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ORBITAL DEBRIS: THE GROWING THREAT TO SPACE OPERATIONS

Nicholas L. Johnson*

For nearly 50 years the amount of man-made debris in Earth orbit steadily grew, accounting for about 95% of all cataloged space objects over the past few decades. The Chinese anti-satellite test in January 2007 and the accidental collision of two spacecraft in February 2009 created more than 4000 new cataloged debris, representing an increase of 40% of the official U.S. Satellite Catalog. The frequency of collision avoidance maneuvers for both human space flight and robotic operations is increasing along with the orbital debris population. However, the principal threat to space operations is driven by the smaller and much more numerous uncataloged debris. Although the U.S. and the international aerospace communities have made significant progress in recognizing the hazards of orbital debris and in reducing or eliminating the potential for the creation of new debris, the future environment is expected to worsen without additional corrective measures.

INTRODUCTION

Although the very first object cataloged by the U.S. Space Surveillance Network (SSN) in 1957 was a piece of orbital debris, *i.e.*, the rocket body for Sputnik 1, the orbital debris population did not begin to grow significantly until the first on-orbit explosion of a man-made vehicle in June 1961 created nearly 300 trackable debris. Just prior to the explosion, the total artificial satellite population of the Earth, including operational spacecraft and orbital debris, was only a little more than five dozen objects. In the ensuing 45 years, the population of large orbital debris (> 10 cm) grew at a rate of nearly 300 objects per year, excluding the two-year period of 1989-1990 associated with a higher than normal period of solar activity.[1]

The primary source (52% by end of 2006) of the cataloged orbital debris population in low Earth orbit (LEO; less than 2000 km mean altitude) was the numerous fragmentations of space vehicles, although derelict intact spacecraft and launch vehicle orbital stages continued to accumulate. By the beginning of 2007 a total of 190 satellites had been involved in known breakups not associated with reentry into the atmosphere, and another 50 orbital vehicles had experienced lower level, anomalous fragmentation events.[2] However, on a more positive note, national and international policies and practices had clearly curtailed the frequency of major satellite fragmentations with long-lived debris since the mid-1990's (see below).

Unfortunately, major satellite breakups, both intentional and accidental, have dramatically increased the number of debris in LEO since the start of 2007 (Figure 1). In particular, the deliberate destruction of the Chinese Fengyun-1C spacecraft in 2007 and the accidental collision of an American and a Russian spacecraft in 2009 alone have increased the large object population in LEO by approximately 70%. Another major launch vehicle stage explosion in early 2007 also created hundreds of debris in elliptical orbits passing through LEO.

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* Chief Scientist for Orbital Debris, Orbital Debris Program Office, NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058.

