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# Space Debris: An Overview

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*Abstract*

*Space debris, a pressing concern in space operations, poses a significant threat to operational spacecraft due to the increasing frequency of collisions. This environmental factor requires careful consideration in the planning, designing, and operating of space missions to ensure their safety and sustainability. Initiatives to remove space debris have accelerated recently, indicating the critical need to address the threats posed by large debris items in orbit. Innovative technologies and missions demonstrate ongoing efforts to tackle the challenges of space debris accumulation. Developing frameworks for space debris reduction and removal emphasizes the need for cooperative measures to maintain the long-term sustainability of space activities.*

*KEYWORDS:* Space debris, Debris mitigation*, ADR, Laser, Space Tugs, Robotic Arm, Ion* Beam Shepherd.

# *1. INTRODUCTION*

Space debris is an artificial, nonoperational space object in orbit around the Earth. It may be a completely nonfunctional artificial satellite or part of its launch vehicle, a lost object or tool by astronauts in orbit of the mission while carrying out activities in space, or fragmentation events that are either of accidental or intentional origin. They have all sizes, from very microscopic to large, such as an entire idle spacecraft. These space debris exist from 160 to 36,000 km above our Earth's surface. The United States Space Surveillance Network, which tracks, correlates, and catalogs objects greater than 5–10 centimeters in Earth's orbit, is the primary source of information on space debris.

As the reliance on space-based technologies continues to grow, the issue of space debris has become a critical concern for the scientific community, policymakers, and the general public.

The mass and number of Earth-orbiting space debris have steadily increased since the beginning of space exploration. According to the European Space Agency (ESA), there are currently more than 28,000 trackable objects in Earth's orbit, with an estimated 900,000 pieces larger than one centimeter and over 128 million pieces smaller (ESA's Space Environment Report 2021, 2023) than one centimeter.

## *2. SOURCES OF SPACE DEBRIS*

Most space debris come from breakup events caused by explosions and collisions, many of them deliberate. Fragmentation debris is the largest source of space debris. Three countries in particular are responsible for roughly 95% of the fragmentation debris currently in Earth’s orbit, viz., China (42%), the United States (27.5%), and Russia (25.5%).

Satellites that are no longer operational, whether offline, dead, or completed their mission, become space debris. The satellites which are positioned at altitude less than 600 km plunge into atmosphere in several years, while those at 800 km takes decades and those beyond 1000 km have lifetime of centuries. For example, Vanguard 1, launched in 1958, has an orbit lifetime of 240 years around the Earth. Satellites in Geostationary Earth Orbit are moved to a Graveyard orbit at the end of their mission and can then remain there for thousands of years with very little change in orbit. The waste apparently exhausted by the engines in orbit lingers for weeks. They can be in the form of aluminum oxide from solid rocket engines whose size ranges from 1 to 10 microns. Centimeter sized aluminum slag also released from the engines acts as debris. Small fraction of propellant mass expelled in the final cutoff of the engine. These particles remain in space for a longer time.

All these in-orbit explosions result in a large amount of junk. In fact, it is thought that the in-orbit explosions have produced about 750,000 particles larger than one centimeter. This junk may be caused by meteoroids crashing onto orbiting objects or remnants of fuel which sometimes explodes in the fuel tanks and fuel lines of state-of-the-art satellites or spacecraft. It's because of the extreme conditions in space, where mechanical integrity degrades, starting to cause fuel leakage and leading to an explosion. Also, there is solar radiation adding pressure to fuel tanks and can blow up. In addition, overcharged batteries eventually blowout.

# *3. IMPACT OF SPACE DEBRIS*

The dangers and concerns brought about by space debris, compounding from defunct satellites and rocket stages and pieces of old satellites, rocket stages, and fragments from crashes and explosions, have become a weighty issue for safe satellite operations and on-orbit safety considerations and environmental stewardship. In this respect, the section takes into account the overall multifaceted effect of space debris on the various aspects associated with space exploration and the earth's environment.

- Orbital velocities of the space junk that is bunched around the Earth are above several kilometers per second, posing a broad collision risk for operational satellites and spacecraft. Small fragments at this speed can cause catastrophic damage on impact.
- Impacts by orbital debris in crewed spacecraft pose a serious risk to space operations. Different mitigation strategies for these unfavorable situations are orbital maneuvers dependent on tracking data to minimize collision risks and assure astronauts' safety.
- In particular, space debris collection near critical orbits, such as LEO and GEO, is prone to be potentially a risk to the sustainability of future space missions. That non-stop production of space junk through collisions may occur in an increasingly exponential manner, known as the Kessler Syndrome, has been a huge threat to satellite deployment and further space operations.
- While most of the space debris get consumed at the moment of their re-entry into Earth's atmosphere, larger objects can survive and pose a risk to populated areas. This underlines one of the challenges of real-time monitoring and management for orbits of space waste, so as to minimize potential impacts on terrestrial environments.
- Junk in space attains large accumulation, placing huge costs on satellite operators and space agencies—from monitoring orbit for junk, to way-avoidance maneuvers, to replacing satellites in case of collisions or damage.

