Removal of Active Man-made Orbital Debris – A Great Challenge to Space Scientists

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Abstract: ***After more than fifty five years of space activities, the sky above the Earth being highly polluted with orbital debris, has become the cause of serious concern for safe placement of satellites in the desired orbits as well as in their safe functioning. Orbital or Space debris are the fragmented parts of nonfunctional satellites and used rockets orbiting the Earth at speeds of up to several kilometers per second. Satellites are placed in different orbits for performing different functions, majority of which are at Low Earth Orbit (LEO) up to altitude of 2000 kilometers, some are in Geostationary Earth Orbit (GEO) up to altitude of 36000 kilometers and few are also in High Earth Orbit (HEO). More than 7000 man-made objects launched in various orbits around the Earth since the dawn of space age, about 2/3 rd of these are in LEO. It is estimated that there are now roughly 5 lakh pieces of orbital debris available of which nearly 3.7 lakhs debris present in LEO are of the size between 1 cm to 10 cm while nearly 22000 debris are of the size greater than 10 cm. Due to high impact speed in space, even sub millimeter debris poses risk of collision and severe damaging of the satellite placed already in orbit or to be placed in future. Since the risk of collision is growing super-linearly due to 'Kessler Syndrome' and is of great concern to all satellite operating nations, sincere effort to reduce orbital debris is getting importance. Active removal of existing large objects like non-functional space craft and residues of lunch vehicle from orbit at least five numbers per year can prevent future problems. There are substantial technical, economic, political and legal barriers to develop, deploy and operate active debris removal systems. Hesitation arises due to similarities between space debris removal systems and space weapons. The system which can remove the nonfunctional space object from the orbit can also remove the useful one of others. Efforts are going on to develop different debris capture systems to reduce debris accumulation in almost all orbits, from low to geostationary altitudes. Space scientists have to face a great challenge for smooth running of their space program. All space-faring nations have to reach a Consensus on Active Debris Removal (ADR), Cooperate for removal of debris of space craft of different countries, Collaborate like a single entity to achieve the goal and Contribute in cost sharing for preserving the space for future generation.***

Keywords: Active debris removal, Kessler syndrome, Low Earth Orbit, Orbital debris, Space debris

1. Introduction

With the launch of Sputnik – 1 satellite by Soviet Union in 1957 into sky orbit, the space has become an essential resource for science as well as for public and commercial utilization, and satellites have become an integral part of human society due to their critical role in information and entertainment sectors, telecommunications, navigation, meteorology, remote sensing, commerce, national security, etc. Human beings are gradually becoming heavily dependent on space technology in their day-to-day activities. Global Positioning System (GPS) precision timing and navigational signals are a significant component of the modern global economy; a GPS failure could disrupt emergency response services, cripple global banking systems, and even interrupt electric power grids [1]. Today over 900 active satellites, operated by both State (Government) and non-State (Private) sectors are playing important role to serve the mankind. The Figure 1 represents the Orbital spacecraft launched by different countries during 2001 to 2010 [2]. For avoiding initial space race between USSR and USA 'The Outer Space Treaty of 1967 (OST)', the International Space law unambiguously declares that the outer space being as universal commons must be free for exploration and use by all states and further prohibits the appropriation of space or celestial bodies by any single nation [3]. Unfortunately, the decades of unrestrained space activities have left behind an undesirable byproduct – orbital debris, a great threat to current and future space activities.

2. Basics of Orbital Debris

Orbital debris, better known as Space debris or Space junk is the remaining refuse of more than 7000 man-made objects launched into orbits since 1957. It includes non-functional satellites, discharged rocket components, loose nuts and bolts, space tools lost by astronauts and even flecks of paint from space craft, etc orbiting around the earth [4]. Figure 2 presents the generation of huge amount of waste during launching of a single satellite [5]. Size and mass of debris are two important characteristics for classification. This debris ranges in mass from few grams to tons and in diameter from few millimeters to several meters (Table 1). Fragments exist from 100 km to more than 36000 kilometers above Earth's surface. Satellites are placed in different altitude and different orbits according to their purposes. Most of the early launched satellites were placed in the low earth orbit (LEO), with a maximum altitude of 2000 kilometers. Currently many countries are placing their communication satellites in geostationary earth orbits (GEO) at around 36000 kilometers. The orbits in between LEO and GEO are known as high earth orbit (HEO). Since the space activity carried out by mankind is mainly in both LEO and GEO, the density of space debris is also more in these two orbital zones.

