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OPTIONS FOR CONTROLLING ORBITAL DEBRIS

W. Flury, ESA/ESOC, Darmstadt, Germany
D. McKnight, Kaman Sciences, Alexandria, USA

ABSTRACT

This paper, which is a shortened draft of the IAA Position Paper on Orbital Debris, describes the current space debris situation and makes clear how significant and severe the continued placement of orbital debris into the near Earth environment is to the future use of space for all mankind. It provides also some clear guidelines as to how the international community might wish to proceed in order to combat this growing space environmental hazard. Several actions are recommended for immediate application in a first phase.

1. INTRODUCTION

The International Academy of Astronautics (IAA), being concerned about artificial space debris which causes a growing threat for the future of spaceflight, initiated a study to be performed under the supervision of its Committee on Safety, Rescue, and Quality. The objectives were to elaborate on the need and urgency for action and to indicate ways for their implementation. Pursuing this task, the Committee created an ad hoc group of experts (see Annex) which compiled a position paper on orbital debris. It is now submitted to the President of the International Academy of Astronautics for further review aiming at approval and subsequent widest distribution as a Cosmic Study of the Academy.

Since 1957, mankind has performed more than 3,400 space launches into Earth orbit. The large number of spacecraft, rocket bodies, and other hardware associated with these missions subsequently encounter one of three fates: (1) reentry into the Earth's atmosphere, (2) escape from Earth orbit into deep space, or (3) remaining in Earth orbit.

After nearly 35 years of international space operations, almost 22,000 objects have been officially cataloged with approximately one-third of them still in orbit about the Earth (Fig. 1). "Cataloged" objects are considered to be objects larger than 10 - 50 cm in diameter for LEO and 1 m in diameter in higher orbits, which are sensed and maintained in a database by the United States Space Command's Space Surveillance Network (SSN).

The purpose of this position paper is to review the growth of the population of man-made objects

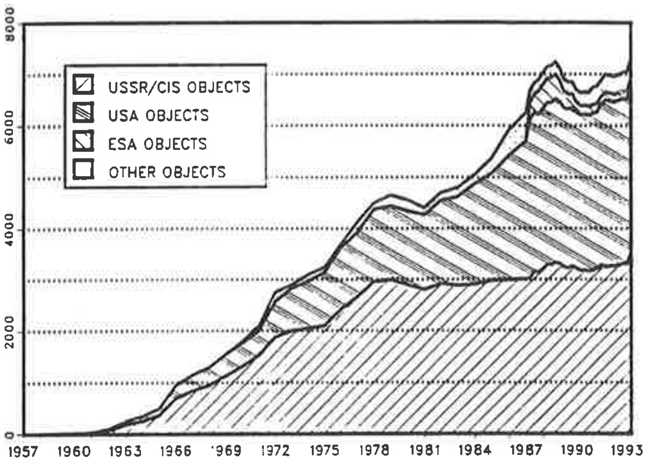

Figure 1. Cataloged objects in orbit.: Cataloged objects are considered to be objects larger than 10-50 cm diameter for LEO and 1 m diameter in higher orbits.

in Earth orbit, with emphasis on orbital debris and on the hazard presented to current and future space operations, and to assess preventive measures for debris reduction.

Orbital debris is herein defined as any man-made Earth-orbiting object which is non-functional with no reasonable expectation of assuming or resuming its intended function or any other function for which it is or can be expected to be authorized, including fragments and parts thereof. Orbital debris includes non-operational spacecraft, spent rocket bodies, material released during planned space operations, and fragments generated by satellite and upper stage breakup due to explosions and collisions. Only about 6% of the catalogued objects are operational satellites. About one-sixth of the objects are derelict rocket bodies discarded after their use, while over one-fifth are non-operational payloads. Pieces of hardware released during payload deployment and operation are considered operational debris and constitute about 12 percent of the catalogued population. Last, the remnants of the over 100 satellites and rocket stages that have been destroyed on-orbit account for over forty percent of the population by number. These proportions have varied only slightly over the last 20 years. Small-size orbital debris (size ranging from 1/1000 mm to 1 mm) include particles from paint, coating, aluminum oxide of solid motor propellant, and fragments of breakups. This derelict hardware is strewn across a wide range of altitudes, but is clustered around regions where space activity has been the greatest: LEO and GEO. A lesser amount of debris currently resides in HEO. Orbital debris continually passes through space shared with functioning fragile and expensive spacecraft, manned and unmanned, performing vital navigation, communications, remote sensing, surveillance and scientific missions. Orbital debris may present a variety of problems to the spacefaring community, from the possibly catastrophic collision hazard to the corruption of astronomical observations and intermittent interruption of RF paths.

