Space Debris and Their Impact on LEO

Balasubramanian.S[1] , Adithya.S[2] , Sre Vignesh.S[3] , Senthilmurugan.S[4]

[1,2,3]Dept. of EEE, SRM Institute of Science and Technology, Kattankulathur - 603203, Kancheepuram Dt., Tamil Nadu, India

[1]Balasubramanian_sendilcoumar@srmuniv.edu.in

[2]Adithya_srinivasan@srmuniv.edu.in

[3]Srevignesh_saravanan@srmuniv.edu.in

[4]Assistant Professor, Dept. of EEE, SRM Institute of Science and Technology, Kattankulathur - 603203, Kancheepuram Dt., Tamil Nadu, India

sen.accet@gmail.com

ABSTRACT: **Humans have created a lot of garbage not only on earth's surface but also up in the atmosphere which is equally colossal. Although it does not pose a serious health hazard, it is a significant problem for future space programs and man-made satellites without which modern day telecommunication is impossible. The Lower Earth Orbit (LEO) environment is becoming crammed with space debris as more objects are being added faster than getting removed or decayed. Collisions at orbital velocities can be dangerous causing tremendous disruption in communication networks and surveillance systems. Knowing the likelihood of a collision for satellites operating in LEO is of extreme importance and interest to the global community. Collisions can produce even more space debris in the process, creating a domino effect, also called Kessler Syndrome. This paper analyses the complications caused by space debris particularly in the Lower Earth Orbit (LEO). The discussion includes debris history and its development over the years. Statistics on the debris growth and its effect on satellites and space crafts located in LEO orbit are examined. The paper discusses three preventive and rectification methods that could be implemented to solve the problem posed by space debris. The main question this paper address is how the debris is being created in LEO, their growth impact and credible prevention techniques.**

KEYWORDS: **Space, Debris, Pollution, Satellites, LEO (Lower Earth Orbit), Collision, Analysis, Mitigation**

I. Introduction

A. Definition

Space debris is man-made objects orbiting in space. There are two types of debris, *natural* and *artificial.*

- Natural space debris consists of small pieces of cometary and steroidal material called meteoroids. These meteors are visible to the naked eye when they travel through the earth's atmosphere.
- Artificial space debris is any non-functional man-made object in space which usually floats in the earth orbit. Low earth orbit is 500 km above the earth's surface. This is where most of the junk is and also the region where most of the manned made spacecraft and many scientific satellites resides.

Orbital debris is any man-made object in orbit about the Earth which no longer serves a useful function. Such debris includes non-functional spacecraft, abandoned launch vehicle stages, mission-related debris, and fragmentation debris.

There are more than 20,000 pieces of debris larger than a softball orbiting the Earth. They travel at speeds up to 17,500 mph, fast enough for a relatively small piece of orbital debris to damage a satellite or a spacecraft. There are 500,000 pieces of debris the size of a marble or larger. There are many millions of pieces of debris that are so small they can't be tracked.
Even tiny paint flecks can damage a spacecraft when traveling at these velocities.

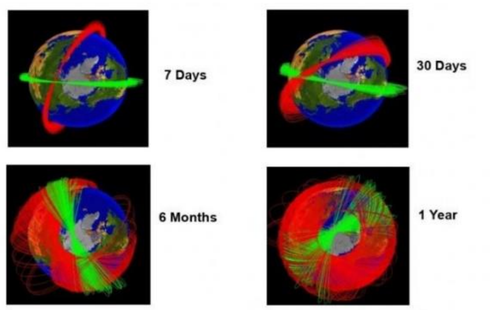

Fig – 1 Spread of Debris with Time

B. LEO Space Debris

1) Lower Earth Orbit(LEO):

LEO altitude of about 500 km contains the most number of manmade spacecraft and many scientific satellites such as international space station (ISS) and Humble Space telescope. Based on previous studies, LEO has the biggest amount of functional satellites with 46%, MEO with 42%, whereby GEO is 36%. Figure 1 shows the operational satellites percentage in different orbits.