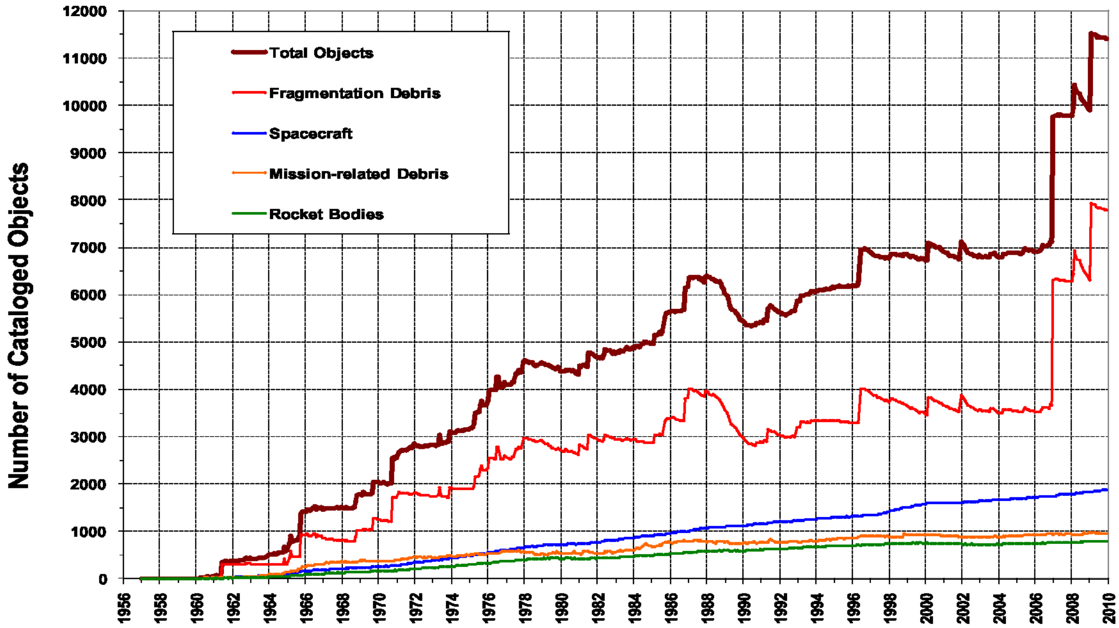

Figure 1. Growth of the cataloged satellite population. Note that some debris from the major breakups of 2007 and 2009 have yet to be officially cataloged.

In the long-term, the accumulation of mass in LEO will govern the future hazards to operational spacecraft as a result of accidental collisions among resident space objects. Excluding the components of the International Space Station (ISS), the annual rate of growth of mass in LEO has recently been on the order of 50 metric tons (Figure 2).

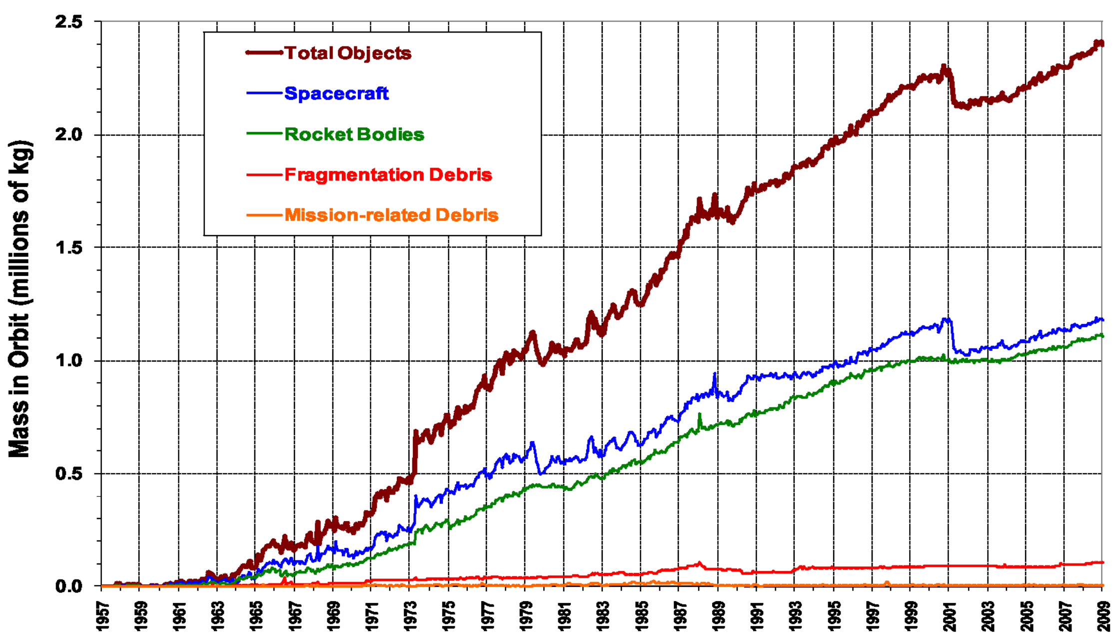

Figure 2. Accumulation of mass in low Earth orbit, excluding components of the ISS. The decline in 2001 was due to the de-orbit of the Mir space station.