# *4. MITIGATION METHODS*

A variety of active removal systems for junk have been proposed over the last decade, but none of the systems followed through on removing any debris from Earth's lower orbit. A big concern with active space removal technology is its reliability. It is a term that relates to the physical stability and endurance of the systems on broad or precise removal missions.
One more challenge faced is avoiding additional collisions with the removal system when removing space debris.
Some of them are more reliable, accessible, and likely to be successful. Methods of active space removal will be briefly discussed here.

## *4.1 TETHERS*

Tether refers to using a momentum exchange tether, which acts like a swing to pull an object out of orbit, or, rather, an electrodynamic tether that causes a drag on the satellite due to the magnetic field of the Earth. While this complex process has not yet been proven, the removal of large-mass orbital debris can be done by using tethers. An electrodynamic or conductive tether is a long conducting wire that generates electric potential as it moves through the earth's magnetic field. It could be attached to a targeted piece of orbital junk, whereby the movement of the tether would create an electric current that would build up, creating, even if very small, an analogous charge, deorbiting the vehicle and bringing it down into the atmosphere far more quickly than it would do if it were left in orbit. While this approach could be effective in deorbiting larger targets in LEO, it is hugely complex and costly.

## *4.2 LASERS*

This is a method used to slow down objects using high-powered lasers fired from Earth so that they move out of orbit. Laser technologies could remove a large quantity of small-sized debris. The concept is to lock onto orbital debris using ground, air, or space-based lasers, then vaporize some part of the junk, which gives a thrust that changes the orbit of the junk. This would reduce the lifetime of the junk. Such an approach, however, raises questions of arms control, violation of the United Nations Treaty for ground- and air-based lasers, and space-based lasers. Also, it would be an enormous task for the number of hazardous, small debris is quite large (many millions).

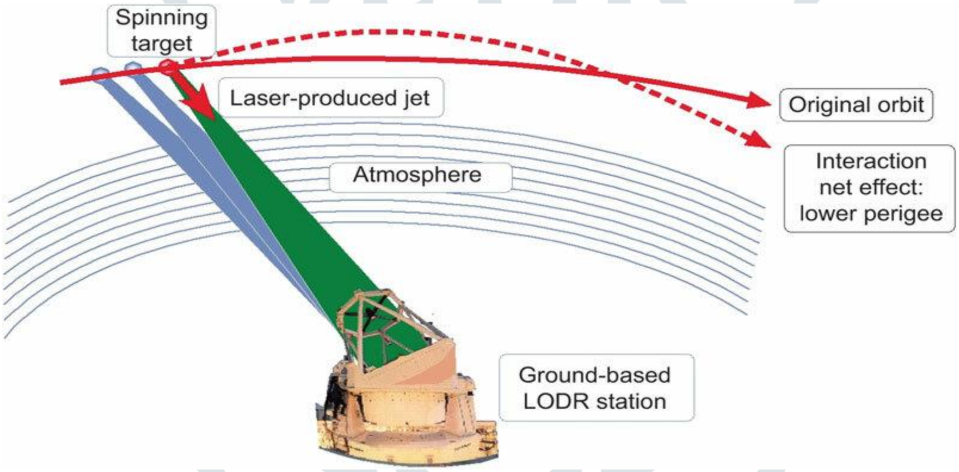


*Fig 1: Representation of Laser Based Space Debris Cleaning*

## *4.3 ROBOTIC ARM ATTACHMENT*

This technology would approach the junk and, if not used to actually pull said junk down to the Earth's surface, would be able to positively alter the rotation and path of that junk to make it easier to remove a short time later. For this to be an effective method, the rotation of the junk would need to decrease in speed with the separate technology of the satellite. Here, it becomes quite hard or even impossible for the robotic arm to grasp the space debris properly and move it in case it is rotating fast or in an unpredictable manner. This would work far better with another system of active removal of medium-sized pieces of space debris, not small-sized ones. This method is reasonable in the sense that the system can be programmed to move space debris to certain areas, but it would not be effective quickly enough for small or large removals of space debris.