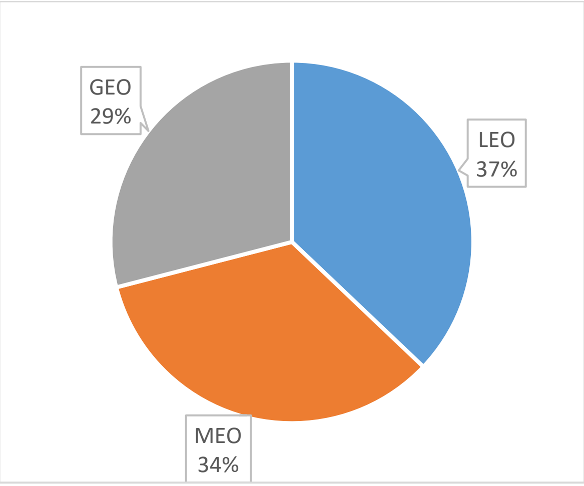

Fig - 2 Operational satellites percentage in different orbits

Satellites launched into LEO are continuously exposed to aerodynamic forces from the tenuous upper reaches of Earth's atmosphere. Depending on the altitude, after a few weeks, years or even centuries, this resistance decelerates the satellite sufficiently so that it re-enters the atmosphere. At higher altitudes, above 800 km, air drag becomes less effective and objects will generally remain in orbit for many decades.

At any given altitude, the generation of debris through normal launch operations, breakups and other release events is counteracted by natural cleansing mechanisms, such as air drag and lunisolar gravitational attraction. The result of these balancing effects is an altitude dependent concentration (spatial density) of space debris objects. Maximum debris concentrations can be noted at altitudes of 800-1000 km and near 1400 km. Spatial densities in GEO and near the orbits of navigation satellite constellations are smaller by two to three orders of magnitude.

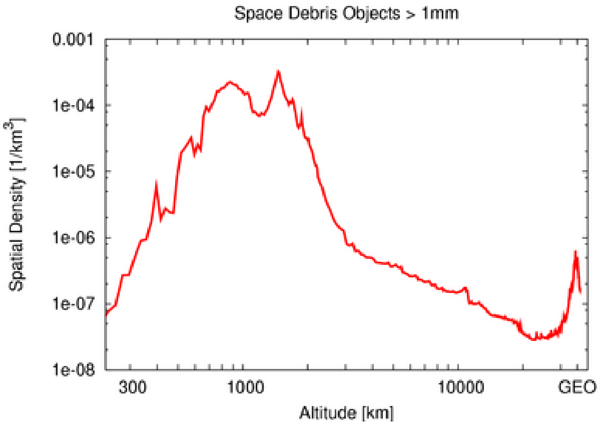

Fig – 3 Comparison of debris densities at different altitudes

2) Space Debris – LEO:

In March 2010, Parliamentary Office of Science and Technology (POSTNOTE), stated that debris poses a growing threat to satellite present in LEO and could prevent the use of valuable orbits in the future. In the altitude below LEO orbits, the object can easily fall to earth atmosphere and will be burnt up. Some of these objects are:

• Defunct space: such commercial satellite with lifespan 15 years.
• Spent rocket bodies that used to launch a satellite into orbit.
• Objects released during missions of the satellite.
• Small fragmentation caused by collisions, explosions

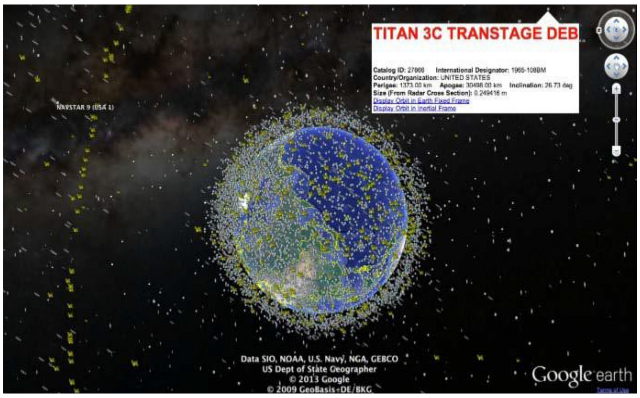

Figure – 4 Image Google Earth-based interactive showing details about satellites and debris in orbit.

The green objects in Figure 4, represent the active satellites, and the grey represents the objects which are the debris. As seen in the picture, most of the objects and debris are concentrated at very low altitude. The debris is not distributed equally in all earth orbits but most are in LEO orbit.