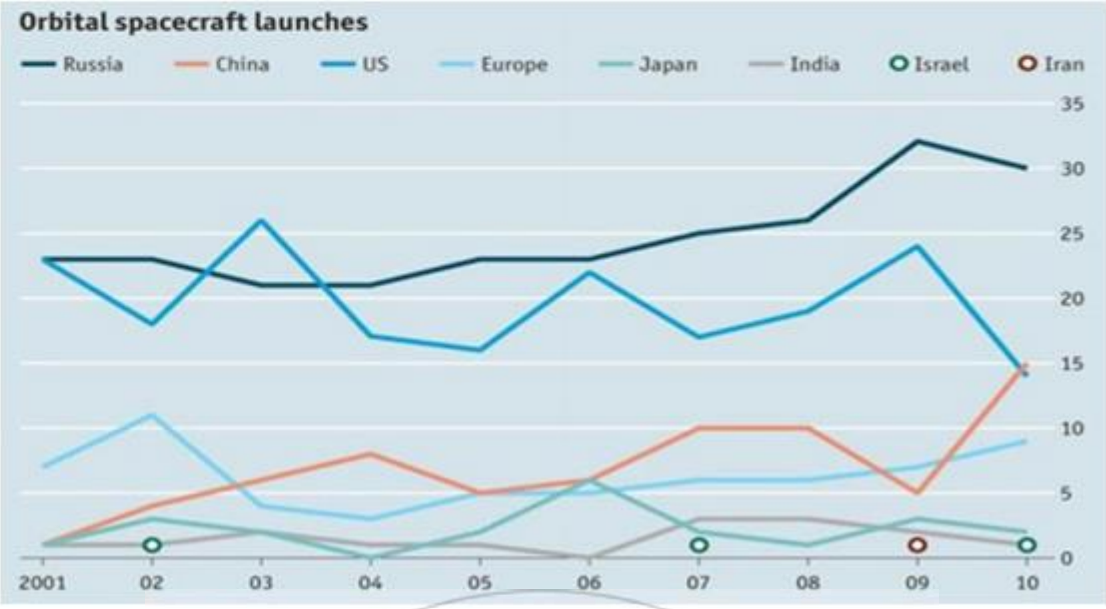

Figure 1: Orbital Spacecraft launches by different countries during 2001 – 2010

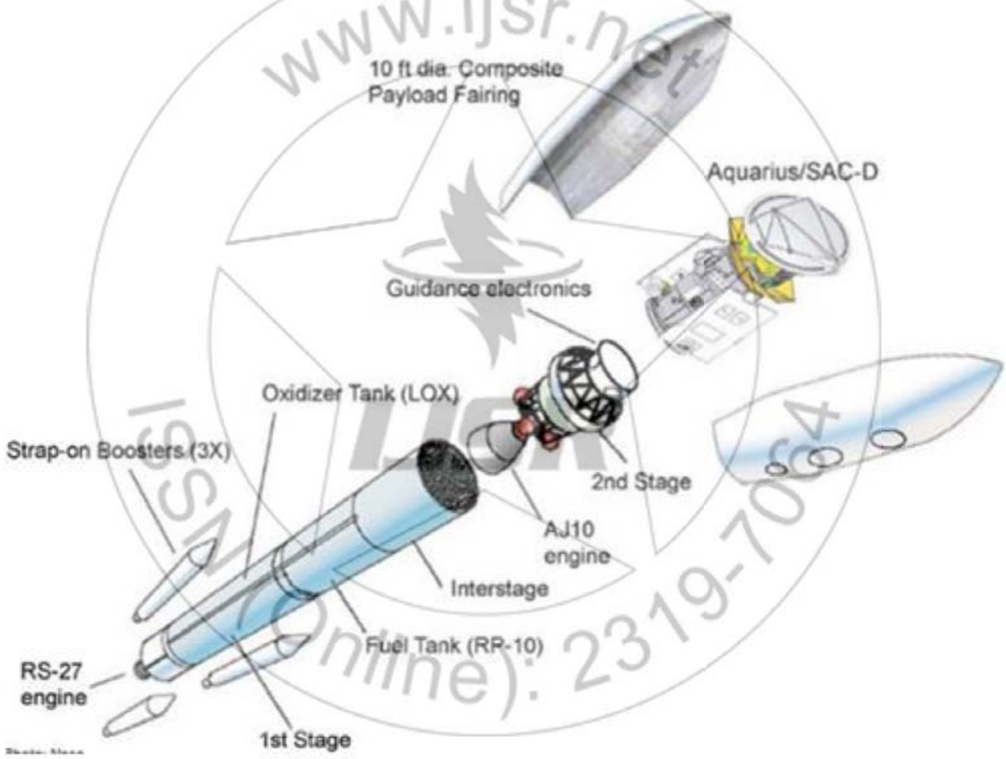

Figure 2: Generation of debris from launching of a single satellite

About two third of currently active satellites are working in LEO. It is estimated that there are nearly 5 lakh debris in the LEO of which nearly 3.7 lakh debris are of the size between 1 cm to 10 cm while nearly 17 thousands debris is of the size greater than 10 cm. HEO accounts for around

Table 1: Classification of orbital debris as per diameter and mass

Size of debris	Spacecraft categories	
1) Small – 1 cm or smaller	i). Pico - < 5 kg	iv). Mini – 100 to 500 kg
2) Medium – 1 cm to 10 cm	ii). Nano – 5 to 20 kg	v). Medium – 500 to 1500 kg
3) Large – 10 cm or larger	iii). Micro – 20 to 100 kg	vi). Large - > 1500 kg

40 thousands debris. The number of debris is very less in GEO but of bigger size, mainly satellites [6]. As of January 2012 the U. S. Space Surveillance Network (SSN) has tracked through powerful radars and cataloged 22 thousands debris objects of $\geq$ 10 cm size. The current total mass of materials orbiting the Earth is close to 6300 tons and 43% of it (2700 tons) is in the low Earth orbit (LEO), 97% of which belongs to space craft and rocket bodies. The three major peaks as shown in Figure 3 located near 600, 800 and 1000 kilometers indicate that the distribution of mass is not

uniform. The 600 – kilometer peak is dominated by space craft while other two peaks are dominated by rocket bodies [7].

The man-made space objects or its debris can either (i) reenter the earth's atmosphere due to natural orbital decay caused by 'Atmospheric Drag' (a phenomenon of frequent collision between the gas molecules of the atmosphere and the debris) or 'Tidal Effects' (Impact of tidal force created by orbiting body on debris body to push down the orbit), or (ii) remain in earth orbit, or (iii) escape from earth orbit into deep space. According to 1999 updated report of Space Debris Subcommittee of International Academy of Astronautics, France the Earth's atmosphere produces drag forces that retard an orbiting object's motion and causes it to spiral into denser regions of the atmosphere where it typically burns up due to air friction effect. But the effect of this natural removal mechanism of debris decreases with orbital altitudes of the debris as shown in Table 2 [8]. Unfortunately the debris present in altitudes higher than 1000 km will stay for 100 to millions of years, resulting steady accumulation of debris mass. Three countries in particular are responsible for roughly 96 percent of the fragmentation debris currently in Earth's orbit : China (43 %), USA (27.5 %) and Russia (25.5 %) [9].

