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A Comprehensive Study on Space Debris, Threats posed by Space Debris, and Removal Techniques

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I.ABSTRACT\

After exploring space for more than 50 years for research, study and defense purposes, the region above the atmosphere of earth is highly polluted by orbital debris. Figure 1 shows the total number of rocket launches in period of nine years. This has become a concern for placing satellites in their respective orbits and their safe functioning during their mission. Space debris or orbital debris colloquially known as space junk are parts of the non-functional satellites, thermal blankets, booster stages of the rockets. Those satellites are placed in the several orbits according to their missions. Mainly, they are placed in LEO (Low Earth Orbit), an earth centered orbit ranging from 200 to 2000 kilometers. Some are also placed in GEO (Geostationary Earth Orbit), at an altitude of 36000 kilometers and some are placed in the Higher Earth Orbit. Since the dawn of space age, approximately 7000 rockets have been launched, placing their payloads in several orbits of the Earth, revolving at several kilometers per second. And more than half of these objects are present in LEO. It is estimated that their sizes vary from a few millimeters to few meters, the largest being the European Envisat. Because of their high speeds, pieces of debris not more than a millimeter apart also poses a huge risk to current and upcoming space missions. Since the risk is increasing exponentially and is of great concern for all the space-faring nations, there is a need for the active removal of space debris. Hence, in this paper, the authors have analyzed the threat that space debris poses, and some of its removal techniques that have been proposed by scientists and space organizations. The authors have also suggested a few more of these Active Debris Removal techniques.
Keywords: Space debris, Orbit, tracking, Active Debris Removal (ADR).

II.INTRODUCTION

Space has become a vital resource for exploration. Although space is usually alleged to be a desolate expanse, the region around earth swarms with millions of artificial rubble that are potential hazards for their functioning neighbours. The problem of this “space debris” was enclosed in the agenda of the Scientific and Technical commission at its session in February 1994, in accordance with General Assembly resolution 48/39 of 10 December 1993. Furthermore, as for public and business utilization, satellites have become an integral a part of human society because of their essential role in information and recreational sectors, telecommunications, navigation, meteorology, remote sensing, commerce, and national security. The Subcommittee agreed that consideration of space debris was important and international cooperation was needed to evolve appropriate and affordable strategies to minimize the potential impact of space debris on future space missions.[7] In its further sessions, the Sub-committee continued its consideration of orbital debris on a priority basis. The Subcommittee concluded that it was important to have a firm scientific and technical basis for future action on the complex attributes of space debris and that it should, therefore, focus on understanding aspects of research related to space debris, including: debris measurement techniques; mathematical modelling of the debris environment, characterizing the space debris environment; and measures to mitigate the risks of space debris, including spacecraft design measures to protect against space debris.

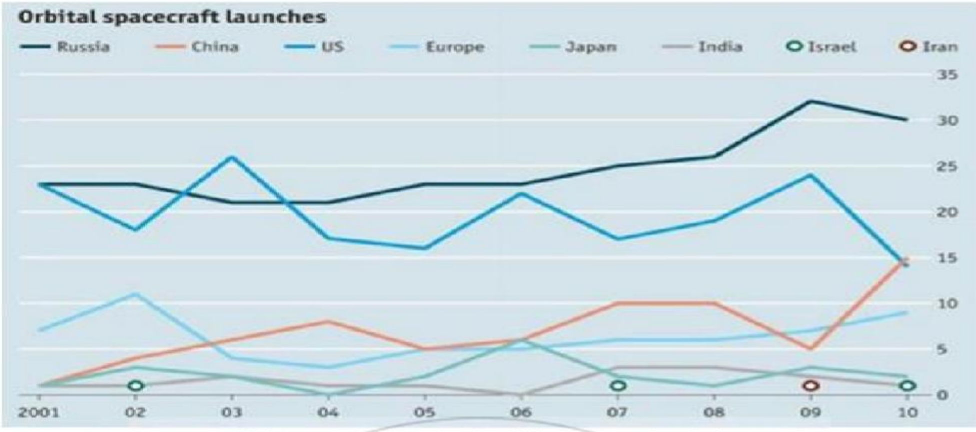

FIG 1: Total rocket launches in the period of the 2001-2010 by various nations[19]

III. BASICS AND CLASSIFICATION OF ORBITAL DEBRIS

A. Sources

Major sources of orbital debris are natural and man-made. Natural sources are those such as micrometeoroids, and dust. Man-made sources are spent rocket stages, explosions of satellites and rockets, the Anti-Satellite Missile Test, satellite collisions, slag particles from rocket motor firings in orbit. Man-made sources have contributed greatly over the past 60 years of space exploration.

