ORBITAL DEBRIS HAZARDS AND MITIGATION STRATEGIES

AN AIAA INFORMATION PAPER

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PREFACE

Why this Report?

The risk of collision of man-made orbital debris with spacecraft in near Earth orbits continues to increase. Since the dawn of the space age there have been about 4000 launches into Earth orbit that have created about 26,000 known objects in orbit from spacecraft explosions, breakups, and parts separation. Nearly 10,000 of these objects remain in orbit and are tracked. Thousands of debris particles too small to track are also in Earth orbit. In the next decade we may see 2000 additional spacecraft launched into orbit. Without debris mitigation measures, orbital debris growth will impose undesirable safety and economic consequences on near Earth space operations. As we enter the next millennium, AIAA believes the time has come for international actions to establish regulations for mitigation of orbital debris hazards.

Orbital operations are inherently global and operate in the public domain of space. All space-faring nations and agencies need to cooperate in orbital debris mitigation practices. Compliance is needed uniformly. Ultimately, standard practices and enforcement appear necessary. A laissez faire approach to orbital debris mitigation based on general guidelines and a “good neighbor” policy is unlikely to succeed.

This report summarizes the current and projected status of orbital debris hazards. It also highlights interagency and international activities. AIAA will join with other professional societies, such as the International Academy of Astronautics (IAA) and the International Astronautical Federation (IAF), to facilitate and support international agreements on space debris mitigation. AIAA encourages the U.S. government to continue its leadership role in defining potential debris mitigation practices as addressed together with industry in its January 1998 Workshop in Houston. Continuing government and industry dialogues such as this should lead to draft orbital debris mitigation standards. Draft standards and implementation recommendations could then be considered by the 10 nation member Interagency Space Debris Coordination Committee (IADC), currently the most active international forum, for evaluation, refinement, and adoption.
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SPACE DEBRIS ENVIRONMENT

1. Introduction

Future satellite designs should take account of space debris in addition to the natural environment consistent with mission requirements and cost effectiveness. Man-made space debris differs from natural meteoroids because it is in Earth orbit during its lifetime and is not transient through the regions of interest. As a consequence, a given mass of material presents a greater challenge in the design and operation of spacecraft because of the extended time period over which there is risk of collision.

Past design practices and inadvertent explosions in space have created a debris population in operationally important orbits. The debris consists of spent spacecraft and rocket stages, separation devices, and products of explosions.

Much of this debris is resident at altitudes of considerable operational interest. Two types of space debris are of concern: 1) large objects whose population, while small in absolute terms, is large relative to the population of similar masses in the natural flux (by a factor of about 1000); and 2) a large number of smaller objects whose size distribution approximates natural meteoroids. Products larger than 10 cm in low orbits can be observed directly. The existence of a substantially larger population of small fragments can be inferred from terrestrial tests in which the particle distributions from explosions have been assayed. Statistical measurements and returned surfaces from space confirm the existence of a large number of very small particles in orbit.

Some efforts to provide a better assessment of the orbiting debris problem have been and are being made by various government agencies and international organizations. Principal areas of investigation are the hazards related to the tracked (cataloged), untracked, and future debris populations. Studies are being conducted in the areas of technology, space vehicle design, and operational procedures. Among these are ground- and space-based detection techniques, comprehensive models of Earth-space environments, spacecraft designs to limit accidental explosions, and different collision-hazard assessment methods. Occasional collision avoidance and orbit-transfer maneuvers are being implemented for selected satellites. The results and experience gained from the activities will, in time, create a better understanding of the problem and all its implications so that appropriate actions can be taken to maintain a relatively low-risk environment for future satellite systems.

Impact protection from space debris may not be feasible in most cases because of very high approach velocities and the fact that certain protuberances, especially those of relatively large areas such as solar arrays and antennas, cannot easily be shielded permanently. Evasive-maneuvering techniques may reduce the present probability of collision for specific satellites in certain circumstances.

