Review

SPACE DEBRIS – THE SILENT ENVIRONMENTAL CHALLENGE

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Abstract: The increasing reliance on satellite-based technologies for communication, navigation, and Earth observation has led to an unprecedented growth in the number of artificial satellites, particularly in low Earth orbit. Alongside their benefits, this expansion has resulted in a growing accumulation of inactive satellites and orbital debris, raising serious environmental and safety concerns. This review examines the ecological implications of the space debris problem, with particular emphasis on the risks posed by uncontrolled fragmentation, long-term orbital persistence, and cascading collision scenarios such as the Kessler syndrome. Existing and emerging mitigation measures are discussed, including active debris removal technologies and satellite end-of-life protocols. The paper highlights the urgent need to recognize near-Earth space as a vulnerable environmental domain, requiring global coordination and sustained technical innovation to ensure its long-term usability and safety.

Key words: artificial satellites, Kessler syndrome, space-debris mitigation, satellite end-of-life disposal, orbital environment

1. INTRODUCTION

Artificial satellites are an indispensable part of modern society, enabling telecommunications, broadcasting, navigation, and precise timing systems. They also play a crucial role in Earth observation, supporting scientific research on environmental changes such as air pollution, ocean health, oil spills, glacier melting, and coastal sea-level rise (Copernicus Programme., n.d.-a; European Space Agency, n.d.-a). However, the rapid expansion of satellite-based technologies in recent decades has raised significant environmental concerns. Distant and silent, satellites are often overlooked, making it easy to ignore the growing number of objects orbiting Earth. The aim of the present contribution is to raise the awareness of the ecological and operational threats related to the Kessler syndrome – a self-sustaining chain reaction of space debris accumulation (Kessler & Cour-Palais, 1978) – and the necessity of urgent and active measures to prevent them.

2. SATELLITE-BASED TECHNOLOGIES

The first idea of communication satellites is attributed to Arthur Clarke, the science fiction writer and a coauthor of *2021: Space Odyssey*, who in 1945 addressed the problem of radio communication over large distances (Clark, 1945). Radio and micro-waves travel through the atmosphere by line of sight, thus preventing signal transmission between distant points on the curved Earth surface. Clarke proposed “extra-terrestrial relays” via artificial satellites in geostationary Earth orbit (GEO). Placed at approximately 36,000 km above Earth, GEO satellites follow Earth's rotation (with a 24-hour orbital period) and thus appear stationary in the sky. Due to their high altitude, only three or four GEO satellites are needed to cover the entire globe, enabling signal transmission between distant locations.

Clarke's vision was realized within a relatively short time. The first artificial satellite, Sputnik 1, was launched by the Soviet Union in 1957 (Launius, n.d.; NASA, n.d.-a). A simple metallic sphere, about 60 cm in diameter and equipped with silver-zinc batteries to power its radio transmitter, orbited Earth at an altitude of about 550 km, transmitting signals for nearly three months. It was soon followed by the more sophisticated American satellite Explorer 1, equipped with 8 kg of instruments for monitoring micrometeorites and solar radiation in the Van Allen belt (Launius, n.d.). Thus began the space age.

A significant milestone in telecommunications was the launch of the first satellite into GEO, the Syncom (Synchronous Communication Satellite) in 1964. Marked by the live broadcast of the Tokyo Olympics to the USA, it was followed by rapid expansion of GEO-based long-distance communications which dominated phone, radio, and TV broadcasting for decades, especially in remote regions lacking terrestrial infrastructure (European Space Agency, n.d.-b).

