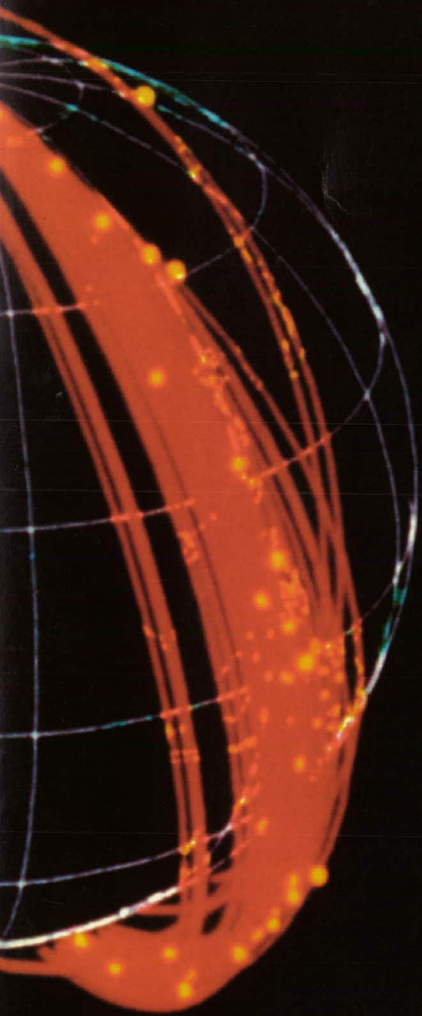
The National Science and Technology Council
Committee on Transportation Research and Development

Interagency Report on Orbital Debris

1995



November 1995

About the Cover

When an explosion occurs in space many fragments are generated and each has a slightly different velocity. The paths of the many fragments are illustrated in this image. As they progress through the orbit they converge at the point at which the explosion occurred and again on the opposite side of the orbit. Over time the orbits of the individual fragments precess relative to one another and become separated.

About the National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. This cabinet-level council is the primary means for the President to coordinate science, space, and technology policies across the Federal Government. NSTC acts as a "virtual" agency for science and technology to coordinate the diverse parts of the Federal research and development enterprise. The NSTC is chaired by the President. Membership consists of the Vice President, Assistant to the President for Science and Technology, Cabinet Secretaries and Agency Heads with significant science and technology responsibilities, and other senior White House officials.

An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments in areas ranging from information technologies and health research, to improving transportation systems and strengthening fundamental research. The Council prepares research and development strategies that are coordinated across Federal agencies to form an investment package that is aimed at accomplishing multiple national goals.

To obtain additional information regarding the NTSC, contact the NTSC Executive Secretariat at 202-456-6100.

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The Office of Science of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on all questions in which science and technology are important elements; articulating the President's science and technology policies and programs, and fostering strong partnerships among Federal, State, and local governments, and the scientific communities in industry and academe.

To obtain additional information regarding the OSTP, contact the OSTP Administrative Office at 202-395-7347.

Interagency Report on Orbital Debris

by

Office of Science and Technology Policy

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THE WHITE HOUSE
WASHINGTON

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The use and exploration of space is vital to our civil, national security, and commercial interests. As the United States and other spacefaring nations continue to open the frontier of space, we must focus on new and better ways to monitor the current orbital debris environment and to reduce debris levels in the future.

During the past year, the National Science and Technology Council (NSTC), through the Committee on Transportation Research and Development, undertook an interagency review of the U.S. government's 1989 *Interagency Report on Orbital Debris*. As part of this process, the interagency review team also considered the results of the National Research Council orbital debris technical assessment study sponsored by the National Aeronautics and Space Administration.

This 1995 report updates the findings and recommendations of the 1989 report and reflects our progress in understanding and managing the orbital debris environment. It provides an up-to-date portrait of our measurement, modeling, and mitigation efforts; and a set of recommendations outlining specific steps we should pursue, both domestically and internationally, to minimize the potential hazards posed by orbital debris.

John H. Gibbons
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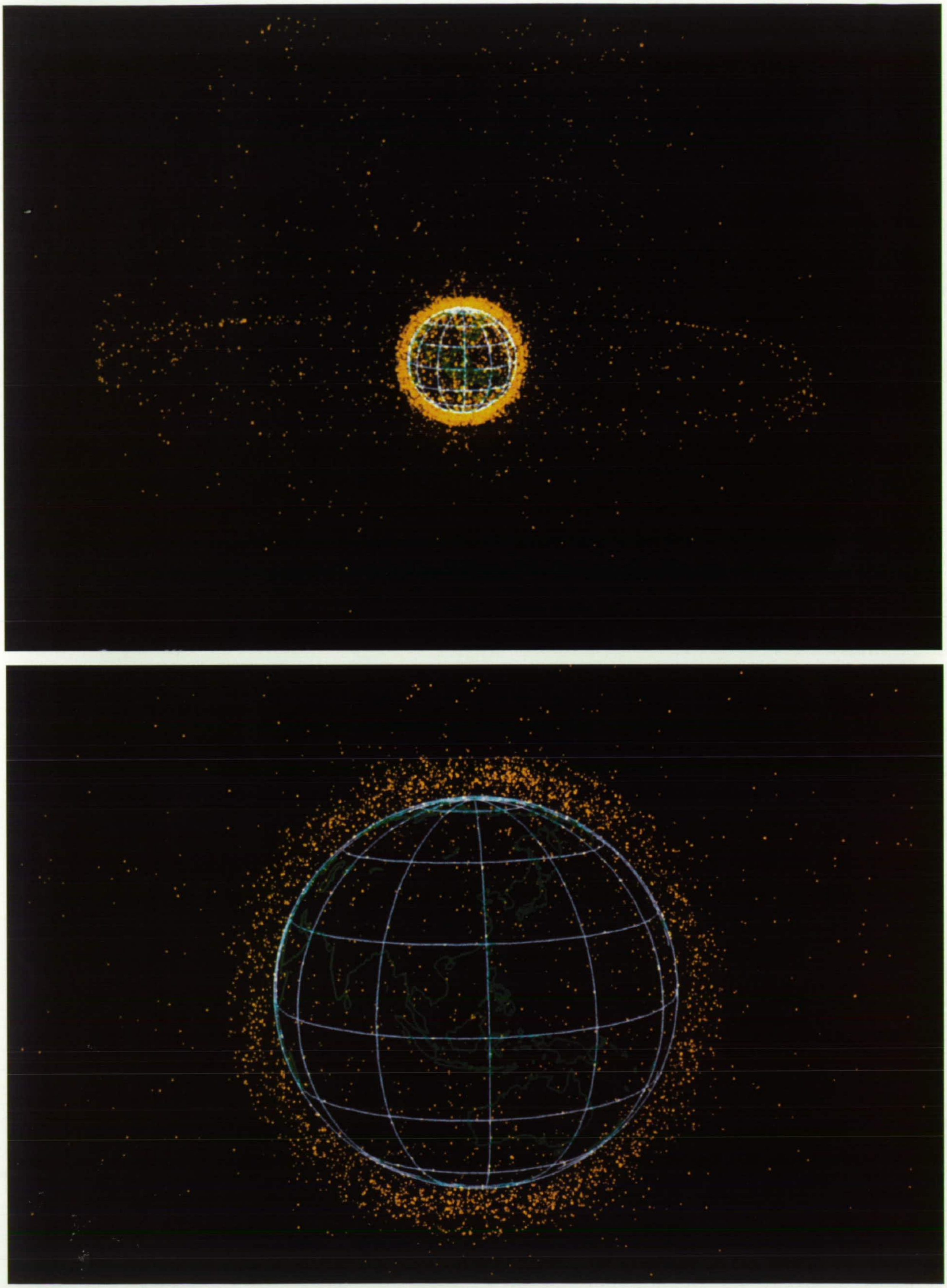

This computer-generated view illustrates the population of Earth orbit satellites on December 14, 1990, and is typical of such a view at any time. In the lower image are those in low Earth orbit predominantly below 2000 km. Most of the satellites are either at very high inclination, nearly crossing the poles, or at relatively low inclination, rarely going above thirty degrees latitude.

In the upper image the view is from far out in space; one can see the geostationary arc over the equator and the highly inclined Molnia orbits used by the Russians for communication at the very high latitudes.

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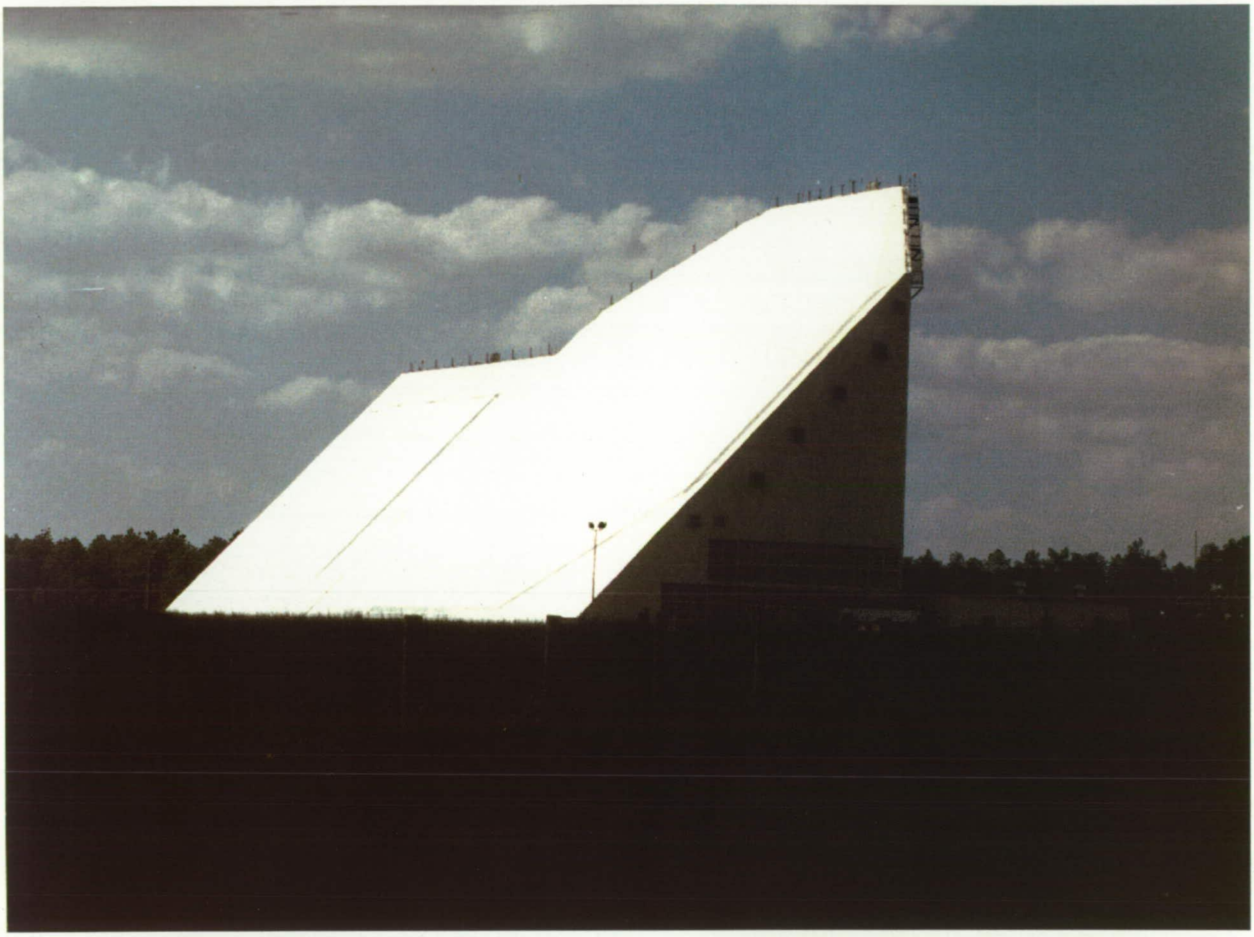

The FPS-85 phased array radar at Eglin AFB, Florida. This radar is a major Space Surveillance Network facility for tracking satellites and space debris. It is capable of tracking several different objects simultaneously.

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Executive Summary

The 1989 Report on Orbital Debris noted the lack of definitive measurements on the debris environment. Since that time NASA, with the assistance of DOD, has conducted an extensive program to measure the LEO debris environment. There has now emerged a comprehensive picture of the orbital debris environment in LEO. The current Haystack measurements indicate populations a factor of two lower than predicted in 1989 at Space Station altitudes and a factor of two higher at the 1000 km altitude. In GEO, however, NASA has only conducted an exploratory campaign to measure the debris environment. Both of these efforts should continue in order to refine our understanding of the current environment as well as to monitor changes in the environment with time.

Contributions to the current debris environment continue to be essentially proportional to the level of space activity by a given spacefaring nation. Of particular concern is the sustained rate of fragmentation events since 1989 despite the active efforts of the spacefaring nations to reduce the probability of such occurrences.

The orbital debris environment in LEO continues to present problems for space operations that involve large spacecraft in orbit for long periods of time. Taking note of all that has been learned since 1989, the International Space Station Program has taken steps to maximize protection from debris penetration by implementing state-of-the-art shielding; utilizing existing ground radars to track and avoid larger debris; and actively developing operational and design options which will minimize the risk to the crew and the Station.

Since release of the 1989 Report, there have been a series of proposals to develop large LEO satellite constellations. These constellations could present a significant new concern for the orbital debris environment. For those constellations which have a large aggregate area, the collision probabilities are sufficiently high that additional means of protection need be considered. The problem is particularly acute because the high inclination of their orbits lead to high spatial density over the poles.

The development and utilization of predictive models has improved significantly since 1989. This improved predictive capability when combined with our increased knowledge of the debris environment, leads to the conclusion that failure to take any mitigation action could lead to significant increase in orbital debris in the coming years. Assuming a continuation of launch activity at the same average rate as over the last ten years, average future solar cycles, and future operational practices that will minimize but not eliminate the possibility of explosions in orbit, most models predict that an increasing fraction of future debris will originate from breakups due to random collisions between orbiting objects. The use of operational practices to limit the orbital lifetime of spent upper stages and payloads have the potential to mitigate the growth of orbital debris.

In 1989 National Space Policy Directive-1 (NSPD-1) was approved. NSPD-1 called for agencies to "seek to minimize the creation of space debris." Since that time orbital debris concerns have caused changes in the plans and activities of some agencies, particularly NASA. NASA has issued a comprehensive agency policy concerning orbital debris. The Department of Defense (in particular the Air Force and the U.S. Space Command) have adopted broad policies concerning orbital debris. Beyond the general statement in NSPD-1, there remains no comprehensive statement of USG policy on orbital debris.

The 1989 Report called for NASA and the DOD to develop a plan to monitor the orbital debris environment. Since that time NASA, utilizing many DOD assets and NASA's own capabilities, has expended considerable effort to accomplish this recommendation. The modification of the Haystack Radar for orbital debris measurements has greatly enhanced our ability to monitor the LEO debris environment. Today, data measurements as well as data management limitations significantly affect the capability of the Space Surveillance Network to detect and track smaller debris objects. Statistical techniques are being utilized to characterize the current debris population.

Since the publication of the 1989 Report, the United States and a number of national and international spacefaring organizations have begun to address orbital debris concerns. As a result of the recommendations set out in the 1989 Report, the United States and other spacefaring nations have taken voluntary design measures (i.e., tethering of operational debris such as lens caps and the use of debris free devices for separation and release) as well as operational procedures to prevent the generation of orbital debris. More than ever, it is clear that closer international cooperation is necessary for dealing effectively with orbital debris. It is in the broad interest of the United States to continue to maintain a leadership role in international considerations relating to orbital debris. The United States considers the development of technical cooperation and consensus to be a prerequisite for any potential international agreements, regulatory regimes or other measures relating to orbital debris. The unilateral application of debris mitigation measures could put U.S. satellite and launch vehicle industries at a competitive disadvantage.

Five specific recommendations are proposed to address issues raised in this report. They are:

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

List of Figures

Unnumbered figures are illustrations provided to enhance clarity, but are not referenced in the text.

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The Ground Electro-Optical Deep Space Surveillance System (GEODSS) is the instrument used to monitor geosynchronous orbit and other orbits above 5000 kilometers. These 1-meter telescopes use image-intensified video sensors to record the data. This photograph illustrates the Experimental Test Site (ETS) at Socorro, Mexico, where the prototype system was deployed.

By having these large telescopes stare vertically at dawn and dusk—when objects in orbit are illuminated by the sun but the telescope is in darkness—one can detect satellites in orbit including debris objects. This is useful because many objects have poor radar response but good optical reflectivity. Twice as many small objects, < 30 cm, are viewed optically as by radar.

In this image the two streaks represent two different objects passing in nearly opposite directions. The two telescopes are nearly 60 meters apart, so parallax can be used to determine the altitude.

Acronyms and Abbreviations

A

AFSPC	Air Force Space Command

C

CCDS	Charge Coupled Device System
CFR	Code of Federal Regulations
COPUOS	United Nations Committee on the Peaceful Uses of Outer Space

D

DOD	Department of Defense
DOC	Department of Commerce
DOE	Department of Energy
DOT	Department of Transportation

E

ELV	Expendable Launch Vehicle
ESA	European Space Agency
Eureca	European Retrievable Carrier
EVA	Extravehicular Activity

F

FCC	Federal Communications Commission

G

GEO	Geosynchronous Earth Orbit
GEODSS	Ground Electro-Optical Deep Space System
GLONASS	Global Navigation Satellite System
GPS	U.S. Global Positioning System
GTO	Geosynchronous Transfer Orbit

I

IADC	Inter-Agency Space Debris Coordination Committee

L

LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit

M

MEO	Medium Earth Orbit
MIT/LL ETS	Massachusetts Institute of Technology Lincoln Laboratory Experimental Test System

N

NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NOAA	National Oceanic and Atmospheric Administration

P

PL/AMOS	Phillips Laboratory Air Force Maui Optical Station

S

SOCIT	Satellite Orbital Debris Characterization Impact Test
SPADOC 4	Space Defense Operations Center, block 4
SRM	Solid Rocket Motor
SSN	Space Surveillance Network
STSC	COPUOS Scientific and Technical Subcommittee

U

USSPACECOM	U.S. Space Command

The Long Duration Exposure Facility (LDEF) was deployed in orbit to measure the environment by exposing a number of different materials in a controlled manner so that the meteoroid and orbital debris too small to be measured remotely could be quantified and assessed. It was recovered after nearly six years in orbit and is a major source of data on the relative frequency of natural as opposed to man-made debris.

More than 32,000 impact craters visible to the unaided eye have been observed. The largest impact crater was 0.5 cm in diameter. Analysis indicates that approximately one-half of the larger craters were of orbital debris origin and one-half were meteoroids; nearly all of the smallest craters are due to orbital debris.

This one-square-meter panel of teflon thermal blanket contains a large number of hypervelocity-induced “pin holes,” each surrounded by a larger darkened area. The darkened area is believed to be caused by the shock of the impact and possible reaction of the material to ultraviolet radiation.

Part One:

Dimensions of the Orbital Debris Problem

This painting by Bill Hartman of the University of Arizona illustrates the major source of the orbital debris, explosions in space. Many accidental explosions of upper stages and spacecraft batteries, and some deliberate explosions, account for more than half of the almost 8000 objects that are cataloged. Through cooperative international efforts, most upper stage operations have been modified their to preclude explosions by venting all stored energy fuels and gasses.

Chapter 1: The Current Environment

Introduction

The meteoroid, or natural debris, environment has historically been a spacecraft design consideration. Meteoroids are part of the interplanetary environment and sweep through Earth orbital space at an average speed of 20 km/sec. Observational data indicate that, at any given instant in one time, a total of about 200 kg[46] of meteoroid mass is within 2000 km of the Earth's surface, the region containing the most-used orbits. Most of this mass is in meteoroids about 0.01 cm in diameter. This natural meteoroid flux varies in time as the Earth revolves about the Sun.

Man-made space debris (referred to as "orbital debris" throughout the rest of this document) differs from natural meteoroids because it remains in Earth orbit during its lifetime instead of passing through the space around the Earth. This study considers only the orbital debris environment and not reentering debris.

The estimated mass of man-made orbiting objects within 2000 km of the Earth's surface is about 2,000,000 kg.[45] These objects are in mostly high inclination orbits and pass one another at an average relative velocity of 10 km/sec (about 22,000 mph). Most of this mass is contained in about 3000 spent rocket stages, inactive satellites, and a comparatively few active satellites. A smaller amount of mass, about 40,000 kg, is in the remaining 4000 objects currently being tracked by space surveillance sensors.

Most of these smaller objects are the result of over 115 on-orbit fragmentations and 20 anomalous events in which objects separate from spacecraft but the parent body remains intact (see Appendix 1 for a detailed list).[24] Scientists recently conducted a detailed analysis of hypervelocity impact pits from orbital debris on returned surfaces of parts replaced on the Solar Max satellite, the Long Duration Exposure Facility (LDEF), Eureca (European Retrievable Carrier), Hubble Space Telescope and other surfaces exposed in space. Their investigations result in an estimate of 1000 kg for the total mass for orbital debris smaller than 1.0 cm and 300 kg for orbital debris smaller than 0.1 cm. The deduced distribution of mass and relative velocity is sufficient to cause the orbital debris environment to be more hazardous than the meteoroid environment to most spacecraft operating in Earth orbit below 2000 km. There is also clear evidence of unidentified sources of small debris in elliptical orbits.[58]

Information about the current debris environment is limited by the inability to track and catalog small objects. Although the mission of the Space Surveillance Network (SSN) is to track all man-made orbiting objects, technological and natural constraints serve to limit the effective tracking of objects smaller than 10 cm. Further, fiscal limitations limit the alternatives for modifying existing sensors or adding new systems.

This report is intended for internal agency and interagency planning purposes only. New programs or activities aimed at modifying existing systems or constructing new ones recommended in this report do not reflect Administration approval and must compete for funding in the budget process.

I. Description of the Space Environment

A. Background

Three types of orbital debris are of concern.

(1) Objects larger than 10 cm in diameter which are commonly referred to as large objects. These large objects are routinely detected, tracked, and cataloged.
(2) Objects between 1 and 10 cm in diameter which are commonly referred to as risk objects. Risk objects cannot be tracked and cataloged. Depending on their relative impact velocities, risk objects can cause catastrophic damage.
(3) Objects smaller than 1 cm in diameter are most commonly referred to as small debris or in some sizes microdebris.

The population of debris objects smaller than 10 cm is derived from statistical measurements made either in situ or from ground-based sensors.