The original particulate design environment for spacecraft considered meteoroids exclusively. These are natural particles ranging in size typically from a fraction of a micron to millimeters. These objects are in heliocentric orbits and as the Earth passes through them in its orbit around the sun, they are seen as "shooting stars" in the night sky. Their presence varies with the time of year as the Earth revolves around the sun. Such meteoroids are traveling at very high speeds, on average two and a half times the velocity of objects in LEO and the material of these objects is quite similar to grains of sand. On the other hand, debris from man-made activities are of larger size, of much more dense materials and continuously orbit the Earth.

Discussion and evaluation of the consequences of objects which have escaped Earth orbit or have returned to Earth through uncontrolled re-entry, while meriting attention as a separate issue, are not further discussed here with the exception of one point: All reasonable effort should be made to avoid the accidental uncontrolled re-entry of large objects, which could partially survive entry heating and pose a potential hazard to people and property on ground.[1]

The natural meteoroid environment, which is successfully countered with established design features, is employed as a reference by which the orbital debris hazard can be placed into proper perspective. Orbital debris markedly exceeds the meteoroid population for objects larger than 1 mm, and as a result is now considered the design environment for manned and unmanned space systems.

Space is a "commons" used by many for their individual and collective benefit. If it is to be protected so that all can continue to exploit its unique attributes, there must be concerted and cooperative action among the spacefaring nations. In part, this is necessary to make economic competition equitable, but it is also necessary to keep valuable operational regions technically and economically viable for the future.

Since operational lifetimes are generally much shorter than the orbital lifetime of both LEO and GEO satellites, it becomes clear that some active control of these regions of space must be required. In LEO, both inadvertent and deliberate explosions have added significantly to this spatial population. To minimize collisions among objects large enough to generate substantial further debris some active control may be required.

The purpose of this position paper is to convey clearly the urgency of taking action to control the growing orbital debris population and to make recommendations for possible methods to initiate selected control options. Efforts to increase awareness of orbital debris and to develop methods for debris mitigation have gained momentum over the last few years, although scientific uncertainties remain in a number of critical areas. This paper recommends certain initiatives that could be implemented immediately to mitigate and control future debris generation.

2. PRESENT STATUS

Most of the cataloged objects are located in LEO. Maxima of the spatial density are near 1000 km and 1500 km altitude. The collision risk in LEO is much higher than in GEO because of the higher relative velocities. The number of objects in LEO has doubled since 1978, while the population in GEO has more than doubled since 1982. Today about 6 percent of the tracked object population resides in GEO or near GEO orbits. In total, about 350 - 400 spacecraft have been inserted in the geostationary ring. Over a 100 upper stages and several separated Apogee Boost Motors (ABM)[2] are located in the geostationary ring or its vicinity.

During the space age, the cataloged population (all altitudes combined) has grown at nearly a net linear rate of 200 entries per year. Apart from a few exceptions (luni-solar perturbations of highly eccentric orbits, solar radiation pressure), air-drag is the only natural mechanism removing objects from orbit. Its effect decreases with altitude. The Earth's atmosphere produces drag forces that retard an orbiting object's motion and cause it to spiral into denser regions of the at-

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1 Most re-entering spacecraft and upper stages are destroyed by entry heating. In rare cases some solid pieces reach the Earth's surface (Skylab, Kosmos 954, Salyut-7/Kosmos-1686).

2 Apogee Boost Motors are used to insert spacecraft into the geostationary orbit. They are usually spacecraft-integrated propulsion units with solid propellant.

mosphere where it typically burns up due to air friction effects. The less "massive" the object for a given cross-sectional area, the greater its drag will be, resulting in a shorter lifetime in orbit. The atmospheric density at a given altitude increases with solar flux, which has an 11-year cycle. This accounts for the periodic "cleansing" effect which reduces the orbital population during high solar cycle periods.

At higher altitude this mechanism becomes less efficient (Table 1), and objects will in general remain for extended periods in orbit. Therefore, at higher altitude the consequence is a steady accumulation of man-made objects.

Orbit altitude (km)	Lifetime
200	1 - 4 days
600	25-30 yrs
1000	2000 yrs
2000	20000 yrs

Table 1. Lifetime of circular orbits: For an average-type satellite the lifetime for several circular orbits is shown.