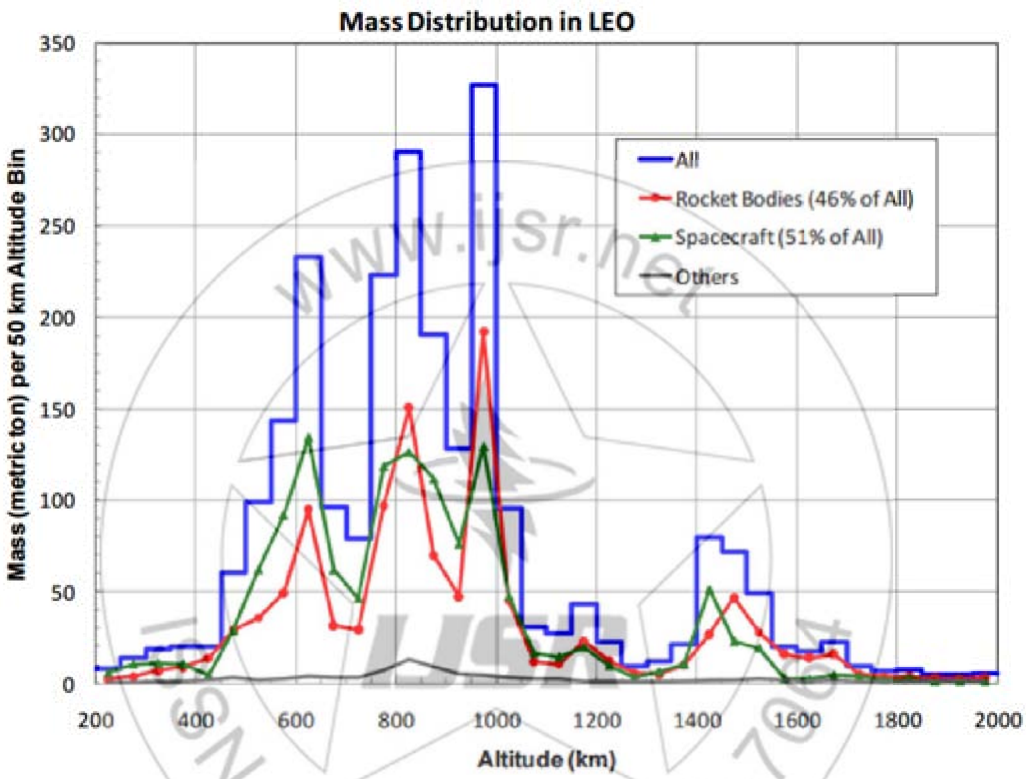

Figure 3: Distribution of Mass of Space objects in low earth orbit (LEO)

3. Problems of Orbital Debris

Since orbital debris of different sizes are moving in orbits around the earth in a non-controllable condition they become a potential risk to satellite launch program. The category of debris with their potential risk to satellites is given below in Table 3 [10]. Debris larger than 10 centimeters can incapacitate any satellite but those can be avoided being large enough to be tracked. Debris in the 1 – 10 cm size range, though too small to be tracked by operational radar system and to be sensed by most ground system, are large enough to cause serious damage to many satellites. These most dangerous pieces of debris poses an invisible threat to operating satellites. There is no practical method for shielding spacecraft against them [11]. In LEO the average relative velocity between any two orbiting objects is about 10 km/sec. At this speed an 80 g object (about 5 – 10 cm size) introduced the kinetic energy equivalent to 1 kg TNT (Tri nitro toluene, an explosive). For a typical LEO satellite of mass 500 – 1000 kg, a 1 kg object would probably completely destroy it upon impact (IAA

Table 2: Life times of objects in lower earth orbits of different altitude

Orbit altitude (km)	*Life time of objects*
200	1-4 days
600	25-30 years
1000	2000 years
2000	20000 years

Table 3: Category of orbital debris with potential risk to satellites

Category	Size of debris	Estimated population	Potential risk to satellites
Trackable	> 10 cm in diameter	22000 +	Complete destruction
Potentially Trackable	> 1 cm in diameter	Several hundred thousands	Complete to partial destruction
Untrackable	< 1 cm in diameter	Many millions to billions	Degradation, loss of certain sensors or subsystems

Report, 1999). Orbital debris smaller than 1 cm , in contrast, cannot be tracked or avoided, but those may produce mission degrading effect on spacecraft which they encounter. However, space craft can be protected against these smaller debris by using relatively simple shielding [11]. During 1992 – 1998 about 236 encounters could be identified on the US Shuttle orbiter windows. Small particle impacts on the Shuttle required replacing on average one of the eight main windows after each flight.