LEO has the most space debris among the other orbits MEO or GEO. The simple reason for this is due to LEO characteristics itself where the most number of satellites are in LEO orbit. LEO satellites are at around 500-2000 km altitude, the nearest to the earth surface. LEO orbiting satellites are less expensive to launch into orbit. These satellites also do not require high signal strength and give less time delay due to the latitude near to earth. LEO satellite life span is around 5 years. Once it stops functioning it stays there in the orbits. LEO are mostly used for communication applications.

Table – 1 Category of LEO Debris

Physical Size	Potential Risk to the Satellites	Impact	Numbers of Objects
>10 cm	Can be tracked.No effective shielding	Catastrophic Complete destruction	14,000
1-10 cm	Larger objects in range may be tracked.No effective shielding	Severe damage or complete destruction	400,000
< 1cm	Cannot be tracked. Effective shielding exists	Damage	>10,000

II. An Empirical Baseline

In the first half of the twentieth century, before man-made objects were launched into space, some scientists suggested that the space around the Earth might be littered with undetectably small chunks of natural debris that could hinder manned spaceflight. Some, like astronomer Fred Whipple, were concerned about small meteors streaking past the planet. In
1946, Whipple warned that a spaceship traveling toward the moon would have a one in twenty-five chance of being destroyed by a meteoroid Others, like astronomer William Henry Pickering, envisioned small natural satellites orbiting the Earth. As recently as 1954, Dr. GM. Clemence, director of the Nautical Almanac Office of the US Naval Observatory, said that the chances that there were one or more small satellites orbiting the Earth nearer than the moon were "very good." He explained that they would be difficult to find because they would be moving too fast to be captured by usual photographic methods and that "most of the time they are in the Earth's shadow, and thus do not shine.

Amid such speculation, astronomer Clyde Tombaugh formulated a plan to search for natural debris near both the Earth and its moon. Among the purposes, he thought this project would address where the threat of collision with space vehicles and the possibility of using a natural satellite near the Earth as a "base in the establishment of an artificial satellite or space Station." Tombaugh, who had discovered the then-planet Pluto in 1930 and was head of the Optical Measurements Section for missile tracking at White Sands Proving Ground from 1946 to 1955, devised new techniques and equipment for conducting the search. Funded by the Army Office of Ordnance Research, Tombaugh and his staff used photography and visual sightings in the project from 1953 to 1958, first at the Lowell Observatory in Arizona and later at an equatorial site near Quito, Ecuador. The 1959 final report stated that no natural satellites had been discovered. Tombaugh concluded that "we could send rockets out in space with very little risk of collision with natural objects.
The timing of Tombaugh's "Search for Small Satellites of the Earth" was fortuitous. Just before he planned to stop the observations, the Soviet Union launched Sputnik 1, the first artificial satellite, into orbit on October 2, 1957. Tombaugh's telescopes detected the 58 cm diameter sphere and photographed it as it orbited elliptically between 215 km and 939 km above the Earth. Not only was this observation important in itself, but it supported the conclusion that if natural satellites had existed in low-Earth orbit (LEO), they would have been detected as well.

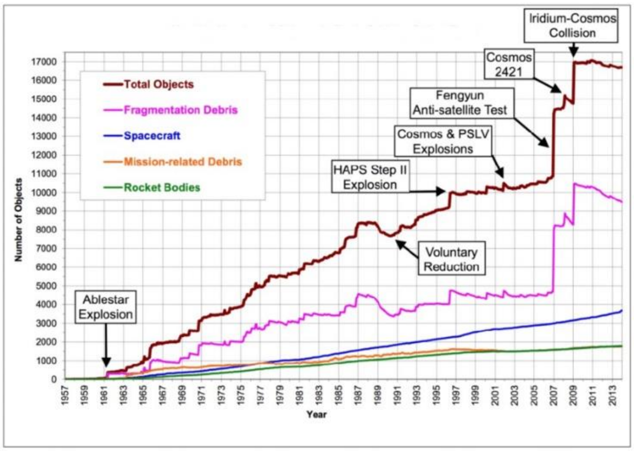

Fig – 4 Graph showing growth of Space Debris over the years

III. Debris Mitigation Standards

Today's orbital debris mitigation standards are the result of a gradual evolution on both domestic and international fronts. The current U.S. guidelines were developed in the late 1990s in a collaborative effort between the Department of Defence (DOD) and NASA, and adopted by the National Security Council as national guidelines in December 2000.1 Immediately thereafter, the U.S. began the long process of gaining international acceptance of the guidelines to encourage existing and emerging spacefaring nations to use best practices that would help control the growing debris problem. This effort was eventually successful in establishing voluntary international guidelines very similar to those followed by the United States.
Global adoption of best practices for mitigation is ongoing, but even broad success in this area would not