The major concern with orbital debris is that it might strike an operational satellite or other massive object, causing any of a wide variety of detrimental consequences. If a trackable object were to strike another trackable object (like an operational satellite) both would most likely be destroyed, due to the large relative kinetic energy available. The available kinetic energy for the encounter, as seen by the satellite, is a function of the impactor mass and the relative velocity between the impactor and satellite. In LEO the average relative velocity between any two orbiting objects is about 10 km/s. At this speed, an 80 gram object (about 5-10 cm in size) introduces the kinetic energy equivalent to 1kg of TNT. Upon impact, a 1kg object would probably completely destroy a LEO satellite of 500-1000kg mass. Even a 1cm fragment has sufficient energy to significantly disrupt any satellite's operations.

There is a wide variety of causes for satellite and rocket stage breakups: battery failure, deliberate detonation, overpressurisation and/or ignition of fuels, accidental collision, and weapons testing. The severity of a fragmentation event is largely a function of two parameters: the available energy for breakup, and the efficiency by which the energy is coupled to the vehicle.

Debris in the 1 - 10 cm size range, though too small to be sensed by ground systems, are large enough to cause catastrophic damage to many satellites. Particles of this size have been produced by the thousands from many of the 109 known spacecraft and rocket body breakups to date. The rate of breakup events has not subsided, despite the increased concern and awareness of orbital debris. The on-orbit evolution of these centimeter-sized debris is determined by the physical characteristics of the fragments, initial velocity distribution, and the various perturbing forces. At altitudes where atmospheric drag is less pronounced, the population of these types of objects may be much larger than the trackable population, possibly by factors as large as two to ten.[3] At altitudes below 600 km, these smaller objects may be less populous than the trackable population because the lower mass to area ratio makes them more susceptible to atmospheric drag. The trackable population is growing at a faster rate at higher altitudes than lower altitudes, due partially to the reduced influence of atmospheric drag.

Orbital debris in the 1 mm - 1 cm size range may produce mission-degrading effects on spacecraft which they encounter. These objects are thought to be more numerous than larger ones in orbit even though there have been few, if any, actual measurements of impacts by fragments of this size. Characteristic ballistic coefficients of these small debris and the influence of non-gravitational effects (e.g., solar pressure), may, however, lead to more rapid orbital decay.

On the other hand, numerous measurements of impacts by fragments smaller than 500 microns have been recorded on surfaces exposed to the space environment, e.g. NASA's LDEF (Long Duration Exposure Facility). A recent analysis has identified more than 50 impact features on the U.S. Shuttle orbiter windows over 40 missions (up to May 91), leading to the replacement of nearly 25 panes of them.

In general, the impact flux increases as fragment size decreases.

The risk to operational assets in orbit varies by altitude, inclination, spacecraft characteristics, and year. The probability that two items will collide in orbit is a function of the spatial density of orbiting objects in a region, the average relative velocity between objects in that region, the collision cross-section of the scenario being considered and the time the object at risk is in the given region. There are an infinite number of possible combinations, but two specific situations might be illustrative. First, for a 20 square meter cross section satellite at 850 km, the probability of a

[3] Recent radar measurement from Haystack indicate that in some low-altitude bands the population of centimeter-sized objects may be about an order of magnitude larger than the catalogued population.

collision with a trackable object is 1:10,000 per year. An operational satellite in this region will have a 99.9% probability of surviving a 10 year mission without being struck by a cataloged object.

The probability that any two trackable objects will collide (collision rate) in this altitude region, 800-1000 km, during one year is 1:100. At this level of hazard it is likely (greater than 50% chance) that a collision-induced breakup of a trackable object by another trackable object will occur in the next ten to 15 years.

It has been estimated that there are two to ten times as many 1 - 10 cm orbital debris fragments in LEO as there are trackable objects. Assuming that this ratio has been at least five since the mid-1970s, there is a 40 - 70 % chance that one of the breakups in the 800 - 1000 km altitude band was caused by the impact of a piece of orbital debris in the 1-10 cm size range.

The second orbital case considered is that of a particular 50 square meter controlled spacecraft in GEO.[4] It has a 1:1,000,000 chance per year of being struck by an uncontrolled and trackable object. The collision rate among all trackable objects will only be approximately 1:500 per year. Due to the inability to sense objects smaller than one square meter, the hazard from objects greater than 10 cm in size for GEO may be underestimated at this time.

