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SPACE DEBRIS

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INTRODUCTION

1. Within only a few decades, space has become an essential resource for science and for public and commercial use. Space activities are, however, increasingly at risk because of uncontrolled production of artificial space debris. Currently, more than 8,600 catalogued objects are orbiting the Earth, of which only about 500 objects can be considered operational spacecraft. Approximately another 1,000 are being tracked but have not been catalogued. A statistical sample of the environment has determined that a much larger number of objects 1 cm in size or larger are in orbit as well. Collision of any of these objects with an operational spacecraft may lead to damage or even functional loss because of the large amount of kinetic energy involved. The catalogued population is an important observable parameter for the prediction of the future state of the orbital environment. Figure I plots the growth of the trackable orbital debris population from 1960 to the present. The fragmentation of satellites and rocket upper stages (due to explosions) is a major source of catalogued objects (42 per cent). Therefore, a major mitigation technique consists of minimizing the rate of future explosions.

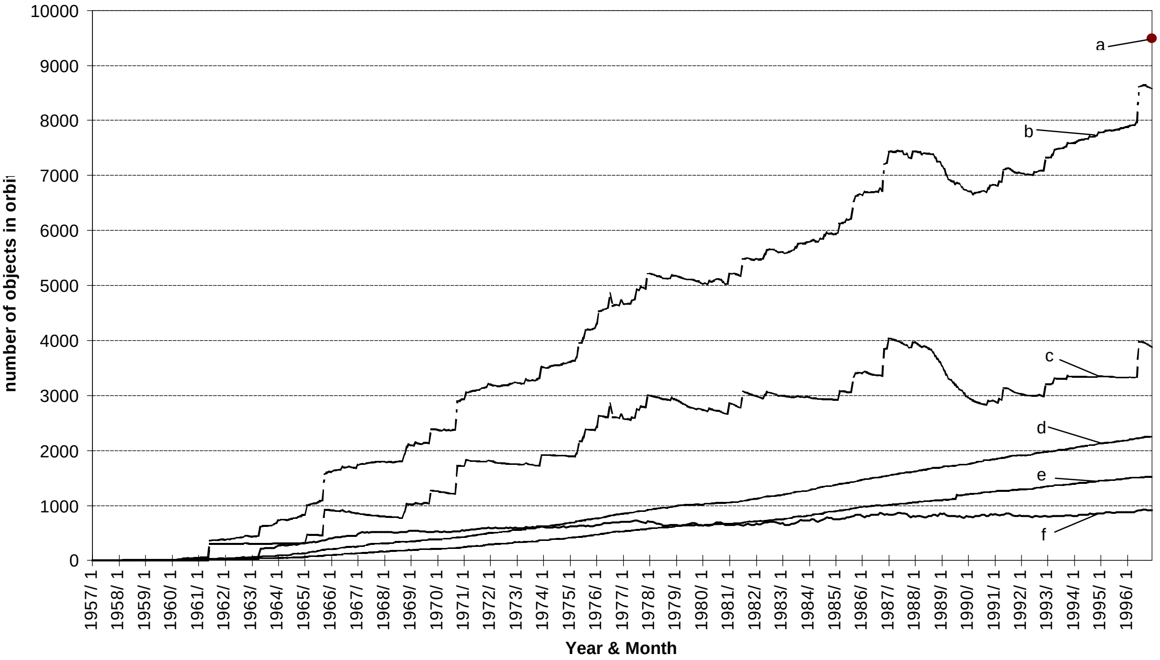

Figure I. *Growth of catalogued population.* The growth of the catalogued Earth orbit population has been nearly linear with major changes caused by breakup events and solar activity cycles. a: total number of objects, including objects not contained in the official catalogue; b: total number of objects, based on the official catalogue; c: fragmentation debris; d: spacecraft; e: rocket upper stages; f: operational debris.

2. A potential longer term source for the growth of the catalogued population is fragmentation due to collisions between catalogued objects. If the rate of catalogued objects continues to increase, the fragmentation rate due to collisions could exceed the explosion fragmentation rate. Several studies have been conducted that discuss the possibility of a cascading effect occurring in LEO, when the rate at which debris is produced by collisions 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 debris despite mitigation efforts to limit the rate of future explosions. Possible future debris growth can be illustrated in figure II, which displays the possible long-term growth for objects larger than 1 cm in size.