Other orbital ranges also became increasingly populated, particularly Low Earth Orbit (LEO), below 2,000 km. Since 1998, the International Space Station, orbiting at 408 km, has enabled numerous scientific experiments under microgravity conditions (NASA, n.d.-b). Freed from atmospheric interference, space-based instruments could now study both the cosmos and Earth. Since its launch into LEO in 1990, the Hubble Space Telescope has transmitted images of distant galaxies millions of light-years away, advancing our understanding of the universe (NASA, n.d.-c). Simultaneously, extensive data on global changes on Earth have been provided by environmental satellites - first by the eight-ton Envisat, launched into LEO in 2002, and later by the Sentinel satellites, an expanding fleet of increasingly sophisticated sensors. Operating across the electromagnetic spectrum, they monitor atmospheric composition, ozone, surface and ocean temperatures, sea level and currents, melting glaciers, wildfires, and pollution (European Space Agency, n.d.-a; Copernicus Programme, n.d.-b).

Meanwhile, the Global Navigation Satellite Systems (GNSS) such as the American GPS, Russian GLONASS, Chinese BeiDou, and European Galileo have been developed in Medium Earth Orbit (MEO), at about 20,000 km. Enabling precise positioning, navigation, and timing, they are now indispensable for air, land, and sea transport, construction, military applications, information and communication technologies, high-frequency trading, power grids, and Smart Grids (Wikipedia contributors, n.d.-a).

In the 21st century, following the convergence of internet, telephone, radio, and TV broadcasting, and the growing demand for low-latency communication, the number of artificial satellites has accelerated. Satellites began descending from GEO to LEO, which offers lower launch costs, reduced power requirements, and smaller antennas. At the turn of the century, the Iridium network, consisting of 66 cross-linked satellites at 780 km, pioneered global voice and low-speed data communication, including polar regions (Iridium Communications Inc., n.d.).

To meet the rising demand for high-speed connectivity in remote areas where terrestrial infrastructure is inadequate, commercial satellite mega-constellations emerged. In 2021, Starlink became operational with about 1,500 satellites at 550 km. As of now, its fleet has grown to about 10,000, with plans to expand to several tens of thousands. Simultaneously, the Eutelsat-OneWeb constellation is being developed at 1,200 km, aiming to deploy 3,000 satellites to deliver data with latency of only 50–100 ms (OneWeb, n.d.; Wikipedia contributors, n.d.-b)

Integration of LEO communication satellites with 5G and future 6G networks is also anticipated, particularly as a backup during natural or man-made disasters when terrestrial networks often fail. Their broad coverage and broadcasting capabilities make them vital for IoT applications and remote sensing. By providing real-time data on floods, wildfires, and oil spills, satellites support early warning systems and search-and-rescue coordination, becoming an essential component of the resilience and functionality of critical infrastructures.

3. THE KESSLER SYNDROME

Since the launch of the first artificial satellite in 1957, more than 20,000 objects have been placed into orbit around Earth – and this number continues to grow rapidly. While indispensable to modern science and technology, including significant contributions to environmental research, satellites have also introduced new environmental challenges. Bright reflections from satellite surfaces can hinder night-sky observations and interfere with both optical and radio-based astrophysical studies. Concerns have also been raised about potential disorientation of organisms that rely on celestial cues for navigation (Sutherland et al., 2021). Nevertheless, most scientists agree that the current number of active satellites, relative to the vastness of space, does not yet pose a critical problem—provided they remain functional and under terrestrial control.

The major concern, however, lies in the large proportion of inactive satellites, which now account for nearly half of all objects in orbit (European Space Agency, 2025a,2025b). Whether due to fuel depletion or electronic failure, defunct satellites are no longer maneuverable and/or cannot communicate with Earth. As a result, they are highly vulnerable to fragmentation caused by collisions, accidental or intentional explosions, or damage from solar radiation. Once fragmented, the resulting debris is dispersed unpredictably, significantly increasing the risk of further collisions and initiating a chain reaction in which the number of debris fragments rises exponentially.

Incidents such as the 2009 Iridium 33–Kosmos 2251 collision, which occurred at an altitude of 789 km, clearly illustrate this hazard (Nicholas, 2009; Wang, 2010). Colliding at a speed of 11,700 m/s, the satellites generated thousands of fragments, many of which may remain in orbit for decades. A similar risk surrounds the eight-ton Envisat, which unexpectedly lost communication with Earth in 2012. Now drifting uncontrollably at approximately 782 km altitude, Envisat is considered one of the most dangerous defunct objects in space. It is expected to remain in orbit for around 150 years, during which at least two close approaches (within 200 m) by other space objects are anticipated annually (European Space Agency, n.d.-a).