In GEO, we basically have three different collision risks for operational spacecraft. First, a piece of debris may collide with an operational station-kept spacecraft, as stated above. Second, operational spacecraft located within the same longitude window (colocated spacecraft) could collide with each other. The heavy use of the geostationary orbit makes it necessary to place several active spacecraft in the same longitude window of typically 0.2 degree (=colocation). The chance of a close approach of 50 m (measured center to center) in the second scenario for a four-spacecraft cluster in a typical longitude box is about 60 % per year, assuming that the spacecraft are operated independently by different control centers. This high probability is explained by the minimum-fuel station-keeping strategies.

A third potential collision risk in GEO is connected with station-acquisition maneuvers (reaching the nominal longitude after launch) and the relocation of geostationary satellites. Relocation is achieved through a neighboring transfer orbit, either a few km above or below the geostationary orbit.

The present hazard to satellites in orbit from debris varies depending on altitude, mission, satellite construction, etc. Manned missions require shielding due to reliability and safety considerations. Sensitive parts of satellites may also need protection. The Radarsat spacecraft of the Canadian Space Agency became the first unmanned satellite to incorporate shielding to counter the projected debris collision hazard. The complexities of determining whether a satellite is at risk is very mission and user dependent. The most distressing aspect of the orbital debris problem is that it is getting worse in many regions and may begin to grow out of control at some altitudes within the next few decades. The uncertainty involved in many of the present analyses highlights the need for technological developments to more accurately depict the hazard from orbital debris, prevent its creation, and provide protection from its impact.

3. NEED FOR ACTION

The cataloged population is an important observable parameter for the prediction of the future state of the orbital environment. On average its increase is about 200 objects per year. The evolution of the orbital debris environment cannot precisely be predicted due to the possibilities of increased launch rates by a growing number of spacepowers, especially in light of new smallsat technology, but may be tempered somewhat by the possible decline in former Soviet space activity.

Several studies have been conducted that discuss the possibility of a cascading effect occurring in LEO, where the rate at which debris is produced by collisional encounters creates debris more quickly than it can be cleansed via atmospheric drag. This phenomenon could then cause an increase in the growth rate of orbital

[4] The ideal geostationary orbit has a radius of 42164 km and lies in the equatorial plane. The direction of motion is in the same sense as the rotation of the Earth. A satellite in this orbit would complete an orbital revolution after one sidereal day or approximately 23h 56m 4s.
Due to orbital perturbations caused mainly by the ellipticity of the Earth's equator and gravitational attraction by Sun and Moon, orbit adjustments are necessary which involve the use of onboard thrusters and expenditure of propellant. Once all the propellant is consumed, or if the spacecraft is no longer controllable, the spacecraft will begin its free motion. The inclination will cyclically vary over a period of about 53 years and reach a maximum of about 15 °. It will typically traverse the geostationary orbit in North-South direction twice every day, reaching a maximum relative velocity with respect to controlled satellites of about 800 m/s, which is about three times faster than a jet transport. Its longitudinal position will no longer be kept constant.

debris, resulting in much greater collision hazard for nearby satellites. This population density (called the critical density) may have already been attained at some altitudes near 1000 km.

Much more research is needed to determine if this methodology is an accurate and appropriate measure of merit. Other analyses have stated that the population in LEO need only double for the onset of a runaway growth to take effect. From Figure 2 it can be seen that this might occur in the next 10 to 15 years, if there are no changes to the way operations are conducted in space. When, or if, this situation is reached, the population will grow exponentially (Fig. 2).

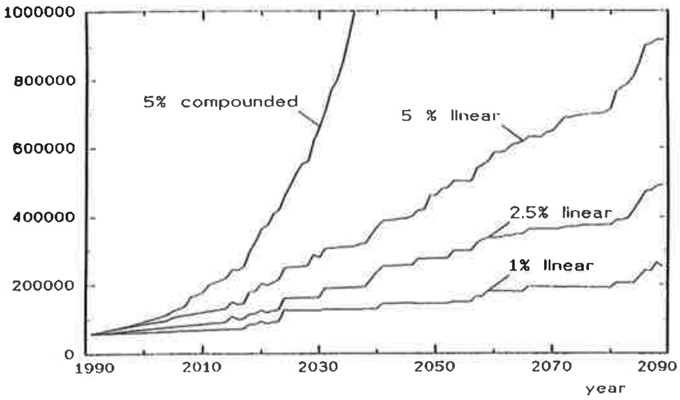

Figure 2. Long-term evolution of debris > 1 cm: Depending on the growth rate of cataloged objects the long-term evolution of debris larger than 1 cm is displayed (linear rates refer to the initial population of 1990, compounded rates to the preceding year).