## *4.4 SPACE TUGS*

Space tugs involve the use of a robotic grappling device on another spacecraft to tug an object into a new orbit or cause it to re-enter destructively in the atmosphere. In reality, a space tug can be considered as a spacecraft with which several pieces of junk are moved to disposal orbits in GEO. In this scenario, a tether is attached to one artifact; once a link is obtained, the artifact is moved to the disposal orbit, and the process is repeated with a second piece of orbital debris. The approach has the potential to be effective for the disposal of objects in

GEO, and its capability of multiple targets makes it attractive. Again, however, it is unproven, complex, and costly to use.

### *4.5 ION BEAM SHEPHERD*

It is a contactless-based removal method in which a highly collimated, neutralized plasma beam is ejected onto debris by lowering or increasing its altitude. The Shepherd satellite is fitted with a propulsion system that ejects a highly collimated, quasi-neutral plasma beam with huge momentum toward space debris. The neutralized plasma beam technique is used to avoid the net charge on satellites and spacecraft. The following will provide an effective method for contactless orbital debris removal.

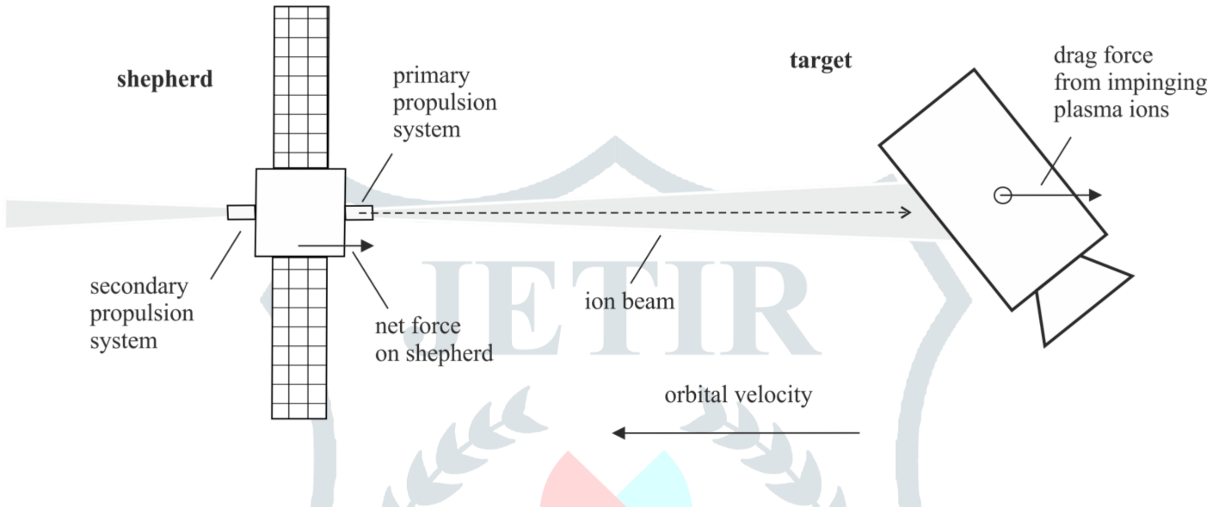


*Fig 2: Representation of Ion Beam Shepherd method in Space Debris*

## 5. CONCLUSION

The risk to spacecraft in orbit needs to be limited by space agencies and spacecraft engineers; the best way to deal with space debris is not to create more. Early screening at pre-launch can help reduce the chances of creating further junk and ensure that newly launched space assets reach their intended orbit without endangering human life. The quality of tracking data and the tools and methods in use continually improve, so better predictions of collisions will become possible. Aerospace continues to refine the collision avoidance process for the protection of space missions and the preservation of the utility of space itself. Work protecting from impacts of larger objects is needed—and on debris avoidance—but some experts believe that there is potential in the future for a commercial removal service. This also includes the limitation of risk to humans, which agencies and engineers of spacecraft have to do following the re-entry of a spacecraft.

The high risk posed to humans by this scenario can be mitigated in three ways. The first is controlled re-entry, executed by a space system operator over a large ocean area. On one hand, this method reduces the risks for humans substantially; on the other hand, the process of controlled re-entry is very cumbersome and costly, so it is the last remedy to be applied. Another way of mitigating the risk is to propel the spacecraft into a graveyard orbit—a long-term orbit above 2,000 km. This method is also expensive and not a good solution for the long run. The best case from the perspective of orbital debris mitigation and reduction of human risk is the redesign of spacecraft before they are built to reduce the risk of human casualties upon their reentry. All space users need to follow the international mitigation guidelines ratified and signed.

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