The orbital debris situation in geosynchronous orbit (GEO) has also been evolving negatively. Although removal of spacecraft from GEO at the end of mission has been recommended for decades, the number of large objects in GEO continues to grow, in part due to the increased number of operational spacecraft and in part due to the failure or abandonment of spacecraft and launch vehicle stages in or near GEO. During the 10 year period of 2000-2009, the number of spacecraft entering GEO exceeded that being removed by more than two to one. New data also indicate that the smaller, uncataloged debris population near GEO already exceeds that of the known satellite population (Figure 3).[3]

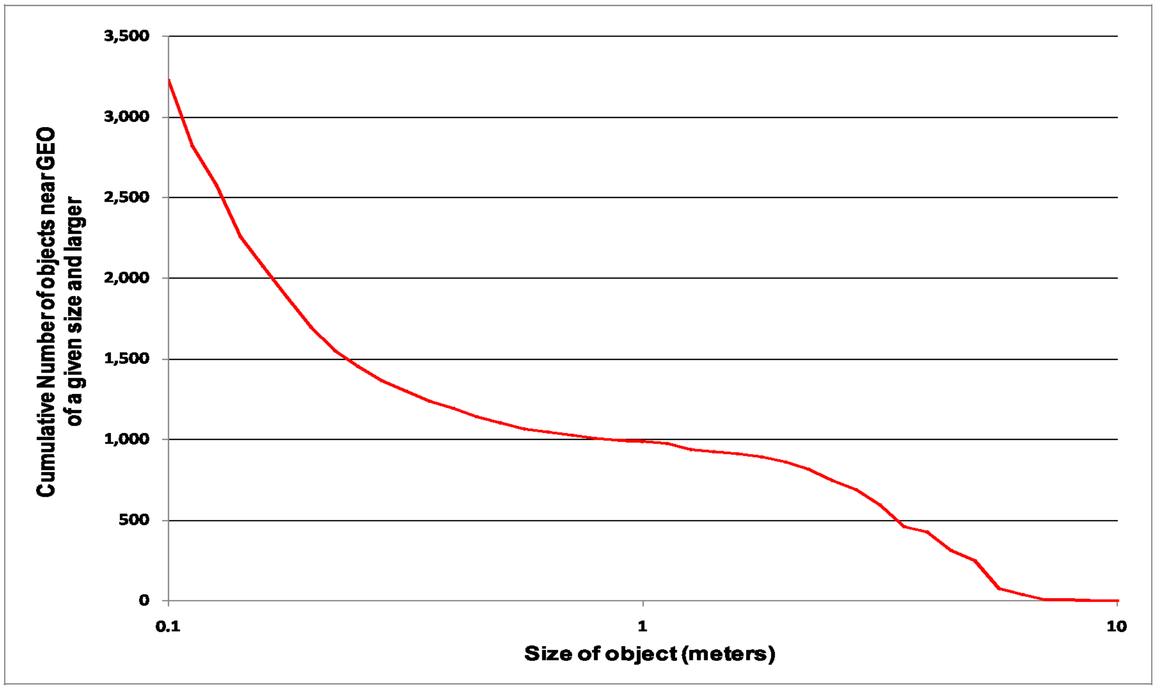

Figure 3. NASA assessment of the near-GEO satellite population.

RECENT EVENTS

By far the most devastating impact on the LEO environment was the Chinese anti-satellite (ASAT) test conducted on 11 January 2007 and which resulted in the destruction of the Fengyun-1C meteorological satellite in a circular orbit with a mean altitude near 850 km.[4-5] No ASAT test had created orbital debris in more than 20 years prior to 2007. By the third anniversary of the Chinese test, the U.S. Space Surveillance Network had officially cataloged nearly 2700 debris from Fengyun-1C, and hundreds more were being tracked but not yet cataloged. Only 2.5% of the cataloged debris had fallen back to Earth, and many of the debris will remain in orbit for several decades, some for more than a century. By comparison, less than 300 debris were cataloged from the 1985 U.S. ASAT test and all had decayed within 19 years of the test. Likewise, nine orbital debris clouds created by the former Soviet Union during 20 ASAT tests in the 1960-1980's left only 80 cataloged debris on average per test.

The February 2009 collision between the operational Iridium 33 and the non-functional Cosmos 2251 spacecraft was only a little less detrimental to the LEO with more than 1600 cataloged debris and hundreds more detected and awaiting cataloging.[6] Figure 4 indicates the distribution of the debris from Fengyun-1C, Iridium 33, and Cosmos 2251 throughout LEO with the heaviest concentrations in the 750-900 km regime, which hosts many critical operational scientific and applications spacecraft.