The only natural mechanism opposing debris buildup is removal by atmospheric drag. This process can take a very long time, however, especially from high altitudes, and causes debris to migrate from higher to lower altitudes. Another mechanism, collection by a spacecraft, would be extremely difficult and very expensive. Prevention of debris formation is the most effective approach.

At the present time, the collision hazard is real but very low relative to other hazards of space operations. Consistent with National Space Policy and the 1995 Office of Science and Technology Policy (OSTP) report, this hazard can be minimized by initiating studies and implementing their results in five major areas: 1) education, 2) technology, 3) satellite and vehicle design, 4) operational procedures and practices, and 5) national and international space policies and treaties.1,3

2. Space Debris Environment: Low Earth Orbit (LEO)

At any one time, there are about 200 kg of meteoroid mass moving through altitudes below 2000 km at an average speed of about 20 km/s. Most of the mass is found in particles of about 0.1-mm diameter.2 The meteoroid environment has always been a design consideration for spacecraft. The Apollo and Skylab spacecraft were built to withstand impacts on critical systems from meteoroids having sizes up to 3 mm in diameter. Larger sizes were so few in number as to be of no practical significance for the duration of the mission. Some small spacecraft systems required additional shielding against meteoroids as small as 0.3 mm in diameter in order to maintain an acceptable reliability. The trend in the design of some future spacecraft (as for example, the International Space Station) is toward larger structures, lighter construction, and longer times in orbit. These factors increase the concern about damage from particles in the 0.1- to 10-mm size range.

It is no longer sufficient, however, to consider only the natural meteoroid environment in spacecraft design. Since the time of the Apollo and Skylab programs, launch activity has continued and increased. As a result, the population of orbital debris has also increased substantially. The total mass of debris in orbit is now approximately 2300 tons at altitudes below 2000 km. Relative to one another, pieces of debris are moving at an average speed of 10 km/s, or only half the relative speed of meteoroids. The significant difference between the orbital debris population and the meteoroid population is that most of the debris mass is found in objects several meters in diameter rather than 0.1 mm in diameter as for meteoroids. This large reservoir of mass may be thought of as a potential source for particles in the 0.1- to 10-mm range. That is, if only one ten-thousandth of this mass were in this size range, the amount of debris would exceed the natural meteoroid environment. The potential sources for particles in this size range are many:
1) Explosions: More than 145 spacecraft are known to have exploded in LEO and account for about 42% of the U.S. Space Command (USSPACECOM) Catalog.

2) Hypervelocity collision in space: One known satellite collision (CERISE) and several near misses have been recorded in recent history.

3) Deterioration of spacecraft surfaces: Oxygen erosion, ultraviolet radiation, and thermal stress are known to cause certain types of surfaces to deteriorate, producing small particles. Returned surfaces from orbit (SOLAR MAX, LDEF, SFU, EuReCa, Euro Mir '95, and others) have provided some information on this effect.

4) Solid rocket motor firings: Up to one-third of the exhaust products of a solid rocket motor may be aluminum oxide particles in the size range 0.0001 to 0.01 mm. Slag (up to several centimeters in diameter) may be generated during and after the burn of solid rocket motors.

5) Unknown sources: Other sources are likely to exist. Particulates are commonly observed originating from the Space Shuttle and other objects in space.

**a. Debris Measurements**

What is currently known about the orbital debris flux is from a combination of ground-based and in-space measurements. These measurements have revealed an increasing population with decreasing size. Beginning with the largest sizes, a summary of these measurements follows.

The USSPACECOM tracks and maintains a catalog of "all man-made objects" in space. The catalog, as of 31 December 1998, contained 8674 objects, most in LEO. Figure 1 shows the growth of the satellite population from 1957 through 1994. This plot excludes space probes (over 100 of which were still in orbit). The linear growth rate of about 210 cataloged objects in the last 40 years provides a good approximation of the actual growth rate, which is a function of satellite breakup rates and cyclic solar activity.