The interaction among these three classes of objects combined with the long residual times in orbit of the larger fragments leads to further concern that there may be collisions producing additional fragments and causing the total debris population to grow.

The space around the Earth is generally divided into four orbital regimes:

(1) Low Earth Orbit (LEO) - defined by objects orbiting the Earth at less than 5500 km altitude; this equates to orbital periods of less than 225 minutes.
(2) Medium Earth Orbit (MEO) - defined by objects orbiting the Earth between LEO and GEO altitudes.
(3) Geosynchronous Earth Orbit (GEO) - defined by objects orbiting the Earth at an altitude of approximately 36,000 km; this equates to an orbital period of approximately 24 hours.
(4) Other - defined by highly eccentric and transfer orbits that transit between LEO and higher orbital altitudes.

Within these four regimes, orbits can be characterized as:

(1) Circular - the object remains at a near constant distance from the center of the Earth for its entire orbit. The object's velocity remains constant throughout each revolution of the Earth. Circular orbits are special cases of the more general elliptical orbits and only "approximate" true circles. Most large objects are in circular orbits.
(2) Elliptical - the object's distance from the center of the Earth varies as it follows the shape of an ellipse during each revolution. The closest point of approach to the Earth is called the object's perigee; the farthest point from the Earth is called the object's apogee. Objects achieve maximum velocity at perigee and achieve minimum velocity at apogee. Most fragmentation debris is in elliptical orbits, making it more difficult to acquire and track.

The greatest number of tracked objects are in LEO, the next greatest are in GEO, and the remaining objects are in MEO. Two navigation systems (the U.S. Global Positioning System (GPS) and Russian Global Navigation Satellite System (GLONASS) satellite constellations) are the first major users of MEO. There are a large number of upper stages used to deliver spacecraft to geosynchronous orbit and to the MEO orbits that are tracked in deeply elliptical orbits. The Russian Molniya spacecraft also use a deeply elliptical orbit.

The altitude distribution of objects tracked in orbit is illustrated in Figure 1. Equivalent objects referenced in the figure are defined as the average number of objects that can be observed in the altitude bin at any given instant in time. The limiting size is a function of the altitude of the orbit varying from 10 cm radar cross section in LEO to 1 m at geosynchronous altitudes. The peak population is near 1000 km orbital altitude where the population is about 100 objects in a 10 km altitude band. At 350 to 500 km orbital altitude where the International Space Station will operate, the population is about 10 objects in a 10 km altitude band. As noted in the figure, the distribution of objects by altitude is not uniform. There are peak usages in LEO for observation

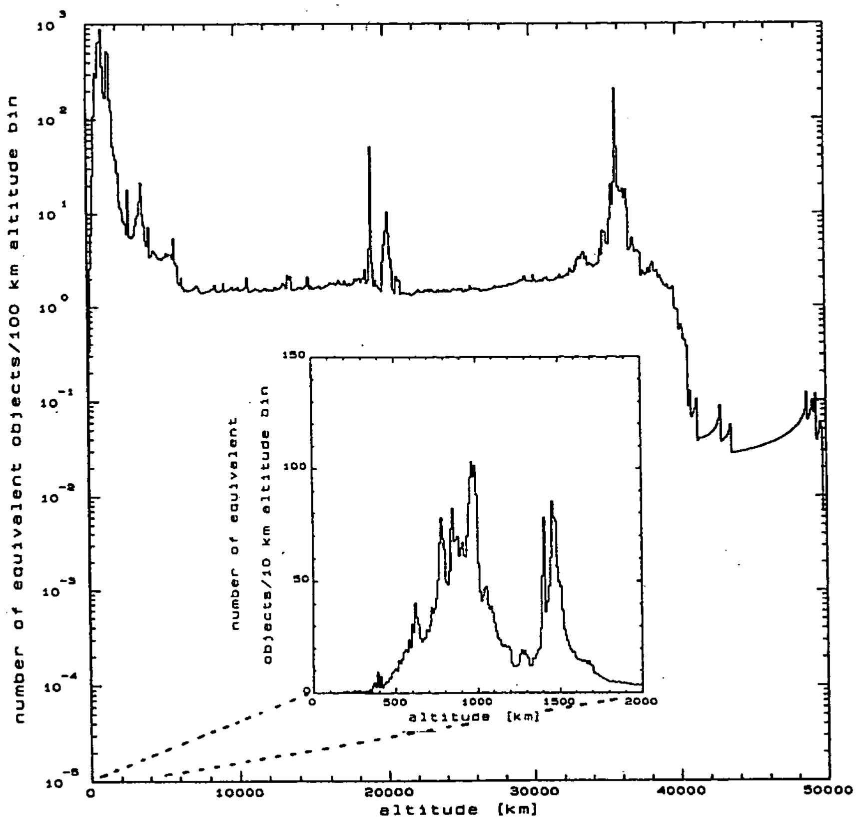


Figure 1. Distribution of Satellites in Earth Orbit

satellites, in MEO for navigation satellites, and in geosynchronous orbits for communications satellites.

Figure 2 shows a "snapshot" of the geographic distribution of tracked objects in GEO by their longitude. Most objects along the 0-degree latitude (equator) band are maintained in geostationary orbit. The other objects, rocket bodies and spacecraft no longer actively controlled, have a slightly inclined orbit which causes them to trace a figure-eight pattern on the ground about a point on the equator, traversing from the northern to the southern hemisphere and completing the pattern once every 24 hours.

B. Debris Distribution

U.S. Space Command (USSPACECOM) presently maintains a catalog of more than 7000 objects in space. The great majority of these cataloged objects are low Earth orbiting objects and are approximately 10 cm apparent radar cross section or larger. Due to sensor characteristics, as the altitude increases so does the size of the smallest detectable objects. Radar cross section and physical size are the same value only for a sphere; since the shapes of the debris fragments are unknown, the most conservative assumption is that they approximate spheres. The breakdown of the cataloged objects, indicated by Table 1, reveals the relative distribution of the objects by altitude as of November 1, 1995.

Table 1. Cataloged Objects by Altitude Ranges

Orbit Type	LEO	MEO	GEO	Other	Total
Cataloged Objects	5747	134	601	1447	7929

There is a well-characterized cataloged population of more than 7000 objects that accounts for the largest fraction of the mass on orbit. There are sample measurements by radar and optical sensors and returned surfaces from space that indicate the number of cataloged objects are a small percentage of the total debris population larger than 1 mm. Table 2 shows the estimated debris population from both a numeric and mass-on-orbit perspective.

Small debris are the product of the breakup events noted above. Most of the fragments are too small to be routinely tracked by the SSN; their number must be estimated from other observations. Telescopic observations using the Ground Electro-Optical Deep Space System (GEODSS), Massachusetts Institute of Technology Lincoln Laboratory Experimental Test System (MIT/LLETS), NASA Charged Coupled Device System

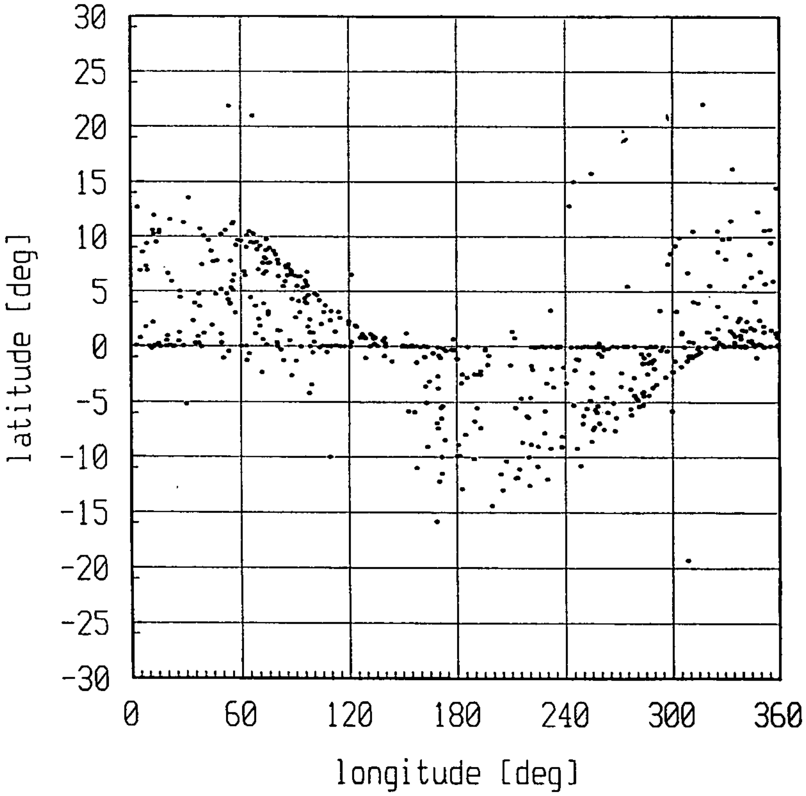


Figure 2. Distribution of Objects In and Near Geosynchronous Earth Orbit

(CCDS) and some European telescopes combined with the Haystack and Goldstone radars, and the examination of materials returned from space provide data samples which form the basis for statistical models of the debris environment. These environmental models contain submodules for simulating breakup events. These events include explosions or collisions at varying energy levels. Assumptions about the number and type of breakup events lead to modeled or predicted detection rates for special optical or radar sensors and impact rates for spacecraft surfaces exposed to the space debris environment. Figure 3 illustrates the particle distribution expected from each type of event. As expected, the few large fragments account for most of the mass while the many smaller fragments account for a large number of ejected debris particles.

Table 2. Estimated Debris Population

Size	Number of Objects	% number	% Mass
>10 cm	8,000	0.02%	99.93%
1-10 cm	110,000*	0.31%	0.035%*
0.1-1 cm	35,000,000*	99.67%*	0.035%*
Total	35,117,000*	100.0%*	2,000,000 kg#

* statistically estimated values

\# calculated value from reported data

In addition to the 8000 cataloged objects, based on the statistical samples, it is estimated that there are several million objects between 0.1 and 1 cm and more than a hundred thousand between 1.0 cm and 10 cm.

C. Orbital Lifetime

An orbiting object loses energy through friction with the upper reaches of the atmosphere and various other orbit perturbing forces. Over time, the object falls into progressively lower orbits and eventually falls to the Earth. As the object's potential energy (represented by its altitude) is converted to kinetic energy (energy due to its velocity), orbital velocity must increase as the altitude decreases. As an object's orbital trajectory draws closer to Earth, it speeds up and outpaces objects in higher orbits. In short, a satellite's orbital altitude decreases gradually while its orbital speed increases. Once an object enters the measurable atmosphere, atmospheric drag will slow it down rapidly and cause it to either burn up or deorbit and fall to Earth.

In LEO, unless reboosted, satellites in circular orbits at altitudes of 200 to 400 km reenter the atmosphere within a few months. At 400 to 900 km orbital altitudes, orbital lifetimes range from years to hundreds of years depending upon the mass and area of the satellite. Satellite Earth-orbit lifetimes are a function of atmospheric density and ballistic coefficients. The more mass per unit area of the object, the less the object will react to atmospheric drag. For example, a fragment with a large area and low mass (e.g., aluminum foil) will decay much faster (and hence a shorter orbital life) than a fragment with a small area and a high mass (e.g., a ball bearing). The combination of a variable atmosphere and unknown ballistic coefficients of space objects makes decay and reentry prediction difficult and inexact.

Orbital lifetimes for objects in elliptical orbits can vary significantly from lifetimes of objects in circular orbits. For elliptical orbits, the lower the perigee altitude, the greater the atmospheric drag effects. Therefore, considering a circular and an elliptical orbit with the same average altitude, an object in an elliptical orbit will have a higher apogee decay rate and a shorter on-orbit lifetime. If the elliptical orbit perigee height is equal to the circular orbit altitude, the circular orbit will decay faster because it is subject to the denser atmosphere during all of its orbital period.

The natural decay of earth-orbiting debris is also greatly affected by the 11-year solar cycle. The previous solar cycle peaked in 1981 and was above average in solar activity. The current solar cycle, peaked in 1991, and has also been associated with greater atmospheric drag and enhanced natural decay rates. High solar activity heats the Earth's upper atmosphere, which then expands and extends to higher altitudes. With this heating, the upper atmosphere density increases, causing satellites and debris to decay more rapidly. As a result, the debris population changes with solar activity depending on altitude and size. Above 600 km, the atmospheric density is already so low that the change in density does not noticeably affect the debris population, but below 600 km there are very noticeable changes. Over the course of the average 11-year solar sunspot cycle, the Earth's atmosphere is excited and rises significantly above its median altitude. However, this natural process of "cleansing" (during the entire solar cycle) is slow above 600 km and alone cannot offset the present rate of debris generation. Figure 4 illustrates the influence of the solar cycle on orbital lifetime of a typical spacecraft as a function of altitude.

In some high altitude orbits, there are significant effects due to the tidal influence of the Moon and the Sun. In some cases, these forces can

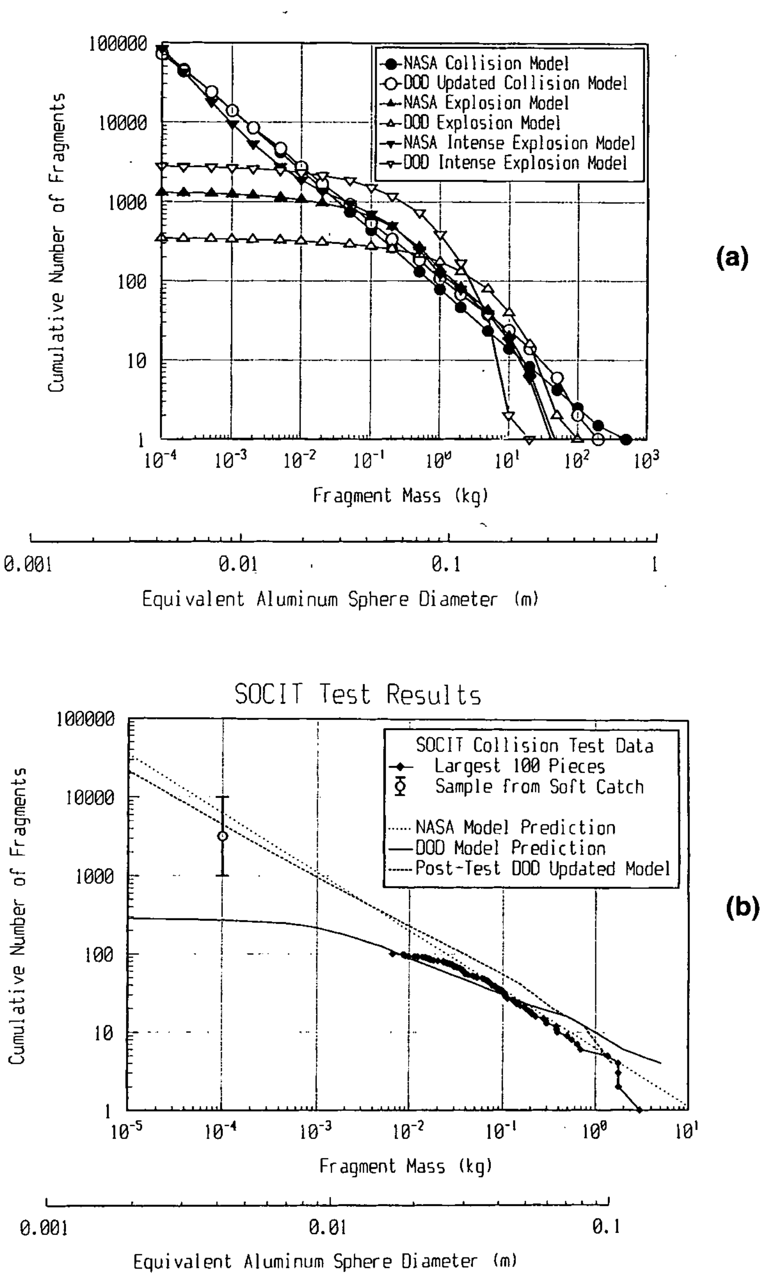


Figure 3. Alternative Models of explosion and collision fragment distribution are illustrated in frame a, and the test and model distribution for hypervelocity collision are illustrated in frame b. The Satellite Orbital Debris Characterization Impact Test (SOCIT) was a series of laboratory tests impacting small spacecraft with a 150-g aluminum sphere at 6ms in a test chamber.

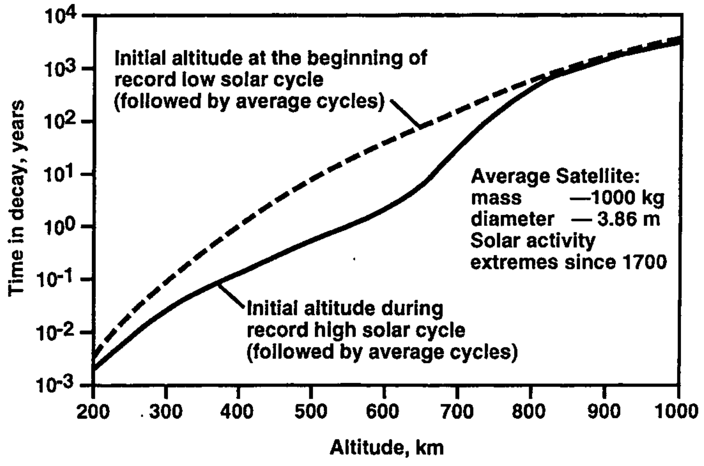


Figure 4. Influence of Solar Cycle on Orbital Lifetime of a Spacecraft as a Function of Altitude

be used to accelerate the decay of geosynchronous transfer orbit (GTO) debris. They also cause the north-south migration of objects in geosynchronous orbit that are not station-kept. In geosynchronous orbit and MEO, there are no significant natural cleansing forces.

Objects in geosynchronous orbit have orbital lifetimes in excess of a million years. Once released from station-keeping the solar and lunar forces cause the object to migrate through a region roughly 22,000 km north to south (from 15 degrees north to 15 degrees south) and 52 km above and below the geosynchronous arc. Terrestrial gravitational influences cause migration east and west around the Earth. The net effect of these motions is to create a torus around the Earth which contains 600 billion km^3 in which approximately 500 satellites are either actively station-kept or are derelicts drifting under the influence of the perturbing forces. The average distance between satellites is in excess of 60,000 km except for a few spacecraft that are kept at a particular longitude and actively controlled.

D. Debris Effects

The effects of orbital debris impacts depend on velocity, angle of impact, and mass of the debris. Throughout this document, all orbital debris is assumed to be of the same material composition; thus, mass and particle diameter will be used interchangeably. For spacecraft design, it is useful to distinguish three debris size ranges:

(1) Sizes below 0.01 cm
(2) Sizes 0.01 cm to 1 cm
(3) Objects larger than 1 cm

For debris of sizes less than about 0.01 cm, surface pitting and erosion are the primary effects. Over a long period of time, the cumulative effect of individual particles colliding with a satellite might become significant since the number of particles in this size range is very large in LEO. Debris of sizes 0.01 cm to 1 cm produce significant impact damage which can be serious, depending upon system vulnerability and defensive design provisions. Objects larger than 1 cm can produce catastrophic damage.

For debris larger than about 0.1 cm, structural damage to the satellite becomes an important consideration. The kinetic energy in an aluminum sphere with a diameter of 1.3 mm at 10 km/second is the same as that in a 22 caliber long rifle bullet.

It is currently practical to shield against debris particles up to 1 cm in diameter, a mass of 1.46 grams or 0.05 ounces. For larger sizes of debris, current shielding concepts become impractical. Advanced shielding concepts may make shielding against particles up to 2 cm diameter reasonable, but it is possible that the only useful alternative strategy for large particles will be avoidance. While such a collision avoidance system is feasible, none is currently planned. For average size spacecraft, the number of particles larger than 10 cm is still small enough that a collision with them is unlikely. For very large spacecraft, collision probabilities are sufficiently high that an alternate means of protection may eventually be required.

Since debris damage is a function of relative velocity and the velocities at geosynchronous altitudes are relatively low, 1/10th those in LEO, the consequences are less dramatic, yet could still be significant. The danger of impact is also much lower due to the smaller number of objects and the larger region in which they orbit.

E. Uncertainty in the Orbital Debris Environment

Figure 5 illustrates the data used to define the orbital debris environment. As noted in the figure, the only continuous source of data is the SSN observations. All other data sources, whether they are the special radar or optical observations or returned surfaces, are statistical sample measures. These techniques are the only means available to measure the smaller objects in orbit. The returned materials can be analyzed to determine the chemistry of the event and identify the proportion of man-made as opposed to natural meteoroids in the very small objects. The observations are then mathematically modeled to define the environment expected for future observations.

The illustration in Figure 6 represents the present state of understanding as measured or estimated from various data sources. It is intended to present a visual picture where the overlapping figures indicate areas where the various instruments can observe similar objects.

In this figure, the outer circle contains all natural and man-made debris of all sizes. The next circle inside is all man-made debris (down to .01 cm). Of all man-made debris, the cataloged objects are shown within the central circle around the typical 10 m^2 spacecraft and, as discussed previously, the LEO population consists primarily of objects larger than 10 cm observable by radars. This population has been maintained continuously for the last 30 years and is the best known portion of the population. There are other observations which have been conducted periodically to make measures below the threshold of routine maintenance.