provide a full solution to the debris problem. The next step, removal of debris, has been discussed for decades without advancing to the implementation stage due to technical and affordability limitations. Policy and international law concerns were identified, but these remained in the background as the formidable technical challenges pushed the testing and deployment of remediation systems well into the future.

Advances in robotics, satellite bus design, automated rendezvous and docking, and low-mass orbital maneuvering systems, coupled with a variety of efforts to reduce launch costs, may make debris remediation practical in the next 10 to 15 years. Using the same technologies, commercial space operators have demonstrated an interest in developing satellite servicing capabilities in even shorter timeframes.[2,3] Meanwhile, NASA conducted risk-reduction demonstrations for satellite refueling aboard the International Space Station starting in 2011[4] and in December 2016 awarded a contract for a satellite servicing demonstration spacecraft, Restore-L, to be flown in 2020.[5] If practical technological solutions are starting to appear on the horizon, it’s not too early to give attention to hurdles in policy and international law that need to be surmounted if remediation efforts are to be successful. The two most significant hurdles are 1) international law that treats salvage in space differently from salvage at sea, and 2) remediation technologies and operations that look like and could double as anti-satellite (ASAT) systems.

IV. Modeling the Long-Term Evolution of Orbital Debris

Current space missions around the earth have to deal with a problem mostly ignored just 25 years ago: man-made orbital debris. Besides the more than 9,000 objects (50% of which are break-up fragments) routinely tracked by the U.S. Space Surveillance Network, typically larger than 10-20 cm and with a combined mass exceeding 5,000 metric tons, the circum-terrestrial space is populated by a very large amount of smaller particles, down to sub-millimeter sizes, which is continually being replenished by international space activities.

While the impact of large objects is potentially able to induce catastrophic fragmentations, particles in the millimeter and centimeter size range can severely damage critical spacecraft sub-systems. A cost-effective shielding against millimeter-sized debris is sometimes feasible, but avoiding penetration following the impact of a particle close to one centimeter is considerably more difficult and expensive. The best approach to investigate the future evolution of orbital debris and the practical effectiveness of mitigation measures is to develop models and software codes able to realistically describe the relevant physical processes (orbital dynamics, air drag, on-orbit explosions, slag discharge from solid rocket motors, collisions, surface degradation, etc.) and the operational practices connected to the space activities in orbit around the earth.

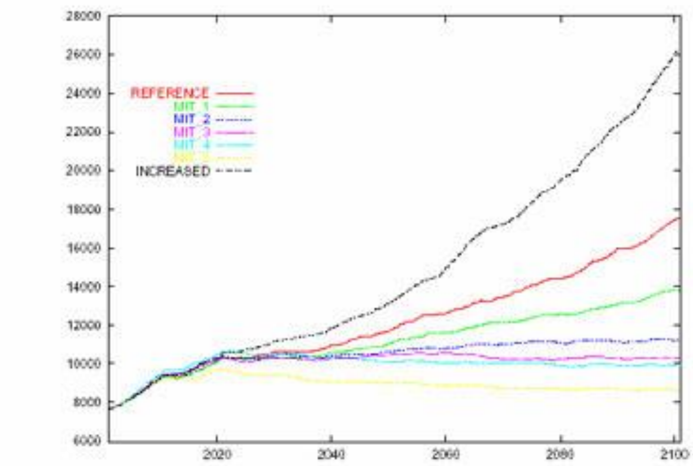

Fig - 5 Long-term evolution below 2000 km of the number of objects larger than 10 cm

Figure 5 shows the long-term evolution, below the altitude of 2000 km, of the number of objects larger than 10 cm, according to different mitigation scenarios investigated with SDM. Each line was obtained by averaging twenty Monte Carlo runs. The reference case is characterized by the current launch activity, taking into account the phasing out of obsolete launchers and the introduction of new rocket families. Mission-related objects are released according to present practices, while break-up prevention measures are progressively introduced, leading to no more explosions after 2030.