The origin of the satellite and debris population is given in Table 1 and its composition is illustrated in Fig. 2. As can be seen from Fig. 2, nearly half of the objects in the catalog have resulted from fragmentation of more than 145 satellite breakups. The ability to catalog small objects is limited by the power and wavelength of individual radar sites, as well as the limitations on data transmission within the network of radar sites. Consequently, objects smaller than 10 to 20 cm are not usually cataloged.

An estimate of USSPACECOM's capability to detect objects in Earth orbit is illustrated in Fig. 3 (Refs. 5 and 8). Only the region to the right of the heavy line is accessible to operational radar and optical systems. The capabilities of the infrared astronomy satellite (IRAS) extended the measurements to smaller objects, as indicated.

![Fig. 1 On-orbit satellite population growth (from Ref. 4)](image)

The tracked (>10-cm) object densities are illustrated in Fig. 4. The peak object densities appear at about 800-, 1000-, and 1500-km altitude and are caused by heavy use of these altitudes. A number of high-intensity explosions or breakups of spacecraft and rocket stages have also contributed to the debris population in this environment. The inclination distribution of the catalog population is shown in Fig. 5.

Nearly all of the orbital debris measurements to date show an orbital debris flux that exceeds the meteoroid flux. These measurements are summarized and compared with the meteoroid flux in Fig. 6 (Ref 5, 6).

**Table 1 Orbital Origins (31 December 1998) (from Ref 4)**

<table>
<thead>
<tr>
<th>Country/Organization</th>
<th>Payloads</th>
<th>Rocket Bodies &amp; Debris</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>24</td>
<td>202</td>
<td>125</td>
</tr>
<tr>
<td>Russia</td>
<td>1340</td>
<td>2579</td>
<td>3919</td>
</tr>
<tr>
<td>ESA</td>
<td>24</td>
<td>213</td>
<td>237</td>
</tr>
<tr>
<td>India</td>
<td>17</td>
<td>4</td>
<td>21</td>
</tr>
<tr>
<td>Japan</td>
<td>65</td>
<td>49</td>
<td>114</td>
</tr>
<tr>
<td>U.S.</td>
<td>828</td>
<td>3139</td>
<td>3967</td>
</tr>
<tr>
<td>Other</td>
<td>266</td>
<td>25</td>
<td>291</td>
</tr>
<tr>
<td>Total</td>
<td>2564</td>
<td>6110</td>
<td>8674</td>
</tr>
</tbody>
</table>
b. Future Debris Population Estimates

Currently there are a number of models that predict future orbital debris environments, such as NASA’s EVOLVE, ESA’s CHAINEE and MASTER, the UK’s IDES, and the Russian Space Agency models. Given certain assumptions these and other models predict an exponential rise in the orbital debris population. Principal uncertainties involve future launch rates and object intercollision rates that would produce more fragments than would decay from atmospheric drag. A key question in this regard is the estimation of the number of fragments from a collision or an explosion. Improved breakup models are required to reduce the uncertainties in this area.
In summary, the future space debris environment will depend on:

1. On-orbit breakups (explosions/collisions)
2. Non-fragmentation debris sources
3. Constellation deployments
4. Models of future traffic

3. Space Debris Environment: Geosynchronous Orbit (GEO)

As of the end of 1996 there were a total of 509 payloads launched into the geosynchronous orbit regime, not including 186 upper stages. Of these there were some 250 spacecraft (functional and non-functional) in the geostationary orbit. The others are either geosynchronous or highly elliptical (Molnyia) semisynchronous orbits.

