Indian Journal of Radio & Space Physics
Vol. 46, March 2017, pp. 20-26

Space debris: Reasons, types, impacts and management

Habimana Sylvestre[a]* & V R Ramakrishna Parama[b]

[a]University of Rwanda, P.O. Box 4285, Kigali, Rwanda

[b]University of Agricultural Sciences Bangalore, Bengaluru 560065, India

Received 24 October 2016; revised 14 February 2017; accepted 5 July 2017

Space debris consists of millions of pieces of man-made material orbiting the Earth at speeds of up to several km s^{-1}. Although, the majority of these fragments result from the space activities of only three countries, viz. China, Russia, and the United States, yet pose a continuous threat to all assets in Earth's orbit. Debris poses a growing threat to satellites and can prevent the use of valuable orbits in the future. Many pieces of debris are too small to monitor but too large to shield satellites against. Based on increase in space debris, certain measures have been taken to address this global issue. In particular, internationally adopted debris mitigation guidelines are reducing the introduction of new fragments into Earth's orbit. However, there is a growing consensus within the space debris community that mitigation is insufficient to constrain the orbiting debris population. Also, ensuring a safe future for space activities will require the development and deployment of systems that actively remove debris from Earth's orbit. In this context, efforts have been made to present the reasons and origin of space debris, their types and impact and the management strategies, which can be taken into consideration in preserving the near-Earth space environment from the impact of the junks in orbit.

Keywords: Space debris, Debris management, Debris mitigation

1 Introduction

1.1 Space debris and orbit

Space debris is any type of space object that is man-made, no longer in active use, and in Earth's orbit. This can be either an out of mission entire spacecraft, launch vehicle or a fragment of them, or any released object or tools lost by astronauts during the mission in orbit activities; and fragmentation events, which can be either accidental or intentional. They are in all sizes, microscopic particles or large size like entire inactive spacecraft. These space debris exist from 160 to 36,000 km above our Earth's surface[1].

The main source of information on space debris is the Space Surveillance Network of the United States, which tracks, correlates and catalogues the objects larger than 5-10 cm in Earth's orbit. Additional data are collected by means of research radars and telescopes in several nations including European Space Agency (ESA) Member States. Some of the observations are coordinated in common campaigns, e.g. within the Inter-Agency Space Debris Coordination Committee (IADC). For small-size debris, most information is deduced from the impact analyses of space exposed surfaces that have been returned by the US Space Shuttle.

*Corresponding author (E-mail: shabimana@gmail.com)

The Earth's atmosphere causes air drag that extracts orbital energy and leads to a reduction in the orbital altitude and final re-entry of a space object. Upper layers of the atmosphere are supported by lower layers, which are compressed under the weight of the air column above them. The air density increases and hence, the increase in air drag with decreasing altitude is progressive.

Changes in air density at a given orbital altitude are mainly driven by the Sun, which varies its activity in a 11-year cycle. Thus, every 11-years, lower parts of the atmosphere are heated and expanded toward higher altitudes, where the air density increases causing higher air drag on objects in space. As a consequence, space debris is periodically cleaned from the lower orbital regions (but these are subsequently re-filled by objects descending from higher orbits).

After sufficient exposure to air drag, the orbit decays and the object re-enters into the denser Earth atmosphere where the air drag converts orbital energy into heat. This heating process is normally sufficient to destroy an object. Approximately 20-40% of the mass of larger-size spacecraft or rocket bodies or parts made of particularly high melting steel or titanium alloys may survive the re-entry.

1.2 Reasons and origin 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%)[2].

In the 1960s, several spacecrafts were intentionally destroyed through self-destruct mechanisms or anti-satellite tests (ASAT). The two worst events in the growth of the space debris population (Table 1) were the deliberate destruction of the Chinese Fengyun-1C satellite (defunct weather satellite orbiting at about 900 km) by missiles launched from Earth on 11 January 2007; and the accidental collision of Iridium 33, an active US communications satellite; and Cosmos 2251, a defunct Russian satellite on 10 February 2009 occurred 800 km above Northern Siberia. They collided at a speed of over 40,000 km h^{-1}, causing complete break-up of both satellites. Those two events added more than 3,300 and 2,200 fragments, respectively to the catalog of tracked objects and perhaps hundreds of thousands of smaller fragments[3].