V. Collision Probability Analysis and Application of Catalogued Space Debris

.Since the neglect of the space debris environment in the past century, the total number of orbital space debris increases rapidly, which leads to an unacceptably large risk of collision to spacecraft. Space Debris Collision Avoidance (SDCA) is the only strategy to reduce the risk of collision when the dimension of space debris is larger than 10cm. The decision whether the avoiding maneuver is necessary depends on the analysis of conjunction, the rigorous calculation, and assessment of collision risk between spacecraft and debris and compare to the collision criterion. Collision probability is a new type of warning criterion, which not only takes the distance into consideration but regards all the geometrical parameters during the approach as the factor to the collision risk, combining with all influence of these parameters.

Eventually, with the detailed analysis, the effect of the covariance or uncertainty to the collision probability has been drawn to the surface, which plays an indispensable role in measuring the risk of collision. The attitude of the error ellipse which is constructed by the covariance has also affected the result of collision probability. Based on the analysis of covariance, the method of collision probability posts many advantages to the Box method. Especially, the rate of false warning has been decreased dramatically.

A general method for calculating spacecraft collision probability is developed. In this method, the input required to perform a calculation includes the respective state vectors, position error covariance matrices and physical sizes of objects involved. The method is valid for the general case because it only relies on the general form of error covariance matrices. The relative velocity is assumed to be a vector having constant direction, and then the collision probability problem can be reduced to two dimensions in encounter plane normal to the relative velocity vector by eliminating the dimension parallel to the relative velocity vector. Three kinds of method resolving the two dimensions problem are developed and compared. Test case results indicate the method is valid and applicable. To evaluate the probability of collision the *Cube* approach is followed. The Cube approach samples uniformly in time rather than space and is thus compatible with any orbital evolution simulation as it does not impose assumptions on the orbital geometry. This is particularly important in LEO, where orbital progression is significant in the considered time frame. The SGP4 orbital propagator is used to calculate the evolution of the ephemerides (i.e., position and velocity) of an orbiting object given its TLE description. Ephemerides of all objects are calculated at regular time intervals. Space is then partitioned by a regular 3D-lattice and for any pair *i*, *j* of objects that fall into the same volume, the collision probability is evaluated as follows:

$$P_{i,j}=s_i s_j V_{rel} \sigma U,$$

Where $s_i = s_j$ are the spatial densities of object *i* and *j* in the cube, $\sigma = \pi (r_i + r_j)^2$ is the cross-sectional collision area, V_{rel} is the collision (relative) velocity of the two objects, and *U* is the volume of the cube. For each pair, a pseudo-random number *x* is generated from a uniform distribution over the interval [0, 1]; if $P_{i,j} > x$, a collision event is triggered.

The NASA standard breakup model is used to generate a population of fragments resulting from a collision event. The NASA/JSC breakup model is a widely accepted stochastic model of the fragmentation process of in-orbit collisions and explosions based on multiple ground-tests and radar observations of past events. The model provides distributions for size, mass and ejection velocity of the fragment population parametrized by total mass and collision velocity of the parent objects. The number of fragments larger than a characteristic length-scale follows a power-law, the area-to-mass ratio follows a multivariate normal distribution, and the ejection velocity is sampled from a log-normal distribution. For each sampled fragment, a new TLE entry is created using the fragment's osculating elements, and add it to the population of objects being propagated. Although the breakup model also covers explosions as well as non-catastrophic collisions, only catastrophic collisions (i.e., events leading to complete disintegration) are considered in this work.

