Journal of Law and Human Rights
Volume 6, Issues No. 1, 2026
P-ISSN: 1998-4278, E-ISSN: 3106-9665

Space Debris: Environmental Impact, Mitigation Strategies, and Future Directions

[1]Md. Al-Amin
Lecturer, Department of Law, Bangladesh University

[2]Kazi Sonia Tasnim
Senior Lecturer, Department of Law, Bangladesh University

[3]Md. Mosharraf Hosain
Lecturer, Department of Law & Justice, Bangladesh University of Business &Technology

ABSTRACT

Orbital debris, commonly referred to as space debris, are non-operational human-made objects and remnants in orbit around the Earth. That includes defunct satellites, spent rocket boosters, debris from accidental collisions, and debris from anti-satellite missile testing. Since the beginning of the space age in 1957, many launches have led to the collection of objects in the neighborhood of the Earth's orbit. The number of items being launched into orbit has grown considerably with the rapid development of commercial space ventures, large constellations, and networks of satellite communications. While space debris is not a conventional pollutant in terms of the Earth's atmosphere or surface, it is a troublesome rising pollutant outside of our planet. The increasing amount of junk in low Earth orbit (LEO) threatens operating satellites, manned space missions, scientific research, and future space accessibility. It argues that responsible management of orbital debris requires international cooperation, responsible space activities, better spacecraft design, proactive debris removal technologies, and strict regulations.

Keywords: Orbital debris, celestial contamination, Kessler Syndrome, satellite, debris management, proactive debris elimination, Earth Orbit.

I. Introduction

The universe has become one of the great frontiers of modern civilization. Satellites are used for communication, navigation, weather prediction, disaster response, scientific research, military, and global economic development. But years of space flight and industrial progress have created a new environmental hazard, the buildup of manufactured garbage in the earth's orbit. The term "space junk" is used to refer to obsolete human-made items left orbiting the Earth. Debris is manmade, not natural things in space such as meteoroids. It contains dead rocket stages, non-working satellites, explosion debris, and minor items lost during operations. Orbital space is limited, and hence the problem with space debris has expanded dramatically. Low Earth Orbit (LEO), from around 160 to 2,000 kilometers above the globe, is exceptionally crowded, and several critical orbital regimes are getting even more congested. (UNOOSA). Collisions with other things that are moving really fast could create a lot of extra debris, which would increase the risk of further collisions. The situation has been compounded by the growth of commercial space sectors. Thousands of additional satellites have been launched into orbit to provide internet access over the entire world in massive

satellite constellations. The orbital environment could become progressively more expensive and riskier to operate in without proper oversight. If not properly managed, the space environment could become more hazardous and expensive to operate. (ESA).

2. Development and Growth of Space Debris

The problem of space debris started soon after the launch of the first artificial satellite, Sputnik 1, in 1957. Early space missions have left behind rocket stages, pieces of satellites, and mission-related artifacts.

Major sources of space debris include:

2.1 Abandoned Spacecraft

Technical problems, fuel depletion, or mission completion are the reasons many satellites eventually stop working. Unless they are removed in a controlled fashion, these spacecrafts can stay in orbit for many years, even centuries.

2.2 Rocket Bodies

The rocket stage is used in launches and remains in orbit long after payload deployment. Some of these older rocket bodies contain residual fuels that could ignite, causing explosions that leave a handful of debris.

2.3 Accidental Collisions

When two space bodies are blown up, more fragments are created. In 2009, the dead Russian satellite Cosmos 2251 smashed into the working American one, Iridium 33. The event left a few detectable remnants. (ESA)

2.4 Anti-Satellite Weapon Tests

Military displays incorporating anti-satellite weapons have produced large debris shells. In 2007, a Chinese anti-satellite missile test of the Fengyun-1C in low Earth orbit generated thousands of pieces of debris, many of which still threaten spacecraft.

3. Environmental Impact of Space Debris

3.1 Threat to Space Operations

Out of all the ecological effects of space debris, the most crucial is that it does pose a threat to operational spacecraft. As little as tiny debris can inflict a great deal of damage. Orbital velocities could be hundreds of kilometers per second! Space debris can punch holes in spacecraft integrity and destroy solar arrays or critically necessary systems with a minuscule piece of metal flying at orbital velocity. Gunmetal, even a small amount flying at orbital speed, can find it by burrowing through spacecraft structures, damaging solar panels, or destroying key systems.

3.2 Risk to Human Spaceflight

Human missions are extremely sensitive to debris effects. Space stations need shielding and constant vigilance against the danger of collisions. There have been close calls where astronauts on board the International Space Station have had to take precautions because of debris approaching. Uncontrolled orbiting objects could also endanger future moon and outer space trips. (NASA)

3.3 Threat to Scientific Research

Hence, stable orbital conditions are required for scientific satellites of astronomy, Earth observation, and climate monitoring. This could be damaging to climate change, disaster research, and environmental monitoring if such satellites were war destroyed.