Periodically since 1983, NASA has conducted a series of special observation campaigns using such optical systems as the ETS and GEODSS at Maui

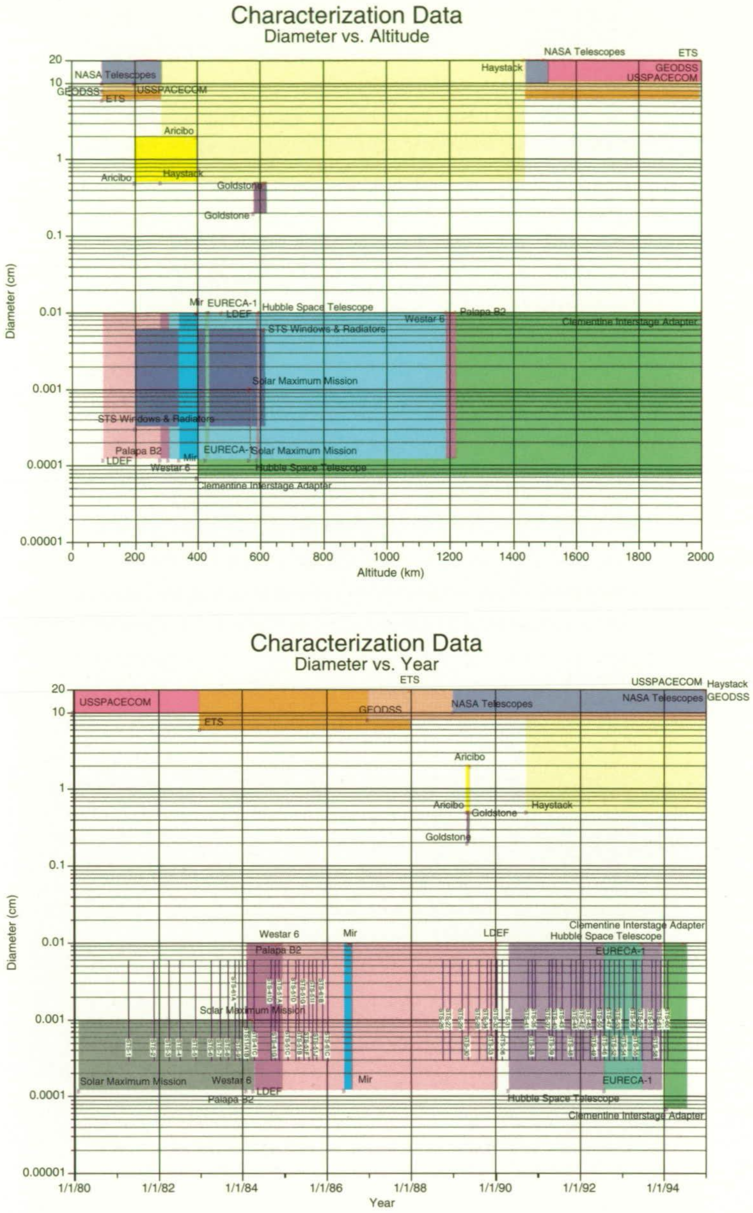
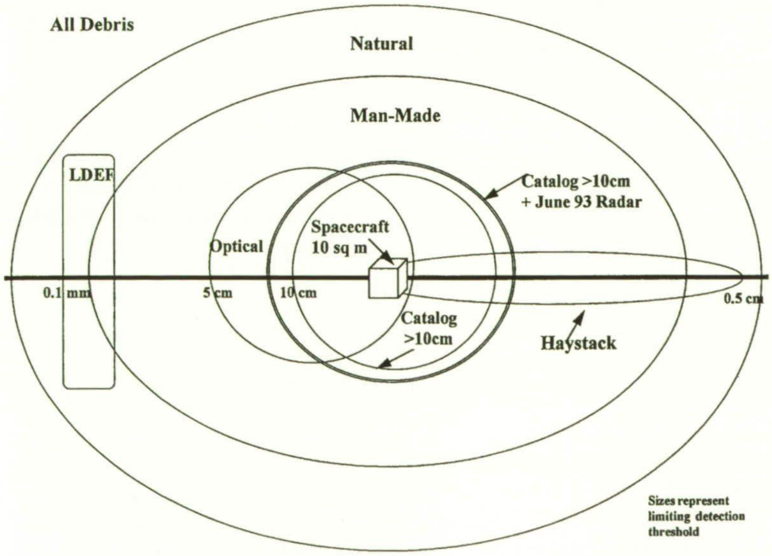


Figure 5. Data Sources for the Definition of the Space Environment



Sizes represent limiting detection threshold

Figure 6. The Relationship of Various Data Acquisition Sources to Each Other and the Natural and Man-Made Environment

and Diego Garcia; a portable CCD telescope at Black Birch, New Zealand, and Rattlesnake Mountain, Washington; and such radars as Goldstone and Arecibo. These observations indicated that there were orbiting objects that were more readily observed optically than by radar.

During June 1993, a special debris search campaign was conducted by the Air Force Space Command (AFSPC) to test the ability of the network to detect smaller objects with the current sensors, making concurrent radar and optical measurements. Roughly 1000 additional tracks were observed by increasing the sensitivity of the network. This led to the identification of approximately 100 new objects. This is represented in Figure 6 by the double circle outside the catalog circle.

To detect still smaller objects, observations have been made with more sensitive instruments which of necessity have smaller fields of view. The optical systems have fields of view ranging from 1 to 6 degrees while the most sensitive radars have fields of view of a few hundredths of a degree.

The optical systems used by the Department of Defense (DOD) are capable of seeing about 80% of the cataloged objects. During the June 1993 campaign, the percentage of newly detected objects revealed that 40% of these unknown new objects in LEO were not in the catalog. Further analysis showed that only 10 to 15% of the unknowns were seen by both radar and optical devices. Therefore, the optical circle in Figure 6, which overlaps 80% of the catalog population, is 40% larger and overlaps 10 to 15% of the double circle. Some objects have poor radar reflectivity but good optical reflectivity or the converse because of the materials properties and the shape of the object.

The Haystack radar observations provide another significant source of data. The Haystack radar, while it can certainly see most cataloged objects, has concentrated on seeing small debris, the majority of which is uncataloged. Because of the extreme sensitivity of the Haystack radar, it can also see some natural meteoroid debris passing close to the Earth. The elliptical shape of the Haystack figure indicates that it is sampling a small portion of the total population. The Goldstone radar is also used to make measurements of the small debris population.

In addition to all these ground-based remote measurements, objects returned from space have allowed us to sample impacts from very small debris (0.1 cm and smaller) and obtain a sample measurement of the ratio of man-made to natural debris in very low Earth orbit. The shape of the LDEF region in Figure 6 is symbolic of the distribution of the measured impact craters on exposed surfaces, none of which were observable from the ground but represented both man-made and natural impact events.

II. Sources of Orbital Debris

A. General

The U.S. and Russia have contributed in roughly equal proportions to the orbital debris environment. Figure 7 shows a steady growth in

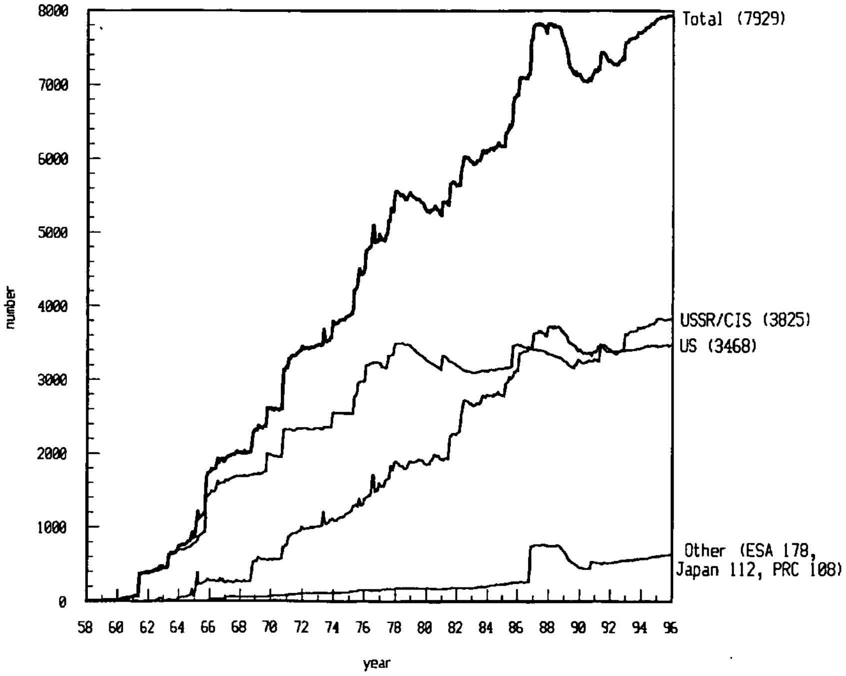


Figure 7. The Number of Catalogued Satellites in Orbit by Nation of Origin

the cataloged satellite population over the past 30 years. Only during the periods 1978 through 1981 and 1989 through 1992 did the catalog growth rate decline. This decline in the growth rate resulted from an expansion of the upper atmosphere caused by a strong solar maximum. The atmospheric expansion significantly accelerated the decay of satellites and debris in orbits below about 600 km.

Satellite fragmentations (see para. II.B.) are the primary source contributing to the increase in the number of cataloged Russian objects which started in 1993. Similarly, the single breakup of a French Ariane rocket body in 1986 is the source of the increase in the number of "Other" cataloged objects shown in Figure 7.

Operational spacecraft represent only 5% of the cataloged objects in Earth orbit. The remainder constitute varying types of orbital debris in four general categories:

(1) Operational Debris
(2) Fragmentation Debris
(3) Deterioration Debris
(4) Solid Rocket Motor Ejecta

B. Operational Debris

Operational debris is composed of inactive payloads and objects released during satellite delivery or satellite operations, including lens caps, separation and packing devices, spin-up mechanisms, empty propellant tanks, spent and intact rocket bodies, payload shrouds, and a few objects thrown away or dropped during manned activities. This class of debris is diminishing as designs are adopted which no longer release such objects. Of the cataloged objects in Earth orbit, 95% can be considered orbital debris as opposed to operational spacecraft.

Table 3 presents the altitude distribution of the sources of tracked objects discussed above. As shown by the table, the majority of tracked objects are in LEO. This is an indication both of the capabilities of the tracking sensors and the level of space activity in LEO.

Table 3. Cataloged Objects by Altitude Regime

	SPACECRAFT	ROCKET BODIES	DEBRIS FRAGMENTS	TOTAL
LEO	1292	712	3743	5747
MEO	107	24	3	134
GEO	465	133	3	601
Transfer	75	276	147	498
Other	359	361	229	949
TOTAL	2298	1506	4125	7929

C. Fragmentation Debris

Of particular concern is the sustained rate of fragmentation events despite the active efforts of spacefaring nations to reduce the probability of such events by making all their systems passive at

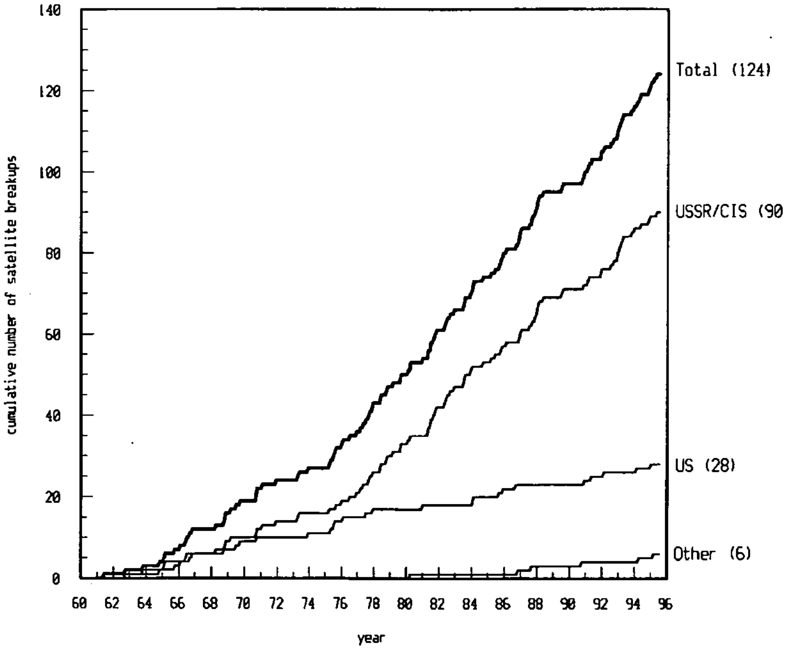


Figure 8. History of Fragmentation Events

mission end by expelling residual propellants and other forms of stored energy. Figure 8 indicates the cumulative number of breakup events by year (see Appendix 1).

In the past 4 years, there have been 19 breakup events. Three of these involved spacecraft and the other 16 were rocket bodies, many being the booster units of the Russian Proton D-1 stage. Figure 9 illustrates the number of fragmentations by year since 1961. Despite the introduction of procedures to eliminate stored energy, there has not yet been a change in the rate of breakups.

Since the first detected fragmentation of the Omicron rocket body in June of 1961, 124 fragmentation events have been documented. These fragmentation events serve as the dominant mechanism in the creation of larger sizes of debris. Generally, fragmentations may result from either explosions or collisions. There are several explosive mechanisms including: (1) the catastrophic failure of internal components such as batteries, (2) propellant-related explosions (high energy explosions), (3) failure of pressurized tanks (low energy explosions), and (4) intentional destruction. Fragmentation may also be caused by collisions with other orbital objects, although no such events have been confirmed. Each type of event produces a characteristic size and velocity distribution of the resulting debris cloud. For example, low energy explosions typically produce fewer small objects than high energy explosions. In LEO, a hypervelocity collision would typically produce many more small objects than a high energy explosion since the impact and resultant shock wave melts and vaporizes satellite materials. A prominent example of high energy explosions is the Delta rocket body breakups in LEO. As a class, debris from these breakups dominate the catalog.

Figure 10 shows a Gabbard diagram of a recent Delta rocket body breakup. Gabbard diagrams are used to identify and analyze breakup events. In the diagram, the apogee and perigee of each object are shown by a pair of points. Fragments that receive a posigrade impulse are distributed along the right side of the diagram and retain their original perigee altitude. Conversely, pieces receiving retrograde impulses are distributed to the left and retain their original apogee altitudes. The original rocket body

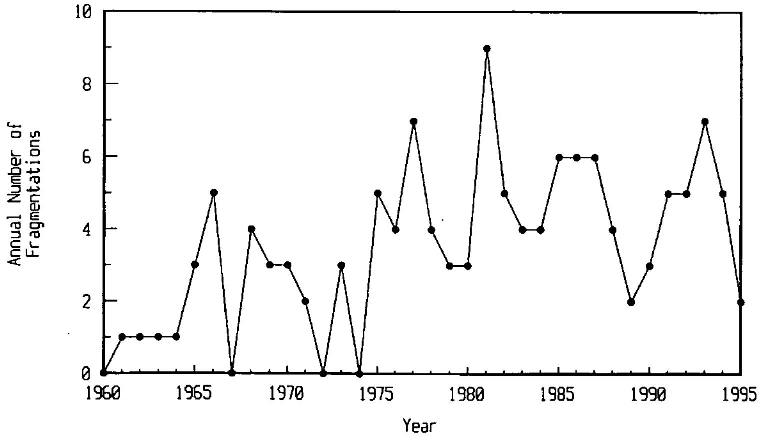


Figure 9. Number of Breakup Events by Year of Occurrence

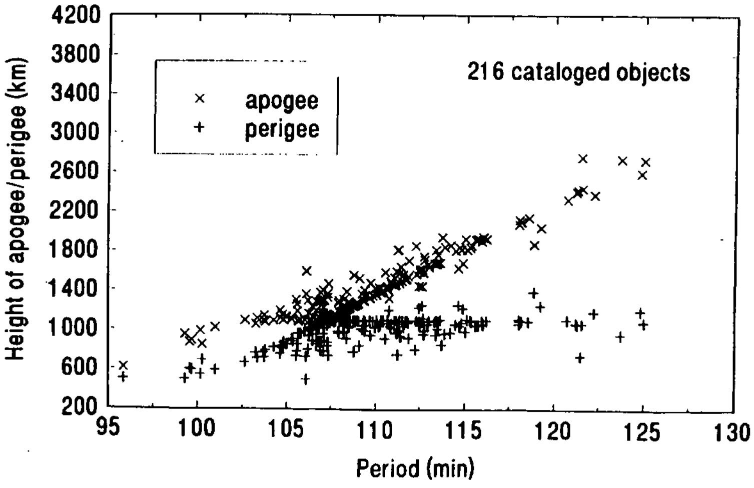


Figure 10. Gabbard Diagram of the Breakup of Nimbus 6 Delta Second Stage

was located at the center of the cross. This cross is characteristic of breakups from near circular orbits. The collapse of the left arm of the Gabbard is indicative of the cleansing effect of atmospheric drag on the objects with lower perigees. Moreover, the diagram illustrates that breakup events distribute debris over a wide range of altitudes.

Two fragmentation events appear to have taken place in GEO. Also, nonoperational satellites in GEO are frequently not tracked for long periods of time during which unobserved fragmentations could occur. In the absence of data to the contrary, it is believed that there is not a significant number of objects in GEO to create a problem at this time.

The causes of many fragmentations (22%) remain unknown, in part, due to the limited data available for analysis. Table 4 lists the causes of fragmentations as currently known.

Table 4. Causes of Satellite Fragmentations

Cause	% of Events	% Fragments Still in Orbit
Unknown	22	43
Propulsion Related	36	42
Deliberate	38	13
Systems Related *	4	2

* Electrical, command and control systems

D. Deterioration Debris

Very small debris particles are created by the gradual disintegration of spacecraft surfaces as a result of exposure to the space environment. This deterioration includes paint flaking and plastic and metal erosion. It has been hypothesized that paint flaking is caused by the erosion of organic binders in the paint due to exposure to atomic oxygen. The dramatic consequences of even small paint flakes can be seen in the widely reported impacts on the Space Shuttle window.[54]

Deterioration debris is not limited exclusively to the smaller objects. Several orbital objects have been observed to periodically shed materials over long periods of time. Much of this material may be deteriorating thermal blankets and insulation. Examples include debris from the U.S. Snapshot payload/rocket body complex, Ariane upper stages, and Russian Proton upper stages in GTO.

E. Solid Rocket Motor Ejecta

Solid rocket motors (SRMs) typically are used to transfer objects from LEO to GEO, and they eject thousands of kilograms of aluminum oxide dust into the orbital environment. This ejected dust is very small, with characteristic sizes believed to be less than 0.01 cm. Nonetheless, long-term exposure of payloads to such particles is likely to cause erosion of exterior surfaces, chemical contamination, and may degrade operations of vulnerable components such as optical windows and solar panels. Recent chemical analysis of impacts on LDEF indicates that a significant fraction of the impact craters contain traces of aluminum. In some cases, larger chunks of unburned SRM propellant or slag may be released (ignited propellant will not burn completely outside the pressurized confines of the rocket body). Some of these chunks may be released long after the completion of the burn.

Since SRM particles are ejected in the rocket plume, most have very large retrograde velocities (~3 km/s). This fact, combined with the low mass of the dust and low altitude parking orbits used in current mission profiles, will cause the particles to decay very rapidly, probably within a few perigee passages. Those that do not quickly reenter are dispersed by solar radiation pressure. Thus, the operational threat of SRM dust is probably limited to brief periods of time related to specific mission events. Even the majority of the ejecta from the GPS SRM semi-synchronous insertion burns has a perigee height at or below the Earth's surface.

The Haystack radar located near Boston, Massachusetts, has been used to monitor the orbital debris population for the past four years. It is operated in an unconventional mode: the antenna is fixed, and debris objects that fly through the radar beam are detected. This radar is one of the most powerful in the world, and is capable of detecting 1-cm objects orbiting at 1000-km altitude. Measurements with this radar have provided the best and most complete picture available of the small debris population.

The purpose of the Orbital Debris Calibration Spheres (ODERACS) experiment was to calibrate the radars and telescopes used for orbital debris measurements by putting objects of the size of interest into orbit for observation. One of the pair was polished, the other diffuse. The three pairs were two, four and six inches in diameter. The illustration is a composite of the deployment of the spheres from the Shuttle payload bay.

Chapter 2: Trends and Implications

I. Trends

A. Launch Activity

For the first 25 years of human involvement in space, only the U.S. and the former Soviet Union launched significant numbers of spacecraft. Currently, the seven countries listed in Table 5 have launched objects into Earth orbit. During the past 10 years, there has been a decline in government launches and an increase in commercial launch activity. This trend is expected to continue. In the next decade, additional countries are expected to develop the capability to launch satellites. The launch rates for the seven leading launching nations over the past 11 years is illustrated in Table 5.

Past space activity at most altitudes has placed debris in orbit faster than the natural effect of drag removes it. As a result, the cataloged population of orbital debris increased by about 200 to 300 objects per year, on average, during a time when launch rates were fairly constant. The effect of high solar activity may be seen in the decline in cataloged objects during the late '70s and the early '90s (fig. 7).

B. Debris Modeling

In order to project the future debris environment, assumptions have to be made concerning debris sources and sinks. With regard to debris sources, assumptions have to be made concerning launch and fragmentation rates. Uncertainties arise from traffic model predictability, observational limitations, unmodeled sources, limitations of breakup models, debris propagation and lifetime models, and variability in solar activity.

Another challenge involves modeling the propagation of a class of objects that are apparently anomalous. This subset of debris is subject to poorly modeled orbital perturbations. The associated problems with their detectability and their ability to be accurately maintained in the catalog influence collision avoidance operations.

Both the DOD and NASA have different types of debris models for a variety of applications. The NASA models can be classified fundamentally into two types: research models and engineering models. The research models use traffic models, atmospheric density models, and satellite fragmentation models to predict the current and future debris environment. The research models are tested and calibrated by data obtained from measurements from laboratory experiments and measurements of the environment. The results of the research models and measurements are then synthesized into a simplified model which can easily be used by the engineering community.

Atmospheric models are derived from the orbital decay characteristics of known objects as well as density measurements. Since the geophysical indices driving these models do not parameterize the atmospheric density very well, the atmospheric drag cannot be modeled accurately; however, the atmosphere represents a small uncertainty in orbital debris models. A significantly larger uncertainty results from the breakup models which describe not only the number and size of fragments produced from a satellite breakup, but their new orbits and the object's susceptibility to atmospheric drag. These models are based on a limited number of ground tests, and represent the largest uncertainty in debris research models.

Table 5. Worldwide Launches

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
U.S.	18	18	22	22	17	6	8	12	18	27	18	28	23	27
Russia	98	101	98	97	97	91	95	90	74	75	59	54	47	49
Japan	3	1	3	3	2	2	3	2	2	3	2	1	1	2
ESA	2	0	2	4	3	2	2	7	7	5	8	7	7	8
India	1	0	1	0	0	0	0	0	0	0	0	1	0	2
China	1	1	1	3	1	2	2	4	0	5	1	4	1	5
Israel	0	0	0	0	0	0	0	1	0	1	0	0	0	0
Total	123	121	127	129	120	103	110	117	101	117	88	95	79	93

The DOD has developed and enhanced a variety of predictive models in support of debris research dealing with the generation and propagation of orbital debris resulting from the breakup of space assets. These models range in purpose from modeling the breakup of space assets to modeling the population of the LEO debris environment. The models also range in complexity from personal computer-based empirical models to workstation and super computer-based theoretical models. Empirical breakup models describe the mass and velocity distributions of the debris resulting from the breakup (explosion or hypervelocity collision) of space assets. A theoretical model is used to predict the physical response of satellites and satellite components to explosions and hypervelocity impacts.

For space debris environment modeling, the DOD borrowed the framework of the NASA research model EVOLVE and made several modifications. One significant change was to replace the empirical breakup model in EVOLVE with DOD empirical breakup model called IMPACT. Other modifications dealt with making the code more efficient and user-friendly.