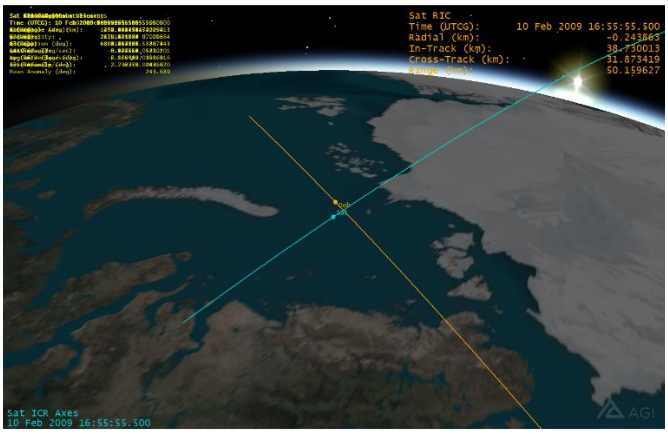

Fig – 6 Simulation of collision and data analysis

VI. Space debris removal using a bi-directional plasma thruster

Orbiting space debris has an angular momentum where the centrifugal force is balanced against the gravitational force and a constant altitude is maintained if no drag forces act on the debris. Most of the contactless concepts (laser-ablation and IBS) have proposed imparting a force to the debris thereby decelerating them in a direction opposite to their velocity to transfer them to a lower altitude where they finally re-enter the Earth's atmosphere and naturally burn up. In the case of imparting a force to the debris by plasma ejection from a satellite using an electric propulsion device, such as the IBS method, the satellite is simultaneously propelled in the opposite direction, making it difficult to maintain the distance between the debris and the satellite. The IBS proposal would require two ion-gridded thrusters on the satellite, one of which imparts a force to the debris and another balances the thrust by ejecting plasma in the direction opposite to the debris.

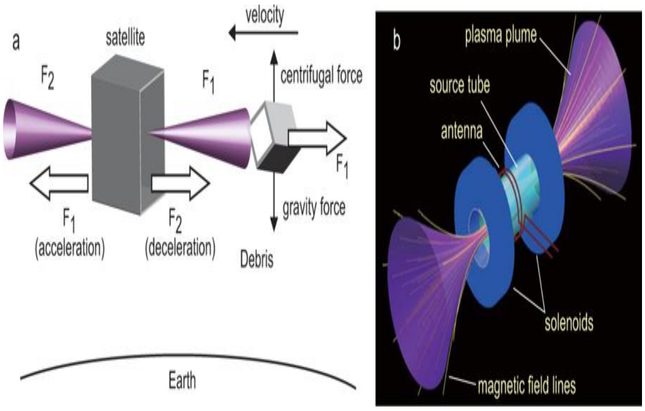

Fig – 7 Demonstration of Space debris removal using a bi-directional plasma thruster

In general, the thrust is given by the rate of the change of momentum, corresponding to the flux of momentum ejected from the satellite, which can be derived from the momentum conservation law. Considering the ejection of plasma having momentum flux F_1 and F_2 to the right and left sides of the satellite, the net thrust exerted on the satellite and the force on the debris are given as $(F_2 - F_1)$ and F_1, respectively, where the positive force is defined as the rightward direction. According to an analysis, a deorbit time of between 80 and 150 days for a 1 to 2-tonne object would require a thruster performance of about 60 mN and a specific impulse of about 1800 sec. A similar analysis performed has also shown similar requirement of about 30 mN thrust at 2.5–3 kW power level and discussed the beam divergence effect on the momentum transfer efficiency to the debris, considering a safe distance to the debris to be about 7 m, where typical beam divergence for the ion gridded thrusters and the Hall thrusters are about 10–20 and 40–50 degrees half angles, respectively. Therefore, the active removal of the large size debris clearly requires the high power electric propulsion device operated at the thrust level of several tens of mN at the power level of about a few kW.

In the present study, a bi-directional plasma ejection from a magnetic nozzle of plasma thruster having two open sources exists is demonstrated in a laboratory experiment, where both the forces exerted on the thruster and a target plate simulating the debris are simultaneously measured. The measurement shows that by a judicious selection of experimental parameters, the force decelerating the debris can be imparted to the target while maintaining a zero net force on the thruster. This is accomplished by varying either the magnetic field configuration or propellant gas flow rates using two gas inlets located left and right of the source center. Consequently, the presence of plasma thruster can produce all three required operational modes in ONE electric propulsion device; the debris removal mode, the acceleration mode and the deceleration mode of the satellite, the latter two being useful for adjusting the satellite velocity relative to the debris.

