocket stages, and fragments from collisions, poses a real and sometimes tangible risk when it re-enters Earth's atmosphere. While most debris burns up upon re-entry, larger fragments made of durable materials can survive and reach the ground, potentially causing damage to property, the environment, or even endangering human and animal life. Over the decades, multiple incidents around the world have demonstrated the hazards of uncontrolled space debris, emphasizing the need for stricter tracking, mitigation, and international cooperation.

1. Kosmos 482 (1972 - New Zealand):⁵⁰

In April 1972, fragments from the Soviet Venus probe Kosmos 482 crashed near Ashburton, New Zealand. Several hot titanium alloy spheres, each weighing about 13.6 kg and measuring 38 cm in diameter, fell within a 16 km radius. They scorched crops and dented the soil, though fortunately, no injuries were reported. This incident highlighted the potential agricultural and property damage from re-entering debris.

2. Kosmos 954 (1978 - Canada):⁵¹

Kosmos 954, a Soviet reconnaissance satellite equipped with a nuclear reactor, malfunctioned during re-entry and broke apart, scattering radioactive debris over northern Canada, including parts of Great Slave Lake in the Northwest Territories. The event prompted Canada's Operation Morning Light, a significant cleanup and monitoring campaign to remove radioactive fragments. This incident remains one of the most serious examples of the environmental and health hazards posed by space debris.

⁵⁰ Jacinta Bowler, Soviet Spacecraft Kosmos 482 Expected to Crash Back to Earth (May 2, 2025), ABC News, <https://www.abc.net.au/news/science/2025-05-02/kosmos-482-re-entry-soviet-venus/105237772>

⁵¹ Eric Moses, Operation Morning Light Podcast Examines Soviet Satellite Kosmos 954 (May 23, 2023), CBC News, <https://www.cbc.ca/arts/operation-morning-light-podcast-soviet-satellite-exploded-traditional-dene-land-1.6650994>

3. China's Long March Rockets (India - 2022):⁵²

In April and May 2022, debris from China's Long March 3B rockets fell in the Indian states of Maharashtra and Gujarat. The debris included metallic rings and composite vessels, one of which reportedly struck and killed livestock. The incident underscored the cross-border risks of uncontrolled rocket stage re-entries and raised concerns about debris mitigation practices.

4. Foton-M Debris (Australia - 2023):⁵³

In July 2023, debris identified as an unburnt section from an ISRO PSLV rocket's third stage washed ashore in Western Australia. The Australian Space Agency confirmed its origin, highlighting the ongoing challenges related to end-of-mission disposal practices and the potential for debris to affect coastal regions far from launch sites.

5. Falling Fragments from the ISS (USA - 2024):⁵⁴

A debris fragment, likely originating from an ISS cargo pallet, crashed through a roof in Florida, narrowly missing a sleeping child. The incident led the affected family to sue NASA for property damage, demonstrating the legal and liability concerns when debris impacts populated areas.

6. Recent Incident in the Philippines (August 2025):⁵⁵

In August 2025, a fragment from China's Long March 12 rocket produced a bright fireball and sonic boom near Palawan, Philippines. Although there were no casualties, the incident caused panic among residents and highlighted ongoing safety and diplomatic concerns related to space debris.

⁵² India Today, Chinese Rocket Crashes Next to Residential Area After Deploying Satellite in Space (Oct. 21, 2025), <https://www.indiatoday.in/science/story/chinese-rocket-crashes-next-to-residential-area-after-deploying-satellite-in-space-2806262-2025-10-21>

⁵³ Mystery Object on Australian Beach Identified as Part of ISRO Rocket, The Hindu (Sept. 12, 2023), <https://www.thehindu.com/sci-tech/science/mystery-object-on-australian-beach-identified-as-part-of-isro-rocket/article67141161.ece>

⁵⁴ Reentry of International Space Station (ISS) Batteries into Earth's Atmosphere, European Space Agency, https://www.esa.int/Space_Safety/Space_Debris/Reentry_of_International_Space_Station_ISS_batteries_into_Earth_s_atmosphere

⁵⁵ John Eric Mendoza, Pinoy Fishers Told: Report If Chinese Rocket Debris Found in PH Waters, Philippine Daily Inquirer (Apr. 1, 2025), <https://globalnation.inquirer.net/271194/pinoy-fishers-told-report-if-chinese-rocket-debris-found-in-ph-waters>

RECOMMENDATIONS.

1. Strengthen International Cooperation.

All nations must work together under binding treaties and agreements to share responsibility for debris mitigation. This ensures that spacefaring countries cannot act unilaterally, reducing the risk of conflicts and unregulated debris generation⁵⁶.

2. Invest in Active Debris Removal (ADR).

Technologies such as robotic capture missions, nets, harpoons, and lasers should be deployed to remove large debris objects from orbit. ADR helps reduce the overall debris population and prevents future collisions, mitigating risks like the Kessler Syndrome.

3. Design Satellites for Safe Re-entry (“Design-for-Demise”)

Satellites should be constructed so that they burn up completely upon re-entry. This minimizes the chances of surviving fragments reaching Earth and reduces hazards to populated areas.

4. Improve Space Situational Awareness (SSA) Systems

Tracking and monitoring debris, especially smaller fragments, allows timely collision warnings. Enhanced SSA systems help operators adjust satellite orbits and protect both spacecraft and astronauts.

5. Develop a Global Cost-Sharing Framework

Cleaning up orbital debris is expensive, and a shared funding mechanism ensures that all nations contribute fairly. This also encourages accountability and cooperation in debris mitigation efforts.

6. Promote Public Awareness and Policy

Governments, private companies, and academic institutions should raise awareness of space debris risks. Clear policies and regulations will encourage sustainable practices in satellite

⁵⁶ United Nations Office for Outer Space Affairs, Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (2010), https://orbitaldebris.jsc.nasa.gov/library/space-debris-mitigation-guidelines_copuos.pdf

launches and end-of-life disposal.

7. Recycling Space Debris

Large defunct satellites and spent rocket stages can potentially be reused as raw materials in orbit.⁵⁷ Instead of letting debris accumulate, components made of metals like aluminum, titanium, and rare alloys could be collected and repurposed for new satellites or space structures. Recycling not only reduces the volume of debris but also decreases the need to launch fresh materials from Earth, lowering launch costs and environmental impact. Several research projects and startups are exploring in-orbit recycling technologies, though the technology is still in its early stages.

CONCLUSION.

As Dr. Alice Gorman, an Australian space archaeologist, wisely noted, “Space is not an infinite dumping ground; it is a shared and fragile environment.” This statement reminds us that the debris we leave behind is not merely a technical issue, but a responsibility shared by all humanity. While science and technology can help us track and remove debris, only robust laws, effective enforcement, and global cooperation can ensure the sustainable use of outer space. The decisions we make today will determine whether future generations inherit a clear and secure orbit or a crowded space filled with hazards and debris.

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