Warnings came early. In 1978, Kessler predicted that the quantity of space debris could reach a critical threshold, leading to exponential growth in collisions – even without the launch of new satellites (Kessler & Cour-Palais, 1978). Unfortunately, current data support his prediction. Scientists now track more than 20,000 objects larger than 10 cm and estimate over one million smaller fragments (European Space Agency, 2025b; Inter-Agency Space Debris Coordination Committee, 2025-a). Traveling at several kilometers per second, even tiny debris can severely damage operational spacecraft. The Kessler syndrome, once a theoretical scenario, is now a growing risk, particularly given the rapid deployment of commercial mega-constellations.

4. SPACE-DEBRIS MITIGATION EFFORTS

The growing proliferation of artificial objects in near-Earth space is now widely recognized as a serious environmental and safety challenge. Space debris data is regularly monitored and published by ESA Space Debris Office (Fig. 1). It has been estimated that even in the absence of future launches, collisions among existing objects could still lead to a continued increase in the orbital debris population (European Space Agency, 2025b).

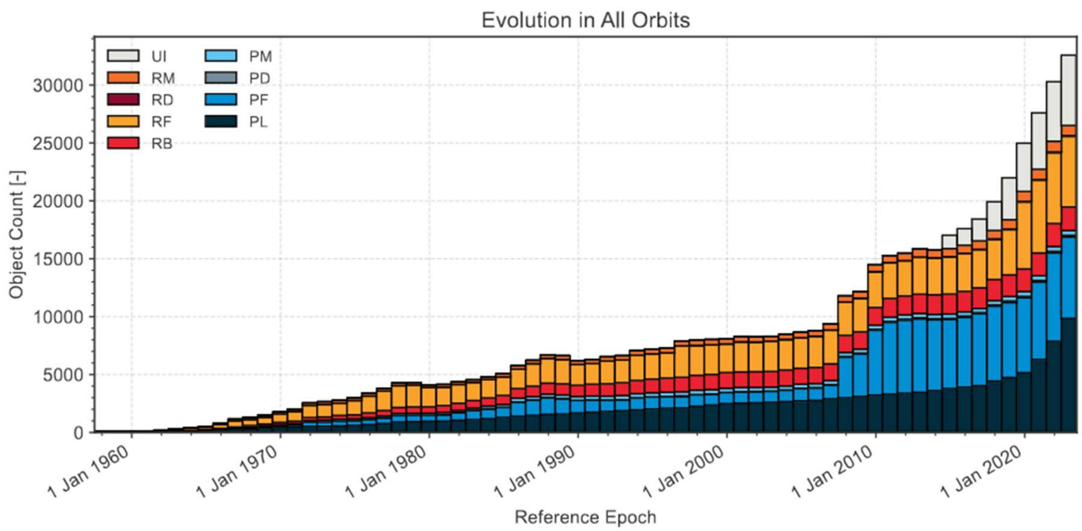

Fig. 1. Objects in orbit by type. PL = Payload, PF = Payload Fragmentation Debris, PD = Payload Debris, PM = Payload Mission Related Object, RB = Rocket Body, RF = Rocket Fragmentation Debris, RD = Rocket Debris, RM = Rocket Mission Related Object, UI = Unidentified (Reproduced from ESA'S ANNUAL SPACE ENVIRONMENT REPORT 2022, GEN-DB-LOG-00288-OPS-SD).

Today, the risk of collision with debris is routinely factored into mission planning. Many modern satellites, including those in the Starlink constellation, are now equipped with collision avoidance systems and end-of-life deorbiting protocols. Spacecraft conditions are continuously monitored during operation in orbit, and detected anomalies are collected and analysed for mission plan reassessment. Additional measures are being developed to reduce the risk of accidental breakups due to onboard sources, such as by depleting all remaining energy at end-of-life, venting fuel and pressurants, and discharging batteries (European Space Agency, 2025b).