3.4 The Kessler Syndrome

Kessler Syndrome is a possible event where colliding orbital objects generate space debris, increasing the chance of further collisions.
This is the process through which this can happen:

a) Two objects collide with each other.
b) The collision sends millions of fragments into the air.
c) These chunks run into other vessels.
d) More fragments are generated.
e) Some of the regions in orbit get almost impossible to use.

This has the potential, if left unchecked, to cripple humanity's ability to safely work in space.

4. Monitoring and Tracking Space Debris

To deal properly with debris, we need to track objects in orbit correctly. Among others, government agencies and research institutions of international repute maintain tracking systems. This is why space surveillance networks use radars and telescopes, balancing computer models with ground data to monitor large debris fragments. Yet tracking the millions of pieces is smaller than tracking hundreds of thousands of objects that are too small to monitor all the time.

Current challenges include:
a) Unable to detect small rubbish.
b) Orbital movement prediction is not certain.
c) Increasing of Artificial Satellites.
d) Absence of mechanisms for global data-sharing.

The need for new tracking technologies, such as radar and AI-based prediction models, is growing more important.

5. Space Debris Mitigation Strategies

5.1 Spacecraft Design Improvements

Modern spacecraft can be designed to reduce debris generation. Important approaches include:

1. Designing satellites for controlled re-entry.
2. Using materials that reduce fragmentation.
3. Preventing accidental explosions through fuel removal.
4. Developing spacecraft with automatic disposal systems.

5.2 Post-Mission Disposal

The global rule of thumb is that operators of spacecraft are supposed to de-orbit their satellites after their missions are finished. To reduce future dangers, satellites in low Earth orbit can be arranged to make a controlled reentry into the atmosphere or to go to disposal orbits.

5.3 Collision Avoidance Systems

Operators are increasingly using tracking information for collision avoidance maneuvers.

Satellites can change position when a possible collision is foreseen. But more satellites mean more cooperation.

5.4 Active Debris Removal

Active debris removal involves capturing and removing existing large debris objects.
Possible technologies include:

1. Robotic spacecraft.
2. Robotic arms.
3. Nets and harpoons.
4. Drag sails.
5. Electrodynamic tethers.
6. Laser-based methods.

Although promising, these technologies face technical, financial, and legal challenges.

6. International Legal and Policy Framework

Space activities are governed primarily by international agreements, particularly the Outer Space Treaty of 1967. (OST).
The treaty establishes principles such as

a) National space activities are the responsibility of nations themselves.
b) Space objects are still subject to the jurisdiction of their state.
c) Nevertheless, there are no specific rules existing in international law governing space debris mitigation and liability for damage caused by space debris.

However, existing international law does not provide detailed rules specifically addressing space debris removal and liability. However, it should be followed;

1. Monitoring debris mitigation.
2. That is why maintaining international licenses concerning debris management is important.
3. Creating tracking information.
4. Financial responsibility for debris creation.
5. Agreements on active debris removal missions.

7. Challenges in Space Debris Management

Hence, debris removal becomes an intricate operation due to the uncontrolled state or damage upon impact of the object and rotation.

a) Debris removal missions are expensive.
b) Questions remain regarding who should pay for removing abandoned objects.
c) Taking a satellite from another country to put it back on orbit without permission could potentially lead to international legal and political entanglements.
d) The rise of private space companies and satellite constellations adds further strain on orbital assets.
e) Removing debris is difficult because objects may be uncontrolled, damaged, or rotating unpredictably.

8. Future Directions

It takes a blend of technology, policy, and truly international cooperation to ensure sustainable use of space.

8.1 Artificial Intelligence and Autonomous Systems

Artificial intelligence can improve:

a. Collision prediction.
b. Satellite navigation.
c. Automated avoidance decisions.
d. Space traffic management.

8.2 Sustainable Satellite Design

Future satellites should include:

a) Effective satellite design.
b) Automated disposal mechanisms.
c) Modular repair capabilities.
d) Environment-based materials.

8.3 Space Traffic Management

The global satellite traffic management might help optimize satellite operations and also reduce the possibility for collisions. And such a system would function like air traffic control but operating in the orbital environment.

9. Conclusion

Space debris is an important environmental issue associated with the current space activities. Orbital pollution does not directly harm Earth's ecosystems in the traditional sense, but it threatens the sustainability and security of the space environment, which modern society increasingly relies upon. “Debris management is a must if we are to continue launching satellites at ever-increasing rates, especially for commercial satellite constellations. Not acting would mean allowing debris to build up, becoming a barrier to future space exploration and economic activity. The future of space flight is not only about technological advancement but also about mankind’s capacity to wisely conserve and shepherd the orbital ecosystem.

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