Space operations in some altitudes will then be severely hampered.

Previous studies assumed satellite populations fairly evenly spread across hundred of kilometers, but the advent of constellation architectures, such as Iridium and Brilliant Pebbles, may add another dimension to this analysis. Multi-satellite constellations clustered in narrow altitude bands may be much more sensitive to population densities leading to collisional break-ups. The individual satellite system designers should pay careful attention not only to how they deploy and operate their own systems, but also to the actions of users in neighboring space regions.

4. DEBRIS CONTROL OPTIONS

The need to change the manner in which space missions (launch, deployment, operations, and termination) are conducted has been debated at length. All investigations addressing the long-term evolution of orbital debris conclude that, without changes to the way space missions are performed, regions of near Earth space will become so cluttered by debris that routine operations will not be possible. The options available to decrease the growth of orbital debris depend greatly on the altitude of the mission, design of the hardware, and the commitment of the international spacefaring community.

The amount of debris can be controlled in one of two ways: debris prevention or debris removal.[5] Table 2 shows individual techniques under each of these categories.

PREVENTION	REMOVAL
Design and operations Expulsion of residual propellants and pressurants Battery safety (vent or fuse) Retention of covers and separation devices Propulsive maneuvers (reorbit)	Retrieval Propulsive maneuvers (deorbit) Drag augmentation Solar sail Tether Sweeping Laser

Table 2. Methods to reduce debris population

Several of these techniques are already practiced by space users at this time. The fact that some debris minimization techniques are already being used voluntarily bodes well for the future, but it is not clear at this time which of the methods are most effective and how to measure the cost-benefit tradeoffs for each. Continued research is required in this area. Identification of realistic and effective methods is the most important issue.

Some prevention methods already in limited use include: application of debris catchers for explosive bolts, fewer releasable parts, and multiple payloads on a single launch. These have been incorporated on several launch vehicles to date.

Debris removal options have been used on a few occasions to date, e.g. retrieval via the U.S. Space Shuttle or deorbit. Debris removal has

5 Removal means to remove from orbit.

been used in the Soviet manned program through the deorbiting of Progress supply vehicles and space stations into oceanic areas, except Kosmos 557, Salyut 2, and Salyut 7/Kosmos 1686.

An important category of debris prevention methods is safing of hardware to avoid breakup by explosion. The retrieval of large derelict objects may be expensive and difficult, but it is certainly more difficult and expensive to recover the debris created from the fragmentation of such an object. For LEO rocket bodies, the expulsion of propellants and pressurants has been used successfully in the past and provides a significant measure of safety for the future. Several rocket vehicles routinely perform these expulsion procedures for hardware in sun-synchronous orbits (Ariane and Delta) already to reduce the chances of future fragmentation events. From flight V59 onward all Ariane upper stages will be vented, irrespective of the type of orbit. The Delta second stage is burned to depletion after deployment of the payload and execution of a maneuver to avoid a collision. The Japanese H-1 second stage (LE-5) has vented main-engine residual propellants and gas-jet propellant after completion of payload separation. This action was conducted irrespective of mission and was not limited to sun-synchronous missions. A similar procedure is planned for the H-2 launch vehicle. The Chinese Academy of Sciences is also investigating similar procedures for the Long-March upper stage.

Unfortunately, fuel venting has not been applied to the more than 100 liquid upper stages in the vicinity of the geostationary orbit. Such a procedure should be initiated as soon as practical and include the liquid attitude and trim systems of solid rocket boost-stages.

On several previous occasions the overcharging of a battery on a satellite has caused small breakup events and precautions should be taken to prevent this type of occurrence in the future.

Another important category of preventive action is reorbiting into a disposal orbit. For example, in GEO satellites at end-of-life may be boosted several hundreds of kilometers above GEO to prevent continual interaction with other operational craft. The re-orbiting move is presently the only practical way to reduce the collision risk in GEO. This procedure has been performed over 60 times. A minimum orbit raising altitude of 300-400 km is recommended. The velocity requirement for reorbiting is 3.63 m/s for every 100 km altitude increase. A multiple-burn strategy should be adopted which takes into account uncertainties in the propellant estimate. In the long run, a more permanent disposal method must be considered.