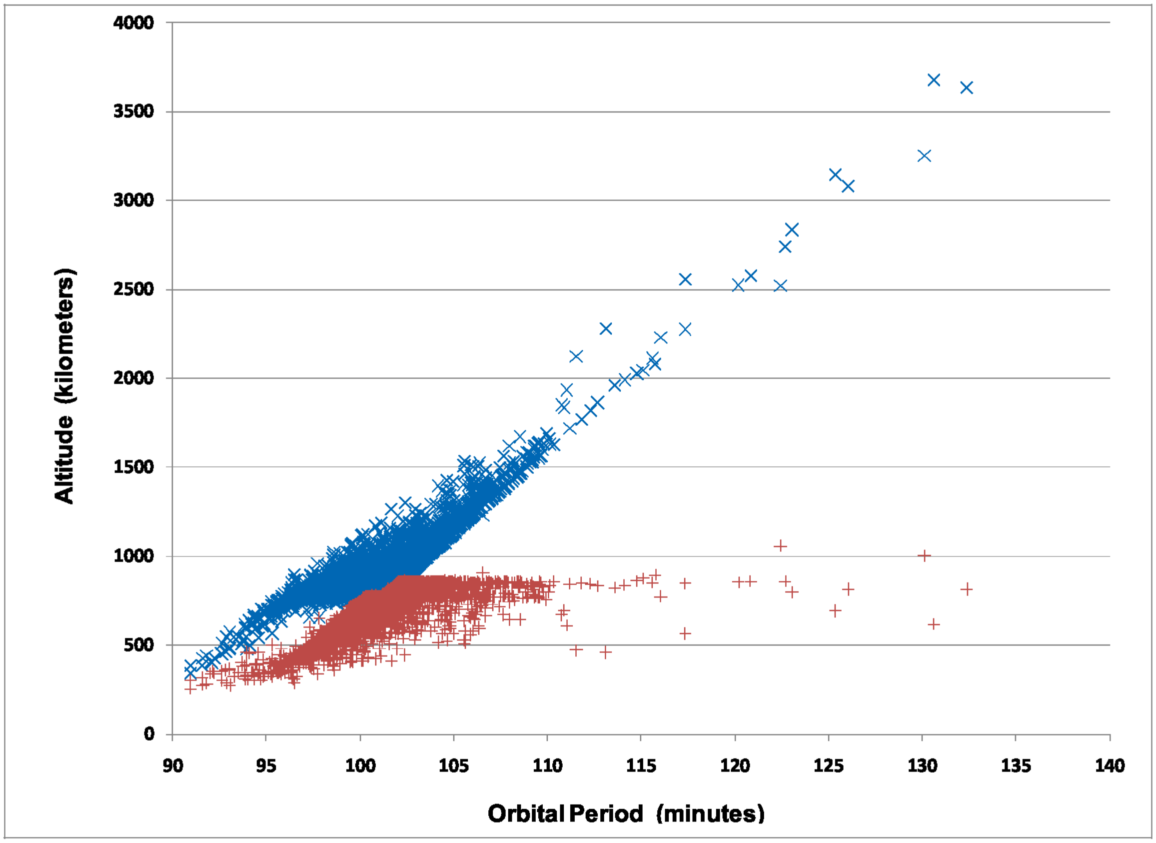

Figure 4. Nearly 4200 cataloged debris from Fengyun-1C, Iridium 33, and Cosmos 2251 in January 2010. Legend: x denotes apogee and + denotes perigee.

A second severe satellite fragmentation also occurred in 2007. In 2006 an upper stage of a Russian Proton launch vehicle failed shortly after the beginning of the second of four planned ignitions, stranding the stage and its payload in elliptical orbits with perigees near 500 km altitude.[7] Almost exactly one year later the upper stage, which still contained a large amount of unused propellant, exploded, creating as many as 1000 large debris. These debris are hard to track, and less than 100 have been cataloged to date.

The estimated 6,000 large debris (>10 cm) created in the three incidents cited above are but a fraction of the much more numerous smaller debris which pose hazards to operational spacecraft. The Fengyun-1C fragmentation alone is estimated to have produced over 150,000 debris larger than 1 cm, each capable of disabling any manned or robotic spacecraft.[8]

COUNTERMEASURES

The absolute risks to operational spacecraft from collisions with man-made debris remain low, as evidenced by only one known permanent loss of a functioning spacecraft (Iridium 33) to date. However, the threat to approximately 1000 operational satellites now in orbit about the Earth increases with the growth of the orbital debris population. The three principal countermeasures to this threat which are being employed are shielding, collision avoidance, and curtailment of the creation of new debris through design and operational practices.