Operational activities provide the source of much space debris including the largest objects. Nearly 50% of the total mass of space debris derives from spent upper stages that are left in orbit after depositing their spacecraft in orbit. Individually, they are less massive than spacecraft, but present a relatively large cross-section to other space objects. Because upper stages are often placed in high, long-lived orbits; they can become a major source of debris. The exhaust from solid rocket upper stages, which places small particles of aluminum oxide in orbit, can also be considered operational debris. Paint flakes and particles from thermal insulation are also released into space during space operations.

Conducting operations in space has also resulted in the ejection of miscellaneous hardware into orbit. For example, spacecraft are generally separated from their upper stages by explosive devices that may eject dozens of small fragments. In addition, the process of deploying a spacecraft on orbit often involves the release of protective shields, covers, and other incidental hardware items. Even ice from the Shuttle waste management system has been suspected of contributing to orbital debris. Finally, inactive spacecraft that have remained in space beyond their useful lives also contribute to the debris population.

Fragmentation is the most significant source of orbital debris by number. Since 1961, 25 breakups have contributed to more than 100 cataloged fragments apiece; eight events exceeded 240 pieces each. What makes fragmentation such a hazard is the continual spread of fragmentation remnants about the center of mass of the original spacecraft. Fragmentation derives from a variety of causes that fall into three general classes: accidental failures related to the propulsion systems, deliberate actions, and unknown causes.

Propulsion-related failures often produce a striking amount of debris because they result from explosions of the propellant, either while carrying spacecraft into high orbits or in the case of liquid-fueled rockets afterward, because some propellant is left in the stage. Some of the latter explosions have occurred from several months to 3 years after the stages delivered their spacecraft to orbit. The chances of such explosions have been greatly reduced. ESA, Japan and

Table 1 — Ten worst satellite breakups (based on cataloged debris)

Common name	Owner	International designator	Cataloged debris*	Debris in orbit*	Year of breakup	Altitude of breakup	Cause of breakup
Fengyun-1C	China	199-025A	3218	2989	2007	850km	Intentional collision
Cosmos 2251	Russia	1993-036A	1559	1371	2009	790	Accidental collision
STEP 2 Rocket Body	USA	1994-029B	710	58	1996	625	Accidental collision
Iridium 33	USA	1997-051C	567	487	2009	790	Accidental collision
Cosmos 2421	Russia	2006-025A	509	0	2008	410	Unknown
SPOT 1 Rocket Body	France	1986-091C	492	32	1986	805	Accidental collision
OV 2-1/LCS 2 Rocket Body	USA	1965-082DM	473	35	1965	740	Accidental collision
Nimbus 4 Rocket Body	USA	1970-025C	375	245	1970	1075	Accidental collision
TES Rocket Body	India	2001-049D	370	111	2001	670	Accidental collision
CBERS 1Rocket Body	China	1999-057C	343	178	2000	740	Accidental collision
Total			8616	5506			

*As of March 2012 [*Source:* National Aeronautics and Space Administration (NASA), *Orbital Debris Q News,* (2010)][4] the United States now often vent their upper stages following payload delivery.

Deliberate destruction of satellites in space, as opposed to accidental explosion, is another source of orbital debris, most of these have been carried out by the Soviet Union when its military satellites reach the end of their useful lives. Some have come as a result of space weapons testing. A total of 12 breakups are attributed to space weapons tests, which amount to about 7% of the current cataloged debris population. Table 2 lists each weapons test breakup and its impact on the near-Earth satellite population. However, Table 2 does not reflect the total amount of debris produced by these events because small objects cannot be cataloged. Many fragments do not stay in orbit long enough to be cataloged. For example, 381 objects were detected as the result of the Delta 180 Strategic Defense Initiative Organization (SDIO) experiment of 1986, but only 18 were ever cataloged.

Hypervelocity impacts - the high velocity of some space debris relative to spacecraft gives the debris extremely high energy on impact with the spacecraft. Such hypervelocity impacts are much more probable in Low Earth Orbit (LEO), where collision velocities are higher (averaging about 10 km s^{-1}) than in other orbits. Impacts involving relative velocities above about 5 km s^{-1} generate such temperatures and pressures that the impacting materials may vaporize, producing hundreds of thousands of smaller debris objects and gaseous products. Lower velocity impacts create a special problem from a shielding perspective. If the object does not vaporize when it hits the outer shield, and remains relatively solid, successive layers are less effective in stopping it. In lower velocity collisions, all of the ensuing debris is likely to be large. There is no vaporization and hence, no molecular condensation.