Orbits in the geosynchronous regime may be classified as 1) low or high inclination, and 2) sub- or supersynchronous-altitude drifting orbits. The ideal geostationary orbit has an altitude of 35,787 km and a period of 1436.2 min. A satellite whose period of revolution is equal to the period of rotation of the Earth about its axis is called a geosynchronous satellite. A geostationary satellite is a geosynchronous satellite in a circular orbit that lies in the plane of the Earth’s equator and rotates about the Earth’s polar axis in the same direction. Consequently, it remains “fixed” over a point on the equator.

The GEO object population density vs range from GEO altitude is illustrated in Fig. 7.

GEO orbital debris is more difficult to detect and track than debris at lower altitudes (see Fig 3). Consequently, GEO debris characterization lacks detail in small objects and fragmentation and breakup debris. Plans for an international effort in GEO debris characterization were prepared by the 14th IADC working meeting (InterAgency Space Debris Coordination meeting) involving US, ESA, Japanese, Russian, and Chinese facilities to conduct GEO orbital debris surveys. A debris population in GEO down to 10 cm from the present 1 m limiting size would provide a more accurate object density and enhance the estimates of the collision probabilities for active and large inactive objects in GEO.

COLLISION HAZARDS

The collision of the French CERISE spacecraft and a fragment from the SPOT 1 Ariane I upper stage on 24 July 1996 marked the first time that two objects in the U.S. satellite catalog have collided. This collision with CERISE’s stabilization boom caused the spacecraft to tumble end-over-end. Collisions with smaller particles that are below the threshold for detection and tracking are more frequent and also can cause serious damage. An example of the damage potential is shown in Fig. 8, which shows the 4-mm-diam crater on the Shuttle window from the STS-7 mission. Energy-discursive x-ray analysis was used to determine the composition of partially fused material found in the bottom of the pit. Titanium oxide and small amounts of aluminum, carbon, and potassium were found added to the pit glass. Crater morphology places the impacting particle diameter at 0.2 mm, with a velocity between 3 and 6 km/s. From these data, it is concluded that the particle was man-made and probably an orbiting paint fleck.

Fig. 7 Population density as a function of range and latitude from GEO. (from Ref. 1)

Fig. 8 STS-7 window impact (from Ref. 5)
1. Collision Probability

The probability of collision is a function of the spacecraft’s size, the orbital altitude, and the period of time the spacecraft will remain in orbit. The orbital debris environment in LEO presents a problem for space operations that involve large spacecraft or satellites in orbit for long periods of time. A space station is the primary example of such a spacecraft and must be shielded over large areas in order to achieve the design safety limits. Earlier manned space programs addressed only the natural meteoroid environment, but the current Shuttle and the International Space Station (ISS) requirements address both the natural meteoroid and the orbital debris environments.

The LEO probability of collision is illustrated in Figure 9.

Fig. 9 Impact Rates on Average Small Satellite (from Ref. 2) altitude - 800 km: inclination - 80 deg

2. International Space Station Protection Example

The International Space Station is being designed for survivability. This requires that critical items be located and oriented to minimize impacts of debris and meteoroid particles. Also, it will provide redundancy of critical functions. The survivability requires development of robust and damage tolerant designs as well as provision for damage detection and repair capability.

For the ISS the risk of a 1 cm particle or larger impact is 1 in 95 years. For a 10 cm or larger object it is about 1 in 10,000 years.

Operational practices to enhance survivability will include crew training, survival aids, hatch protocol, and pressurized system operation. Flight attitude and altitude could also be optimized to minimize debris impact on critical areas.

MITIGATION STRATEGIES

About 13 percent of the present cataloged orbital debris population consists of objects discarded during normal satellite deployment and operations. The rest is the result of orbital breakups (42%), rocket bodies (17%), and inactive payloads (22%). Current mitigation strategies are therefore focused on limiting these sources of orbital debris in the future. They include:

1. Passivation of spacecraft and upper stages
2. Deorbiting of rocket bodies
3. Reorbiting of satellites to storage orbits
4. Collision avoidance and shielding technology

The passivation methods include the expulsion of residual propellants by burning or venting the discharge of electrical storage devices, the release of pressurized fluids, thermal control and safing of unused destruct devices and the unloading of momentum wheels and similar attitude control devices.