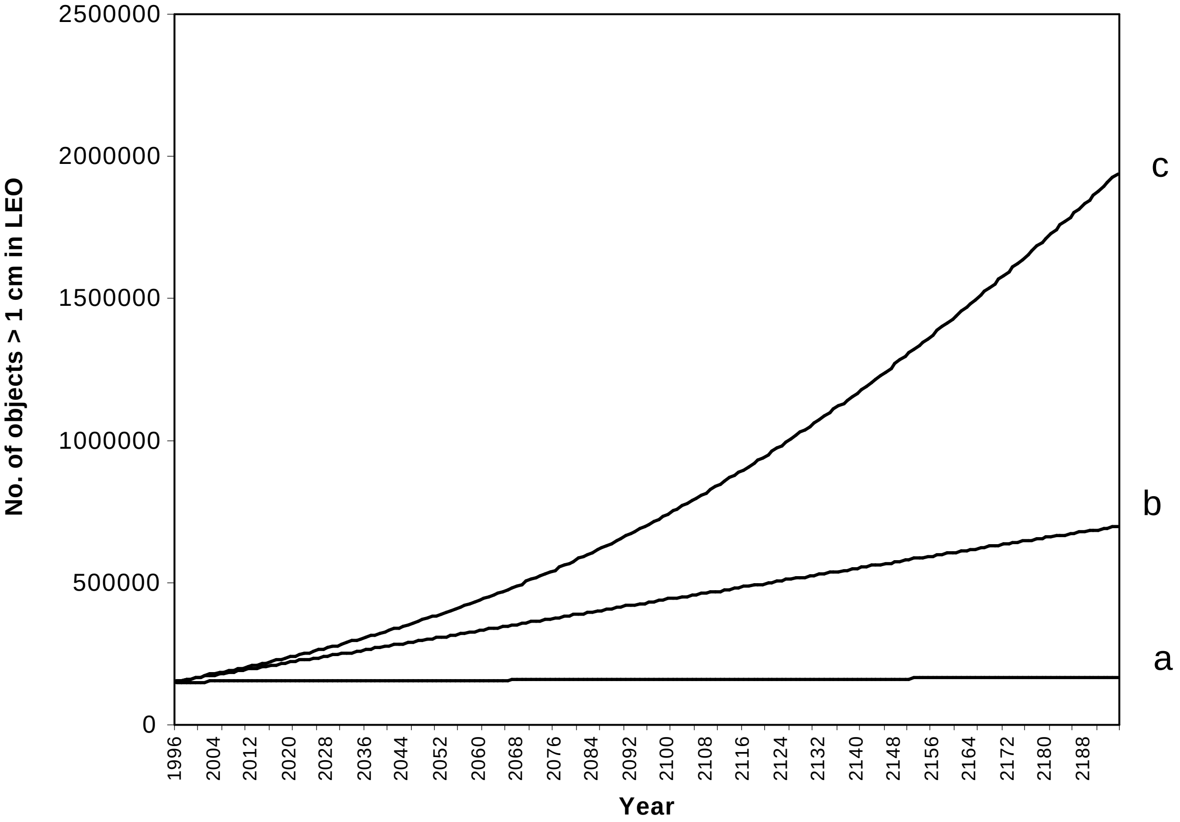

Figure II. *Long-term evolution of debris greater than 1 cm* (business as usual). Various sources contribute to the future population growth: a: satellites, rocket upper stages and mission related objects; b: explosion fragments; c: collision fragments.

3. The business-as-usual curve shows that the orbital debris environment will continue to grow. In the near term, this continued growth is primarily the result of explosions. In the long term, as a consequence of break-ups due to random collisions between larger objects, a strong increase of the debris population will occur (collisional cascading). Space operations in some altitudes will then be severely hampered. Therefore, accumulation of large objects in densely populated regions has to be avoided, in order to eliminate the possibility of collisions becoming a significant source of debris.

4. Previous studies assumed that satellite populations were spread fairly evenly across hundreds of kilometres, but the arrival of constellation architectures, such as Iridium or Teledesic, 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. Individual satellite system designers and operators should pay careful attention not only to how they deploy, operate and dispose at end of mission their own systems, but also to the actions of other users in neighbouring space regions.

5. The evolution of the orbital debris environment cannot precisely be predicted due to the possibilities of increased launch rates by a growing number of space users, especially in light of new smallsat technology and the advent of constellations of communications satellites. The uncertainty in the future environment is also increased by the uncertainty in the frequency of future explosions and collisions. A collision between two objects may result

in the creation of numerous fragments whose number and size depend on several factors, such as mass of colliding bodies and collision velocity.

6. Mitigation includes two aspects: first, protection against the impact of space debris (collision avoidance), and secondly, measures to avoid the creation of space debris. In our presentation we will focus on the debris control issues. Since currently economically feasible methods for cleaning up in space do not exist, debris control measures have to focus on those that avoid the creation of debris.

DEBRIS CONTROL OPTIONS AND ISSUES

7. The need to change the manner in which space missions are conducted during launch, deployment, operations, and termination has been debated at length. All investigations addressing the long-term evolution of orbital debris conclude that, without changes in the way space missions are performed, some regions of near Earth space will become so cluttered by debris that routine operations will be more expensive in the future. 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 space-faring community.