Micrometeoroids: These are small particles of rock present in space. Typically weighing less than a gram, they are remnants of the larger rock and dust present during the formation of the Solar System and can be widely found throughout, in orbit or between the orbits of planets. These small particles usually have high velocities and their continuous impact on spacecraft can eventually wear out the materials present.

Spent Rocket Stages: Typical launch systems whose mission is to place satellites or other payloads into Low Earth Orbit or higher have 2 or more stages. The first stage, or the booster stage may or may not be reusable and is generally jettisoned within the atmosphere. The second and third stages are fired in space. After achieving orbit and their jettisoning, these rocket stages contain no fuel and are generally defunct, and contribute to orbital debris. Continuous collisions lead to breakage of these rocket stages into smaller debris.

Explosions of Satellites and Rocket Stages: Satellites that have reached their end of mission due to time or a malfunction may contain fuel and other high energy substances capable of causing explosions. Sunlight and micrometeoroids continuously degrade these and may cause the formation of cracks, leakage of propellants and eventually explosions which increase the number of orbital debris. Table 2 shows the break up of satellites and their causes, as well as the number of trackable objects produced.

Anti-Satellite Missile Tests: The USA, Russia, China, and more recently, India, have conducted Anti-Satellite (ASAT) missile tests over the years. These tests have added considerably to the amount of trackable and potentially dangerous orbital debris.

Satellite collisions: In 2009, a defunct Russian communication satellite, Kosmos-2251, collided with a functional United States' Iridium-33 satellite, a part of the communication satellite constellation owned by Iridium communications. This collision destroyed both satellites, and produced at least a thousand pieces of trackable debris, less than or equal to 10cm in size, in conjunction with smaller debris, many times that in number. Since then, only two satellite collisions have been recorded.[9]

B. Size

Size is a key consideration for orbital debris. Generally, a larger piece of debris also weighs more and hence has a high potential to damage other objects in space. For an 80gram piece of orbital debris, orbiting in Low Earth Orbit, its kinetic energy is equivalent to 1 kilogram of TNT (Trinitrotoluene).

Size of a particle also decides whether or not it is trackable. Visual tracking of debris is not possible because of their heights and sizes. Hence, RADAR (Radio Detection and Ranging) is used. One drawback of RADAR is that the sensitivity decreases with a factor of the square of the distance. Also, the RADAR cross-section of a particle also plays a part in whether or not it is trackable. Table 1 details the numberof orbital debris of different RADAR cross section. RADAR cross-section determines the detectability of an object. Larger the RADAR cross-section of the object, more is the Radio energy reflected back to the source.NORAD (North American Aerospace Defense Command), SSN (Space Surveillance Network), and Russian military'sSSS, (Space Surveillance System), are the two agencies continuously tracking orbital debris. Both SSS and SSN can track debris having a RADAR cross-section of 0.01 m^2.Figure 2 is a plot showing the number and types of orbital debris versus the years in which they formed.

Table 1: Different sizes of the orbital debris present in space

SIZE	NUMBER OF TRACKEBLE DEBRIS
<1 CM	128,000,000
1 – 10 CM	900,000
>10 CM	34,000

C. Orbits

Low Earth Orbit: The highest number of orbital debris can be found in Low Earth Orbit (LEO). Hence, the collision hazard is much higher than in, say, Geosynchronous Orbit. The 2009 satellite collision and the 2007 Chinese anti-satellite missile tests further added to the debris field. Figure 3 shows the number of orbital debris with respect to the heights at which they are present. Although, atmospheric drag, perturbations in the orbit due to the unevenness of the earth's surface, the collisions can occur from any direction and the speed of impacts may exceed 14 kilometers/s.

But atmospheric drag in LEO also helps clear the debris field. This is the reason manned missions are carried out at about 400 kilometers or 250 miles. Also, due to changes in space weather, the height of the atmosphere can increase, further clearing the debris.

Geostationary Orbits, Interplanetary transfer orbits, geostationary transfer orbits: The orbital debris in these orbits are harder to get rid of, since they do not experience the amount of atmospheric drag large enough to re-enter. But, perturbations due to the earth's surface and moon, radiation pressure and solar wind can gradually bring the debris down, although this could take hundreds, if not thousands, of years. Many communication satellites in GSO have orbits that intersect. This poses a collision hazard. The speed of collision, however, is limited to about 1.6 kilometers/s due the fact that these satellites have very low speed, compared to those at LEO.