Deorbiting of rocket bodies and spent satellites is recommended in LEO at end of mission or not to exceed a 25 year lifetime in orbit. For space objects at higher altitudes, moving (reorbiting) vehicles into disposal orbits can also be effective in the short term. For example, the transfer of geostationary orbit spacecraft at end of mission at least 300 km above GEO not only protects operational spacecraft but also reduces the probability of derelict objects colliding with one another and creating debris that might threaten the GEO regime. A standardized reorbit distance has been suggested by the Inter-Agency Space Debris Coordination Committee (IADC) consisting of the representatives of ten space faring countries as

\[ H = 235 \text{ km} + C_r \times 1000 \times A/m \]

Where \( H \) = reorbit altitude above GEO (in km), \( C_r \) surface reflectivity constant, and \( A/m \) is the area-to-mass ratio (m²/kg) of the vehicle.

The collision avoidance during orbital insertion and on-orbit operations is technically possible. However, current space surveillance systems cannot track objects in LEO with a radar cross section of less than 10 cm in diameter. In addition, it is difficult to maintain orbital parameters on small objects because of the higher area-to-mass ratio, and consequently, a higher dependence on the atmospheric density variations.

The United States Space Surveillance Network (SSN) and the Russian Space Surveillance System monitor the LEO environment to warn of an object approaching the Space Shuttle or the MIR space station within a few kilometers. Thus, if an object is predicted to pass through a box measuring 25 km x 5 km x 5 km oriented along the flight path of the Space Shuttle, the SSN sensor network intensifies its
tracking of the potential collision object. If the improved fly-by prediction results in a conjunction within a box measuring 5 km x 2 km x 2 km, an avoidance maneuver may be performed. The Space Shuttle has performed four such evasive maneuvers since 1986.

A collision avoidance maneuver affects satellite operations in several ways and should be minimized consistent with spacecraft safety and mission objectives. The impact on propellant consumption, payload data and service interruptions, and temporary reduction in tracking and orbit determination accuracy can be reduced with the improvement of tracking observation accuracy.

**ECONOMIC IMPLICATIONS**

Orbital debris will increase the cost of space missions through costs incurred to conform to debris remediation policies and/or losses that result from debris impacts. Cost effective orbital debris remediation policies, in the long term, reduce mission costs (below those that would result from pursuing a policy of no orbital debris remediation), but may increase mission costs in the short term. This is the typical investment dilemma; is it desirable to make an investment and incur costs in the near term in order to achieve benefits in the long term? Decisions regarding orbital debris remediation policies are quite similar to most investment decisions (i.e., spend now for future rewards) except that the time frame is considerably longer (measured in terms of perhaps 50 to 100 years or more) than that encountered in most investment decisions. In fact, it is likely that the generation incurring the costs will not be the generation obtaining the benefits. This long time frame opens up the distinct possibility that normal and prudent business decisions may not produce results that are in the public interest and may result in the need for the development of a regulatory environment.

1. Regulatory Consideration

    The need for regulatory consideration is the result of market failure caused by externalities. An externality is said to occur when one party’s actions impose uncompensated benefits or costs on another outside the marketplace. Environmental problems are a classic case of externality. The clutter of space with orbital debris is an environmental problem. The consequences of orbital debris may be of minor import today, but if appropriate measures are not taken in the near term to restrict or reverse the growth of the orbital debris population, long term effects of orbital debris may be irreversible and disastrous. Market failure is the result of the long time delays (perhaps 50 to 100 years) between cause and effect and the lack of economic incentives to make near-term investments by those who will not be around to be affected by the long term debris environment.