Another threat posed by orbital debris is the falling back of space objects on earth over populated areas. Majority of those objects, being of small sizes are burnt during reentry due to friction with the atmosphere, but some of them (e.g. Skylab, Cosmos 954, Salyut 7 / Cosmos 1686, Delta II second stage, etc.) do reach the surface of the earth (Table 4). Apart from this, some satellite carry very dangerous matters and this could cause indirect casualties and pollute an environment long after their initial crash. Everyday fragments of satellites and rocket stages enter into the denser layers of the atmosphere where they usually burn up. At that altitude the space craft fragments move with a typical velocity of 28000 km/hour. Friction with the atoms and molecules of upper atmosphere heats up the spacecraft or its fragments which ultimately melt up and evaporate. In case of very solid and massive spacecraft parts (mass of several tons), the melting and evaporation will not be complete and fragments of the vehicle may reach the ground [8]. The orbit of reentering spacecraft is strongly perturbed by atmospheric forces. Since the air density in the upper atmosphere depends on several factors, such as solar and geomagnetic activity, which cannot be predicted precisely, the prediction of reentry of debris are of limited accuracy. Orbital debris did not receive much attention until the mid 1970s. The series of Delta 2nd stage explosion events (First break up in December 1973) proved to be the catalyst for major research activities in the area of orbital debris. The remarkable space events like (i) the damage of functioning French satellite CERISE with a fragment from an Ariane Rocket body in July 1996, (ii) destruction of Chinese Fengyun-1C satellite with Anti satellite missile (ASAT) on January 11, 2007, (iii) accidental collision between an active Iridium 33 satellite and a defunct Russian military satellite Cosmos 2251 on February 10, 2009 and (iv) carrying out 13 debris avoidance maneuvers during 1999 to 2011 by National Aeronautics and Space Administration (NASA), USA to avoid potential collisions between International space station (ISS) and pieces of space debris, etc have raised a alarm to space faring nations, space operators, academics, politicians and other space activity stakeholders. The Chinese ASAT test was the largest debris creating event in history, producing at least 150,000 pieces of debris larger than 1 cm spread into near polar orbits ranging in altitude from 200 to 4000 km. Similarly the accidental collision in 2009 also created two debris clouds holding more than 200,000 pieces of debris larger than 1 cm at similar altitudes to those of 2007 Chinese ASAT test [5]. In 1978, Donald J. Kessler predicted that by the turn of 21st century, the growth of debris population in low earth orbit (LEO) would have become self fuelling as a result of random debris-debris collisions and would potentially become exponential [12]. The accidental collision in 2009 supported 'Kessler Syndrome". The National Research Council of USA also suggested in its 2011 report that Space might be just 10 or 20 years away from severe problems [4]. The projected growth of the future debris population for the next 200years on the basis of LEGEND model developed by NASA Orbital Debris Program Office is shown in Figure 4 [7]. Considering nominal launches and no debris reduction measure, the effective number of debris ($\geq$ 10 cm) in future will be very high in LEO (200 – 2000 km altitude), however the population will not b e severe in MEO or HEO (2000 – 35,586 km altitude) and GEO (35,586-35,986 km altitude).

Table 4: Reentered space craft with reentry locations

Date of Reentry	*Spacecraft/ Rocket name*	*Type of vehicle*	*Mass in orbit (tons)*	*Reentry location*
January 1978	Cosmos 954	RORSAT	4 tons	Canada Great Slave lake.
July 1979	Skylab	Space Station	77 tons	Indian Ocean, Australia
February 1991	Salyut -7/ Cosmos 1686	Space Station	40 tons	Chile, Argentina
January 1997	Delta II 2nd stage	Upper Stage	1 ton	Texas