The most serious consequence of collisions with space debris is the possibility of a cascade effect or chain reaction, in which debris proliferates as collisions generate more and more debris, independent of any further introduction of man-made objects[5].

1.3 Types of space debris

Space debris, generally, refers to man-made material in orbit that no longer serves a useful purpose. Because of the high speeds of objects in orbit (7.5 km s^{-1} is typical in low earth orbit), even small pieces of debris can be very damaging in a collision. There are several types of debris:

- Defunct spacecraft, such as satellites that have ended their useful life. Commercial satellites have an average lifespan of around 15 years due to the harsh radiation environment in space;
- Spent rocket bodies used to launch satellites into orbit;
- Objects released during missions such as waste vented from the Space Shuttle;
- Small fragments caused by collisions, explosions or deterioration of active satellites or larger pieces of debris[7].

Table 2 — Space weapons tests

Class of breakups	No. of events	No. debris cataloged	No. debris in orbit
Phase 1: Soviet ASAT	7	545	296
Phase 2: Soviet ASAT	3	189	154
P-78 Breakup	1	-	-
D-180 test	1	18	0
Total	12	1,037	488

[*Source*: Johnson Nicholas L & Nauer D, History of on-orbit satellite fragmentations, 3d ed, CS88-LKD-001, (Teledyne Brown Engineering), 1987][6]

2 Impact of Space Debris

There are now roughly 300,000 pieces of space debris large enough to completely destroy operating satellites upon impact[8,9]. US Space Surveillance Network (SSN) has categorized the space debris based on their size and impact. The first category includes objects that are approximately 10 cm in diameter (fist-sized) and larger, which can be tracked by SSN and are listed in a resident space object catalog. An impact from an object, of this size, is the equivalent of a bomb blowing up inside the spacecraft. Because debris objects of this size can be tracked, conjunctions with other bodies can be predicted, and in some cases, an at-risk satellite can be maneuvered to avoid a collision. The SSN can often track debris smaller than 10 cm, but that depends on the shape and composition of the object, considered in concert with the size of the debris. The lower limit for reliable tracking of an object is somewhere between 5 and 10 cm. There are currently more than 22,000 objects being tracked by the SSN.

The next category of space debris is objects smaller than 10 cm, down to 1 cm. An impact from a 5 cm object in the middle of the range is the equivalent of being hit by a bus traveling at highway speed. Debris objects in this range cannot be tracked but are large enough to destroy a satellite or rocket body if the debris collide with the main body of the spacecraft (collisions with solar arrays, booms and antennas may not completely destroy a satellite).

It is currently estimated that there are approximately 500,000 of these fragments in orbit at LEO altitudes. Everyone has the potential to cause catastrophic damage to an active satellite. Space debris larger than 1 cm has the potential to completely fragment any object it hits. If that object is a large mass, such as a satellite or rocket body, the resulting collision will add tens of thousands of new space debris fragments to the population.

Debris objects between 3 mm and 1 cm make up the next category of space debris. An impact from an object of this size ranges from the equivalent of being hit by a bullet (damaging but not necessarily destroying the satellite) up to being hit by an anvil falling from a height of two stories (in which destruction of the satellite is certain). These objects also cannot be tracked, and it is estimated that there are millions of them in LEO. However, because particles near the lower limit of this category are so small, they will usually cause only localized damage. Any such damage may still end a satellite's mission if the debris hits a critical component such as a computer, sensor, or propellant tank, but the impact will usually not add a significant amount of space debris as would be the case if the debris fragment was larger.

The last category of space debris comprises objects that are smaller than 3 mm. An impact of a mm aluminum particle is equivalent of being hit by a baseball thrown by a major league pitcher. These small particles cause localized damage, particularly in configurations where the surface condition of the impacted spacecraft is important to its function, such as solar arrays and optical systems (telescopes, star trackers, cameras, etc.). Some spacecraft components can be shielded to prevent damage from debris of this size, but not all of them. There are an estimated 10 million space debris objects in LEO that are smaller than 3 mm. They are still a risk to space based assets, but one that can often be effectively dealt with through better designs and shielding[10].

In addition to these, there are subsequent impacts, such as:

Pollution in the form of gases and particles is created in the exhaust clouds formed when second stage rockets are used to boost a payload from LEO into GEO. A single solid rocket motor can place billions of particles of aluminum oxide into space, creating clouds that may linger up to 2 weeks after the rocket is fired, before dispersing and re-entering the atmosphere. The particles, therefore, represent a significant threat of surface erosion and contamination to spacecraft during that period.