    Some space missions already perceive economic incentives that encourage taking of cost incurring actions in the near-term so as to eliminate or substantially reduce the economic consequences of orbital debris—GEO comsats are moved to higher altitudes near end of useful life and LEO comsats are likely to be moved to other orbits [including reentry] near end of useful life. However, because of the lack of uniformity of economic incentives coupled with the long time between cause and effect, externalities exist of sufficient concern to warrant the consideration of the need for regulation.

    Current U.S. National Space Policy requires that orbital debris mitigation measures be “consistent with mission requirements and cost effectiveness.” These debris mitigation measures will result in some added cost or payload penalty. By implementing these measures during the system design process, economic penalties can be kept to a minimum. A requirement to deorbit upper stages, for instance, entails weight and performance changes that increase launch costs. In determining what steps the U.S. government should take to address the orbital debris problem, it is necessary to consider the economic impact of regulations on the domestic launch and satellite industries. Unlike government, the private sector functions in a highly competitive environment. The cost of orbital debris measures is passed on to the customer. If the same launch and orbital operations requirements are not imposed on foreign competitors in the space industry, U.S. industry may have to operate at a competitive disadvantage. Similarly, added costs can have a direct bearing on the competitiveness of space-based technologies (e.g., satellite communications) as compared to terrestrial alternatives (e.g., fiber optics communications).

2. Economic Analyses

    Economic analyses are needed to identify cost-effective approaches to satisfy requirements while indicating the importance, or lack thereof, of the regulatory requirement on the approaches. In other words, it is necessary to identify the least cost approach to satisfying the requirement and the sensitivity of the result to the level of the requirement. Economic analyses must identify who bears the costs and who obtains the benefits and when the costs and benefits occur so that the equity of impacts may be observed. Costs must take into account all effects of changes in launch vehicle capability (resulting from meeting requirements) as they affect user “value.” A reduction in lift capability may be translated into shorter satellite lifetime which will affect mission economic value. This reduction in economic value must be contrasted with the effects of orbital debris on increased mission costs if the remediation measure were not taken. The bottom line is that the economic analysis should develop the case that debris, if the regulatory action is not taken (i.e., no remediation), will lead to costs that will
exceed remediation costs and that, because of market failure, regulatory action is required.

A first step in performing the economic analyses identified above is the establishment of a set of requirements (i.e., the specific goal or objective of the regulatory action as manifested in terms of specific operational requirements). A step in this direction has already been taken by NASA. NASA has developed a set of guidelines and methods to comply with NASA policy to limit debris generation. The guidelines serve to help ensure that launch vehicles, upper stages, and payloads meet acceptable standards for limiting debris generation. These guidelines are imposed upon NASA missions and have been recommended for industry adoption with regard to the generation of debris. The guidelines are specific with regard to orbital debris size, mass, and duration in orbit. The economic impacts of these agency self-imposed guidelines have not been widely analyzed. It is this set of guidelines that may serve as a reasonable starting point for regulatory economic impact analyses and for developing alternatives that must be considered (for example, timing of initiation and different regulatory requirements for different altitudes and inclination angles) when seeking to establish a regulatory regime.

In summary, the use of the space environment has become extremely important to the functioning of the world’s economy. The rate of growth of the orbital debris population, if allowed to continue unabated, may in the long term substantially reduce the ability to utilize the space environment. Debris remediation measures, possibly in the form of a regulatory regime, may have to be introduced sooner rather than later to protect this precious resource.