Debris control options

8. The amount of debris can be controlled in two ways: debris prevention or debris removal. Removal means to remove from orbit immediately or with some delay. It includes the transfer to an intermediate orbit with an orbital lifetime not exceeding a specified maximum. Table 1 shows individual techniques under each of these categories.

Table 1. Methods to prevent or remove debris

Prevention	*Removal*
Design and operations	Retrieval
Passivation	Propulsive manoeuvre
Retention of covers and separation devices	Deorbit with tether, drag increase, solar sail
Transfer to graveyard orbit	Laser

9. Several of these techniques are already practised voluntarily by space users at this time. However, 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:

- Passivation of upper stages;
- Application of debris catchers for explosive bolts;
- Fewer releasable parts;
- Transfer to graveyard orbit (GEO);
- Multiple payloads on a single launch.

10. Debris removal options have been used on a few occasions to date, e.g. retrieval via the United States Space Shuttle or deorbit, e.g. Progress supply vehicles.

Passivation

11. An important category of debris prevention methods is passivation of hardware to avoid breakup by explosion. Passivation denotes the removal of all stored energy from the spacecraft or upper stage by depleting and/or venting propellants and pressurants and open circuit the batteries so that the object becomes inert. 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 objects. 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 already to reduce the chances of future fragmentation events. From flight V59 onwards all Ariane upper stages have been vented, irrespective of the type of orbit. The Delta and Long March upper stages are burned to depletion after deployment of the payload and execution of a manoeuvre 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. A similar procedure is applied for the H-2 launch vehicle. The Proton fourth stage and the Centaur upper stage deplete propellant at end of mission. Unfortunately, fuel venting has not been applied to more than 30 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.

Disposal orbits

12. Another important category of preventive action is reorbiting into a disposal orbit. For example, GEO satellites at end-of-life may be boosted several hundreds of kilometres above GEO to prevent continual interaction with other operational craft. Reorbiting is presently the only practical way to reduce the collision risk in GEO. This procedure has been performed over 90 times. A minimum orbit raising altitude of 300 km is recommended. A multiple-burn strategy should be adopted which takes into account uncertainties in the propellant estimate. Eventually, a more permanent disposal method must be considered. Application of advanced technologies, e.g. solar electric propulsion, could offer new possibilities.

Retrieval

13. Retrieval means to return to Earth without damage spacecraft or other space hardware by a space vehicle capable of atmospheric entry, e.g. the United States Space Shuttle or Soyuz capsules. Examples of retrieved space hardware are Palapa-A, Westar-B, LDEF, EURECA, SFU and a solar array from the Hubble space telescope. However, these objects were retrieved for reasons other than debris mitigation. Also, the retrieval capabilities of the Space Shuttle are limited to altitudes below about 600 km.

Deorbit

14. An efficient method for removing objects from space is deorbiting. This includes propulsive manoeuvres to force an immediate destructive entry into the atmosphere, transfer to an intermediate orbit with a limited orbital lifetime (e.g. 25 years), the use of tethers for immediate deorbit or reduction of the orbital lifetime, or the use of other methods (drag augmentation, solar radiation pressure) to reduce the orbital lifetime.

15. Propulsive manoeuvres 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. As long as attitude and control capabilities are maintained on the rocket stage, a small manoeuvre (away from the released spacecraft to avoid contamination from rocket firings), followed by a burn, might produce the appropriate change in orbital elements.

16. In the Russian- and formerly Soviet-manned programme, Progress supply vehicles and space stations were deorbited into remote ocean areas, except for Cosmos 557, Salyut 2, and Salyut 7/Cosmos 1686.

17. The use of drag augmentation, 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, although it would provide some movement for altitudes as high as 1,200 km. 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.

Hazards on ground

18. Since Sputnik 1 about 25,000 Earth-orbiting objects have been catalogued. About 16,000 have entered the Earth’s atmosphere and most have disintegrated or vaporized, with very little remaining to impact the Earth. In some cases solid fragments from spacecraft or rocket stages have reached the Earth’s surface (Cosmos 954, Skylab, Salyut 7/Cosmos 1686) and have been observed. Maybe a larger number of falls have occurred, but unobserved. If survival of spacecraft or rocket stage components is predicted, a controlled destructive re-entry into a remote ocean area is the preferred method of disposal.

Clean-up of derelict space objects

19. The ability to move objects that have never had any propulsive capability, years after their use, presents a difficult problem. The inclusion of some system that remains with the object (spacecraft or rocket body) for possibly many years, then performs a manoeuvre, may create an operational hindrance and safety concern. The installation of some remote propulsion system at the proper time would require a significant amount of effort for rendezvous, attachment (to a possibly hazardous piece of hardware) and coordination of the manoeuvre. 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 shown 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 effective across a wide range of altitudes. The use of a tether may assist object removal in a number of independent ways: via momentum exchange at either deployment or retrieval and electromagnetic drag. In any case, the use of a tether would require some hardware development and manufacture, plus the inherent operational reliability problems of adding other types of hardware to already complex systems. Another possibility is removal of debris from orbit using powerful (ground-based) lasers. Through energy deposition and evaporation a momentum may be imparted to an object in space which may lead to an immediate deorbit or reduced orbital lifetime. This may be an interesting technique for the future, if some of the difficulties can be solved (no damage to operational spacecraft, no creation of additional small-size debris).