Interference with scientific and other observations can occur as a result of orbital debris. Debris may also contaminate stratospheric cosmic dust collection experiments or even interfere with the

debris tracking process itself. The presence of man-made objects in space complicates the observations of natural phenomena. As the number of debris particles increases, the amount of light they reflect also increases causing light pollution, a further interference with astronomer's efforts. Space debris also disrupts reception of radio telescopes and distorts photographs from ground-based telescopes, affecting the accuracy of scientific results obtained[11].

Predictive studies show that if humans do not take action to control the space debris population, an increasing number of unintentional collisions between orbiting objects may lead to the runaway growth of space debris in Earth's orbit[12].

3 Space Debris Management Methods

There are two basic classes of action that can minimize the orbital debris burden:

Preventive measures to preclude explosive failures of spacecraft and upper stages and eliminate placement in outer space of space debris objects; and ***removal procedures,*** which by reducing the number and mass of objects on orbit, reduce the probability and severity of on orbit hypervelocity collisions.

3.1 Preventive measures

The most effective near-term measures are to design and operate launch vehicles and spacecraft so they have minimum potential for exploding or breaking up. For example, launch vehicle upper stages should be depleted of propellants and pressurants after they have completed their mission.

Batteries should include electrical protection circuits to preclude battery explosions resulting from electrical shorts. Such measures reduce or eliminate the potential for chemical explosions and reduce the severity of collisions when they occur because they also remove additional energy stored in the object. Since 1981, NASA has operated its upper stages in a manner that sharply reduces the likelihood that they would explode in space. Japan and ESA have recently adopted similar operational procedures. Costs of these procedures vary depending directly on the design of upper stages and spacecraft, but can be measured in terms of the equivalent weight of spacecraft that would have to be given up to include such measures or the costs required to reduce the dry weight of a spacecraft.

Other preventive measures include designing and building spacecraft so they resist environmental degradation from atomic oxygen and solar radiation and devising spacecraft and upper stage separation procedures that limit the spread of operational debris. The preventive measures and current mitigation activities are summarized in Table 3.

Abandoning the practice of deliberately fragmenting inactive satellites in orbits where atmospheric drag is extremely weak and debris life correspondingly long would contribute markedly to reducing generation of future orbital debris. In very low orbits (less than about 250 km), atmospheric drag causes objects to fall into the atmosphere and burn up or plummet to the surface over time scales of a few months to a year. Though, extremely small, drag forces as far out as 500 to 600 km may force space objects down over periods of a few years. High levels of solar activity cause an expansion of Earth's upper atmosphere, leading to increased atmospheric drag and significant reductions in the debris population in LEO. The reentry of the Solar Maximum scientific satellite on 2 December 1989 demonstrated this phenomenon. The current cycle of increased solar activity, which has been especially strong, brought it down much sooner than expected.

The atmospheric drag experienced at these altitudes has been used on many occasions to remove upper stages and other objects that have completed their missions. For example, the Delta 180 experiment conducted for the Strategic Defense Initiative Organization was carried out in low orbit so that many small objects deployed as part of the experiment would be removed from orbit within a few days.

Table 3 — Summarized current mitigation activities: prevention

S No.	Prevention activities	Effectiveness
1	Limitation of debris release during operations	Low
2	Minimization of potential fragmentation during operations	Low
3	Limitation of the probability of accidental collision	High
4	Avoidance of intentional destruction and other harmful activities	Medium
5	Minimization of potential post-mission fragmentations	Medium
6	Limitation of abandoned spacecraft and launchers in the LEO region	Medium

[*Source*: Inter-Agency Space Debris Coordination Committee (IADC), 53rd Session of the Scientific and Technical Subcommittee United Nations Committee on the Peaceful Uses of Outer Space, 2016][13]

With redesign of the upper stages, it would be possible to place upper stages in elliptical orbits that bring them into the upper reaches of the atmosphere at perigee, causing them to fall back to Earth (deorbit) relatively quickly.