INTER-Agency/International Activities

1. Inter-Agency Activities

Within only a few decades, space has become an essential resource for science, defense, and commercial utilization. These, as well as human activities in space, are however, increasingly at risk resulting from production of man-made space debris. The concern about this problem, which causes a growing threat for the future of space flight, has been recognized in the United States since the early 1980s. In 1987 the DoD Space Policy stated that “...DoD will seek to minimize the creation of space debris in its military operations. Design and operations of space tests, experiments and systems will strive to minimize or reduce debris consistent with mission requirements.” As a result of this policy an Interagency Group (IG) conducted a study in 1989 that recommended:

1. Make debris minimization a design consideration
2. Establish a DoD/NASA joint study group to develop plans for debris measurement, modeling, and mitigation
3. Establish a DoD, NASA, DOT, and commercial operation study to construct a research plan for developing technologies and procedures to mitigate debris

The U.S. National Space Policy on Orbital Debris was issued in 1989 and stated that “All space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments, and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. The U.S. government will encourage other spacefaring nations to adopt policies and practices aimed to debris minimization.”

To carry out the IG (Space) report recommendations, a DoD/NASA study was conducted. That study provided more detailed goals for the research program and recommended that it consist of two phases. In the first phase, emphasis would be placed on increasing knowledge of the debris environment in LEO. The second phase would focus on determining the debris hazard and on improving spacecraft survivability. A program plan was submitted to the National Space Council and approved in July 1990. The DoD and NASA phase one program was completed in December 1993. At this time DoD and NASA results were reviewed and an updated report was prepared under the auspices of the White House Office of Science and Technology Policy (OSTP).

The 1989 study was re-examined by the National Research Council (NRC) in 1993 at the request of NASA. A report issued by the NRC in 1995 recommended that:

1. Models of the future debris environment should be further improved.
2. Uncataloged debris in LEO should be carefully studied.
3. Further studies should be conducted to better understand the GEO debris environment.
4. A strategy should be developed to gain an understanding of the sources and evolution of the small debris population.
5. The data acquired from this research should be compiled into a standard population characterization reference model.

In 1995, the OSTP released a report on space debris, “Interagency Report on Orbital Debris” (an update of a 1989 Inter-agency report). This report gave several recommendations on areas of space debris research and analysis:

- Continue and enhance debris measurement, modeling, and monitoring capabilities;
- Conduct a focused study on debris and emerging LEO systems;
- Develop government/industry design guidelines on orbital debris;
• Develop a strategy for international discussions; and
• Review and update U.S. policy on debris.

On 14 September 1996, President Clinton signed the latest National Space Policy. The policy states that “The United States will seek to minimize the creation of space debris. NASA, the Intelligence Community, and the DoD in cooperation with the private sector, will develop design guidelines for future government procurements of spacecraft, launch vehicles, and services. The design and operation of space tests, experiments and systems, will minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. It is in the interest of the U.S. Government to ensure that space debris minimization practices are applied by other spacefaring nations and international organizations. The U.S. Government will take a leadership role in international fora to adopt policies and practices aimed at debris minimization and will cooperate internationally in the exchange of information on debris research and the identification of debris mitigation options.” The policy is consistent with the goals of the (International) Interagency Space Debris Coordination Committee (IADC), the United Nations’ Committee on the Peaceful Uses of Outer Space (COPUOS), and other intergovernmental working groups.

A U.S. Government Orbital Debris Workshop for Industry was held in Houston on 27-29 January 1998. This workshop included five government agencies and representatives from the aerospace industry. Attendees expressed a desire for orbital debris mitigation standards and cited the need for a “level playing field” both domestically and internationally. The workshop suggested that standards need to be quantitative, explicit, and applied and enforced uniformly. Specific standards (guidelines) recommendations dealt with:

- solid rocket motor debris
- eliminating failure modes leading to explosions
- assuring postmission disposal
- collision avoidance for tethered systems
- favoring reentry over disposal orbits

2. International Activities

(a) The International Academy of Astronautics

The international community represented by the International Academy of Astronautics (IAA) published a position paper on space debris in 1992. Proposed methods of control included options that fall into three categories: those requiring minimal impact on operations, those requiring changes in hardware or operations, and those requiring technology development. Options in the first category recommended for immediate application are given as follows:

1. No deliberate breakups of spacecraft that produce debris in long lived orbits.
3. Safing procedures for all rocket bodies and spacecraft that remain in orbit after completion of their mission.
4. Selection of transfer orbit parameters to ensure the rapid decay of transfer stages.
5. Reorbiting of geosynchronous equatorial satellites at end-of-life (minimum altitude increase 300-400 km).
6. Upper stage and separated apogee kick motors used for geostationary satellites should be inserted into a disposal orbit at least 300 km above the geostationary orbit.