NASA favors use of an orbital debris engineering model which has been in use since 1990.[47] This model is currently being tested against measurements made since 1990, and while there are some differences between the measurements and the model predictions, the differences are not yet considered significant enough to update the model.

The engineering model makes the following assumptions about future space activities:

(1) Launch activity will continue at the same average rate it has for the last 10 years, allowing payloads and upper stages placed into orbit to continue to accumulate at the same rate. This assumption is assessed to be conservative because it does not postulate significant new space-based activities (cf p. 19 re LEO constellations).

(2) Future solar cycles will resemble the average of all past recorded cycles.

(3) Future operational practices will minimize (but not eliminate) the possibility of explosions in orbit.

Using these assumptions, European Space Agency (ESA), NASA, and Russian models predict an increasing probability of orbital collisions over time. These orbital collisions would cause the small debris particles generated by these hypervelocity impacts to increase at a faster rate than predicted by launch and explosion rates alone.

C. Debris Generation Projections

The major source of both large and small debris in LEO has been fragmentation of satellites and rocket bodies. This process has produced more large, trackable debris than has space operations, and much more small untrackable debris. The launching of a payload into space from a booster or upper stage generates orbital debris composed of spent rocket stages, clamps, covers, etc., but does not produce much untrackable debris in LEO. More recent designs and practices eliminate or retain these devices so that they do not become debris.

There are very large uncertainties involved with predicting future debris environments. Making these predictions requires estimates of future debris sources and sinks. This includes estimates of future world launch activity (when, how much mass on orbit, what orbit), estimates of future on-orbit explosions (when, where, what, and how many), estimates of on-orbit collisions (when, where, what, and how many), estimates of future solar cycle activity, and estimates of mitigation strategies and their effect on the debris environment. Another aspect of future predictions that is not modeled by NASA or DOD is the impact of future technology and its effect on reducing the hazard of debris to operational assets.

Because of these uncertainties, DOD does not consider the possibility of future random collisions as a debris source in its orbital debris predictions. DOD considers the concept of random collisions one that requires further validation before it should be incorporated into its models. The results of the DOD analysis at altitudes of 400 and 800 km for the cumulative debris population larger than 1 cm are shown in Figure 11. Imbedded in this DOD projection of the future orbital debris environment are trends in debris growth due to launch activity, breakup events, and solar activity.

Historically, the major energy source for satellite fragmentations has been the stored energy in upper stage propellant, batteries, or pressure containers. In the short term, these energy sources are responsible for the near-term environment of small debris.

In the long term, several models predict that chance collisions could be an important source of satellite fragmentation unless current design and operation practices are modified at some time in the future. Figure 12 illustrates this using a NASA research computer model to predict the future 1 cm orbital debris environment in low Earth orbit using three different operational practices.

All three cases assume the past launch rate of approximately 100 launches per year. Case 1 is the

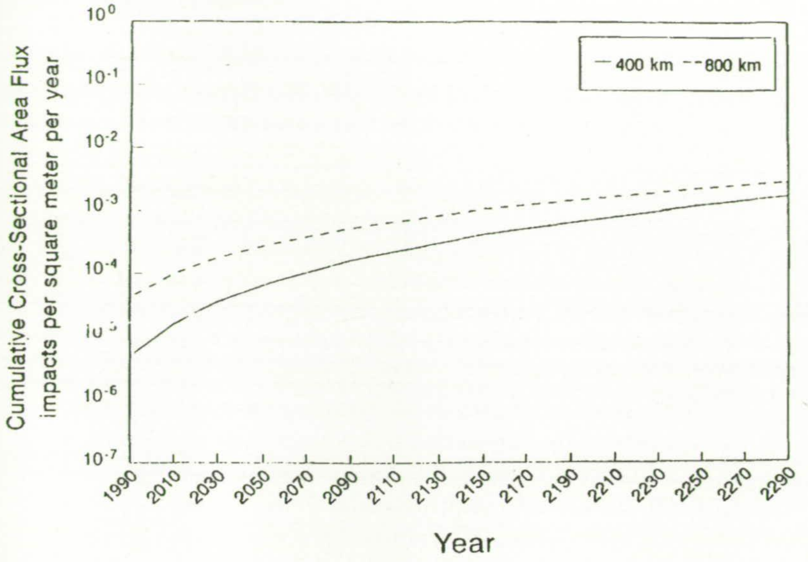


Figure 11. The Expected Future Orbital Debris Environment

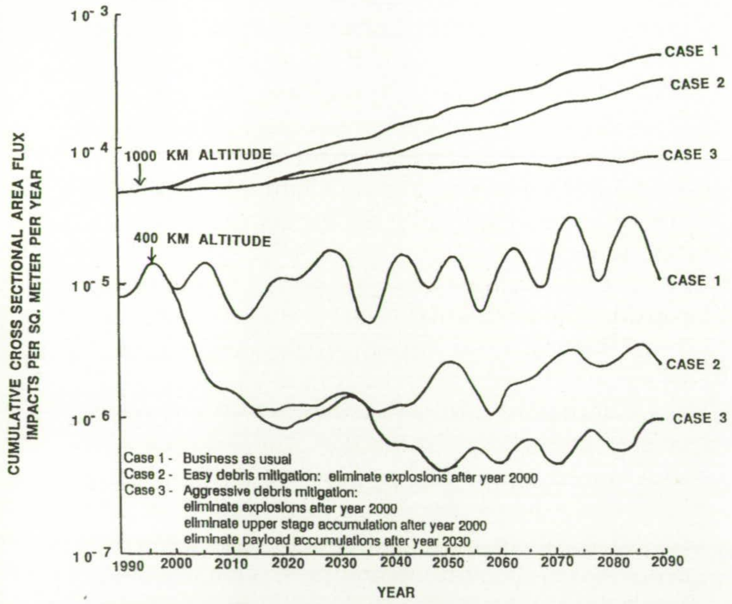


Figure 12. EVOLVE Projections of Future Debris Environment as a Function of Different Future Operations Scenarios

"business as usual" case, where objects are allowed to explode at the same rate they have in the past. Case 2 represents the "easily achieved mitigation" technique of preventing future explosions after the year 2000. Although eliminating explosions produces a short-term reduction in the rate of accumulation of small debris, this action alone does not significantly alter the long-term projection, especially at the higher altitudes of LEO. This is because the NASA model predicts that fragments from random collisions between larger objects become the major source of small debris. Case 3 represents the more "aggressive debris mitigation" of requiring future payloads and rocket bodies to not remain in orbit at the end of their operational life. This reduces the rate of random collisions, and consequently reduces the rate of growth in small debris. Even so, in the long term, this model still predicts a slow increase in the small orbital debris population. ESA independently developed models provide essentially identical results.[54]

It is important to point out that predicting the future debris environment is not intended to be an exact extrapolation to the "true" debris particle density. The predictions presented here are intended to provide an indication of an expected fragment environment for particular initial conditions and assumptions. In this case, the following conditions would exist:

(1) Collisional breakup of space objects may become a source for additional orbital debris in the near future.

(2) Over a longer period of time, the orbital debris environment is likely to increase with time, even though a zero net input rate may be maintained. Ultimately, this could lead to an environment increasingly controlled by collisions and difficult to alter.

The discussion in the preceding paragraphs has been limited to LEO. The situation is considerably different in GEO. There are currently about 920 cataloged objects that traverse GEO altitudes, of which only about 150 are geostationary. The others are in either geosynchronous transfer or semi-synchronous, highly elliptical ("Molniya") orbits. The average spatial density of objects is 2 to 3 orders of magnitude less than in LEO. Low densities combines with low average relative velocities make the current likelihood of a collision insignificant. Thus the near-term concern for debris in GEO is less compelling than for LEO.

II. Implications

The probability of collision is mainly a function of the spacecraft size, the orbital altitude, and the period of time that the spacecraft will remain in orbit. The orbital debris environment in LEO could present a problem even now for space operations which involve large spacecraft in orbit for long periods of time. A space station is the primary example of a large spacecraft, and it will be necessary to shield large areas of it to achieve the design safety criteria.

The "design driver" is the determination of an acceptable level of risk. For example, the specified level of risk of manned space programs from Apollo to the present varied from .01 to .05 probability of penetration over the lifetime of the space system. The actual level of risk experienced by these spacecraft has been significantly less than that specified because other design requirements made the spacecraft more robust. The earlier manned space programs addressed only the natural meteoroid environment, but the proposed Space Station requirement addresses both the natural meteoroid and the orbital debris environments. Substantial growth of the debris environment may also require additional shielding for smaller unmanned satellites.

A. Operational Experience of Orbital Debris Effects on Spacecraft

While there has been no documented case of a spacecraft failure due to an orbital debris impact, there are a number of spacecraft failures for which the cause is unknown. The breakup of Kosmos 1275 is one such failure where an orbital debris impact is the prime suspect. Kosmos 1275 broke up for no apparent reason not long after it was inserted into orbit. An orbital debris impact was suspected because the size and velocity distribution of the fragments following the breakup were characteristic of a collisional fragmentation.[59]

Direct evidence of small orbital debris impacts has been gained from examination of surfaces brought back from orbit by the Space Shuttle. The exterior surfaces of the Orbiter show many impact pits after each mission. Pitting of the Orbiter windows results in replacement of a window every other mission, on average. Similar effects are found on other surfaces returned from space. The largest such area in space for the longest time was the LDEF that was in orbit for 69 months. Its surface was covered with tens of thousands of impact pits, the largest being about 0.63 cm in diameter. Laboratory studies of the pitted surfaces confirm that about half the larger impacts where the source could be identified were caused by debris, while practically all of the smallest impacts were man-made aluminum oxide debris.[58]

We expect to see similar small debris impact effects on the Mir space station. Russia has reported very little direct information on the debris damage to Mir. Informally, we have learned that Mir suffered pitting effects similar to those seen by the U.S. during Space Shuttle missions. The Russians are also reported to have found it necessary to replace Mir's window covers and to shield its exterior light bulbs due to damage from orbital debris. Russia has reported exposing witness plates on Mir; however, these plates have not been completely analyzed. As part of the U.S. Shuttle flights to the Mir station, NASA plans to conduct a photo survey of the Mir in an attempt to quantify and characterize any damage from orbital debris.

Often asked is the question why there has not been a major impact damage observed on LDEF or Mir. Calculations of the probabilities of a damaging collision for LDEF and Mir which take into account the area of these spacecraft, their operational altitude, and their time on orbit predict a low probability of a damaging collision. The observational data is consistent with these calculations.

Figure 13 illustrates the expected impact rate on a typical LEO spacecraft. Because of the relatively modest size of such spacecraft the expected impact frequency is low and that much of the spacecraft is not vulnerable to impact damage e.g., solar arrays. It is worthwhile to note that at these altitudes the man-made environment exceeds the meteoroid environment at all sizes.

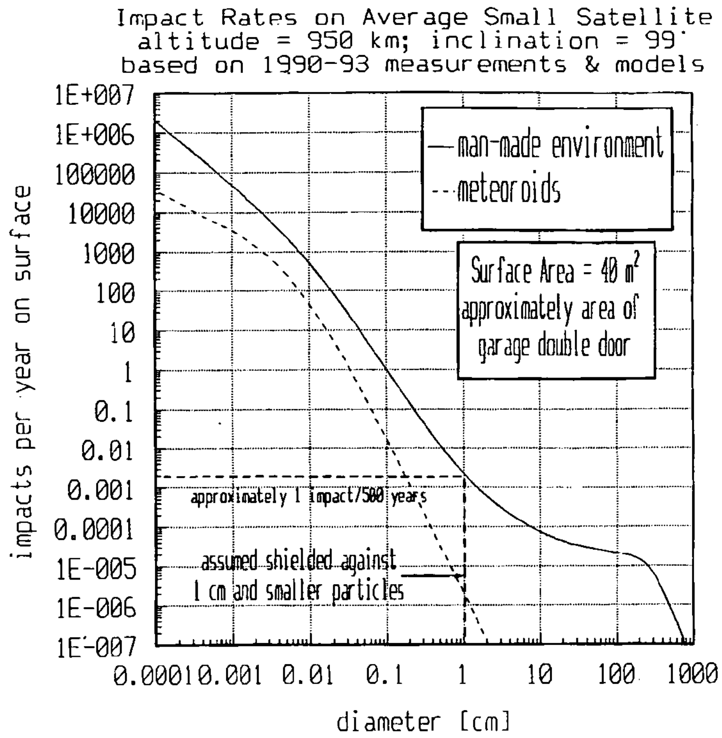


Figure 13. Orbital Debris and Meteoroid Impacts on a Small Satellite at 950 km, 1994-2030

B. Future Operations

Space Station and Extravehicular Activity (EVA) Considerations

The implication of orbital debris growth is important to all aspects of human space flight. Even though the final design of the International Space Station (ISS) is still evolving, it is possible to draw some early conclusions on the effects of orbital debris on the design. Figure 14 illustrates some of the factors that are involved in performing the Space Station orbital debris risk assessment. This assessment is based upon an ISS design with a 5000 square meter exposed surface area, a 400 km operating altitude, and 51.6 degrees inclination.

The ISS is being designed to protect critical areas against the highest probability particles of 1.4 cm and smaller which accounts for 99.8% of the debris population. The analysis shown in Figure 14 predicts the chance of a 1.0 cm or larger object impacting the Space Station in one possibility in 71 years. However, debris larger than 1.4 cm striking the Space Station will not necessarily cause a catastrophic problem.

Impacts with objects too small to cause a penetration or significant structural damage will be the most frequent. Most impacting particles will be in the size range of grains of sand. These very small impacts will cause surface degradation on sensitive surfaces such as optical surfaces and solar panels. This type of damage has been planned for and will be repaired during routine maintenance operations.

As noted, the ISS has been designed to shield for the highest probability impacting particles. However, for protection against a collision with very large debris objects, the ISS will employ an improved version of the type of collision avoidance measures that are now routinely utilized to protect the Space Shuttle and the Mir.

In addition to the measures already discussed, a number of other measures that are currently being pursued are:

1. Proven "hatch position protocols" will be employed to give additional protection within the crew quarters.
2. Internal structures such as equipment racks will be utilized to provide crew protection from a debris impact. Other devices such as spall blankets are being considered and tested.
3. Various Space Station repair methods in work.
4. Modified operational procedures during periods of high flux (i.e., meteor storms).
5. And finally, in the event that the future orbital debris environment is more severe than currently forecast, the Space Station is being designed to accommodate additional debris shields that can be delivered and deployed after the Space Station is operational.

Another very important consideration is EVA since crew members are more directly exposed to the debris environment. The risk is a function of the duration of exposure and the capability of the EVA suit to resist impact events. Presently the risk is small due to small exposed area of the EVA suit and the short duration of exposure.

Potential Effect of LEO Satellite Constellations on the Environment

The advent of large LEO satellite constellations could present a significant new issue for the orbital debris environment. Table 6 lists the proposals that have been put forward as candidates for frequency allocation by U.S. companies and others. In each case, the numbers of satellites shown are the total for the operational configuration of the constellation. The numbers of planes in which the spacecraft are deployed varies widely. Design life ranges from 5 to 10 years. Additional replacement satellites must be launched to replace failed units or those that have reached end of life.

The inclination and altitude bands for these systems places most of them in what are already the most heavily used regions of LEO. Adding the large numbers and cross section characteristic of these constellations increases the probability of collisional damage particularly because the high inclination leads to high spatial density over the poles.

Table 6. Some Proposed LEO Constellations

System	Number of Spacecraft	Altitude (Kilometers)	Inclination
Teledesic	840	700	98.2
Iridium	66	780	86.0
Globalstar	48	1400	47.0
Odyssey	12	10360	55.0
Aries	48	1020	90.00
Ellipsat	24	500-1250	63.5
Vita	2	800	99.0
Orbcom	18	970	40.0
Starsys	24	1340	50-60

While it is uncertain how many of these systems will be deployed, at least three have mature technical definition and a significant fraction of the required financing. An analysis was performed

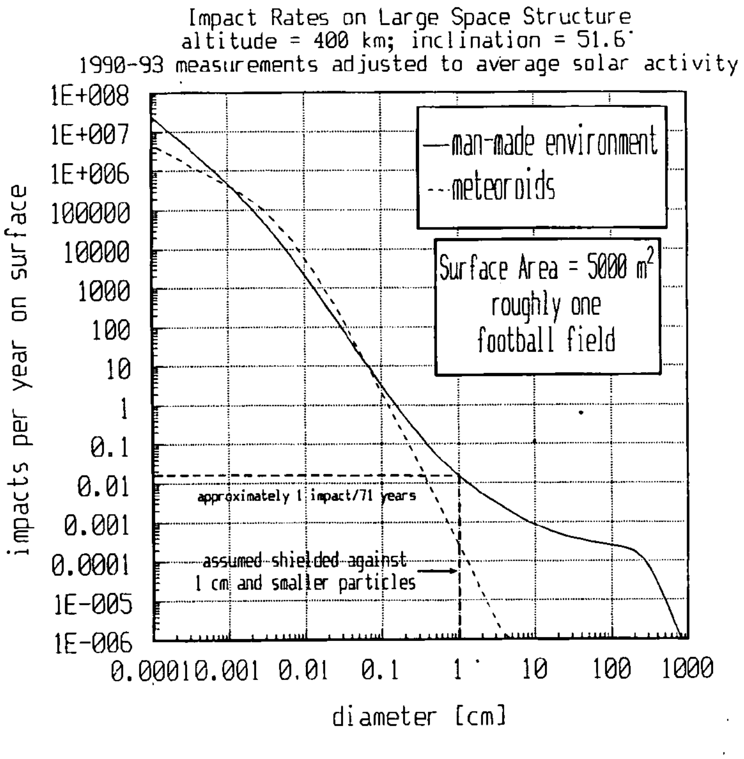


Figure 14. Orbital Debris and Meteoroid Impacts on a Large Space Station at 400 km, 1994-2030

using the EVOLVE model to assess the effect of deploying three of the systems. The analysis assumed that five launches a year would deploy multiple spacecraft and examined the effect of such an increase in LEO activity and the influence of a spectrum of mitigation strategies in the long-term future environment. Mitigation options ranged from actions to eliminate future explosions to removing upper stages and spacecraft from orbit at the end of mission lifetime. As the curves in Figure 15 indicate, failure to take any action will lead to significant increase in orbital debris during the next century, but relatively modest active measures (as identified in cases 3 and 5) can keep the environment essentially as it is today. Teledesic and Iridium both plan to deorbit their upper stages and spacecraft at their end of life.