The proposed thruster can be scaled up in size. The previously reported maximum value of the thrust imparted by the single open end thruster has been about 55–60 mN for about 6 kW rf power, where the source diameter is 9.5 cm and larger than a 6.5-cm-diameter source tube used in the present paper. More recent experiments show a higher performance giving a thrust of 65–70 mN for about 6 kW rf power with a specific impulse of 2000–3000 sec in the laboratory test, where the location of the gas injection port is changed and the thruster efficiency is increased up to 20%. It is found that a 30 mN thrust level can be obtained with rf power less than 1.5 kW and a specific impulse of 1500 sec. It should be mentioned that the thruster operates using Argon, which has a cost advantage. Furthermore, very efficient rf amplifiers and impedance tuning systems are also now under development.

VII. Net Capturing Method

In 1999, on-orbit satellite capture experiments have been carried out successfully by the ETS-VII satellite. Pearson et al. introduced a low-cost solution for LEO space debris removal which is called ElectroDynamic Debris Eliminator (EDDE). This kind of capture uses lightweight expendable nets and real-time man-in-the-loop control. Authors claimed that “EDDE can affordably remove nearly all the 2,465 objects of more than 2 kg that are now in 500–2,000 km orbits”. It is a flexible connection debris capturing technique which uses a canister to eject the net which is thrown on the target to transport it to the graveyard orbit [20]. The net is pulled open by the inertia of the masses in the corner having relatively higher mass compared to that of the net. This method has several advantages over other methods such as allowing larger distances for capturing, close rendezvous and docking is not necessary, one of the cheapest method, and no necessity bulky components. The European Space Agency (ESA) has performed several system studies for orbital servicing, such as ROGER, Conexpress, or MART-OLEV for servicing GEO satellites, as well as CDF studies on active debris removal of large objects. ESA is studying the option of using a tethered capture system for controlled de-orbitation through pulling where the capture is performed using throw nets or alternatively a harpoon.

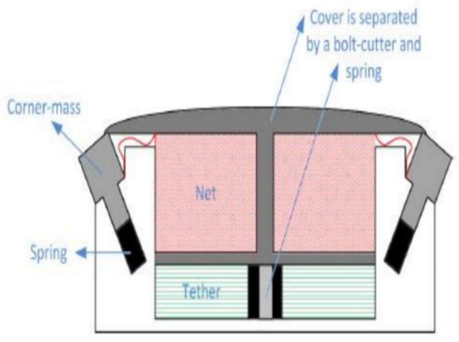

Fig – 8 Net ejection technique

VIII. Scope of Improvement

The key technological requirement for debris removal by electric propulsion is the control of the acceleration and deceleration of the satellite, which can be performed by adjusting the bi-directional plasma ejection. However, mounting two propulsion systems on the satellite will increase its development risk and make the satellite system integration more difficult due to weight and size considerations, which include the propulsion devices themselves, their power supplies and other necessary components.

For long-term operation of satellite for space debris removal, the lifetime of the propulsion device is one of the most important considerations. Operations of the ion gridded thrusters and the Hall thruster are known to be significantly affected by erosion of the electrodes and walls exposed to the plasma, especially for their high power operations.

IX. Conclusion

Human civilization has been the cause for various environmental changes in the earth and now it has also extended to the outer space. It is the sole responsibility of people to address the serious issue of space junk in the LEO. According to the available data on the amount of space debris and other celestial objects, the odds of a collision in space is one in every 4 years.

It is very dreadful to know that to date, no countries have carried out any field activity in debris management, even after repeated awareness in the global forum. The unavoidable need for a comprehensive management strategy for this issue is addressed in this paper.

This paper has listed out all the possible solutions for debris management and an extensive analysis has been carried out on the feasibility of these methods.

A hierarchical approach was carried out in the analysis of the various methods of debris management keeping in mind the history of space debris and their intimidating impacts. Nevertheless all these methods have bouquets and brickbats of their own, and a thorough analysis is to be carried out in prioritising these methods when they are implemented. Although researches are being carried out in various fields of debris management, a complete relief from the threat can only be achieved by curbing the addition of more junk into the space, and this is possible only when all the players in the space research industry cooperate voiding all the differences. With the increasing rates of pollution in the ground level, at least the atmosphere should be left clean for the future generation.

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