Second category options aim for removing used upper stages and dead spacecraft from orbit. This could be accomplished with deorbiting maneuvers to ensure atmospheric entry over ocean areas. Debris control options of category three require new developments where, in general, technical feasibility and cost effectiveness must be demonstrated. Installation of drag enhancement devices and the use of lasers debris sweeps fall into this category.

A revision of the IAA position paper on space debris has been initiated to update the factual information and re-examine some debris control options. The revised position paper is planned for publication in the near future.

(b) The Inter-Agency Space Debris Coordination Committee (IADC)

A preeminent international forum for exchanging technical information on orbital debris research and for coordinating joint studies has been established and is now comprised of 10 members: China (CNSA), ESA, France (CNES), Germany (DLR), Great Britain (BNSC), India (ISRO), Italy (ASI), Japan, Russia (RKA), and the United States (NASA). The IADC is organized in four Working Groups (Measurements, Environment and Database, Protection and Mitigation, and a Steering Group.) Periodic meetings of IADC result in the creation of new action items on the various issues of space debris hazard assessment and mitigation. Four such action items were adopted in Houston in 1997 at the 15th meeting of the IADC dealing with LEO constellation modeling, reentry survivability, preparation of a hypervelocity impact protection manual, and hypervelocity impact test facility calibration. In addition, ongoing cooperation in LEO and GEO debris observation campaigns, a compilation of orbital debris sources, and the exchange of information on risk objects nearing reentry was continued at its 16th meeting at Toulouse, France on 3-6 November 1998.
A Committee on the Peaceful Uses of Outer Space (UNCOPUOS) represented by its Scientific and Technical subcommittee held its thirty-fifth session in Vienna 9–20 February 1998. The representatives from 54 countries including the United States attended the session. Also present were representatives of the European Space Agency (ESA), committee on Space Research (COSPAR), International Academy of Astronautics (IAA), International Astronautical Federation (IAF), International Astronomical Union (IAU), International Society for Photogrammetry and Remote Sensing (SPRS), and International Space University (ISU).

General matters related to space debris were discussed at the meeting where it was agreed that consideration of space debris was important and that international cooperation was needed to expand appropriate and affordable strategies to minimize the potential impact of space debris on future space missions. The subcommittee further agreed that national research on space debris should continue and that Member States and international organizations should make available to all interested parties the results of such research including information on practices adopted that had proved effective in minimizing the creation of space debris.

**SUMMARY AND CONCLUSIONS**

This paper reviewed the nature and the magnitude of the space debris hazard at present and in the near future to operational space systems. Based on the information presented it can be concluded that the threat that orbital debris poses to space activities is currently small but is anticipated to increase in time if appropriate mitigation measures are not implemented. The cost and effort of taking judicious and timely steps now to enhance the understanding of the risk and agree on ways to reduce it can be relatively small. Risks may increase significantly if no action is taken now.

The areas requiring attention fall into four categories: measurements, environment and data bases, impact protection, and mitigation. National and international activities in these areas are presently being conducted with a view of coordinating and agreeing on the appropriate measures to be taken by all space faring nations.

The resolution of uncertainties in the LEO debris population sizes of 0.1 to 10 cm and the GEO population down to 10 cm in size is needed. The impact of the debris environment on LEO constellations needs to be examined. Issues such as the long-term prediction of background collision risk, self-induced collision risk from debris created by potential collisions of constellation satellites, and the long-term prediction of population growth at constellation altitudes are important.

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**REFERENCES**