3.1.1 Key aspects of space debris mitigation guidelines

- Spacecraft and orbital stages should be designed not to release debris during normal operations.
- The potential for break-ups during all phases of mission minimized.
- Spacecraft or orbital stages that are terminating their operational phases in orbits that pass through the LEO region should be de-orbited or where appropriate maneuvered into an orbit with a reduced lifetime (studies have found 25 years to be a reasonable lifetime limit).
- If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk.
- Missions should estimate and limit the probability of accidental collision during the orbital lifetime. Avoidance maneuvers for spacecraft/co-ordination of launch windows should be considered[13].
- Move satellites in higher orbits (particularly GEO), which are too far away to re-enter the atmosphere, into a graveyard orbit well outside the region used by active satellites. This would create a protected zone of a few hundred km either side of the GEO ring[7].

3.1.2 Collision avoidance

Tracking information can be used to predict a collision in time for a satellite to manoeuvre out of the way. For example, the International Space Station (ISS) performs around one avoidance manoeuvre each year. However, the relatively crude information available from the SSN makes it difficult to predict collisions accurately and there are so many close approaches that most cannot be acted on.

This problem may grow as the number of debris items increases. Modeling work has suggested that close approaches may rise from 13,000 a week in 2009 to 20,000 by 2019 and more than 50,000 by 2059, meaning satellite operators may have to make five times as many avoidance maneuvers in 2059 as in 2019. Since each maneuver requires fuel, this shortens the active life of satellites, or requires additional fuel to be carried into orbit thus increasing the cost of launch[7-14].

3.2 Active removal procedures

A few observers have proposed active removal of existing debris. Some proposed methods would be prohibitively expensive and might even be counter-productive. One proposed method would use an orbiting object with a very large cross-section, perhaps a spherical balloon filled with some type of foam, to sweep up small debris over time.

The use of space tethers has also been suggested. This technique would require attaching a tether between the debris object and a remover spacecraft and letting the tether out, causing the remover spacecraft to move higher in orbit, and the debris to move lower. Eventually, the debris object moves close enough to the upper atmosphere that after release from the tether, spirals and burns up.

Satellites can be shielded against smaller pieces of debris and they can attempt to actively avoid larger tracked debris. It is also important to reduce the gap between these two regimes by improving shielding and tracking. In the 1960s, Astronomer Fred Whipple suggested using a dual-wall system to protect space systems from micrometeoroid impacts. In this design, the outer wall (bumper) sacrifices itself to break up the impacting projectile. As a result, the inner wall is subjected only to the impact of many smaller fragments, traveling at lower velocities. This inner wall is often a pressure vessel for the primary satellite structure. According to NASA, the following are some of the proposed methods of debris removal[4]:

3.2.1 Lasers

This method is used to slowing objects using high powered lasers fired from Earth, so that they move out of orbit. Laser technologies could potentially remove a large quantity of small debris. The concept is to lock onto the orbital debris using ground, air or space-based lasers, then vaporize some part of the debris, creating a thrust that causes the debris to alter its orbit. This would lessen the lifetime of the debris. However, such an approach raises issues of arms control (for ground and air-based lasers) and United Nations Treaty violations (for space-based lasers). In addition, it would be an enormous undertaking, as the number of hazardous small debris is quite large (many millions).

3.2.2 Space tugs

Space tugs refers to using a robotic grappling device on another spacecraft to tug an object to a new orbit or to cause it to re-enter the atmosphere destructively. A space tug is actually a spacecraft that is used to move multiple pieces of debris to disposal orbits in GEO. In this scenario, a tether is attached to one object; after a link is achieved, the object is transferred to disposal orbit, and the process is repeated with a second piece of orbital debris. This approach can be effective for disposing of objects in GEO, and its multi-target capability makes it attractive. Again, however, it is unproven, complex and costly to use.

3.2.3 Tethers

Tether refers to using a momentum exchange tether, which acts like a swing to pull an object out of orbit; or using an electrodynamic tether, which causes a drag on the satellite due to the magnetic field of the Earth.

Although this complex process has not yet been proven, removal of a large-mass piece of orbital debris may be achieved by using tethers. A conductive tether, also known as an electrodynamic tether, is a long conducting wire that generates electric potential by its motion through the Earth's magnetic field. Such a tether can be attached to the targeted piece of orbital debris. The current generated by the tether produces a charge that de-orbits the object, causing it to reenter the Earth's atmosphere more quickly than if it had stayed on-orbit. While this procedure can be effective for de-orbiting large objects in LEO, it is complex and costly to use.