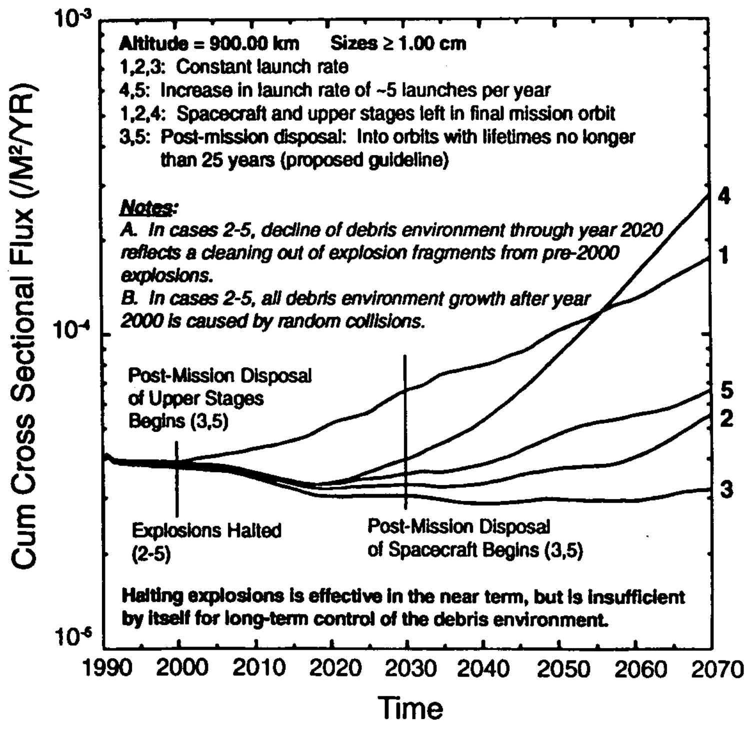
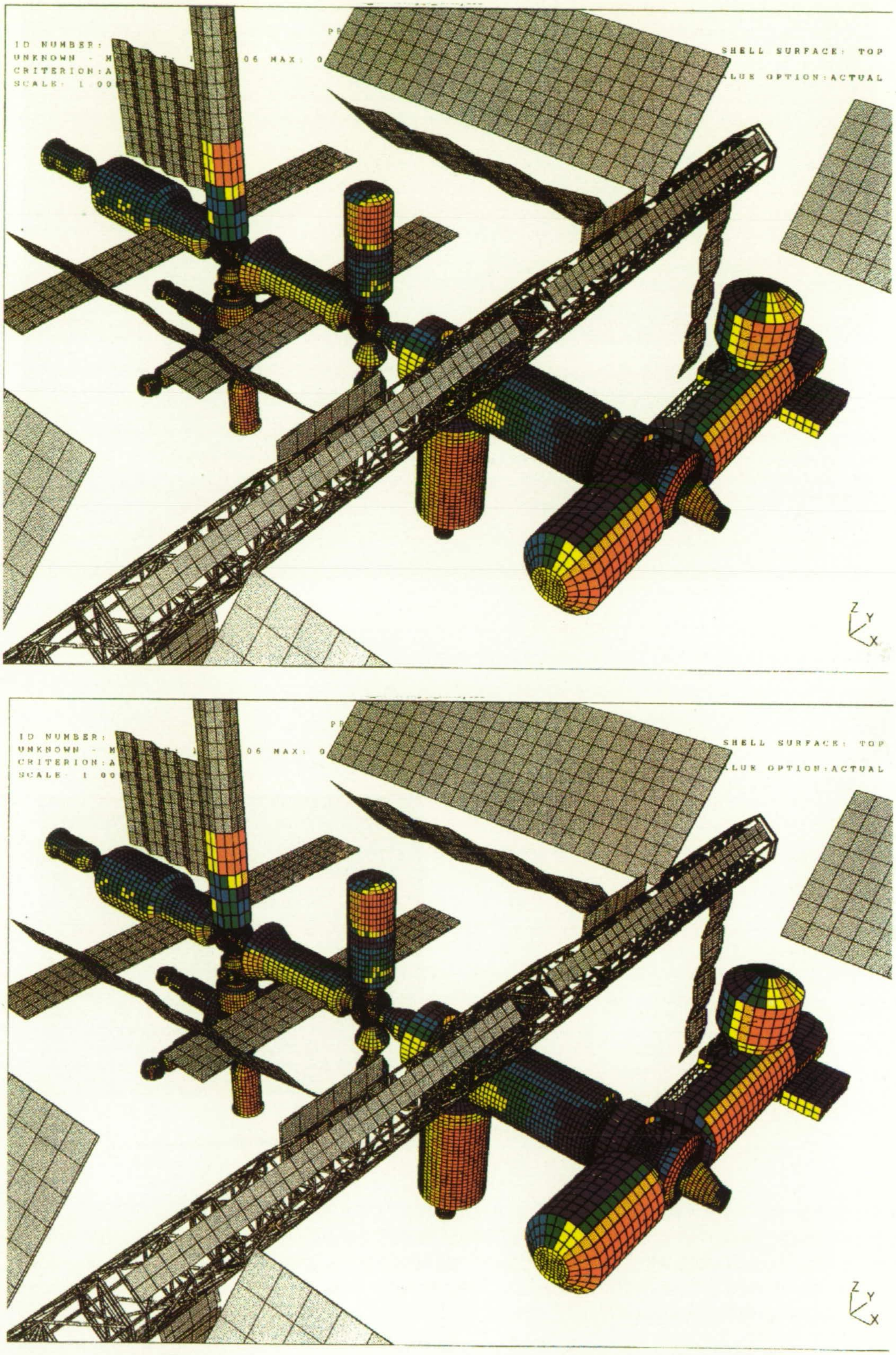
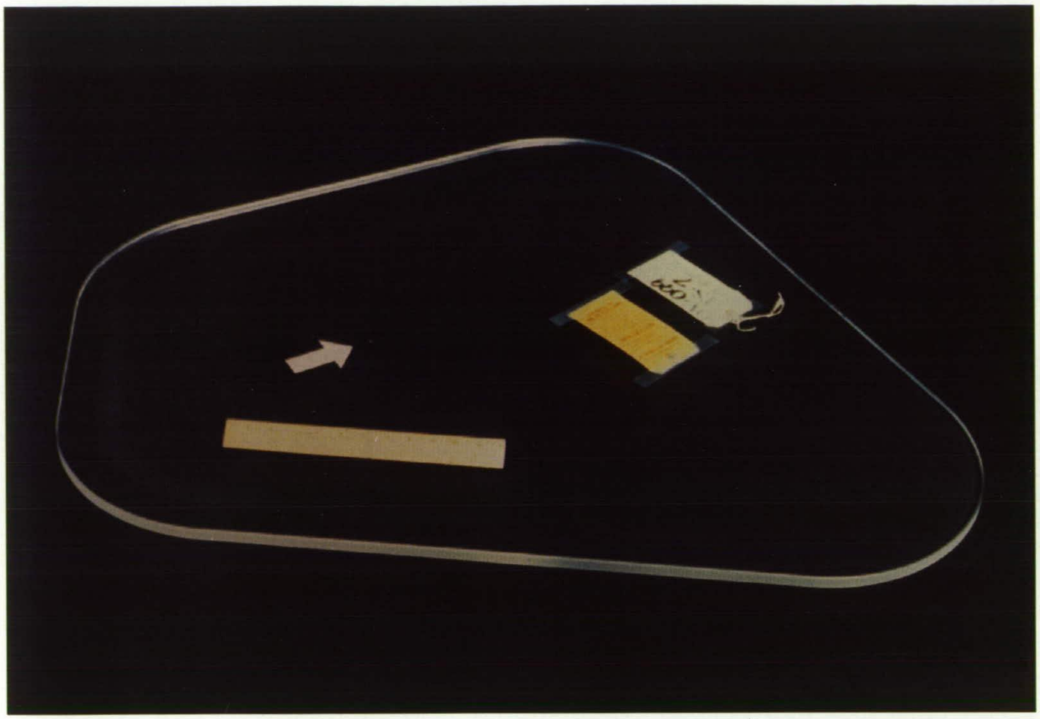
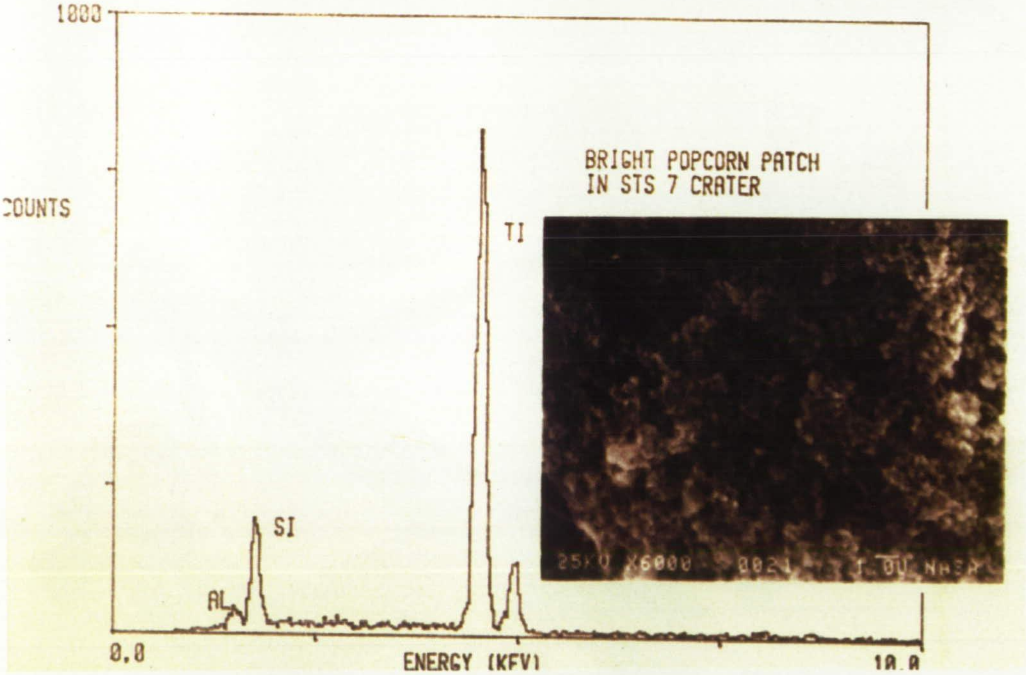


Figure 15. EVOLVE Projection of the Future Environment With Increased Launch and Spacecraft Operation in LEO



NASA uses BUMPER computer code to determine risks of meteoroid and orbital debris impact damage and critical penetration for a number of spacecraft such as the Space Station (shown in figure). BUMPER is also used to determine the most likely areas of the spacecraft to be impacted which can then be designed with more shielding protection. For instance, the forward and side areas of the Space Station will be exposed to the highest concentration of the orbital debris impacts as indicated by the red and orange colors in this figure. These areas of the Space Station will be designed with the heaviest shielding to increase the protection to crew and critical equipment from meteoroid/orbital debris impact.





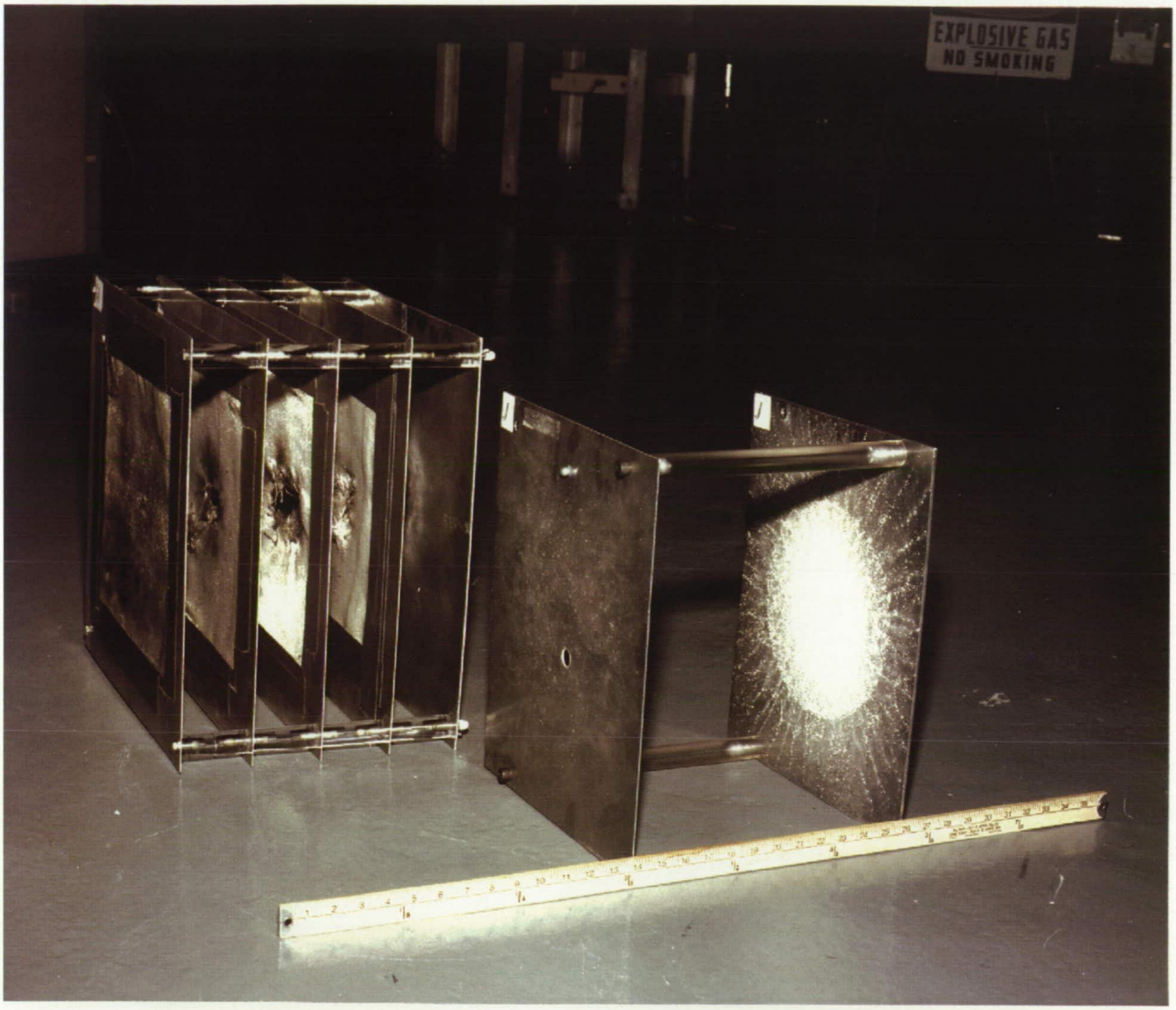
During the 70 flights the Space Shuttle has flown, it—like the LDEF has been hit many times by debris in orbit. Generally, these impact events cannot be observed post-flight because the surface is heated during entry and the evidence is lost. The Shuttle windows and radiator panels on the interior of the payload bay doors, however, do experience impacts and preserve the evidence. This window from the flight of STS-7 experienced an impact event and was subsequently analyzed.

The scanning electron microscope response illustrates that the crater is characterized by the titanium dioxide pigment characteristic of spacecraft thermal control paints and the aluminum silicate binder used to adhere the paint to the spacecraft structure.

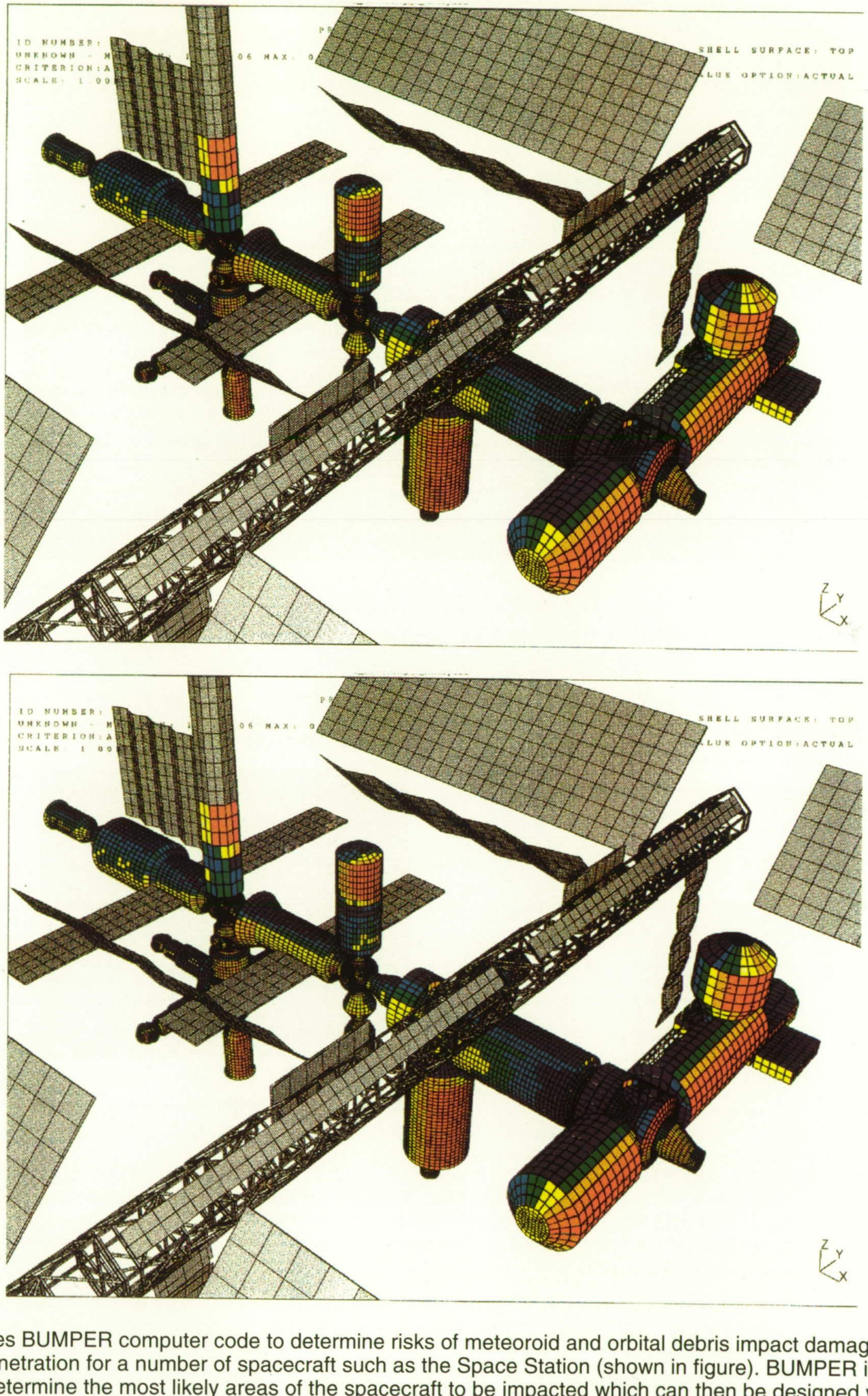
There have been 60 windows replaced on the Orbiter over 70 flights because of hypervelocity impacts. The craters are caused by objects the size of a grain of salt moving at 8 to 10 km/second. The window replaced is not part of the crew pressure vessel but an external window provided to protect the two pressure windows. The window is replaced because, on the next launch, the flaw could cause it to fail due to aerodynamic loads.

Part Two:

Current Policies and Activities, Options, and Associated Research Needs



The NASA Johnson Space Center Hypervelocity Impact Test Facility (HIT-F) developed and patented a lightweight hypervelocity impact shielding concept called the "Multi-Shock" (MS) Shield. The MS shield in the left of the figure weighs ~one-half of the weight of a conventional Whipple shield that is shown on the right. Each shield was designed to protect from a 1-cm-diameter aluminum projectile at ~7 km/sec impacting straight into the shield. Tests at the JSC HIT-F have demonstrated that the MS shield weighs ~50% less than the Whipple shield while providing equivalent or superior protection at normal and oblique impact angles (i.e., stopping the same or larger projectiles) for velocities in the testable range (up to ~8 km/sec).



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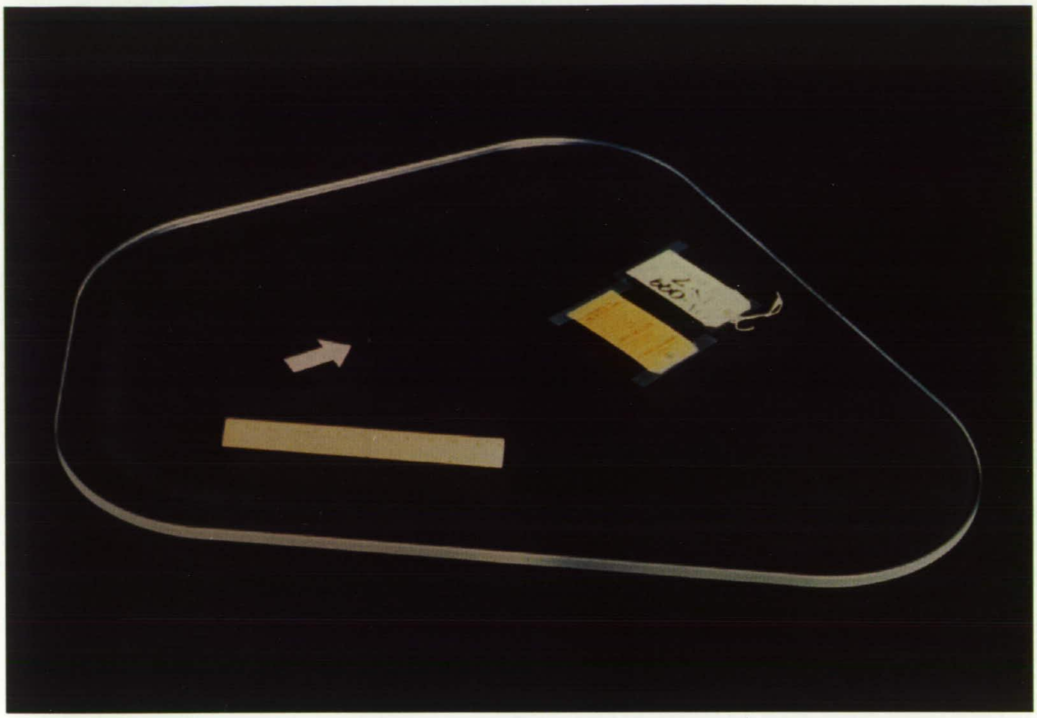

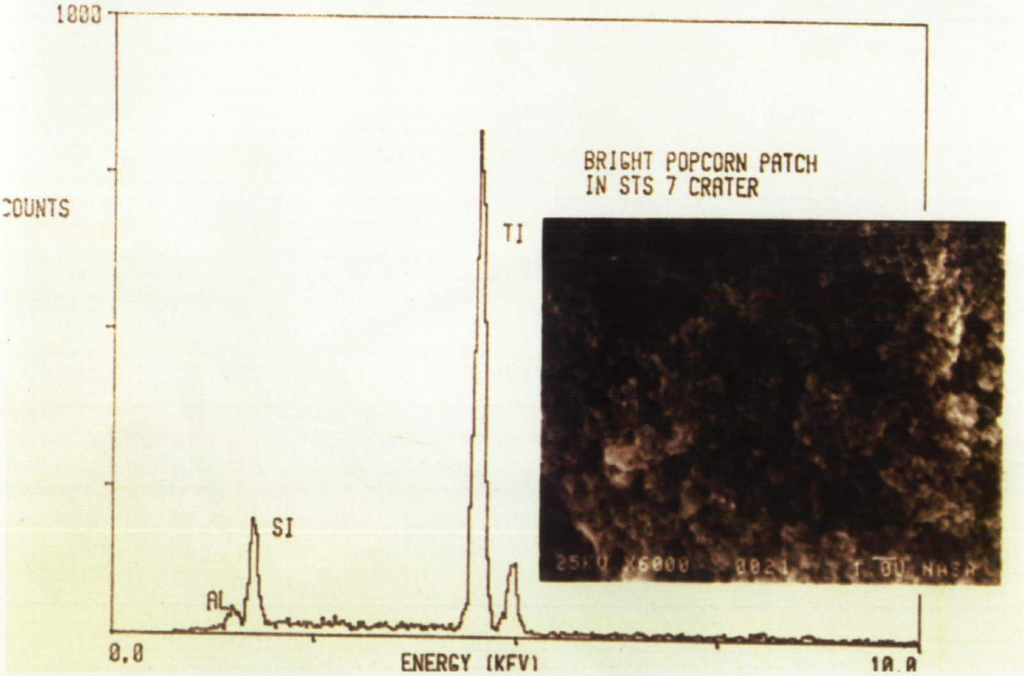

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Chapter 3: Existing Policies Concerning Space Debris

I. National Space Policy

To date, only one policy statement specifically related to orbital debris has been articulated at the Presidential level. The Reagan Administration approved a policy in February 1988 which included the statement that "all space sectors will seek to minimize 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."

II. Agency Policies

NASA Policy

Perhaps the most significant debris-reduction policy has been the NASA requirement instituted in 1982 for the venting of the unspent propellants and gases from Delta upper stages to prevent explosions due to the mixing of fuel residues. This practice was continued when the Air Force began direct acquisition of Delta launch vehicles and McDonnell Douglas initiated commercial launch services. No U.S. hypergolic stages following this procedure have inadvertently exploded.

NASA Management Instruction 1700.8, Policy for Limiting Orbital Debris Generation, identifies its policy to employ design and operations practices that limit the generation of orbital debris consistent with mission requirements and cost effectiveness and requires each program or project to conduct an assessment demonstrating compliance.

DOD Policy

DOD Space Policy, dated February 1987, expressly addresses orbital debris as a factor in the planning of military space operations. The DOD space policy states:

> DOD will seek to minimize the impact of space debris on its military operations. Design and operations of DOD space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements.

Air Force (AFMC, Space and Missile Systems Center) regulation SDR 55-1 directs program directors and managers to adjust satellite development and deployment plans to avoid orbital positioning problems.

U.S. Space Command Regulation 57.2, Minimization and Mitigation of Space Debris, requires the assessment of the impact of design and operations measures to minimize and mitigate debris on military space systems.

Other Policies

The National Oceanic and Atmospheric Administration (NOAA), NASA, and several DOD programs boost their satellites which are no longer functional into orbits above GEO to prevent the creation of additional debris by inadvertent collisions with other drifting satellites and to free valuable orbital slots.

All commercial activities subject to Department of Transportation (DOT) authority are subject to the Office of Commercial Space Transportation's regulations established in Chapter III, 14 Code of Federal Regulations (CFR) Part III. These regulations require each applicant to address safety issues with respect to its launch, including the risks of associated orbital debris, on-orbit safety, and reentry hazards.

