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Techniques for Orbital Debris Control

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This paper will summarize a range of techniques that have been proposed for controlling the growth of man-made debris in Earth orbit. Several techniques developed in studies at NASA Johnson Space Center will be described in detail. These techniques include the retrieval of inoperative satellites with an orbital maneuvering vehicle and self-disposal devices for satellites and upper stages. Self-disposal devices include propulsive deorbit motors and passive drag-augmentation devices. Concepts for sweeping small debris from the orbital environment will also be described. An evaluation of the technical feasibility and economic practicality of the various control methods will be summarized. In general, methods that prevent the accumulation of large debris objects were found to provide greater promise for control of the debris problem than methods of removing small debris particles.

Introduction

MAN-MADE debris in Earth orbit represents a collision hazard to valuable satellites and manned spacecraft. Particles that are too small to continuously track can collide with spacecraft at high velocities and cause catastrophic damage. The probability of a collision between large objects in space is very low. However, collisions among small debris particles and collisions between small particles and large objects are more likely and are the source of a growing debris population.

The control of orbital debris can be approached as a problem of correction or of prevention. This paper will examine both approaches. The corrective approaches include spacecraft shielding, efforts to retrieve derelict spacecraft, and sweeper devices to remove small debris. The preventative approaches include provisions for self-removal of spacecraft and rocket stages and the increased use of reusable space hardware. Cost comparisons, as well as common sense, indicate that preventative measures are the best approach to controlling the growth of orbital debris.[1]

Studies conducted at NASA Johnson Space Center have focused on four general debris control techniques: 1) active retrieval of large objects, 2) provisions for self-disposal in new spacecraft, 3) sweeper devices to remove small debris, and 4) increasing the use of reusable space hardware. These four techniques along with some variations will be discussed in the following sections.

Active Retrieval

One approach for the removal of large debris objects is to collect them with a maneuverable space vehicle. In the evaluation of this approach, it was assumed that rendezvous would be accomplished with an autonomous or remotely controlled vehicle such as the orbital maneuvering vehicle (OMV) currently under development by NASA. The OMV project has been cancelled, but the term OMV will be used here to refer to any maneuverable spacecraft that might be used for debris retrieval.

Assuming the OMV can grapple the target spacecraft, there are two options for disposition. The OMV can perform a deorbit maneuver, separate from the object, and reinsert itself in orbit while the discarded object enters the atmosphere. Or the objects can be collected and maintained together in a safe orbit for possible use as spare parts or raw materials.

The performance cost for deorbit vs collection depends on the mass of the object and its orbital altitude. For objects in low Earth orbit, with a mass of less than 2000 kg, collection in orbit is less costly than deorbit in terms of OMV performance.[2] Another alternative is to rendezvous with an object using the OMV and then attach a separate deorbit device to the object rather than using the OMV for propulsion. The attached device might be a deorbit propulsion package or a passive drag device. Attaching devices rather than maneuvering the objects with the OMV expands the envelope of accessible objects.

Using data from the NORAD catalog of orbiting objects, an estimate was made of the number of objects that could be retrieved with an OMV. Approximately 25% of the objects are large enough for practical retrieval. Of these large objects, 35% originated from the United States, Western Europe, or Japan. Of that population, 65%, or about 350 objects, are within range of the OMV. That number represents about 5% of the total number of cataloged objects.

The majority of objects lie in a few narrow inclination bands. This is fortunate since an OMV based at a particular inclination could reach all of the objects at that inclination if the OMV can wait in orbit long enough for orbital planes to align due to natural precession.

There may be legal and political limitations on the retrieval of space objects. For this reason, the estimate of accessible objects is limited to those of American, Western European, and Japanese origin.

There are several other concerns about using the OMV for debris recovery that should be noted. It may be difficult to grapple uncooperative satellites. The satellites may be tumbling, they may have no convenient points to grapple, and some may contain hazardous materials. The mission time required for orbit phasing and rendezvous could overtax the power supply of the OMV. Objects at the same inclination as the OMV may not be in the same orbital plane, and so the OMV may have to wait while natural precession brings the respective orbital planes into alignment. Propulsive plane changes of more than a few degrees would be impractical.

Reducing the population of large debris would require the use of several OMVs dedicated to retrieval missions, as well as a large number of launches from Earth to deliver and service the OMVs in specific orbital planes. The magnitude of this operation illustrates the desirability of providing new spacecraft with devices for self-disposal.