The objective in a removal maneuver is to prevent objects that are no longer functional from collision with current or future functional systems.

The use of drag augmentation, propulsive maneuvers, solar pressure movement, or tether removal requires the development of hardware not presently available and imposes a performance penalty. Drag augmentation hardware might include inflatable devices that would rigidize upon deployment, presenting a much greater cross-sectional area to the atmosphere to increase the drag forces on the object. Drag augmentation will work best for low altitude missions, below 600 - 700 km. Propulsive maneuvers to force deorbit, or at least a reduction in orbital lifetime, may be immediately possible for some rocket stages but not for the majority of large derelict hardware already in orbit. As long as attitude and control capabilities are maintained on the rocket stage, a small maneuver (away from the released spacecraft to avoid contamination from rocket firings), followed by a burn, might produce the appropriate change in orbital elements. Due to the effect of the Earth's gravitational field, it is most economical to deorbit into the Earth's atmosphere below 25000 km altitude and to boost to a higher altitude above that orbit.

Fig. 3 illustrates the propulsive mass penalty to deorbit a rocket body from a circular orbit.

Additionally, the ability to move objects that have never had any propulsive capability, years after their use, presents a difficult problem. A remotely controlled "space tug" deployed to rendezvous with and deorbit large derelict objects might provide an effective means to remove debris. Conceptual designs for this type of vehicle, however, have indicated that costs are very high with existing technology.

Another method by which a derelict object may be moved is a solar sail, which would use solar radiation pressure to change its orbital elements. This technique would require an increase in hardware costs and would create a very slow change in orbital elements, but would be equally effective across a wide range of altitudes. It should be noted, however, that the use of drag augmentation and solar pressure devices will increase the physical area, and thus the collision cross-section, of the object that is being removed.

The use of a tether will require some hardware development and manufacture, plus the inherent operational reliability problems of adding other types of hardware to already complex systems.

The use of some type of sweeper mechanism has been discussed on numerous occasions. There are several types of technology efforts that must

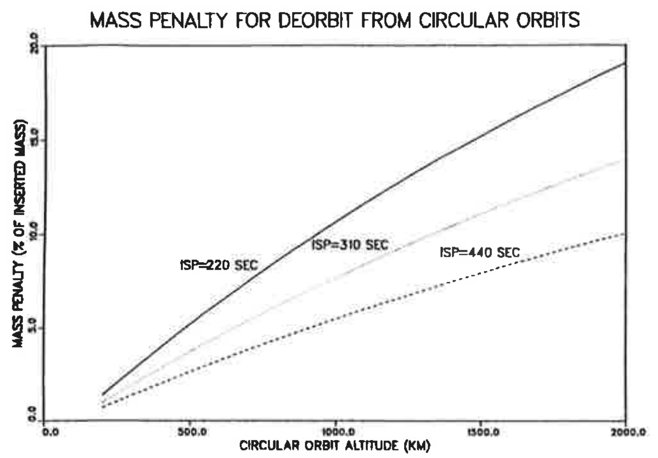

Figure 3. Mass Penalty for Deorbit from Circular Orbits: For different values of specific impulse the mass penalty is displayed.

be initiated in support of this type of removal method, e.g. some material must be developed that will be able to withstand the impact of orbital debris, without releasing more debris than the sweeper has collected. Furthermore, the sweeper should have the capability to distinguish between debris and useful spacecraft. These considerations may make such systems impractical.

5. METHODS OF DEBRIS CONTROL

There is a need to initiate internationally-accepted debris control measures to preserve useful altitudes for functioning spacecraft, but there is debate as to the timing and level of options. One good way to determine what types of techniques and designs to select is to perform a series of thorough cost-benefit tradeoff studies. Though these analyses are vitally important to ascertaining the relative merit of proposed options, there are several actions that should be initiated immediately to ensure the future viability of space travel and these will be listed at the end of this paper. The participation of spacefaring countries and their supporting aerospace industries will address the balance of costs to benefits. The loss of only a few operational spacecraft from orbital debris collisions and/or abandonment of certain altitude bands may exceed the expenditures suggested by the control options identified in this paper.

The control options to be considered fall into three categories: those requiring minimal impact on operations, those requiring changes in hardware or operations, and those requiring technology development.