20. An immediate conclusion from the considerations made before is that cost-effective debris removal implies introducing the corresponding requirements at the beginning of the life cycle of a project. Some minor design changes can open new possibilities for debris removal at a relatively low cost.

RECOMMENDED MEASURES OF DEBRIS CONTROL

21. There is a need to define 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 have to be selected, 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, the International Academy of Astronautics supports the position that there are several actions that should be initiated immediately to ensure the future viability of space operations and these will be listed at the end of this paper. The participation of space-faring 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 measures to be considered fall into two categories: those requiring minimal impact on the design and operations and those requiring significant changes in hardware or operations. Both categories of measures do not require development of new technology. Measures of category I should be applied immediately, while measures of category II should be applied by all space operators from an agreed time point onwards.

Category I measures

22. Category I comprises those measures that require no or limited changes to the design and cost impacts are in general minimal. They may imply changes in hardware and operations. Some performance reduction may, however, result. These have first priority for implementation and should be implemented by all space operators immediately. Category I measures include the following:

(a) No deliberate break-ups of spacecraft that produce debris in long-lived orbits;

(b) Minimization of mission-related debris. Often 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 and separated Apogee Boost Motors (ABM));

(c) Passivation (venting, burning to depletion, and battery safing) of upper stages and spacecraft in any Earth orbit at end of mission;

(d) For spacecraft and rocket upper stages below 2,000 km with excess fuel, at the end of operations, lower the perigee altitude to minimize the orbital lifetime;

(e) Reorbiting of geostationary satellites at end-of-life to a disposal orbit. Minimum altitude increase 300 km (location of perigee above the geostationary orbit) above the geostationary orbit;

(f) Upper stages and spent ABMs 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.

Category II measures

23. Category II comprises those options that require either significant changes in hardware or operational procedures. However, no new technology developments are needed. Category II options are aimed at removing used upper stages and defunct spacecraft from orbit within Tmax years, thus eliminating a major debris source. The measures below provide candidate quantitative values. Agreement on Tmax and the time after which these measures have to be applied should be achieved through discussion and deliberations in suitable international forums, such as the Inter-Agency Space Debris Coordination Committee and the Committee on the Peaceful Uses of Outer Space. There is some urgency for the application of measures of category II in some orbital regions. An undue delay in their application will lead to a further degradation of the space environment. Removal of large or compact objects, which could partially survive entry heating, is accomplished with a deorbiting manoeuvre to ensure atmospheric entry over oceanic areas during the next perigee pass. Objects which will completely burn up during atmospheric entry should be placed in orbits with limited lifetime, say 25 years (Tmax). Hence, in these cases natural perturbations will be exploited. Category II measures include the following:

(a) Removal after end of mission within Tmax years of all rocket upper stages and defunct spacecraft in orbits with an apogee below 2,000 km altitude;

(b) Removal after end of mission within Tmax years of all rocket upper stages and spacecraft in geostationary transfer orbits, transfer orbits to 12-h orbits or other eccentric orbits with a perigee altitude below 2,000 km altitude;

(c) Reorbiting of upper stages and satellites at end-of-life into a disposal orbit (as a temporary measure) for circular orbits above 2,000 km altitude.

24. The debris control measures in categories I and II can be carried out with existing technologies.

Outlook to the future

25. The search for new mitigation methods, technical feasibility and cost-efficiency should be pursued further. Of great benefit for the space environment would be advanced propulsion capabilities and reusable launch systems, in particular reusable upper stages. Advanced propulsion techniques could lower cost for deorbiting or render feasible deorbiting from high-energy orbits.

CONCLUSIONS

26. Despite the application of a number of debris preventative measures, the number and mass of anthropogenic objects in space are steadily increasing.

27. Projections in the future of the debris population show clearly the need for the application of stronger debris control measures in certain orbital regions. Each break-up (collision, explosion) which generates debris in long-lived orbits increases the spatial density of debris and is a burden for the future.

28. The objective of the debris control measures is to keep the spatial density of man-made objects in important orbits within tolerable limits and ensure the safety of spaceflight. Failure to control the growth of the debris population could render some orbital regions useless for space operations.

29. Because of the irreparable degradation of some of the most useful orbital regions, the International Academy of Astronautics urges the space-faring nations to take adequate steps in order to ensure the safety of future space operations.