Momentum tethers may provide another means of de-orbiting a large object. In this scenario, a nonconductive tether is attached to the piece of orbital debris. The tether is first swung back and forth to generate momentum and then severed. Once the tether is cut, the resulting momentum swings the object out of orbit. Like conductive tethers, momentum tethers may effectively de-orbit large masses; but they too are complex and costly to use.

3.2.4 Ion beam shepherd (IBS)

The Space Dynamics Groups of the Technical University of Madrid (SDG-UPM) is the pioneer in exploring this concept by developing analytical and numerical control models. It is a concept in which the orbit and/or attitude of a spacecraft or a generic orbiting body is modified by having a beam of quasi-neutral plasma impinging against its surface to create a force and/or a torque on the target. Ion and plasma thrusters commonly used to propel spacecraft can be employed to produce a collimated plasma beam and point it towards the body. The fact that the beam can be generated on a shepherd spacecraft placed in proximity of the target without physical attachment with the latter provides an interesting solution for space applications such as space debris removal and asteroid deflection[15].

4 Conclusions

Space agencies and spacecraft engineers have to limit the risk to spacecraft in orbit and the best approach to dealing with space debris is to avoid creating more. Pre-launch screening for collisions can reduce the risk of creating debris and helps ensure the newly launched space asset reach its orbit safely. As tools and methods evolve and the quality of tracking data improves, better predictions of collisions will be possible. Aerospace continues to refine the collision avoidance process to protect space missions and preserve the utility of space itself. However, work on protecting from impacts of larger objects, and on debris avoidance, is needed and some experts believe that there is potential in the future for a commercial removal service.

Space agencies and spacecraft engineers have also to limit the risk to humans following spacecraft re-entry. There are three ways to manage this elevated risk to humans. First, the space system operator can execute a controlled re-entry over a broad ocean area. While this approach greatly reduces the risk to humans, the process of controlled re-entry is complex and costly, making it a last resort. A second option is to maneuver the spacecraft into a graveyard orbit, a long-term storage orbit above 2,000 km. But this approach is also costly and not a good long-term solution. The ideal scenario from the perspective of orbital debris mitigation and reduction of human risk is to redesign the spacecraft before it is built to reduce the risk of human casualty upon re-entry. All the space users need to follow the international mitigation guidelines ratified and signed.

Acknowledgement

The authors are thankful to their colleagues and Ph.D. Scholars for their valuable suggestions during the public presentation of this review.

References

1 Kessler Donald J, *Orbital Debris Monitor,* 2 (1989) 4.
2 National Aeronautics and Space Administration (NASA), *Orbital Debris Q News,* (2008).
3 Ted Muelhaupt, *Crosslink Aerospace Corp M Adv Aerospace Technol,* 16 (2015) 2-64,
4 National Aeronautics and Space Administration (NASA), *Orbital Debris Q News,* (2010).
5 US Congress, Office of Technology Assessment, Orbiting debris: A space environmental problem - Background paper, OTA-BP-ISC-72 (Washington, DC: US Government Printing Office), September 1990.
6 Johnson Nicholas L & Nauer D, History of on-orbit satellite fragmentations, 3d ed, CS88-LKD-001, (Teledyne Brown Engineering), 1987.
7 Martin Griffiths, The Parliamentary Office of Science and Technology, Postnote **(**Millbank, London**),** 355 (2010) 7.
8 Wright David, Space debris. *Phys Today (USA),* **60** (2007) pp 35-40.
9 Johnson Nicholas L, *Statement before the House Subcommittee on Space and Aeronautics*, Committee on Science and Technology, 2009.
10 Roger Thompson, A Space Debris Primer, *Crosslink Areospace Corp Mon Adv Aerospace Technol*, 16 (2015) 7-64.
11 Mueller A C & Kessler D J, *Adv Space Res (UK)***,** 5 (1985) 77-86.
12 Liou J C & Nicholas L Johnson, *A sensitivity study of the effectiveness of active debris removal in LEO*: Paper presented at the International Astronautical Congress, Hyderabad, India, 21-28 September 2007.
13 Inter-Agency Space Debris Coordination Committee (IADC), 53rd Session of the Scientific and Technical Subcommittee United Nations Committee on the Peaceful Uses of Outer Space, 2016.
14 Paul M, Space debris threat to future launches, *New Scientist*, (Oct 2009)
15 Claudio B & Jesus P, *J Guidance*, *Control Dyn,* 34 (1985) 916-920.