4. Avoidance of Debris during Space Operation – A Costly Affair

Considering natural orbital decay of debris different space operators did not pay much attention on this problem. According to Kurt [4], the initial launches of numerous spacecraft have been delayed because of the presence of space debris in the planned flight paths. Any delay automatically increases the cost of operation. In 2012, the International Space Station (ISS) performed a trajectory – changing engine – burn to avoid a small piece of debris. Such a maneuver is, no doubt, costly but necessary to avoid the devastating damage to space station. Adding protective shields to satellites can minimize the damage from very small pieces of debris. Shield itself is expensive affair and it increases weight to satellite which thus requires more fuel for operation – a cost increase that is born over the lifetime of the spacecraft. As the amount of debris in space grows, the preventive measures required to conduct activities in space will, therefore, greatly increase the cost of such operations.

5. Reduction in Orbital debris population- a challenge

Every space operator realizes the problem of orbital debris in future launching of satellites but no significant progress on forming a universal guidelines has been achieved so far. Two complementary approaches : Mitigation (Preventive measure) and Active debris removal (ADR), are advocated by the scientific community. Mitigation refers to reducing the creation of new debris, while removal refers to either natural removal by atmospheric drag or active removal by man-made systems. In 2007, the United Nations General Assembly endorsed the Space Debris Mitigation Guidelines of the 'Committee on Peaceful Uses of Outer Space'

(COPUOS). In this procedure, the satellite materials and its launching system will be such that less and less debris will be generated. More emphasis has been given on tracking the orbiting objects to avoid possible collision by identifying orbital debris in the path of satellites or spacecraft. New systems are being developed for tracking the location of objects as small as a softball present within one meter using laser technique [13]. Mitigation Guidelines are completely voluntary and not enforceable. While NASA and the European Space Agency have adopted the Mitigation Guidelines but China's ASAT test was a blatant violation of this guidelines. Issues like drafting the treaty, methods of implementation, monitoring and compliance measures, etc are some of the obstacles always faced to form the international convention on mitigation program.