Shielding Against Orbital Debris

Due to their very large numbers, the greatest threat to operational spacecraft comes from small, untracked debris. The inherent structure of satellites provide some protection from the smallest orbital debris, *i.e.*, less than 1 mm, but most satellites are vulnerable to impacts from particles in the millimeter-class size regime and larger. NASA estimates that on the order of 100 million particles larger than 1 mm now traverse LEO. Of these, about 500,000 are larger than 1 cm.

Shielding technologies have advanced considerably since the 1960's when simple Whipple shields were utilized to guard against the natural meteoroid environment. The ISS employs hundreds of custom-made shields to protect critical components of the extensive structure, including habitable compartments and vital external units and lines.[9] Since the orbital debris environment presents a very asymmetric flux to the ISS, not all critical surfaces need the same level of protection. Figure 5 illustrates one of the stuffed Whipple shields on the ISS, which uses a sandwich of Nextel and Kevlar inserts between the front thin bumper and the larger vehicle wall to increase the stopping power of the configuration within space and mass limits.

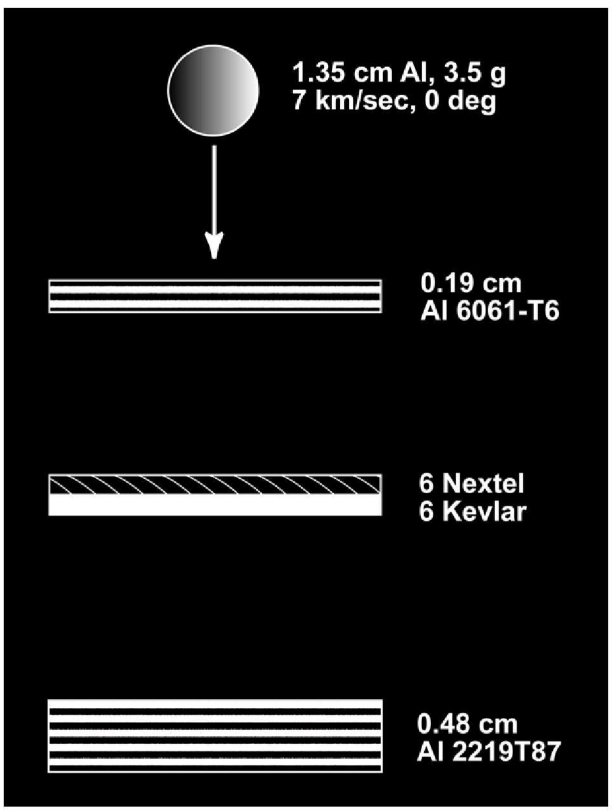

Figure 5. A stuffed Whipple shield used by the International Space Station.

The latest concepts for improved orbital debris shields involve replacing typical Whipple stuffing materials and aluminum honeycomb with new metallic foams.[10] These new designs offer greater protection from the meteoroid and orbital debris environments with less overall structural mass.