The International Telecommunications Union is the controlling body, and requires evidence that the satellites can be de-orbited or be placed in a graveyard orbit. A graveyard orbit is a few hundred kilometres higher than the object's intended orbit, such that the chances of collisions are low. This is done when the delta-V required to de-orbit the satellite is higher than to move it into a new orbit.

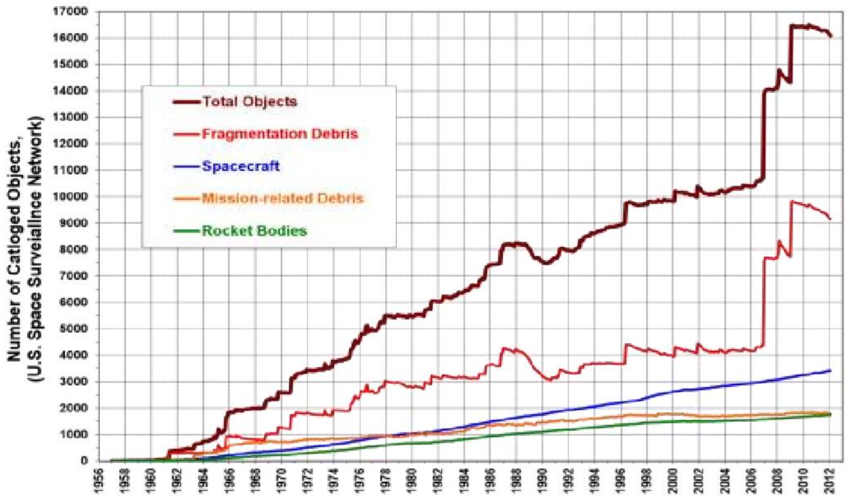

FIG. 2: Number of catalogued objects in space.
(Source: Annual report by U.S. Space Surveillance Network)

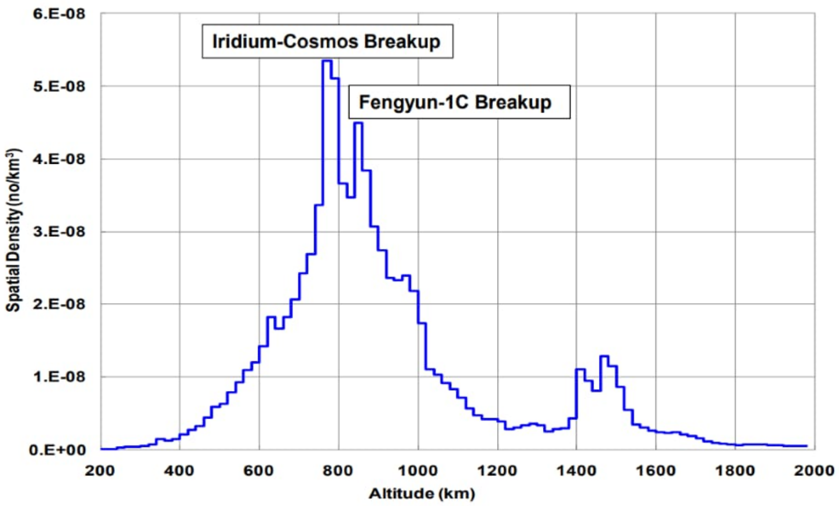

FIG. 3: Plot showing distribution of orbital debris at various altitudes[4]

IV.THREAT ASSESMENT

Kessler Syndrome: The runaway collisions of derelict satellites with each other or other orbital debris causing a massive increase in space debris density is termed as Kessler Syndrome. Proposed by NASA scientist Donald J. Kessler in 1978, this domino effect of events could be triggered by a satellite with sufficient mass to collide with another such satellite or the International Space Station.[11] This can pose a risk for future missions, especially to the Low Earth Orbit and the Medium Earth Orbit.

This region would not be rendered impassable, but would be costly to maneuver around, both in terms of propellant and time. As of March 2019, the only satellite with sufficient mass to cause this and in the LEO is the ESA's Envisat. Weighing 8,200 kilograms, this derelict satellite orbits in a region where the density of space debris is relatively high, with at least two catalogued objects coming within 200 meters of its vicinity every year.

Future Missions: As of January 2019, there have been more than 5400 launches (excluding launch failures). This number will increase exponentially as the number of space-faring nations increases rapidly. These missions will encounter more risks as time progresses, due to more debris being added by previous launches. Collisions with orbital debris could result in mission failure of both manned and unmanned missions. In 1983, the Space Shuttle mission STS-7 (Space Transportation System–7), was struck by a paint fleck in one of its windows, causing a pit, a few millimeters in size. Figure 4 shows the window pit caused by the fleck of paint on STS-7.