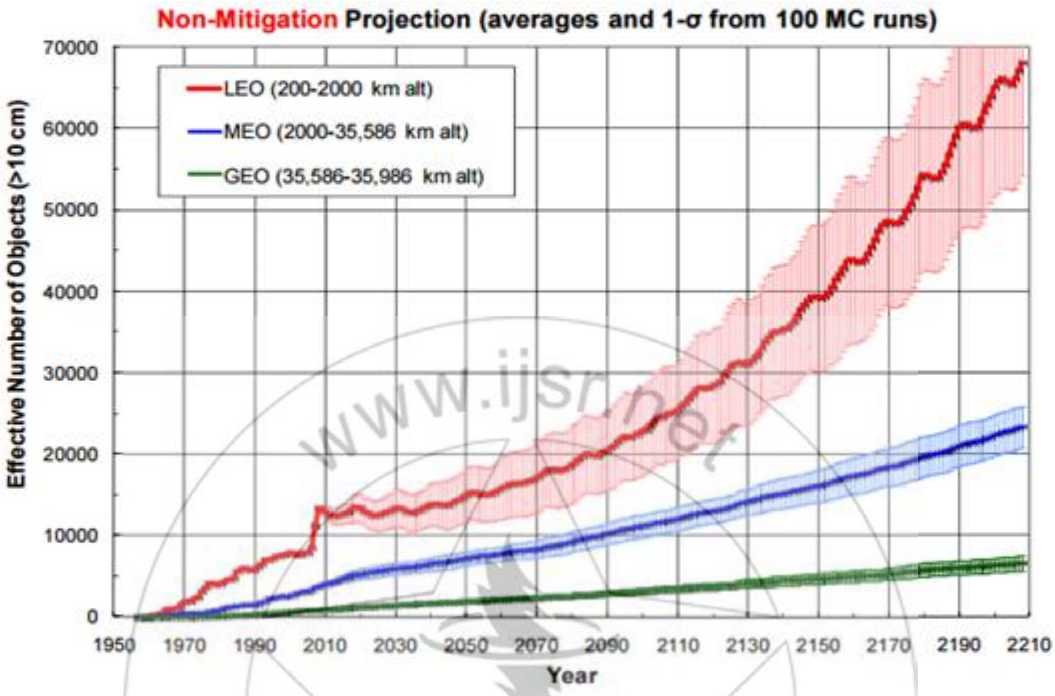

Figure 4: Projected growth of > 10 cm populations in different orbital zones

Active debris removal techniques will help to reduce the space debris either by collecting larger objects from the orbit or by provoking atmospheric reentry of smaller debris and subsequent combustion. There is currently no man-made space debris removal system in operation. The feasibility of numerous active debris removal (ADR) devices like electro-dynamic tethers, solar sails, drag augmentation devices, orbital transfer vehicles, and spaced based lasers, etc are under evaluation. These devices will be very expensive to produce and also have their own benefits and drawbacks. Foust [14] suggested to launch twelve electro-dynamic tethers weighing each one hundred kilogram as secondary payloads to stabilize the population of ≥ 10 cm debris in low earth orbits within five years. Kaplan [15] mentioned about different debris capture techniques like (i) Micro remover tether-extensible gripper with foldable arms suggested by Nishida et al., [16]; (ii) FREND 3 arm system for autonomous unaided grappling suggested by Kelm et al., [17]; (iii) Ranger 8 DOF human – scale grappling arms described by Akin [18]; (iv) OctArm tentacle manipulators suggested by Trivedi, et al.[19]; and (v) ROGER net-based capture concept described by Starke et al. [20], etc. Johri et al. [6] suggested that a mechanical offshoot / arm installed on a satellite would be able to remove multiple debris of size range 10 cm to 100 cm by exerting force and deorbiting those towards earth atmosphere. Attaching a drag enhancement device, such as an inflatable balloon to a debris object is another potential low cost option to deorbit massive ADR targets, causing it to decay more rapidly over time [7].

The simulation study by NASA showed that space debris pieces having masses of 1000 to 1500 kg and 2500 to 3000 kg with orbital inclinations of 70 to 75, 80 to 85 and 95 to 100 degrees, and orbital altitudes of 800 to 850, 950 to 1000 and 1450 to 1500 km were more dangerous than others. Removal of five of these objects per year from LEO zone would help to stabilize the population of debris at a level similar to the current environment [21]. It is also possible to maneuver LEO debris to high altitude graveyard orbit above 2000 km altitude. But this option is not a long term solution. The cumulative debris mass eventually will create a new environment problem (via collisions) in the graveyard orbit and affect other operational regions.

There are substantial technical, economic, political and legal barriers to developing, deploying and operating active debris removal system. Quick development and deployment of cost effective proven technologies can help to remove technical and economic barriers. Political barrier can be removed by building a trust among space faring nation on use of ADR technology for removing orbital debris only, not the active satellites from orbit. Major concern is the similarities between space debris removal systems and space weapons. Any system that can remove a useless object from orbit can also remove a useful one. It should be mandatory to take consent from the appropriate country before any space object is removed from orbit. Legal requirement should ensure compliance of space rules by all space faring nations. Successful implementation of ADR depends on four critical

'Cs' : (a) **C**onsensus on ADR, (b) **C**ooperation between different space faring nations for removal of debris, (c) **C**ollaboration between all space operators for achieving the goal, and (d) **C**ontributions or Cost sharing in ADR program [7].

6. Conclusion

Orbital debris has been emerged as a global problem and needs every nation's support to reduce debris population in low earth orbit zone. The commonly adopted mitigation measures will not be sufficient to fully control the debris population. Active debris removal program has two modes of operations : one for collection of larger objects and other for elimination of smaller debris. In the long term, debris control programs will have to address debris accumulation in almost all orbits, from low to geostationary altitudes. United States of America has to take leadership in ADR since it owns about half of the existing active satellites in orbits and loss of satellite service due to orbital debris will hamper the US Administration as well as military service activity. Implementation of 4 'C's is the 'need of present era' in International arena for achieving success. Active debris removal, though a great challenge to Space Scientists, is must to preserve space for future utilization.

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