Options Category I

Category I comprises those options that will have the greatest impact on population control and that require no technology development and have minimal cost impacts. Some performance reduction may, however, result. These have first priority for implementation. Most have already been effected voluntarily. If a particular option requires major hardware changes for a specific space system, then for that specific system the option shall be considered category II.

1. No deliberate breakups of spacecraft which produce debris in long-lived orbits.

2. Minimization of mission-related debris. In many cases cost-effective engineering solutions are available with low cost for implementation. In several cases, however, the costs will no longer be minor as significant design changes will be needed (e.g. yo-yo devices).

3. Safing (venting) of upper stages and spacecraft in any Earth orbit.

4. Selection of geostationary transfer orbit (GTO) parameters to minimize orbital lifetime of upper stage by keeping the GTO perigee at a low altitude, 180-200 km, and, possibly, by constraining the time of launch.[6] It can mean reduction of launcher performance of several percent.

5. Reorbiting of geostationary satellites at end-of-life to disposal orbit. Minimum altitude increase 300-400 km above the geostationary orbit depending on spacecraft characteristics.

6. If separation of ABM from geostationary spacecraft is needed, then the separation should occur in a super-synchronous orbit

[6] The geostationary transfer orbit (GTO) is a highly eccentric orbit with the perigee at low altitude (180 - 500 km) and the apogee near the geostationary orbit. Characteristic for these orbits is a long-periodic change in the altitude of the perigee caused by gravitational perturbations of the Earth, Sun and Moon. The orientation of the orbit in space with respect to Sun and Moon determines whether the perigee altitude will increase or decrease. The desired effect is an initial decrease of the perigee altitude, leading to increased air-drag perturbations, and ultimately to orbit decay. Unfortunately, the launch time of a geostationary satellite may be constrained by other factors (thermal aspects, attitude sensors, eclipse time) related to the spacecraft design, which can be in conflict with minimum GTO lifetime. However, through appropriate choice of the initial perigee altitude (180-200 km), lifetime in GTO can be significantly reduced. For some launchers the performance will be markedly reduced.

at least 300 km above the geostationary orbit.

7. Upper stages used to move geostationary satellites from GTO to GEO should also be inserted into a disposal orbit at least 300 km above the geostationary orbit and freed of residual propellant.

Options Category II

Category II comprises those options that require either changes in hardware or operational procedures. However, no new technology developments are needed. They have second priority for implementation. Category II options aim for removing used upper stages and defunct spacecraft from orbit, eliminating thus a major debris source. The options below provide candidate quantitative values.

Removal of large or compact objects, which could partially survive entry heating, is accomplished with a deorbiting maneuver to ensure atmospheric entry over oceanic areas during the next perigee pass.

Removal of objects which will completely burn up during atmospheric entry, means to place these objects in orbits with limited lifetime, say ten years. Hence in these cases natural perturbations will be exploited.

1. Removal within 3 months of all rocket upper stages and defunct spacecraft in orbits below 2000 km mean altitude with lifetimes exceeding 10 years.
2. Removal of all rocket upper stages in geostationary transfer orbits and other highly elliptical orbits within 10 years.
3. Reorbiting of upper stages and satellites at end-of-life into a disposal orbit (as a temporary measure) for circular orbits above 2000 km altitude.

Options Category III

Debris control options of category III require new developments and, in general, suitability of the method (technical feasibility, cost-efficiency) must be demonstrated. They have third priority for implementation.

1. Removal with an orbiting maneuvering vehicle requires straightforward engineering but has not proven cost-effective at this time.
2. Removal of objects with drag devices will require investigations into its efficiency and suitability. Despite the shorter lifetime the collision probability remains unchanged. The procedure will be most effective for altitudes below 1000 km.
3. Removal with tethers is an interesting concept which needs further engineering feasibility studies. Grappling of the debris object (e.g. tumbling object with significant rotational energy) and attitude control are two problem areas which must be addressed.
4. Destruction by laser may be useful but it must be performed so that the debris object is totally evaporated, otherwise additional objects are created.
5. Debris catchers/sweeper may be feasible if discrimination or avoidance between debris and useful spacecraft can be realized.

Approaches to Implementation

Essentially, there are two approaches to implementing debris control measures, a technical and a legal approach. The technical approach contemplates discussions within national and international engineering communities leading to recommendations of certain standards of conduct. Such standards may refer to spacecraft design or operational procedures. Institutional frameworks supporting these technical discussions may range from non-governmental organizations (such as IAA and other international groups or national technical and professional groups) to international or national working groups established by national or international space agencies.