One interesting variation of the retrieval scenario would be to extend the debris object from the OMV on the end of a long

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tether. The tether would make it possible to transfer momentum from the debris to the OMV, thus lowering the orbit of the debris and raising the orbit of the OMV. After severing the tether connection, the debris would be left in an orbit from which it would decay quickly.[3]

Self-Disposal

Spacecraft can be designed to provide their own final orbit insertion maneuver so that the upper stage of the launch vehicle never attains orbital velocity and is immediately removed from the space environment. If this is not practical then the upper stage can be designed for self-disposal using its own propulsion system for a controlled deorbit and ocean impact. An alternative for long-duration satellites would be the addition of a separate system for deorbit at the end of the operational lifetime. This deorbit device could be a propulsion package, a drag-augmentation system, or a combination of the two.

Deorbit with a conventional propulsion system is an approach that would be effective for all orbital altitudes. In addition to propulsion, a control system is needed to maintain spacecraft attitude, at least long enough to complete a deorbit maneuver. Several control options that were considered are spin stabilization initiated by a pressurized gas jet system, a simple sun sensor control system, and a tractor rocket.

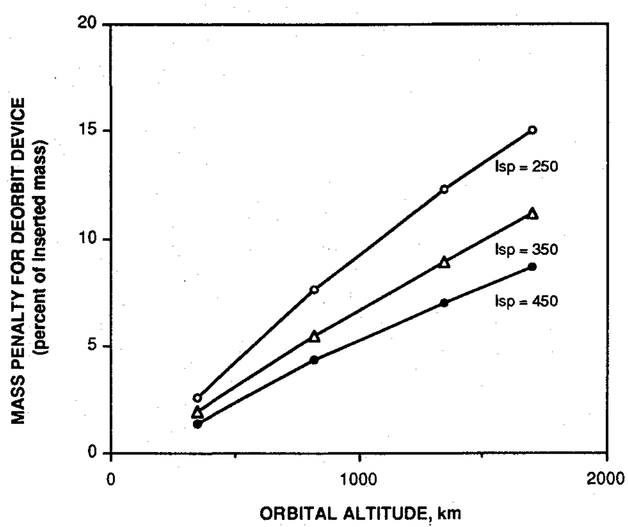

Fig. 1 Mass penalty for propulsive deorbit—circular orbit.

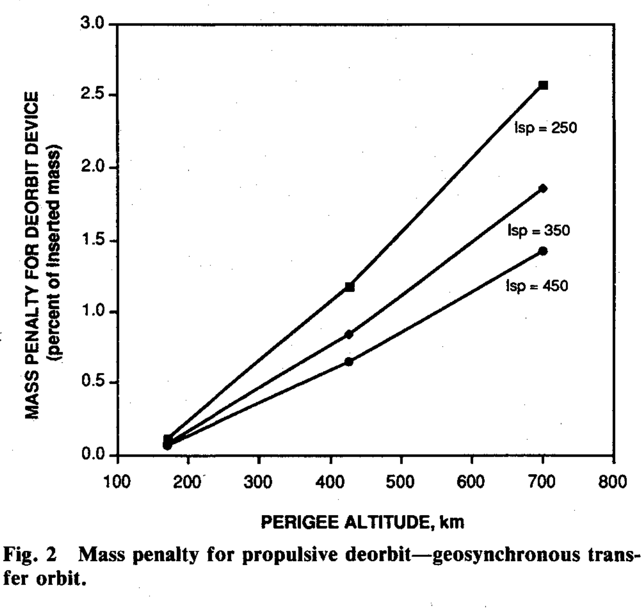

Fig. 2 Mass penalty for propulsive deorbit—geosynchronous transfer orbit.

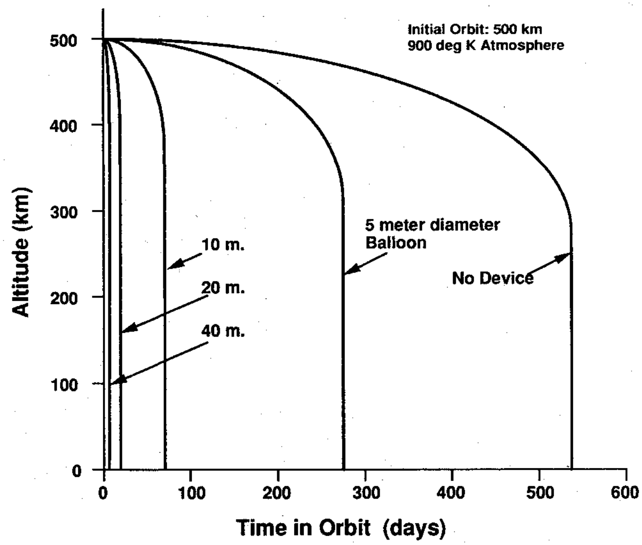

Fig. 3 Orbital decay profiles with drag devices.