Study Group 4 of the International Telecommunication Union's Radiocommunication Bureau, in which the U.S. is a participant, endorsed the recommendation that all geosynchronous orbit satellites be boosted not less that 300 km above the geosynchronous orbit at end of life and that the spacecraft then be made inert by discharge of any residual propellants and gases and "safing" of the batteries.[63]

III. Ongoing Efforts

There is a growing recognition within the Federal government that more formal mechanisms need to be established for addressing debris considerations. Efforts to define the problems and to identify options for dealing with them are expanding.

NASA has created an in-house Orbital Debris Steering Group to examine potential NASA policies and procedures and to make recommendations to the Administrator as to proper approaches to orbital debris problems. Basic and applied research about debris impact behavior and spacecraft shielding is ongoing to provide input to both policy formulation and the design of the International Space Station and other spacecraft.

NASA has established an international coordination working group to exchange data with the other major spacefaring nations. Via these meetings, all other nations have been encouraged to make design and operations modifications to their launch systems to reduce the likelihood of explosions. In addition, these exchanges have led to better understanding of the causes of breakups and appropriate preventive measures.

DOD has created a Space Debris Working Group as a forum to examine and develop policies and procedures and to coordinate space debris activities within the Air Force. Recommendations are provided to the Assistant Secretary of the Air Force for Space.

DOT conducts research activities at the Transportation Systems Center and its contractors. A report, entitled "Hazard Analysis of Commercial Space Transportation (Vol. I: Operations; Vol. II: Hazards; Vol III: Risk Analysis"), devotes explicit attention to orbital and reentry hazards, and to the management of space debris hazards. Current research is aimed at comparing the relative operational space safety and debris type/number characteristics for existing commercial expendable launch vehicles (ELVs), both generically (e.g., typical parking and GTO orbits and orbital life of operational debris) and for specific proposed missions. Further research focuses on the development of rational, risk-based insurance requirements and regulatory standards for the commercial space industry.

DOD and NASA maintain a continuing effort to understand the debris environment and its potential hazard. Coordinated programs of observation and modeling of explosions and collisions and the resulting environment are conducted by both organizations. The research aids satellite and booster program offices by assessing vehicle-specific debris hazards and debris abatement options.

Operating under the Space and Missile System Center Space Test and Experimentation Program Office, DOD has established a tri-service Space Test Range Organization to coordinate and oversee the safe conduct of testing performed in space.

Chapter 4: Monitoring the Debris Environment

I. Current Activities and Research

A. Space Surveillance Catalog

The SSN maintains a catalog of man-made objects in space. To accomplish this task, a worldwide array of sensors has been established. The observations from these sensors are compiled into a single database and its associated document, the Space Surveillance Catalog. There are approximately 7000 on-orbit objects large enough to be cataloged. Only objects which can be consistently tracked and whose source can be identified enter the catalog. It should be emphasized that the SSN was never intended to track the small debris. Debris assessment is secondary to its primary missions. The SSN sensors provide positional data on the objects and a rough approximation of size in terms of radar cross section. Using data from these and other sources, various characteristics about the debris are studied, including radar and optical reflectivity, shape, mass, and orbital characteristics and decay.

Figures 16 and 17 show the location of the SSN sensors. These sensors can be divided into two categories: (1) radars, and (2) optical. Radars are typically used for LEO observations since they provide continuous coverage, independent of weather and twilight conditions. Typically, optical sensors are used for deep space observations since the sensor's sensitivity falls off less rapidly with range. Because of the variation in physical properties of debris, causing some objects to be more difficult to detect by one sensor or the other, the optical and radar measurements are complementary.

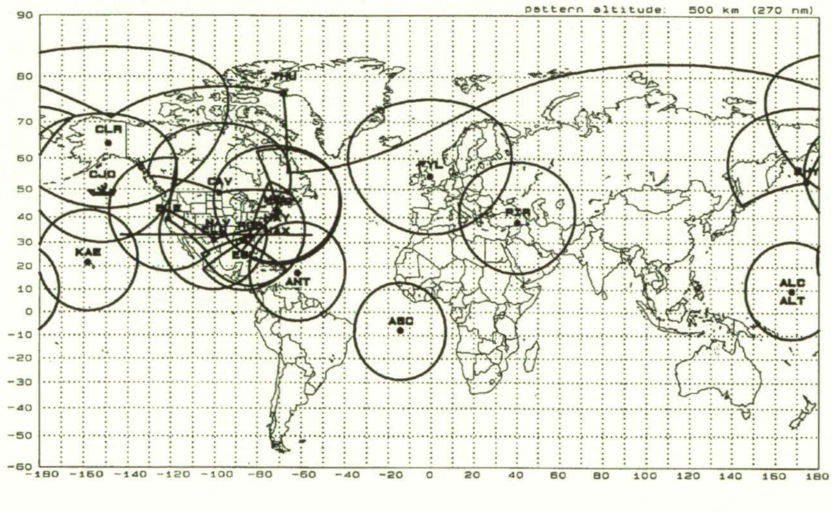


Figure 16. Space Surveillance Network Radar Sensors and Field of View at 500 km Altitude

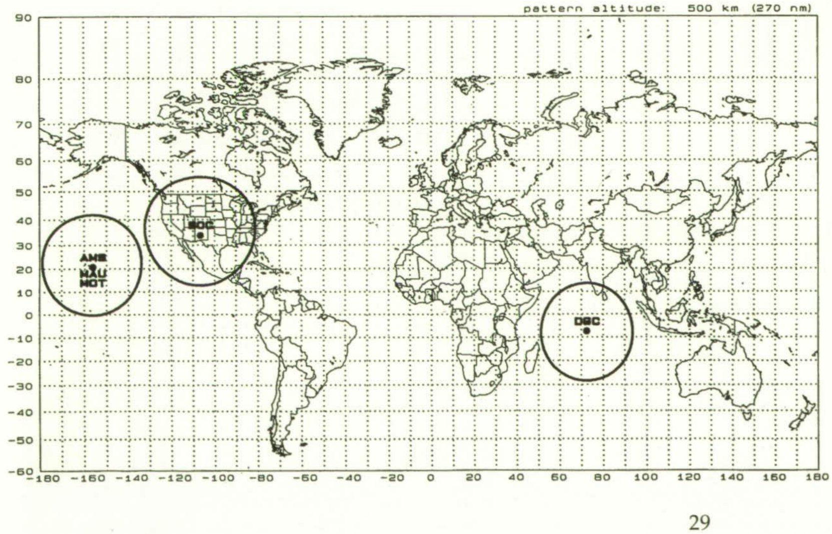


Figure 17. Space Surveillance Network Optical Sensors and Field of View at 500 km Altitude

B. Radar Measurements

One significant source of new data on small debris has come from operation of the Haystack Radar. This radar has been operated in a staring mode for a sufficient number of hours to get statistical data on the population of debris 1 cm and larger at 500 km altitude. In this mode, the radar is positioned near the zenith, and debris objects are detected as they cross the 0.05 degree beam of the radar. Several thousand hours of operation have been completed, and a substantial database has been accumulated. Figure 18 shows a plot of data from this radar, compared with computer model predictions.

The Goldstone Deep Space Network radars have also been operated to obtain statistical data on small debris. This radar is capable of detecting 2 mm objects at 1000 km altitude. Observation time on this radar is very limited because of commitments to the primary mission of these radars, which is to monitor deep space probes.

C. Optical Measurements

Optical sensors provide another technique to measure and study space debris. Several ongoing programs are collecting optical data from various sites around the world.

DOD has sponsored an optical measurements program using facilities located at the Phillips Laboratory Air Force Maui Optical Station (PL/AMOS) and the MIT/LL ETS in Socorro, New Mexico. In this program, the focus has been on estimating the debris population and the development of observational techniques to allow orbital determination of uncataloged debris [ref MIT/LL and PL/AMOS SSW papers 93,94]. These observations have provided the first direct measurements of the orbital elements of small uncataloged debris and exposed significant differences between the orbital distribution of the total space population and the catalog. Hundreds of hours of data have been collected and analyzed to derive a population estimate. Results indicated that there are approximately 20,000 objects larger than 5 cm; this result is consistent with the Haystack results in the same size regime.

There is some evidence that debris may be accumulating in GEO. For that reason, the NASA CCD debris telescope has been used in a search for debris near GEO altitudes. Some small, fast-moving objects with the orbital characteristics expected of debris from breakups have been found. Similar searches are being conducted by the AFSPC at the Maui GEODSS site. NASA is also sponsoring measurements with the Diego Garcia GEODSS site searching for breakups in GTO.

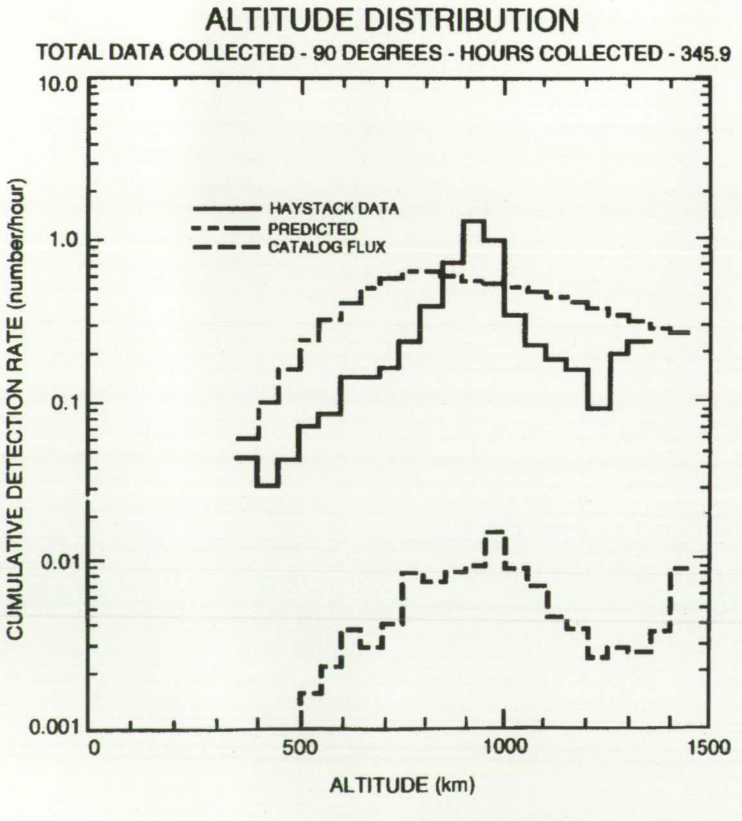


Figure 18. Haystack Small Object Observations. The bottom line is the catalog population. The dashed line is the expected observations and the solid line the actual observations.

II. Opportunities for Improvement and Future Research

A. Evaluate and Exploit Existing Capabilities

The SSN maintains the capability to measure smaller sizes than are currently cataloged. This capability was tested for LEO during June 1993, using the phased array radars at their maximum sensitivity and using the optical sensors usually used for GEO observations. The test showed that the SSN sensors can be used to provide statistical data for debris at sizes below 10 cm in LEO.

It was found that many of the small debris fragments were in elliptical orbits, suggesting that elliptical orbits are more abundant than represented by the catalog. These results are consistent with the conclusions from impacts found on LDEF, statistical measurements by the Haystack radar, and orbital distributions determined by MIT/LL.

It should be emphasized that the SSN was never intended to track small debris objects. The Firepond optical tracking facility at MIT/LL has been coupled to the Millstone and Haystack radars to make simultaneous measurements of radar cross section and optical magnitude.

B. Expansion of Existing Capabilities–Radars

The Have Stare radar, located at Vandenberg Air Force Base in California, is an X-band 200 kw tracking radar that will come on line during 1995. It can detect small debris in the 1 to 10 cm range, depending on altitude. It may eventually be moved to another site, as yet undetermined.

NASA and the DOD have jointly developed the Haystack auxiliary radar. This K-band radar will have a capability similar to Haystack, but will not be quite as sensitive.

C. Expansion of Existing Capabilities–Optical Sensors

Existing ground-based optical systems are intended for tracking satellites above 5000 km altitude. However, they are inherently capable of detecting orbital debris at lower altitudes, with a limit of about 5 cm at 500 km altitude. The use of these sensors to provide statistical debris flux data at altitudes below 5000 km can be explored. Incorporating new CCD technology into existing optical systems could improve the detection and tracking capability for GEO.

D. New Facilities–Optical

A 3-meter aperture liquid mirror debris telescope is under construction by NASA. This instrument will be capable of detecting 2 cm debris in LEO and 10 cm debris in GEO. Since the telescope is zenith-pointing and cannot track objects, only statistical measurements of orbital debris are possible. The instrument must be located near the equator to permit observations of GEO.

The DOD is investigating using the 3.5 meter Advanced Electro-Optical System telescope being built at the PL/AMOS facility for debris measurements.

E. Space-Based Measurements

The Midcourse Space Experiment is a satellite planned for launch by the Ballistic Missile Defense Organization. The optical sensors aboard this satellite have the capability for orbital debris measurement, and several experiments are planned. The optical sensors include the ultraviolet, visible, thermal infrared spectral ranges. Particulate matter spawned by the spacecraft will be monitored by onboard light scattering experiment.

The Clementine mission included a microparticle detector mounted on the adapter between the rocket engine and the payload. This adapter remained in a highly elliptical Earth orbit after the Clementine spacecraft left Earth orbit. The microparticle detector monitored particles in the 1 to 10 micron range.

F. Returned Material Analysis

Impact pits on material that has been exposed to the space environment provide information about the microdebris environment. Chemical analysis of residue in the impact pits is used to discriminate between micrometeoroids and orbital debris. The LDEF was in orbit for 69 months, and has provided a wealth of data that is still being analyzed. Examples of other such material include the Hubble Space Telescope solar panel, witness plates exposed in the Shuttle Orbiter payload bay, and the EURECA. As part of the series of joint Shuttle-Mir manned flights, an experiment is planned that will place on the outside of Mir a sophisticated capture surface that will preserve the chemistry of the impacting particles.

G. Laboratory Studies of Breakups and Collisions

Input data are needed for modeling the effects of hypervelocity collisions and propellant explosions. Laboratory tests have been conducted by DOD and by ESA to simulate the effects of collisions and explosions, respectively.

Because impacts in low Earth orbit occur with an average speed of 10 km/sec, specialized equipment is needed to create and monitor realistic impact events. Current and future studies include: (1) gun research and development, (2) hypervelocity impact research testing to determine the effect of collisions on materials and spacecraft structures, (3) hypervelocity impact modeling, and (4) spacecraft subsystem and component impact testing and analysis.

Shown here is a 3-meter-diameter telescope mirror formed by a rotating pool of liquid mercury. The scientists are wearing masks to guard against toxic mercury vapor. The optical quality of the mirror is excellent, and the cost is a factor of ten or more less than an equivalent glass mirror. NASA is using this mirror as part of a low-cost, large-aperture telescope to monitor the part of the debris population not observed by radar. This telescope can detect orbiting debris objects as small as 2.5 cm at 1000-km altitude. It is currently located in the mountains of New Mexico, near the town of Cloudcroft.

Chapter 5: Managing the Data

Data management limitations significantly affect the SSN capability to detect and track orbital debris. This in turn affects our ability to accurately characterize the debris population and to develop options to minimize debris propagation and to survive the debris environment.

I. Current Data Management Status

The process of keeping track of large objects in space, conducted by DOD, involves three steps: (1) collecting sensor observations, (2) correlating these observations to known objects, and (3) updating the object database with the new observations. The database must be updated daily, for all but GEO objects, to keep an accurate and usable catalog of space objects. The correlation process is crucial to the overall process and in many instances requires analyst intervention.

II. Opportunities for Improvement and Further Research

A. Databases

The Space Defense Operations Center, block 4 (SPADOC 4) is now operational. The addition of SPADOC 4 increases the capability for database management and database size. New computer hardware will allow for cataloging of 30,000 on-orbit objects—this is about three times the prior capability. In addition to enhanced database capability, the system provides enhanced sensor tasking and orbit propagation capabilities.

B. Modeling

There is a need to characterize the orbital debris environment, even when observations are not practical, such as when the size or altitude of objects makes measurements difficult. Modeling, then, is required to combine existing measurements and theory in such a way that predictions can be made. Several types of models are required to make these predictions:

(1) A model to describe future launches, the amount of debris resulting from these launches, and the frequency of accidental or intentional explosions in orbit (traffic model).
(2) A model to describe the number of fragments, fragment size, and velocity distribution of ejected fragments resulting from a satellite explosion or collision (breakup models).
(3) A model which will make long-term predictions of how debris orbits will change with time (propagation model).
(4) A model which predicts collision probabilities for spacecraft (flux or risk model).
(5) A model which predicts hazards in the near term from a breakup event.
(6) Development of models for breakup and dispersion of reentering objects.

Many of these models exist; however, they require elaboration and refinement.

C. Validation and Analysis

Models of an environment or a process must be tested empirically for accuracy and predictability. If the output of the models does not match the real world, or if the predictions produced by the models are not repeatable each time the model is run, the model is not valid and it must be reformulated. To validate the models, test scenarios must be developed to allow empirical data to be compared to model results. The tests normally involve collecting a limited set of data, where possible, and comparing the data set to the model results, having run the model under the same conditions as the collected data. These tests not only validate models but also serve to refine the models for increased accuracy. This validation method certainly applies to debris models. Since several organizations have ongoing debris modeling efforts, models and model predictions are archived for later use as test data for future debris modeling efforts. NASA and DOD both jointly share these tasks.

Chapter 6: Minimizing Debris Generation

I. Current Activities and Research

A. Design Philosophy

Although current hardware and ongoing activities have occasionally been modified for debris prevention, the design of many future systems now includes debris-prevention objectives from the start. There are two good examples of the practical application of this philosophy. These are the studies associated with the disposal of used or waste materials from the Space Station, and the end-of-life deorbit design studies associated with the large mobile communication satellite constellation. The objectives behind these studies are not only to prevent the creation of orbital debris, but also to protect the Station itself and to avoid contamination of the surrounding environment, thus inhibiting the scientific work on the Station.

B. Operational Procedures

Some operational procedures have already been adopted by various agencies to minimize debris generation. The first area in which debris-mitigation procedures have been incorporated is in mission operations, both for launch vehicles and for payloads. The previously mentioned Delta upper stage modifications are a good example of this. The rate of debris fragment accumulation from U.S. sources has fallen to near zero as a consequence of that action alone. The disposal of spent rocket stages during flight has also been examined and in some cases altered for debris considerations. Launch planning is also affected by projections of the Collision Avoidance on Launch Program which warns of potential collisions or near misses for manned or man-capable vehicles before they are launched. Some launches have been momentarily delayed during their countdowns to avoid flying in close proximity to orbiting objects. However, it should be noted that sensor limitations affect the accuracy of any predictions. In addition, the Computation of Miss Between Orbits Program projects proximity of payloads to debris objects soon after launch, and has been used on launches of manned missions. Since 1986 the Shuttle has maneuvered three times for collision avoidance.

Procedures affecting payloads include the use of the disposal orbit for satellites at the end of their functional lives. DOD, NOAA, INTELSAT, ESA, National Space Development Agency of Japan (NASDA), NASA and others have boosted aging satellites to altitudes above geosynchronous orbits, attempting to reduce the probabilities of debris-producing collisions in GEO and freeing up valuable GEO orbital slots.

The second area in which debris-minimizing procedures have been adopted is the in-space testing associated with military programs. This testing is principally accomplished by means of mathematical modeling, but validation tests must be performed in space prior to development decisions. Experience from DOD space experiments involving the creation of orbital debris has proved that we can minimize the accumulation of debris by careful planning. The Delta 180 Space Defense Initiative test was planned in such a way that nearly all of the debris generated by these tests reentered within 6 months. This is because the test was conducted at low altitude to enhance orbital decay of the debris.

Predictions of the amount of debris and its orbital characteristics were made to assess range safety, debris orbit lifetimes, and potential interference with other space programs. The post-mission debris cloud was observed to verify predictions and to improve the breakup models. Such debris-minimizing test operations are now standard procedure, consistent with test requirements.

II. Options for Improvement and Future Research

Options are available to control, limit, or reduce the growth of orbital debris. However, none of them can significantly modify the current debris environment; they can only influence the future environment. The three generic options of debris control are:

(1) Mitigating Options, such as booster and payload design, preventing spontaneous explosions of rocket bodies and spacecraft, and particle-free propellant research.
(2) Disposal or elimination of orbital debris objects.
(3) Active removal or cleaning activities.

A. Mitigation

Launch vehicles and spacecraft can be designed so that they are litter-free; i.e., they dispose of separation devices, payload shrouds, and other expendable hardware (other than upper stage rocket bodies) at a low enough altitude and velocity that they do not become orbital. This is more difficult to do when two spacecraft share a common launch vehicle. In addition, stage-to-stage separation devices and spacecraft protective devices such as lens covers and other potential debris can be kept captive to the stage or spacecraft with lanyards or other provisions to minimize debris. This is being done in some cases as new build or new designs allow. These practices should be continued and expanded when possible.

The task of litter-free operations could combine design and operational practices to achieve the goal of limiting further orbital debris created by any space operations. As a result of these efforts, the growth rate of orbital debris will decline, although the overall debris population will still increase.

When stages and spacecraft do not have the capability to deorbit, they need to be made as inert as feasible. Expelling all propellants and pressurants and assuring that batteries are protected from spontaneous explosion require modifications in either design or operational practices for both stages and spacecraft. For systems that have multiburn (restart) capability, there are generally few, if any, design modifications required. For systems that do not have multiburn capability, design modifications to expel propellants are more extensive. Research could be conducted to develop particle-free solid propellants. If successful, this technology research effort could eliminate the aluminum oxide (Al_3O_2) particulates produced by current solid rocket motor propellants. Such a program already exists for tactical missile propellant, but there is no work currently being performed for space applications.

B. Disposal

Disposal or deorbiting of spent upper stages or spacecraft is a more aggressive and effective strategy than merely inerting spent stages and spacecraft, since it removes from the environment significant mass that could become future debris.

For new spacecraft and launch systems, there are a large number of tradeoffs as to the physical and functional interface between the stage and spacecraft which can minimize the adverse effect of implementing a disposal requirement. Studies are required to assess the cost effectiveness of these tradeoffs, given a particular system and mission.

For near-term concerns, the highest priority for disposal must be given to high-use altitudes. However, disposal of debris at these altitudes is most costly and difficult. Two types of approaches might be explored: mission design and system configuration and operations. Each needs to be applied to both LEO and GEO systems. Studies are required to assess the cost effectiveness of these options given a particular system and mission.