Environment: Although most orbital debris are small in size, bigger ones may pose a risk to the flora and fauna down on Earth. Their size may ensure that they survive re-entry and strike a populated area. The odds of a piece of orbital debris striking any one of the 7 billion people on earth is 1 in 3200. The odds a particular person will be hit by a re-entering piece of debris in 1 in one trillion. This is because most debris will burn up before making landfall.

However, there has been a case of orbital debris striking a person. In 1997, the tiny threat of space debris became a reality for Lottie Williams. The Tulsa, Oklahoma, resident became the only person known to have been hit by a piece of space debris. A DVD-size piece of metal from a Delta II rocket struck her shoulder while she was exercising at a park. Luckily, because of wind resistance, it was fluttering to the ground so slowly that she wasn't hurt.

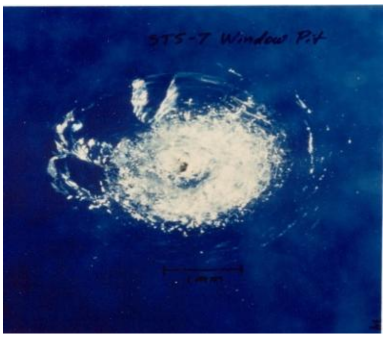

FIG. 4: Window pit due to space debris during STS-7[2]

Table 2: Break-up of satellites and other objects in orbit resulting in the most debris produced

Common Name	Catalogued Debris	Debris in Orbit	Year of break-up	Break-up Altitude	Cause of Break-up
Fengyun -1C	3216	2987	2007	850 km	Collision
Cosmos 2251	1559	1371	2009	790 km	Collision with Iridium 33
STEP 2 Rocket Body	710	58	1998	625 km	Accidental explosion
Iridium 33	567	487	2009	790 km	Collision with Cosmos 2251
Cosmos 2421	509	0	2008	410 km	Unknown
SPOT 1 Rocket Body	492	32	1986	805 km	Accidental explosion
OV 2-1/ LCS 2 Rocket Body	473	35	1965	740 km	Accidental explosion
Nimbus Rocket Body	375	245	1970	1075 km	Accidental Explosion
TES Rocket Body	370	111	2001	670 km	Accidental Explosion
CBERS 1 Rocket Body	343	178	2000	740 km	Accidental explosion

V.REMOVAL TECHNIQUES, THEIR ANALYSIS, AND COMPARISON

Removal of orbital debris should be a primary concern for space-faring nations and those planning for space missions. As such, NASA, Roscosmos, JAXA, and other nations along with departments such as DARPA (Defense Advanced Research Project Agency) are actively working towards the reduction and removal of orbital debris. In 2007, the United Nations General Assembly countersigned the "Space Debris Mitigation Guidelines" to conduct scientific research, and to actively discuss the legal aspects of space debris mitigation, both national and international. This is in addition to the 1968 Rescue Agreement, a treaty that requires nations return any "foreign" space objects that have been discovered in their state to their owners. This was proposed by the United Nations Committee on the Peaceful Uses of Outer Space. Since scientists realized the dangers of orbital debris, there have been many proposals for various techniques for the mitigation, as well as removal of orbital debris.[14] Some of these have been discussed below, in detail.

Kounotori- 6: The Japanese Aerospace Exploration Agency (JAXA), tested the ides of an electrodynamic tether to clear space debris, called the Kounotori Integrated Tether Experiment or KITE. Kounotori-6 was an ISS resupply capsule that included the tether as an additional payload. After de-berthing and undocking from the International Space Station, the spacecraft was supposed to deploy its 700m tether, but failed to do so, and re-entered the Earth's atmosphere seven days later. [15]

Gossamer Orbital Lowering Device: Proposed by Dr. Kristin L. Gates in 2010, the GOLD is a huge gas filled balloon made of gossamer, a very light weight material used in solar sails. The balloon, up to 91 meters in diameter, would latch onto the debris, and would increase its drag in the upper atmosphere, gradually lowering its orbit until the piece re-enters the atmosphere.

Laser Orbital Debris Removal (LODR): This is a method of active debris removal. This technique involves heating a piece of debris using a powerful laser beam either on the ground or in space, such that the material ablates and produces a small thrust in the direction opposite to the ablation.[12] This causes its orbital apogee to be lowered at least into the upper atmosphere, where the drag would eventually slow it down for re-entry. NASA, in 2011, suggested that doing so would change the velocity of the debris by 0.1 mm second, for every hour the debris is hit by the laser beam. Firing the beam at the debris for a few hours for a day, this could alter its course by up to 200 meters. This is not sufficient for re-entry but can be used to manoeuvre the debris to avoid collision. A strong enough laser beam could potentially vaporize the debris, although the power diminishes due to scattering and distance.