Satellites normally have operating lifetimes measured in years, and so the deorbit system would have to safely remain inert for many years and then function on command after other spacecraft systems have failed. Also, in order to be practical, a deorbit package could only weigh a small fraction of the total weight of the spacecraft.

The spacecraft mass penalty for providing deorbit capability is shown in Figs. 1 and 2. The mass penalty is shown as a percentage of total spacecraft mass using propulsion systems with specific impulse values of 250, 350, and 450 s. Figure 1 is for the case of deorbiting from circular orbits below 1500 km. The mass penalty ranges from 2 to 12%. The mass penalty continues to grow with increasing altitude, but the slope becomes relatively flat beyond 10,000 km. For circular orbits above 25,000 km, an escape from Earth orbit is less costly than a deorbit maneuver. Figure 2 shows the mass penalty for deorbit for the special case of a rocket stage in an elliptical geosynchronous transfer orbit. The mass penalty in this case is less than 2%.

In the case of geosynchronous transfer stages, there is another alternative to propulsive deorbit. The orbital lifetime of these transfer stages can be reduced by modifying the perigee maneuver that is used to reach the geosynchronous altitude. The perigee for these transfer orbits is typically 350 km, and the rocket stage can remain in this elliptical orbit for years. If a nonoptimal thrust direction is used for the perigee burn, the perigee can be reduced to 150 km. The stage will decay from this orbit in a matter of months instead of years. The penalty is that the payload mass boosted to geosynchronous altitude is reduced by 18%.

The orbital lifetime of the transfer stage can be further reduced by selecting a certain orientation for the transfer orbit that takes advantage of natural orbit perturbations. This need to select a specific orbit orientation creates additional launch window constraints for the payload.[4]

The effect of atmospheric drag on a satellite can be increased by deploying a large balloon that increases the effective area of the satellite without significantly increasing its mass. For objects orbiting below about 800 km, a balloon with a diameter of about 15 m can reduce the orbital lifetime of the satellite from several years to several weeks. One of the advantages of the drag device concept is that the satellite does not need to maintain any specific orientation and no attitude control system is needed. The balloon could be stored in a canister and be inflated after a rocket stage or satellite completes its mission.

Figure 3 profiles orbital decay for a spacecraft alone and for a spacecraft with balloons of various sizes attached. The initial orbit is circular at 500 km. Attaching a balloon with a diameter of 10 m decreases orbital lifetime from 540 to 70 days.

The drag device and propulsive package each have advantages. Both systems would reduce the time in orbit for inoperative satellites and spent stages, which would decrease the chance of an internal explosion or random collision. One drawback of the drag device is that the decrease in collision probability due to shorter orbital lifetime is offset by the increase in cross-sectional area. The satellite alone and the satellite with the drag device attached would each sweep out about the same volume of space over the course of their time in orbit.

The main advantage of the drag device is that it is simple, passive, and requires no attitude control system. For altitudes below approximately 700 km, drag devices appear to be a lower-mass alternative to propulsion packages.

Solar sails might be an option for disposal of objects in very high orbits. Solar sails are a relatively passive system and they require no propellant storage or engines. Solar sails might be used for moving satellites in geosynchronous orbit into higher orbits or to send the satellites onto Earth escape trajectories. However, deployment and control of the solar sail might present significant technical challenges.

Debris Sweepers

One concept for clearing small debris from orbit, proposed by Donald Kessler of the NASA Johnson Space Center,[5] is to place large foam-filled balloons in Earth orbit. These balloons might have diameters of a mile or more. Small debris would randomly impact the balloon and either become embedded in it or decelerate enough to cause a rapid decay from orbit. However, a passive debris sweeper cannot avoid collisions with functional satellites or with objects that are large enough to destroy the sweeper. Providing collision avoidance with an active control and propulsion system for a huge balloon would be difficult.