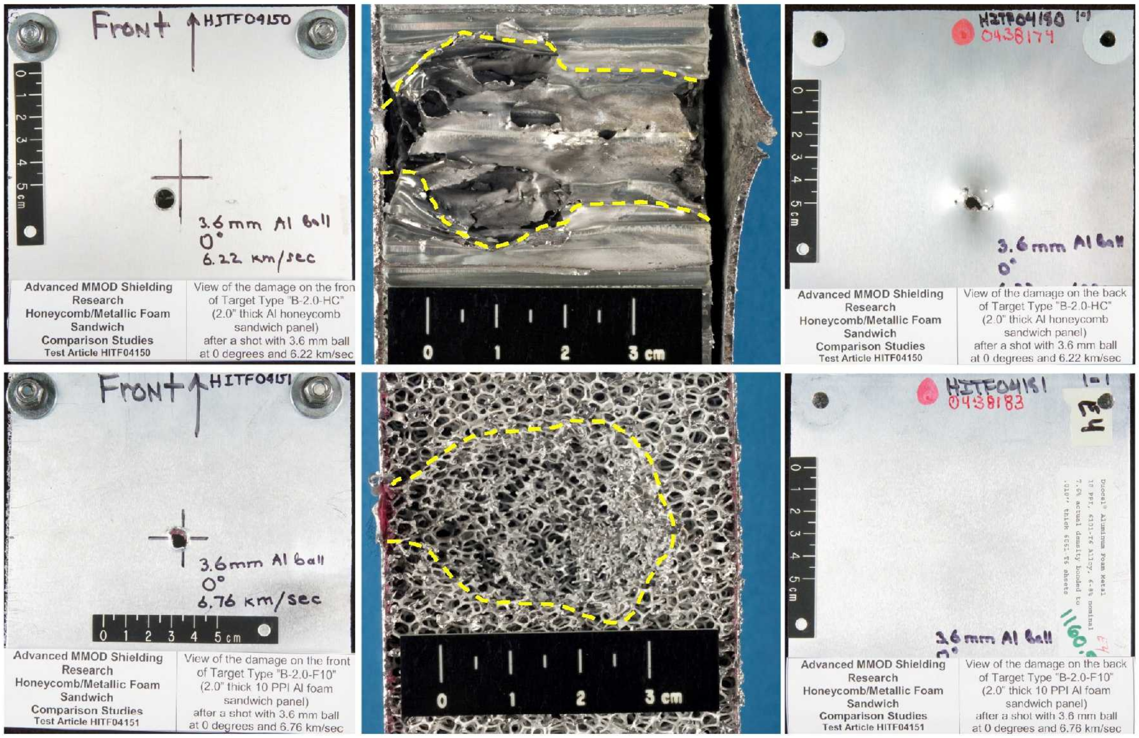

Figure 6. Comparison of damages in a honeycomb core (top) and open-cell metallic foam core (bottom). (From Reference 10)

Shielding techniques, however, are practical only for particles on the order of 1 cm or less. Moreover, many robotic spacecraft cannot not afford the mass penalty associated with orbital debris shields, and payload elements frequently cannot host shields for operational reasons.

Collision Avoidance

NASA implemented collision avoidance procedures for human space flight after the Space Shuttle Challenger accident in 1986. In cooperation with U.S. Air Force Space Command, the conjunction assessment process was significantly improved by the time of the launch of the first element of the ISS, *i.e.*, the Zarya module in 1998. Collision avoidance maneuvers for selected NASA robotic satellites began in 2005, and since 2008 all NASA maneuverable satellites in LEO and GEO are required to routinely have conjunctions assessments performed with the assistance of U.S. Strategic Command.[11]

During 2009 five different NASA robotic spacecraft, as well as the Space Shuttle and the ISS, conducted collision avoidance maneuvers (Table 1). As a result of the collision of Iridium 33 and Cosmos 2251 in early 2009, the Joint Space Operations Center (JSpOC) of the U.S. Strategic Command now conducts conjunction assessments for all operational spacecraft in Earth orbit, regardless of ownership nationality. Any prediction of a close approach, typically within one kilometer, will be shared with the spacecraft owner/operator freely and immediately.

Due to inherent uncertainties in space surveillance measurements, the dynamic state of the atmosphere, and, in many cases, the instability of at least one of the conjuncting objects, predicting the collision of two satellites remains a probabilistic endeavor. Typical collision avoidance maneuver probability thresholds are 1 in 10,000 for human space flight and 1 in 1,000 or more for robotic satellites.

Table 1. NASA Collision Avoidance Maneuvers in 2009.

Spacecraft	Maneuver Date	Object Avoided
TDRS 3	27 Janaury	Proton rocket body
ISS	22 March	CZ-4 rocket body debris
Cloudsat	23 April	Cosmos 2251 debris
EO-1	11 May	Zenit rocket body debris
ISS	17 July	Proton rocket body debris
Space Shuttle	10 September	ISS debris
Aqua	25 November	Fengyun-1C debris
Landsat 7	11 December	Formosat 3D

Contrary to common belief, collision avoidance maneuvers are normally not highly disruptive to satellite operations. Moreover, collision avoidance maneuvers are typically very small, *i.e.*, involve changes in velocity of less than 1 meter per second, and in most cases can be conducted in a manner which does not waste propellant resources. For example, collision avoidance maneuvers performed by the ISS almost always result in a small increase in orbital altitude and thus simply constitute an unscheduled anti-drag maneuver. Similar procedures are used for robotic satellites.