CleanSpace One: In 2012, the École Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology in Lausanne) or EPFL announced its plan to launch a satellite in orbit that would grab orbital debris and then plummet to Earth with it. The EPFL, in the initial stages, proposed using a claw to capture one of the Swiss Cubes, as a technology demonstrator mission. However, in 2015, these ideas were dropped in the favour of using a conical net, which would engulf the Swiss Cube and tighten around it, thus capturing it. Then, it would proceed with its mission to de-orbit itself and the debris.

Space Harpoon: In February 2019, Airbus, with Surrey Satellite Technology, Ltd., conducted the first ever test of a harpoon designed to latch onto orbital debris and retract it towards the parent spacecraft. A pen-sized harpoon developed by the Airbus engineers in the UK, made of titanium, was fired into an aluminum target. It pulled the target out of it orbit and retracted it into the parent satellite.

SpaDE: Space Debris Elimination was a Raytheon BBS Technologies' research into the removal of orbital debris using small bursts of the atmosphere. It proposed a balloon supported platform, which detonated fuel in the upper atmosphere. This causes the atmosphere to expand into space. According to the simulations done by the team, a burst of air 200kilometres in diameter, would stay coherent to up to 600 kilometres into space. A small piece of debris, say about 10 cm in diameter and with a co-efficient of drag of 1.6 would experience a delta-V equal to 3% of its orbital velocity. This would, according to the team, be sufficient enough to de-orbit the debris.

Ion Beam Shepherd: This is also an active debris removal technique. In this, a satellite, the shepherd, using ion thrusters would "guide" the orbital debris, the "target" by trailing in front of the debris. The impinging ions would slow the piece of debris enough to achieve re-entry. The shepherd itself will be using a secondary propulsion system to maintain its position relative to the debris.

Russia's Space Pod: In 2010, Energia, Russia's space programme announced it would be developing a space pod, capable of "grabbing" over 600 defunct satellites and safely de-orbit them, such that they burn up while re-entering earth's atmosphere. Energia proposed it would be nuclear powered, with a mission span of 15 years. The long mission span and the use of nuclear power might suggest the use of ion engines, acting as an ion beam shepherd.[16][17]

All the above techniques are those which have been thoroughly reviewed by the scientific community and their feasibility has been tested. As engineers and humans, we must have the capability to think in a better way and must always be in pursuit of ideas that make humanity's life on this planet a little better. As such, below are some of the removal techniques that the authors have suggested.

Recycling capsules: Taking inspiration from the waste segregation and recycling done by the Bruhat Bengaluru Mahangara Palike (BBMP) and other Palikas in cities all over India, space debris can be collected by a capsule, which would then segregate the debris into magnetic, metallic, and non-metallic components by centrifugal separation. The capsule would then deploy an inflatable heat shield and re-enter the atmosphere. On earth, the capsule would open and the various components be collected. This would also reduce the increasing scarcity of rare-earth elements on earth. Rare-earth elements such as indium, gallium and tellurium are used in solar panels, whereas nickel, lithium, cerium, and lanthanum are used in high capacity rechargeable batteries on satellites. This is a form of active debris removal.

Re-entry package: In this technique, the satellite or payload to be launched into earth orbit would be fitted with a pack of propellant, and rocket motor, a "re-entry package". This would have separate control than the satellite or payload itself and would orient and fire to de-orbit the satellite. This technique would ensure that there is no more formation of orbital debris and going by the idea that not producing debris would amount to the same as removing it. This is a mitigation of debris.

VI. CONCLUSION

Orbital Debris is a by-product of human activities in space, analogous to global warming. Just like the latter, it may not be seen as a major threat to humanity until it directly affects us. NASA has stated that the debris field generated by India's ASAT mission "Shakti" is a potential hazard to the ISS. This is not the first time that the ISS was in danger of being hit by debris and each time this threat arose, the ISS was partially evacuated and its altitude adjusted. There has been a total of ten of these Debris Avoidance Manoeuvres (DAM). It does not matter if the debris is large or small, all travel at almost 10 times the speed of bullets and each of these are a threat to every spacecraft out there in space. Since the launch of Sputnik 1 in 1957, to the March 2019 test of India's own anti-satellite mission, there has been a steady, if not, exponential increase in orbital debris. If nothing is done to prevent its increase, we could reach a point of no return, just as with global warming, hindering future missions and the development of future generations.

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