A concept was developed for solving the collision avoidance problem for debris sweepers. Instead of having a spherical shape, the sweeper material is deployed in large panels, like the vanes of a windmill. The panels rotate continuously around a core spacecraft. The core contains tracking apparatus that monitors objects that are on a collision course with the sweeper. The rotation rate of the sweeper is controlled to selectively avoid or collide with objects.

Although the concept of a debris sweeper may be valid, there are problems with its practical application as a general form of debris control. In order to be effective, the sweepers would have to be enormous with panel areas of a square kilometer or more. In order to sweep the heavily used regions of Earth orbit, there would need to be a number of sweepers operating simultaneously. Launch, deployment, and maintenance of these sweepers would require an extremely large investment.

Sweepers might be more practical if applied on a smaller scale to deal with clearing areas affected by specific debris collision events. This type of operation would be analogous to cleanup activities after a marine oil spill. Another use might be as a shield for a space station or for other important facilities.

Another system for eliminating small debris is the Defender concept, which has been proposed as a debris protection system for Space Station Freedom.[6] Defender is a small free-flying spacecraft that responds to tracking information and quickly maneuvers itself to intercept and absorb debris that might otherwise impact the space station. The Defender spacecraft must be highly maneuverable, which places demanding requirements on its propulsion and control system. It is possible that the rotating debris sweeper concept described above could be combined with the Defender concept to provide a system that does not need to make rapid maneuvers.

Active debris removal might be accomplished with devices that detect specific particles and then transfer energy or momentum to those particles to cause deceleration and orbital decay. Such devices would need to be relatively autonomous spacecraft and could use concentrated dust clouds, particle beams, or laser beams to decelerate the particles. High energy systems might be used to vaporize debris particles. Another possibility would be to impart an electrical charge on debris particles so that interaction with the Earth's magnetic field would cause more rapid orbital decay.

Manned spacecraft such as the space station need to be provided with some level of debris shielding. Past shielding concepts could potentially add to the orbital debris problem to some extent. Although the shield protects the spacecraft, impacts with the shield generate additional debris. Shield concepts that absorb debris particles and do not generate secondary debris would be a definite aid to reducing the debris problem. All shielded surfaces would then act as debris sinks, rather than debris sources.

Reusable Hardware

The design philosophy applied in the design of future space systems needs to take into account the risks and costs associated with a growing debris hazard. Generally, because of the high cost of launching space hardware, all launch vehicle and spacecraft elements are jettisoned as soon as they are no longer needed. Satellites are simply abandoned when critical systems fail because repair is usually impossible and spacecraft designs quickly become obsolete.

The "expendable" philosophy is beginning to change with the more mature space operations now possible with the Space Shuttle and soon to be available with the space station. Single-use satellites could be replaced by multipurpose space platforms that can be repaired and upgraded periodically. Reusable orbital maneuvering vehicles and orbital transfer vehicles could replace the expendable upper stages that litter the orbital environment.

Disposal of used space hardware by destructive atmospheric entry eliminates the debris from the orbital environment. However, consideration should be given to the potential environmental impact of atmospheric disposal of space hardware. Nuclear power systems and other hazardous materials pose an obvious threat, and there may be unforeseen dangers in atmospheric disposal of ordinary materials if done on a large scale over a long time period. Concern about the environment of Earth could also increase the importance of reusability in future spacecraft design.

Conclusion

Since the population of small debris is growing due to collisions with large objects, removing these large objects is an effective method of reducing the debris hazard. The best technique for controlling the population of large debris is to include disposal provisions in the original design of all new spacecraft, including rocket stages. In other words, prevention is the best cure for the orbital debris problem.

For objects below about 700 km, drag devices may be competitive with propulsion systems as a means of self-disposal for satellites and upper stages. The fact that the drag devices require no active control system makes them very attractive. Above 700 km, propulsive systems may be the only practical option. Above about 25,000 km (including geosynchronous orbit), it becomes less expensive in terms of delta-V to boost satellites out of Earth orbit rather than deorbit them.

Large sweepers may not be practical for small debris removal, but smaller, special purpose sweepers that can absorb debris could be useful for protecting important facilities. Absorbing shields for spacecraft would be very beneficial since they offer protection and also reduce the general debris population.

Finally, a change in space operations philosophy from single-use satellites and expendable rocket stages to reusable transportation systems and multipurpose space platforms will have a dramatic effect in eliminating sources of new debris. It may be possible in the future to expand the human presence in space while simultaneously reducing the orbital debris hazard.

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