The legal approach contemplates the use of legal instruments (including treaties, resolutions, laws, regulations, executive orders, etc.) to adopt and enforce certain standards of conduct. Legal instruments may codify standards already recommended by the engineering community or may rely on other technical guidance. It is only through some legal process, national or international, that a standard can become binding on a particular State or space operating entity. Not all legal instruments are binding, such as resolutions or recommendations.

Given the complexity of the debris problem, it is particularly important that the legal action be preceded by discussions in and recommendations by national and international engineering communities. Legal action would be premature without a thorough understanding of the many facets of the debris problem.

For implementation of the control options the committee suggests three avenues of approach. The professional and learned societies (e.g. COSPAR, IAA, IAF, IISL) have an important role of education, facilitating exchange of opinion and establishing common understanding of the issue

on a worldwide scale. However, since orbital debris, and more generally space debris, touch policy aspects of States (economical aspects, safety, national security) eventually international space law will be needed, which requires the involvement of governments.
The three avenues of approach, which could be taken consecutively or independently of each other include:

1. bilateral and multilateral discussions and agreements on space/orbital debris between and among spacefaring nations and international space organizations (e.g. INTELSAT, INMARSAT).
2. global working group of spacefaring nations and international space organizations.
3. discussion at CCIR/ITU and UNCOPUOS and other suitable forums leading ultimately to "Code of conduct", international standards, or space law addressing space/orbital debris.

Regular coordination meetings have taken place at the technical level among spacefaring nations for several years. From these meetings a consensus as to the nature of the issues and the need for action to control the growth of orbital debris has emerged. The community is striving to assess the effectiveness of debris control options already being used, to determine if they should be continued or if others should be developed.

The global working group should be put into place to review the tentative policies suggested by previous international discussions. As the control options used to reduce orbital debris become mature and their cost-effectiveness proven, limited agreements may be put into place. A forum such as the Consultative Committee for Space Data Systems (which coordinates data formats among the space agencies) may need to be established to coordinate multilateral agreements.

The United Nations (UN) Committee on Peaceful Uses of Outer Space (COPUOS) has formulated a number of treaties and resolutions regulating space activities, but has not yet formally concerned itself with space debris. Several States have suggested that it would be appropriate for COPUOS to consider the debris issue. A discussion within the COPUOS might lead to the development of a set of principles or a treaty which codifies the practices and standards adhered to by spacefaring nations.

6. SUMMARY

The objective of this paper is threefold. First, to make clear how significant and severe the continued placement of orbital debris into the near Earth environment is to the future use of space for all mankind. Second, to provide some clear guidelines as to how the international community might wish to proceed in order to combat this growing space environmental hazard. Third, to extend discussion of the debris issue by other international groups to exercise the techniques and dialogue necessary to begin to formulate international agreements on this topic.

The following actions are recommended for immediate application in a first phase:

1. No deliberate breakups of spacecraft which produce debris in long-lived orbits;
2. Minimization of mission-related debris.
3. Safing procedures for all rocket bodies and spacecraft which remain in orbit after completion of their mission.
4. Selection of transfer orbit parameters to insure the rapid decay of transfer stages.
5. Reorbiting of geostationary satellites at end-of-life (minimum altitude increase 300 - 400 km).
6. Upper stages and separated ABM's used for geostationary satellites should be inserted into a disposal orbit at least 300 km above the geostationary orbit.

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Annex

IAA Ad hoc Expert Group on Space Debris

D. McKnight (Co-chair), Kaman Sciences Corporation, Alexandria, USA; W. Flury (Co-chair), ESA/ESOC, Darmstadt, GERMANY; V. Chobotov, The Aerospace Corporation, Los Angeles, USA; R. Hergott, CNES, Evry, FRANCE; N. L. Johnson, Kaman Sciences Corporation, Colorado Springs, USA; J. P. Loftus jun., NASA JSC, Houston, USA; P. L. Meredith, Space Conform, Washington D.C., USA; L. Perek, Astronomical Institute CSAV, Praha, CZECHOSLOVAKIA; D. Rex, TU Braunschweig, Braunschweig, GERMANY; H. Sax, DLR, Köln, GERMANY; A. A. Sukhanov, IKI, Moscow, RUSSIA; M. G. Wolfe, The Aerospace Corporation, Los Angeles, USA; T. Yasaka, NTT, Yokosuka, JAPAN.