Nevertheless, the threat persists, particularly in low Earth orbit. Various pioneering technologies are currently being tested for active debris removal (European Space Agency, n.d.-c; ClearSpace, n.d.). Proposed methods include ground-based laser systems to vaporize smaller debris (1–10 cm) (Colvin, 2024), net-based capture systems for retrieving larger fragments (Axthelm et al., 2017) and drag-enhancing devices such as tethers or deployable parachutes that accelerate orbital decay by increasing atmospheric drag or exposure to solar wind.

Unfortunately, atmospheric orbital decay is largely ineffective at higher altitudes. Above 800 km, atmospheric drag is minimal, allowing debris to remain in orbit for decades or even centuries. Relocating such objects to so-called "graveyard orbits", approximately 300 km above GEO, merely moves the problem out of sight.

An innovative approach involves mission extension vehicles, which are designed to dock with GEO satellites nearing fuel depletion, most of which were not built for in-orbit refueling or repair. These vehicles provide temporary propulsion and attitude control, enabling continued operation before moving on to service another satellite (Northrop Grumman, n.d.). Although not a definitive solution, such missions help extend the operational lifetime of GEO satellites and reduce their premature abandonment.

5. THE LACK OF BINDING INTERNATIONAL OBLIGATIONS FOR SATELLITE END-OF-LIFE DISPOSAL

Despite growing awareness, significant obstacles continue to hinder the effective implementation of active debris mitigation measures. In addition to scientific and financial challenges, legal and political issues – especially those involving international coordination – represent key barriers. Under the 1967 Outer Space Treaty (United Nations Office for Outer Space Affairs, 1967), space objects remain under the jurisdiction and control of their state of registry, even after becoming defunct. This provision prohibits third-party intervention and complicates the enforcement of disposal obligations.

Currently, satellite end-of-life disposal is governed mainly by non-binding technical guidelines, such as guidelines issued by (Inter-Agency Space Debris Coordination Committee, 2025a), the inter-governmental forum for the coordination of activities related to man-made and natural debris in space (Inter-Agency Space Debris Coordination Committee, 2025b). Similar recommendations were adopted in (United Nations Office for Outer Space Affairs, 2010), (NASA National Aeronautics and Space Administration, 2019), (Federal Communications Commission, 2022) and the supporting documents. The aim is to limit the long-term presence of spacecrafts and launch vehicles in orbit and to mitigate the growth of orbital debris through best practices such as the prevention of breakups, and passivation of spacecraft. Removal of and/or relocation of satellites to graveyard orbits within 25 years (or shorter) after mission completion is suggested.

However, adherence to these guidelines remains voluntary and is not subject to international enforcement. Compliance is inconsistent among national and commercial actors, highlighting the need for a binding, globally accepted legal framework. Without such commitments, mitigation efforts will remain fragmented, slow, and insufficient to address the growing threat. Recent studies have even assessed the overall trade-offs between the benefits of satellite-based technologies and the environmental costs throughout their life cycle (Gaston et al., 2023; Giudici et al., 2024).

6. CONCLUSION

Artificial Earth satellites are deeply integrated into modern technologies, supporting critical societal functions ranging from communication and navigation to environmental monitoring and responses to global crises. However, the exponential growth in the number of satellites – particularly in low and geosynchronous Earth orbits – has resulted in a critical accumulation of orbital debris, raising serious environmental and safety concerns.

As debris continues to accumulate, the near-Earth space environment is becoming increasingly unstable, with escalating risks of collisions, fragmentation, and cascading debris generation.

This not only jeopardizes active satellite missions but also undermines the long-term sustainability of space-based technologies essential to modern infrastructure

A global shift is needed: from viewing orbital space as an infinite resource to managing it as a shared, limited, and fragile ecosystem. Long-term preservation of this environment requires more than technological innovation - it demands international collaboration and adherence to well-defined, binding operational and legal standards.

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