In addition to the obvious due diligence aspect of protecting operational spacecraft, one long-term benefit of collision avoidance is the prevention of collisions between two large objects, which in turn could further degrade near-Earth space with large numbers of new debris, as was the case with the collision of Iridium 33 and Cosmos 2251. On the other hand, over 99% of the risk to operational spacecraft from collisions with orbital debris comes from objects too small to track on a routine basis, *i.e.*, smaller than 10 cm. Hence, only an improvement in the orbital debris environment itself can dramatically reduce the risks to operational spacecraft.

Orbital Debris Mitigation Policies and Practices

One of the first comprehensive sets of orbital debris mitigation recommendations was issued by the American Institute of Aeronautics and Astronautics in 1981.[12] Orbital debris mitigation was first mentioned in President Reagan's National Space Policy in 1988.[13] Following the first U.S. government interagency report on orbital debris in 1989, NASA issued in 1995 the first formal orbital debris mitigation guidelines for a U.S. government agency.[14-15] These guidelines served as the basis for U.S. Orbital Debris Mitigation Standard Practices, which was adopted in 2001 after a multi-year coordination with the U.S. aerospace industry.[16]

The purpose of all these documents was to outline spacecraft and launch vehicle design and operational procedures which would reduce the amount of unnecessary orbital debris being generated accidentally or intentionally, thus promoting the safe and reliable operation of spacecraft. The main areas covered were normal operations, accidental explosions, orbit selection, and postmission disposal. The last also addressed the human casualty risk associated with reentering debris.

In 2002 the Inter-Agency Space Debris Coordination Committee (IADC), comprised of the space agencies of 10 nations plus the European Space Agency, adopted space debris mitigation guidelines, which were then submitted for consideration to the Scientific and Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space.[17] After several years of debate and negotiations, space debris mitigation guidelines were accepted by the UN in 2007.[18-19]

Although not rising to the status of an international treaty, the UN space debris mitigation guidelines are recommended for implementation via national procedures. For example, the UN guidelines are compatible with the U.S. Orbital Debris Mitigation Standard Practices, which are implemented for government-sponsored space missions through directives of NASA and the Department of Defense and for commercial space operations through the regulations of the Department of Transportation, the Federal Communications Commission, and the Department of Commerce. Several other nations have invoked similar, non-voluntary orbital debris mitigation requirements.

THE WAY AHEAD

The U.S. and the rest of the international aerospace community well recognize the threat posed by the enormous amount of potentially hazardous debris already in Earth orbit. The major space-faring nations and organizations have implemented and continue to improve effective responses to portions of this threat. In addition, efforts to curtail the creation of new orbital debris have been successful, notwithstanding the recent set-backs associated with the intentional destruction of the Fengyun-1C spacecraft and the accidental collision of Iridium 33 and Cosmos 2251.

However, studies have shown that the orbital debris population will continue to grow without direct intervention, *i.e.*, the removal of large resident space objects.[20-23] Since 2006, the International Academy of Astronautics has been conducting a special study on different techniques to remediate the near-Earth space environment. In December 2009 NASA and the Defense Advanced Research Projects Agency (DARPA) co-sponsored the first international conference on orbital debris removal. Technical proposals for removing orbital debris, both small and large and in low or high orbits, were discussed, as were the related economic, legal, and policy challenges associated with such an undertaking. Whereas some promising concepts have been offered, the magnitude of a program to remove debris from orbit remains considerable, and significant near-term solutions are not anticipated.

SUMMARY

The current orbital debris environment poses a real, albeit low level, threat to the operation of spacecraft in both LEO and GEO. A variety of countermeasures, including curtailment of new debris generation, shielding, and collision avoidance, are being implemented by a growing number of satellite owner/operators. For such countermeasures to be effective, they should be considered very early in the design of each spacecraft and implemented throughout the mission and disposal phases. Remediation of near-Earth space remains a longer term objective.

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