Mission Design. Some debris can be disposed of by careful mission design, but this may sometimes result in a significant performance penalty to both spacecraft and launch systems.

For some missions, the performance of the launch vehicle has a sufficient margin that the stage has propellant available to do a deorbit burn. The stage needs to be modified to provide the mission life and guidance and control capabilities needed to do a controlled deorbit.

When the mission requires delivery of a spacecraft which itself has a maneuver capability, two alternatives are possible. One is to leave the upper stage attached for delivery of the spacecraft to orbit to maximize its maneuver capability. The second is to separate the spacecraft at suborbital velocity so that the stage decays naturally and the spacecraft uses its onboard propulsion to establish its orbit. From a cost-penalty perspective, the first alternative results in a greater mass in orbit, a potential debris hazard, while the second alternative increases the complexity of the spacecraft. Assessing which alternative is more appropriate requires further study.

An alternative to entry and ocean disposal is relocation to a "trash" orbit. In LEO, this is not an advantageous strategy because it generally requires a two-burn maneuver that is more costly in terms of fuel than the single burn that is required for entry. During the 1980's and early 1990's, the Soviet Union used a trash orbit in LEO to dispose of 31 of their nuclear power sources.

Another alternative to a controlled direct entry is a maneuver which lowers the perigee such that the inertial orbital lifetime is constrained to a period such as 25 years. Such a maneuver removes the object from the region of high hazard quickly and removes the mass and cross section from orbit in a small fraction of the orbital lifetime without such a maneuver. This is significantly less costly than a targeted entry. It makes the eventual reentry happen earlier, but raises questions regarding liability issues.

For GEO missions, the pertinent considerations for disposal are the launch date, launch azimuth, and the perigee of the transfer stage. For multiburn systems, positive ocean disposal can be achieved with an apogee burn of a few meters/second if the stage has sufficient battery lifetime and contains an attitude reference and control system.

In addition, there is a set of launch times to GEO which so align the orbit of the transfer stage that natural forces, e.g., Sun, Moon, Earth properties etc., act to lower or raise the perigee of the stage. Consideration of the effect of these forces can minimize the cost of active control of liquid propellant stages and is a low-cost technique for the disposal of solid rocket motor stages. The only alternative strategy for the disposal of solid rocket motors is to orient the thrust vector of the rocket in a direction so that the perigee of the transfer orbit resulting from the burn is at a low enough altitude to cause the stage eventually to reenter (sometimes referred to as an off-axis burn). This strategy results in about a 15% performance penalty for the stage.

Use of disposal orbits is a technically feasible strategy for clearing the geostationary orbit region, but is not the only available strategy. The cost effectiveness of a disposal orbit strategy compared with other strategies has not been examined. If raising the orbit is to be the technique of choice, then it requires planning and reserving the necessary propellant resources to effect the maneuver. Preliminary studies indicate that the orbit needs to be raised on the order of 300 km to serve the intended purpose, not the 40 to 70 km that has been used by some operators. The performance cost to reboost is 3.64 m/s for each 100 km or 1.69 kg of propellant for each 1000 kg of spacecraft mass. To reboost 300 km is comparable to 3 months stationkeeping.

System Configuration and Operations Studies. Mission design appears to be the least-cost option for disposal. However, systems not designed with a disposal requirement have other alternatives available, such as design modifications to current systems or design attributes for new systems.

For LEO stages or spacecraft, it may be feasible to maneuver to lower the perigee and employ some device to significantly increase drag. In geosynchronous transfer stages, the design and operation timeline could be modified so that the separation and avoidance maneuver could provide the velocity increment to cause the stage to enter.

In the mission design studies noted above, preliminary surveys of the concepts have been conducted. However, systematic studies and cost-effectiveness assessments are also required.

C. Removal

Removal is the elimination of space objects by another system. The following discussion pertains only to LEO because at present there is no capability nor perceived need for a removal system at GEO. Removal options may also raise significant international legal issues. These issues are discussed in Chapter 9, Legal Issues.

Large Objects. The removal of large, inert objects requires an active maneuver vehicle with the capability to rendezvous with and grapple an inert, tumbling, and noncooperative target and the ability to properly and accurately apply the required velocity increment to move the object to a desired orbit. These capabilities have been demonstrated by the Space Shuttle, but no unmanned system has these capabilities for higher altitudes and inclinations. OSTP released a Commerce Business Daily (CBD) Announcement during the development of this report. One reply to the CBD Announcement proposed the study of just such a capability.

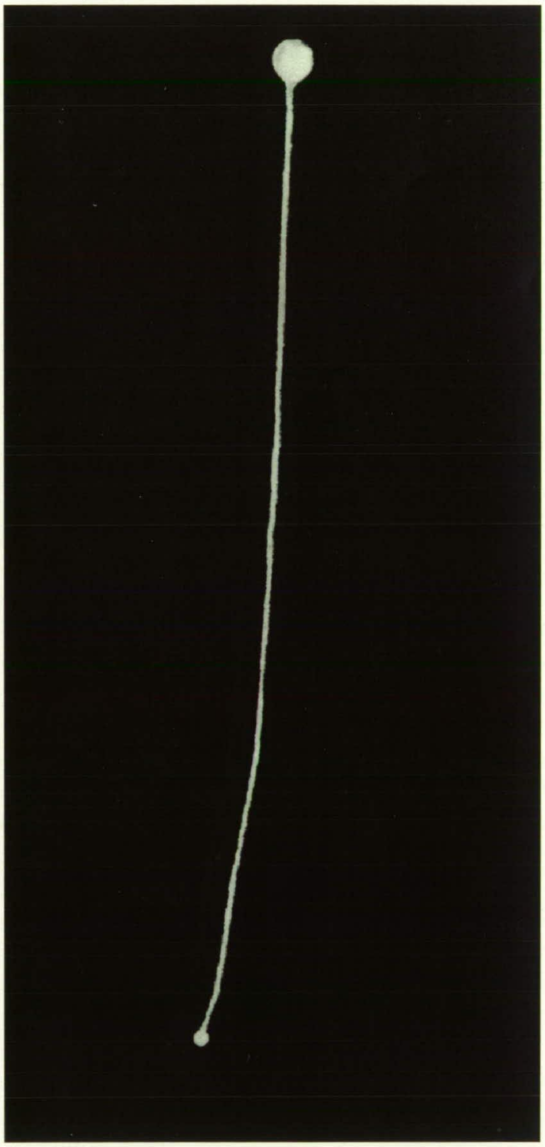
The design, development, and operation of a maneuverable stage to remove other stages and spacecraft requires a high degree of automation in rendezvous, grapple, and entry burn management if operations costs are to be kept reasonable. The long- and short-range systems to acquire, assess the orientation, grapple, secure, determine the center of mass, and plan the duration and timing of the entry burn all require development and demonstration of both capability and cost effectiveness. The component technologies require study and analysis, followed by breadboard and prototype development.

Small Objects. The multiplicity of small objects makes it impossible to actively acquire and enter each object individually. There are two classes of schemes that have been proposed for the removal of such debris. One is the use of active or passive devices to intercept particles with a medium, such as a large foam balloon, which absorbs kinetic energy from the particles. This causes the objects' perigee to fall to regions where aerodynamic drag induces entry. The other is an active device which illuminates the particle with a beam of directed energy, causing the particle either to lose velocity or to be dissipated into fragments that are no longer of significant mass.

Since the intercept balloon does not discriminate between debris and functioning spacecraft, it could inflict damage on usable assets. Avoidance of such damage might require active maneuvers by the intercept balloon. The advantages of a simple system could be lost if the system's operation becomes too complicated.

The active directed energy system requires elements that do not yet exist. This system requires high energy output, high precision pointing and instruments for debris object detection and beam aiming so the intercept can be accomplished without accidentally harming other operational spacecraft.

The development of the detection and aiming instruments has a great deal in common with similar detectors required for the environmental monitoring task and the collision avoidance task. In summary there are many proven debris mitigation options available to builders of future spacecraft. The selection of which of these options to choose is driven mainly by the requirements of a given system. The removal of debris from orbit is a far different issue. While many removal schemes have been proposed, none has yet to reach the stage where it can be considered feasible or practical.



This image of the Small Expendable Deployer System (SEDS) tether shows the 7-kilometer remains of a 20-kilometer tether. The large end mass is the Delta second stage from which the tether was deployed and the smaller end object the frayed end where the tether was severed by a piece of debris or a meteoroid after four days of flight. The image was generated by a Super-RADOT (Recording Automatic Digital Optical Tracker) 1.5-meter telescope at Kwajalein Atoll on March 19, 1994. While only 5 mm, wide the tether is visible to the naked eye and the telescope because of its extended length. At its full length of 20 km, its total area is 20 square meters, or roughly the same size as most spacecraft. It illustrates how a large area and a flimsy structure are vulnerable to even the smallest debris.

Chapter 7: Surviving the Debris Environment

I. Current Activities and Research

The need for protection from orbital debris is influencing the design of new spacecraft. In the past, spacecraft design took into account the natural meteoroid environment. New NASA and DOD spacecraft designs now consider the additional hazards from human-made orbital debris.

Missions can also be planned from the outset to avoid debris-threatening situations. For example, congested altitudes could be avoided, consistent with mission objectives. The NASA Shuttle program has implemented flight rules to fly the Orbiter whenever possible in an orientation having the least hazard from potential orbital debris and meteoroid impacts (that is, with tail forward and payload bay facing the Earth).

Proper treatment of disposable components should also be part of mission planning. For example, NOAA, DOD, NASA and other agencies have begun requiring that some of the hardware involved in upper stage separation be kept attached to the upper stage rather than float away as separate debris objects.

II. Opportunities for Improvement and Future Research

A. Mission Design and Operations

Spacecraft and launch systems can be designed and operated in ways that reduce their vulnerability to the debris environment. The acceptability of any given vulnerability reduction strategy is a function of the mission objective of the space system. Mission design and operations is an option for using current systems in alternative ways to reduce impact hazards. Orbit selection is feasible for some spacecraft missions but not practical for others without significant mission objective compromise. For example, the same observations made from different orbits might require different instruments of varying cost and complexity.

B. System Protection

Spacecraft can be protected from serious damage by using shielding and by designing the spacecraft to be damage tolerant (i.e., providing redundant systems for critical functions with proper separation to prevent single event catastrophes). The most straightforward approach to meeting the protection requirement is shielding. Although shielding against meteoroids has always been a consideration, the existing and anticipated levels of threat from orbital debris make shielding more important. In addition, much of the man-made debris falls into larger size categories than the naturally occurring debris. The method of shielding to be used can significantly affect the design of the spacecraft in configuration, performance, and cost and must be part of the design philosophy from the outset. NASA and DoD have pursued several distinctly different approaches to shielding research. These approaches have proven valuable and should be continued.

Hypervelocity Impact Testing and Facilities. Proposed research includes the capability to determine the effects of projectile shape, density, and velocity on a variety of spacecraft systems using light-gas gun facilities launching projectiles to 8 km/sec and to develop ultra-high speed launchers to 15 km/sec. NASA has developed an inhibited shaped charge launcher that propels gram-size projectiles to 12 km/sec. The Department of Energy (DOE) has developed a technique to launch disks to 10 km/sec. These test methods are required to qualify spacecraft protection systems and to validate hypervelocity impact analysis models such as hydrocodes. Close coordination between NASA, DOE, and DOD should be continued.

Modeling Impact Effects. Research is recommended to develop advanced methods for accurately and efficiently predicting the response of spacecraft structures to impact, including internal shock wave propagation, material phase change, deformation, perforation, and long-term structural effects. Particular attention could be directed to modeling impact response of nonhomogeneous materials, such as composites, ceramics, fabrics, and layered materials, using advanced modeling methods and nonclassical hydrodynamic approaches. Predictive models for impact damage and catastrophic failure of pressurized tanks and other stored energy devices are needed. Modeling effects on complete spacecraft, in addition to discrete sections, need development.

Stored Energy Component Failure Modes. Experimental and analytical programs are needed to understand and predict the hypervelocity impact response of spacecraft systems containing stored energy.

As observational data improves, the largest uncertainty in predicting the future environment is the uncertainty of these breakup models.

Shielding Concepts. This research area could develop shielding concepts for both fixed and deployable shields. The effort could emphasize lightweight designs using advanced materials such as fiber composites or layered materials that pulverize instead of fragment, creating less hazardous debris and capturing a majority of the collision products. EVA-friendly techniques to deploy on-orbit augmentation shield concepts could also be a subject of the effort. A major goal might be to develop effective shielding concepts for debris up to 2 cm in size (approximately 10 to 15 grams) with speeds up to 15 km/sec.

Design Guide, Validation and Certification. This research area uses techniques from all four previous areas and develops analytical and test methods for qualifying the survivability of the entire spacecraft. A design handbook and/or guide could be developed and updated as new knowledge becomes available to assist designers of all future spacecraft in designing optimized protection systems for their spacecraft. Extension of shield capability to such a regime would eliminate one half of the residual risk between current shield capability and SSN collision warning capability.

Closely related to survivability is the concept of redundancy. With redundant systems physically separated on the spacecraft, a collision with debris that damages one or more systems or instruments might still allow the spacecraft to continue functioning.

The ultimate objective of hypervelocity impact research is to develop methods to optimally configure a spacecraft to minimize the damage from meteoroid/debris impact. This involves the assessment of spacecraft response to penetrating impact and the prediction of internal damage. NASA has developed an analysis code called BUMPER to determine the probability of impact damage to spacecraft using currently accepted meteoroid and debris environment models. A program called ESABASE has been developed by ESA for similar purposes. These programs require periodic updating with new knowledge gained from hypervelocity impact tests and modeling that predict the impact response and failure conditions for various spacecraft structures. These programs and additional methods could then be used to compare different techniques for spacecraft shielding, mission design and operations, and redundancy options on the basis of expected safety benefits, weight requirements, spacecraft reliability, performance levels, and costs. The result of the comparisons can be used to select the optimum protection system configuration that includes the best combination of shielding, mission design, operations, and redundancy.

C. Collision Avoidance

Collision avoidance is feasible if one has precise knowledge of the orbits of the objects of interest. It is feasible to construct a ground radar system with the requisite capability, but it is costly.

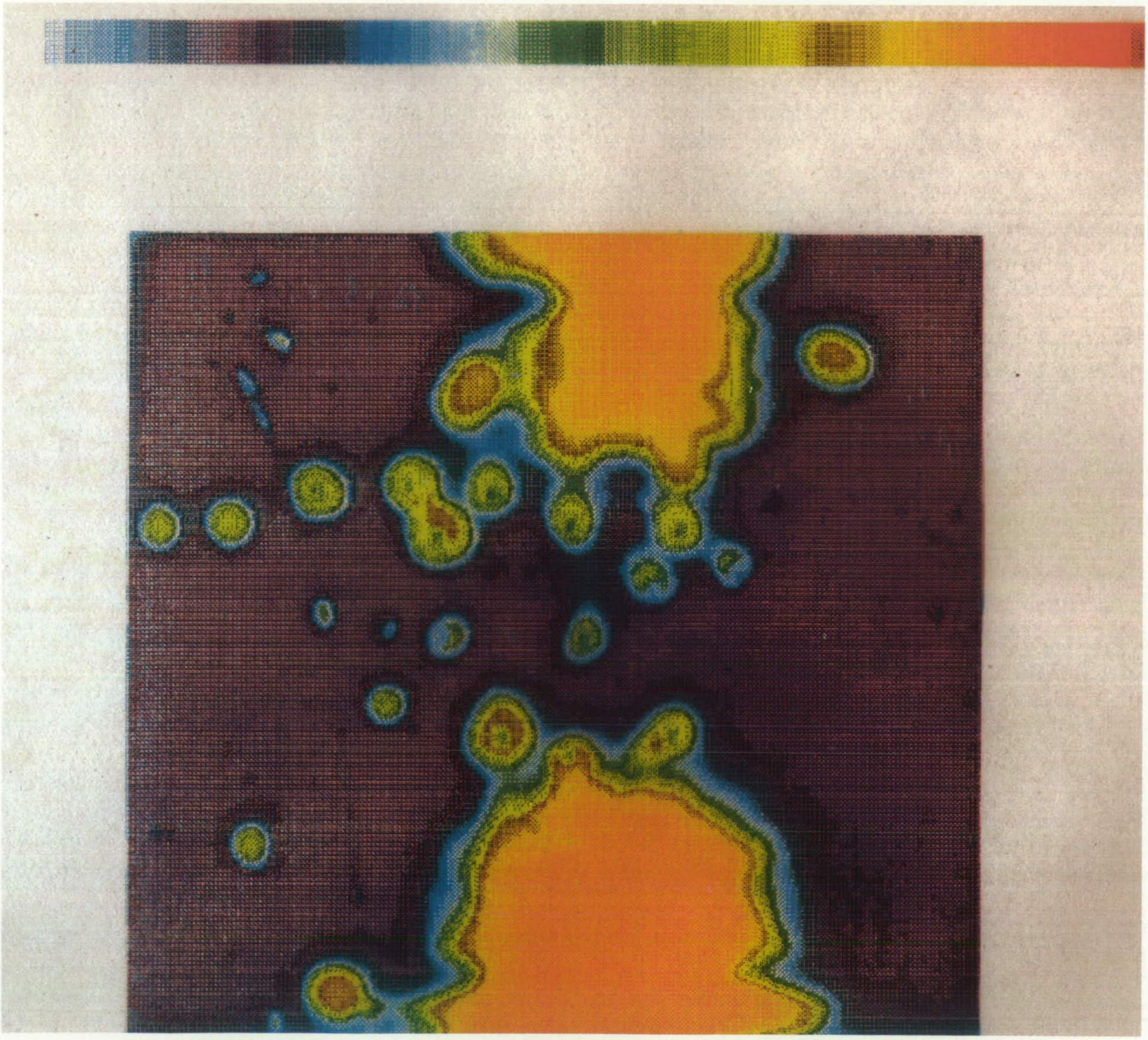
Currently, the warning can only be provided by the existing SSN. There are several limitations to the existing SSN for collision avoidance. The locations of the sensors are not well suited to a collision-warning function because they were sited to meet different criteria. A second important SSN issue is sensitivity. As stated earlier in this report, the minimum size object that can be reliably detected in LEO is about 10 cm in diameter; yet avoidance of particles of 1 cm diameter or larger is desirable. This could require an increase in sensitivity of a factor of 100, requiring a major redesign of most sensors. The increased sensitivity would result in a large increase in the number of objects maintained in the catalog, resulting in a corresponding increase in required computational resources needed.

The current SSN is used to provide collision warning during Shuttle operations. When the Shuttle is on orbit, the SSN monitors its flight path and when another object is forecast to enter a volume 25 km ahead or behind and 10 km above, below or to the side, tasking is initiated to improve the orbit data. In addition, if the object is then forecast to enter a volume 5 km along track of 2 km above, below, or to the side, a maneuver is initiated if it does not compromise mission objectives. Since this practice has been in effect, the warning envelope has been entered 26 times and the maneuver envelope 4 times, and maneuvers have been performed on 3 occasions.

NASA has established the concept of a collision avoidance network that could provide collision warning for most intersections of debris greater than 1 cm with all spacecraft of interest. To achieve the required performance, the system must operate at X-band, and the stations must be so located that every object will pass through the field of view of one of the sensors within two revolutions. To accommodate the large inventory of objects that would be cataloged and to manage the tasking of the sensors, would require a parallel processor system. To create the new catalog requires an X-band "fence" to initiate the detection and cataloging of those objects below the threshold of the current catalog.

Such a system could have an ephemeris uncertainty of 400 m along track for currently cataloged objects contrasted to the 5 km of which the SSN is capable. Recent evidence suggests that providing the required ephemeris accuracy for smaller objects will pose a challenging technical problem.

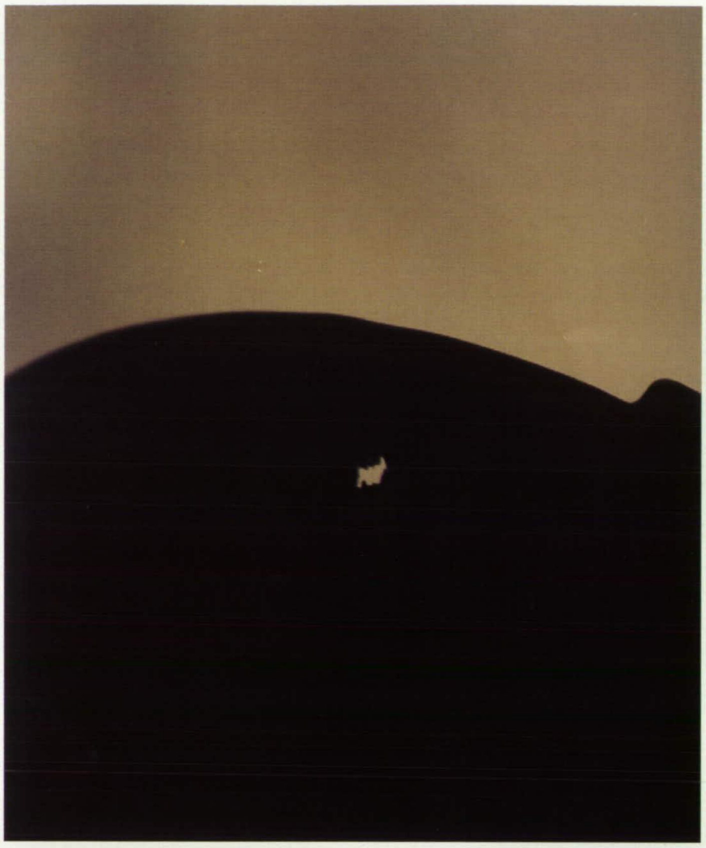
The ground system could be complemented with an onboard optical sensor that could resolve ambiguities as to near miss vs. impact to minimize maneuver requirements. It is not practical to search with an onboard sensor because of its motion relative to all other objects, but if it knows where to look, it can significantly reduce the uncertainty in the relative orbits.



An Ekran direct broadcast television communication satellite in geosynchronous orbit exploded in 1978 while being monitored by ground telescopes. This image shows frames from a video camera that recorded the explosion, which was believed to be the result of the failure of a nickle-hydrogen battery. In February 1992, a Titan Transtage in geosynchronous orbit broke up in view of the Air Force tracking telescopes in Maui, Hawaii. There have been other unrecorded breakups in geosynchronous orbit.

Part Three:

International Activities, Legal Issues, and Regulation



During the STS-61 Hubble Space Telescope (HST) repair mission, the astronauts observed a large hole measuring ~1.9 cm by ~1.7 cm in one of the HST's two high-gain antenna (HGA) dishes. The HGA dishes are ~1 cm thick honeycomb core composites with graphite-epoxy facesheets. The rough edges of the hole in the HGA is typical of impact damage in graphite-epoxy.

Chapter 8: International Cooperation

The 1989 Interagency "Report on Orbital Debris," which this report updates, acknowledged the international importance of orbital debris. The report stated that the "causes and consequences of orbital debris are global in scope" and that "international cooperation is essential to a satisfactory solution." One of the report's recommendations was that

> The U.S. should inform other spacefaring nations about the conclusions of this report and seek to evaluate the level of understanding and concern of other nations and relevant international organizations about orbital debris issues. Where appropriate, the U.S. should enter into discussions with other nations to coordinate minimization policies and practices.

Since 1989, the U.S. and a number of foreign governments and international spacefaring organizations independently have addressed issues of orbital debris, including procedures for the disposal of satellites—at the end of their operational life—in geosynchronous orbit.

For example, the INTELSAT, TELESAT (Canada), INMARSAT and EUTELSAT communications satellite organizations, and the Indian Space Research Organization adopted policies early requiring their future geostationary satellites to be boosted into higher orbits at the end of operational life, and all now have done so, but not to a particular separation requirement above the geosynchronous arc. Russia has adopted a policy of reboosting its satellites to 200 km, and in many instances reboosts to even higher orbits. NASDA requires that its satellites be reboosted to not less than 150 km and advocates 500 km as a desirable goal. ESA and NASA have adopted a reboost standard of 300 km. Based on these institutional practices, the International Telecommunications Union recommended in May 1992 that all operators of geostationary satellites boost spacecraft to 300 km above the geosynchronous arc and make the spacecraft inert at the end of operations.

Nevertheless, the number of nations and organizations who utilize space has grown rapidly, and their varied and expanded activities have implications for the debris environment. By its very nature, orbital debris is now a global space environment issue, and individual national debris research and practice must be supplemented with coordinated international activity. More than ever, it is clear that close international cooperation is necessary for dealing effectively with orbital debris.

The U.S. and other spacefaring nations and organizations together are taking steps to monitor the space environment and manage data and information on debris, minimize its generation, and implement measures to survive contact with debris in space. As a result of this international cooperation, individual efforts in debris research are enhanced through technical coordination and consensus, and are leading to a better understanding of debris and its implications for the utilization of outer space.

The U.S. has taken the lead in the international consideration of orbital debris issues through technical agency and government-to-government contacts. Continuing U.S. participation in the international dialogue on debris should continue to be governed by consideration of U.S. commercial, scientific, civil operational, and national security interests.

I. Technical Agency Information Exchange

In the interest of achieving a technical consensus on all facets of the orbital debris issue, the U.S. has conducted extensive research in characterizing the debris environment and is sharing the results of its studies with the international community.

Discussions on the debris issue have been taking place at one level or another among international space agency scientists, engineers, and managers for almost a decade. These discussions have occurred at technical society conventions and in regularly scheduled bilateral and multilateral meetings.

NASA began to exchange information on space debris issues with ESA in 1987, and has met with ESA on a biannual basis since 1989. Discussions at these meetings have focused on debris research and modeling, and have led to an arrangement to share debris tracking data, environmental models, and explosion and hypervelocity test results. In August of 1992, the two agencies finalized a letter agreement documenting their common interest in continuing joint efforts.

NASA also has signed letter agreements on technical coordination with the French and German space agencies, and has held coordination meetings with Canada, China, Japan, and Russia. Such international consultation has been shown to be productive; for example, in April 1993, the Chinese Academy of Space Technology modified the upper stage of its Long March Launch Vehicle to prevent explosion in orbit and the subsequent creation of additional debris.

As well, in April 1993, NASA, ESA, and relevant space agencies in Japan and Russia established an informal, multilateral Inter-Agency Space Debris Coordination Committee (IADC). IADC members participate in specialized working groups on measurements, the debris environment, databases, and debris protection and mitigation, and as a body exchange information on debris research, recommend cooperative research projects, and identify and evaluate debris mitigation options.

II. Government-to-Government Contacts

At the June 1993 plenary session of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), the U.S. joined a consensus decision to take up consideration of the orbital debris issue beginning at the February 1994 session of the COPUOS Scientific and Technical Subcommittee (STSC).

In its 1994 session, the STSC agreed on the importance of having a firm scientific and technical basis for any future action on the issue of debris. STSC members decided that they should first focus on understanding aspects of international research related to debris, including characterizing the debris environment; debris measurement techniques; mathematical modeling; and protective spacecraft design.

The 1995 session of the STSC addressed the subject of acquisition and understanding of data on the characteristics of the debris environment. STSC members and international organizations presented research results and provided information on practices proven effective in minimizing the creation of debris. The 1995 STSC session also adopted a multiyear work plan, through 1998, on the scientific and technical aspects of space debris.

The 1994 STSC session marked the first time that the scientific and technical aspects of the orbital debris issue were considered by a broad cross section of space and nonspacefaring governments. The STSC will provide a forum to increase overall awareness of the debris issue, to continue communication between the specialist research community and the STSC, and to present members with the results of U.S. research and international coordination on debris. Through the STSC, the U.S. can help establish the necessary solid scientific and technical foundation upon which ongoing international cooperation can build.

III. Policy Objectives

The development of technical cooperation and consensus on the issue of orbital debris should be a prerequisite for discussion of any effective potential international agreements, regulatory regimes, or other measures—identified in the future—deemed appropriate to protect U.S. and other nations' space activities. In this regard, U.S. international activities dealing with debris should be guided by specific scientific, technical, and programmatic policy objectives.

In all international fora, the U.S. should continue to promote and contribute to an increased international understanding of the scientific and technical aspects of the generation, monitoring, and mitigation of debris. This will be particularly important in cases where the knowledge base of interested parties can be enhanced in order to encourage productive technical discussions.

The U.S. should continue to use every opportunity to encourage individual spacefaring nations to limit their generation of debris, since debris generated by other nations will eventually affect space assets belonging to the U.S. In the course of its international contacts on the issue of debris, whether through technical information exchange or government-to-government relations, the U.S. also will strive to ensure consistency in debris policies, standards, and practices among spacefaring nations and relevant international organizations.

To promote consistency in policy and practice, the U.S. should develop and maintain a common approach for achieving U.S. policy and program objectives in formal international organizations such as United Nations fora and in informal, technical, government agency-level multilateral groups such as the IADC.

In pursuing the goal of international cooperation, the U.S. Government should insure that any mitigation measures adopted are cost effective. At the same time we must carefully balance commercial and national security interests with the need to protect the space environment.

Success in the international management of the orbital environment will require an increased understanding on the part of all nations who now, or in the future, operate space systems. It is only through this understanding that consensus will emerge. The productive relationships that have already emerged make future prospects promising.

Chapter 9: Legal Issues

I. The Meaning of "Orbital Debris"

"Orbital debris" is a popular rather than legal term. As such, it does not have a precise definition. The popular term is commonly used to indicate components or fragments of space objects that are spent or no longer functional. Orbital debris usually refers only to tangible, physical objects that are man-made (and not, for example, meteorites). Legal sources that are potentially relevant to orbital debris do not use the term orbital debris. Rather, they use terms such as "harmful interference" or "component parts of a space object." Thus, legal terms must be analyzed case by case to determine whether they could include the popular notion of orbital debris.

II. Applicable Domestic Law

Two kinds of domestic law are potentially applicable to orbital debris: regulatory law concerning standards that must be met to obtain authority to launch and tort law relating to damage that occurs as a result of orbital debris.

With respect to regulatory law, U.S. governmental space activities (both civil and military) do not appear to be governed by legal standards regarding orbital debris. As a legal matter, the National Environmental Policy Act and Executive Order 12114, which require review of the environmental impact of certain federal actions, do not apply to impacts in space per se. Thus, while assessment of potential terrestrial impacts of orbital debris may be required, assessment of potential impacts in space is not (although some agencies have done such assessments as a matter of discretion).

Regarding private commercial launches, the Commercial Space Launch Act gives authority to DOT to prescribe such requirements, with respect to launches and the operation of launch sites "necessary to protect the public health and safety, safety of property, national security interests and foreign policy interests of the United States" (49 United States Code 70105).

In addition, under the Commercial Space Transportation Licensing Regulations, 14 CFR Chapter III, licensees are required to provide information on U.S. objects placed in space as a result of a launch event. The information is then relayed to the United Nations through the Department of State in accordance with the Convention on Registration of Objects Launched into Outer Space.

With respect to remote sensing from satellites, the Land Remote Sensing Policy Act of 1992 (which repealed the Land Remote Sensing Commercialization Act of 1984) provides that a licensee shall "upon termination of operations under the license, make disposition of any satellites in space in a manner satisfactory to the President" (section 202(b)(4), Title II). This provision would appear to permit the Department of Commerce (DOC) to require that a spent spacecraft not be left in a position that contributes to the proliferation of orbital debris. Presumably, design and orbital conditions could be imposed to promote the desired disposition.

With respect to the second kind of applicable law, it is possible that U.S. tort law could potentially be applied in the case of damage caused by orbital debris in the U.S. (A suit against the U.S., as opposed to a private entity, would have to be in accordance with the Federal Tort Claims Act.) U.S. courts might also establish jurisdiction where negligence or a wrongful act in the U.S. resulted in damage caused by debris in space or elsewhere outside the U.S. Thus, even absent federal regulation, the development of a body of common law related to damage caused by orbital debris could lead to the existence of standards regarding the minimization of such debris.

III. Applicable International Law

There are several international agreements potentially bearing on orbital debris. The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, which entered into force on October 10, 1967, contains principles which, although general, would appear relevant to any discussion of orbital debris. First, the Treaty provides that parties bear responsibility for "national activities" in space and that nongovernmental activities require authorization and continuing supervision (see Article VI). This provision makes clear that a party must have some kind of approval/monitoring process for private space activities and that, although the scope of "national activities" is unclear, a party could be responsible for at least certain of its nationals' activities in space.

Second, the Treaty provides that parties are obliged to conduct all their outer space activities with due regard to the corresponding interests of other parties (see Article IX). Although parties are called upon to avoid adverse changes in the environment of the Earth resulting from the introduction of "extraterrestrial matter," it is unlikely that this clause was intended to cover matter originating on Earth. In addition, a party is obligated to consult if an activity planned by it or its nationals would cause "potentially harmful interference" with activities of other parties in the exploration and use of outer space. It would appear that the generation of orbital debris could, depending on the circumstances, be viewed as falling within the scope of this provision.

Third, the Treaty provides that each party that launches or procures the launch of a space object, as well as each party from whose territory an object is launched, is internationally liable for damage to another party (or its natural/juridical persons) by such object (or its component parts) on the Earth, in air space, or in outer space. This principle is further elaborated in the Liability Convention, as discussed below.

Fourth, the Treaty provides that the party on whose registry a space object is launched into outer space retains jurisdiction and control over such object while it is in outer space (Article VIII). The ownership of a space object and its component parts is not affected by their presence in outer space or their return to Earth. These principles are relevant to the issue of destruction or removal of non-U.S. debris, as discussed below.

The treaty that is perhaps most relevant to a discussion of orbital debris is the Convention on International Liability for Damage Caused by Space Objects, which entered into force on September 1, 1972. The Convention imposes upon a launching state absolute liability for damage caused by its space object on the Earth or to aircraft in flight. In the case of damage other than on the Earth to a space object by the space object of another state, the latter is liable if the damage is due to its fault or the fault of persons for whom it is responsible. A "space object" is defined to include "component parts of a space object as well as its launch vehicle and parts thereof"; there is no requirement that such parts be functional. Thus, as orbital debris, a launching state's potential liability under the Convention would continue despite the nonfunctional nature of its orbital debris space object.

In the case of debris causing damage to another space object other than on Earth, the Convention is silent as to what constitutes "fault." Clearly in order to establish fault for damage caused by orbital debris in space, it is necessary to demonstrate more than the mere production of debris as a consequence of legitimate space operations. Otherwise, the fault standard would be indistinguishable from the absolute liability standard applicable to damage caused on Earth by space objects. Analogizing from the tort law of many states, some form of negligence standard might be appropriate. Liability would then depend on whether a state's actions in controlling its space objects were "reasonable." The present state of space technology does not permit activities in space that are completely debris free; hence, a negligence regime might imply an obligation of states to take reasonable steps to prevent foreseeable damage. Many factors would come into play in deciding what steps are reasonable and what damage is foreseeable, including the proximity of other space objects, the reason for the creation of the debris, the cost of preventing the creation of debris, and the feasibility of providing warnings to states potentially affected by the debris.

Under the Convention, joint launching states are jointly and severally liable for damage; as between themselves, they may apportion such liability, but a third state may seek full recovery from either of them. (A "launching state" means a state that launches or procures the launch of a space object, as well as a state from whose territory or facility a space object is launched.) A party that suffers damage or whose natural or juridical persons suffer damage may bring a claim through diplomatic channels. The standard of compensation is to be in accordance with international law and principles of justice and equity, in order to restore the injured party to its pre-damage condition. In the absence of a diplomatic settlement, the Convention provides for the establishment of a Claims Commission at the request of either party. The Commission's award is only binding if the parties so agree; otherwise, it is a recommendatory award that the parties are to consider in good faith.

Although the Liability Convention provides a legal mechanism for establishing liability and damages, there would likely be problems of proof associated with a claim based on damage caused by orbital debris. In the likely event that damage to or destruction of a space object was caused by a small, unobservable fragment, it would be difficult to establish the identity of the launching state and therefore to invoke the Liability Convention.

The Convention on Registration of Objects Launched into Outer Space, which entered into force on September 15, 1976, requires the registration with the United Nations of any space object launched into Earth orbit or beyond. If there are two or more launching states, those states must determine which of them will register the space object. In the event that a piece of orbital debris caused damage, this registration system might assist the state suffering damage in identifying the launching state (or at least one of two or more joint launching states) associated with such debris. If the damaged state were unable to identify the debris which caused the damage through the United Nations registration system, other parties (in particular those possessing space monitoring and tracking facilities) would be called upon under the Convention to respond to the greatest extent feasible to a request from that state for assistance in the identification of the debris.

The Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space, which entered into force on December 3, 1968, also contains provisions potentially relevant to orbital debris. Under this Agreement, a party discovering that a space object or component part thereof has returned to Earth in its territory is obligated to notify both the launching state and the United Nations. If the discovering party has reason to believe that the object or part is of a "hazardous or deleterious nature," that party may notify the launching state, which is to take immediate, effective steps (under the direction and control of the discovery party) to eliminate possible danger of harm.

In terms of radioactive orbital debris, there appear to be three additional relevant international agreements. The Limited Test Ban Treaty, which entered into force on October 10, 1963, obligates parties to prohibit, prevent, and not carry out any nuclear weapon test explosion or any other nuclear explosion, at any place under its jurisdiction or control in, inter alia, outer space, and the atmosphere. The Treaty was intended to prevent the wide-ranging distribution of radioactive debris. It is not clear whether violation of this provision would give rise to any liability in addition to that under the Liability Convention.

The Convention on Early Notification of a Nuclear Accident requires parties to notify potentially affected states in case of an accident involving nuclear reactors in space, or the use of radioisotopes for power generation in space objects, from which a release of radioactive material occurs or is likely to occur and which has resulted or may result in an international transboundary release that could be of radiological safety significance for another state. Again, it is not clear whether violation of this provision would give rise to any liability in addition to that under the Liability Convention.

The Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, to which the U.S. will shortly become a party, establishes a framework under which a party may provide assistance to another party in the event of a nuclear accident or radiological emergency, which could include the presence of radioactive orbital debris.

The destruction or removal (retrieval or deorbit) by one state of debris from outer space owned by another state would raise a number of issues under international law. As mentioned above, under Article VIII of the Outer Space Treaty, the state of registry retains jurisdiction and control over a space object while it is in outer space, and ownership of objects and their component parts is not affected by their presence in space. Ownership would also not be affected by the loss of function of the space object. If the launching state consented to the destruction or removal of its orbital debris, or if it abandoned its rights to the debris through a clear expression of intent, destruction or removal could be considered lawful. However, under customary international law, state property remains state property unless expressly relinquished. (Under maritime law, for example, the U.S. has consistently maintained that sunken state ships remain the property of the flag state until title is expressly transferred or abandoned, and that abandonment cannot be implied from the absence, even over a long period of time, of acts evidencing an interest in such property.)

In order to take destruction or removal measures in the absence of consent or abandonment by the launching state, it would appear that an argument would have to be made that the jurisdiction and ownership rights of the launching state must be balanced against Article IX of the Outer Space Treaty, which, as noted above, requires states to conduct their space activities with due regard to the corresponding interests of other parties. Although a launching state is not legally required to remove its objects from space (i.e., the mere presence of orbital debris is not prohibited), if orbital debris were adversely affecting the activities of other space users, an argument could be made that a state may lawfully take appropriate measures to protect itself from harm.

Chapter 10: Regulation

Introduction

To understand how government regulation will play a role in the commercial space sector's debris-reduction effort, it is necessary to understand the Federal regulatory approach to the commercial sector, as well as the different types of regulation. Following an overview of regulatory authority, this chapter will outline a basic approach for integrating commercial regulation with other debris-mitigation efforts.

I. Regulatory Overview

Most federal regulation falls within one of the following categories: (a) the direct control of commerce and trade under a program of economic regulation, (b) the protection of public health and safety and the environment, and (c) the proper management and control of federal funds and federal property. The functions and authority of the three principal federal agencies involved in the regulation of commercial space activities — i.e., DOT, the Federal Communications Commission (FCC), and the DOC, NOAA—fall into all three categories of regulation.

The authority of both the FCC and NOAA concerns the first category: the regulation of business activities principally for economic reasons. In contrast, DOT and FCC are charged by statute with carrying out the second category of regulation: DOT regulates the commercial launch sector to protect public health and safety, as well as other public interests, and the FCC regulates communications by wire and radio for the purpose of promoting safety of life and property. The FCC's authority also falls into the third category in that it manages and controls the private sector's use of the national radio frequency spectrum, a public good.

The Communications Act of 1934 confers on the FCC the authority to regulate interstate and foreign commerce in communications by wire and radio. The FCC's authority includes the responsibility for allocating radio frequencies and managing their use. The FCC's role in regulating commercial space activities derives from this authority and involves licensing providers of telecommunications services (which may include satellites), assignment of orbital positions consistent with international treaties, and establishment of standards governing transmitter design and operation to ensure appropriate frequency usage (e.g., spacecraft control pointing accuracy and position tolerance). To carry out these responsibilities, the FCC authorizes the construction, launch, and operation of U.S. commercial communication satellites in geostationary, and non-geostationary satellite orbits, while at the same time recognizing DOT's responsibility for safety issues associated with payload launch operations and launch mission.

NOAA's authority with respect to commercial space activities is granted under Title II of the Land Remote-Sensing Commercialization Act of 1992 (which repealed the Land Remote Sensing Commercialization Act of 1984). NOAA is responsible for licensing private remote-sensing space systems to stimulate the development of a U.S. land remote-sensing industry and to promote the continuous collection and utilization of land remote-sensing data while maintaining U.S. leadership in civil remote sensing and fulfilling U.S. international defense and security commitments. Section 202(b)(4) of Title II requires all licenses to include a condition under which the licensee must "upon termination of operations under the license, make disposition of any satellites in space in a manner satisfactory to the President." This clearly provides adequate authority to require that a spent spacecraft not be left in a position that contributes to the space debris problem. Presumably, any reasonable combination of design and orbital conditions could be imposed to promote the desired disposition. By implication, authority to control the disposition of the entire spacecraft would include authority to impose reasonable conditions directed at maintaining a spacecraft intact during operations (i.e., in orbit) or controlling the disposition of any pieces shed during operations. NOAA's authority under Title II does not extend to activities that are part of the launch.

The principal purpose of the authority granted to the Secretary of Transportation under the Commercial Space Launch Act of 1984, as recodified at 49 United States Code Subtitle IX, chapter 701 (the Act), is to oversee and coordinate the conduct of commercial space launch operations in a manner that protects the important national interests associated with such activities: public health and safety, safety of property, U.S. national security and foreign policy interests. The Secretary is empowered to issue licenses authorizing the conduct of commercial launch activities and to establish the regulatory regime for ensuring that they are conducted safely and responsibly. In the course of devising appropriate regulatory guidance, the Secretary may, by regulation and in consultation with other appropriate agencies, eliminate any existing federal requirements otherwise applicable to commercial launch activities that are determined to be unnecessary to protect national interests. The Secretary may also add new requirements to safeguard those interests or to ensure compliance with U.S. international obligations.

DOT's charter as a safety regulatory agency encompasses all non-government launches conducted by U.S. citizens or from U.S. territory, payloads involved in launches subject to DOT licensing requirements, and non-U.S. Government launch sites (e.g., privately operated or state-run spaceports). With specific regard to non-government payloads on non-governmental launch vehicles, proposals to launch payloads that are not subject to licensing by another U.S. Government agency must be regulated by DOT from the standpoint of the national interests that the Department is charged with protecting. If a proposal runs counter to those interests (i.e., would jeopardize public health and safety, safety of property or U.S. national interests), DOT can prohibit the launch of the payload in question.

DOT's broad, general authority over satellites does not extend to those subject to (a) licensing and regulation by the FCC under the Communications Act of 1934 or (b) licensing by NOAA under the Land Remote-Sensing Commercialization Act of 1992. To the extent that a payload requires a license under either of these regimes in order to be launched, DOT may not duplicate the review process of either of those agencies or reconsider the merits of the specific service to be provided pursuant to the license. Nevertheless, DOT continues to have authority to ensure the safety of commercial launch operations involving these otherwise licensed payloads.

Regulatory oversight of the commercial space launch sector for the purpose of preventing and controlling orbital debris would fall into the "safety" category of regulatory functions. As noted above, DOT is expressly authorized to regulate commercial launch activities in terms of public safety and other public interests, and the FCC is expressly authorized to regulate the use of radio to make available an efficient nationwide, and worldwide, radio communication service.

Within the limits of their authority, regulatory agencies may structure their relationship for space purposes in a manner comparable to the existing alignment for terrestrial activities. For example, the FCC regulates mobile land, marine, or airborne radio communications systems and service, while DOT regulates modes of transport (e.g., truck, ship, or aircraft) by which the service is provided. In addition, similar to the way in which the FCC regulates the painting of radio towers consistent with FAA air navigation requirements, the FCC may regulate the physical movement of spacecraft to assure the continued availability of efficient satellite-based services. In terms of space-related activities, therefore, the economic focus of NOAA and the regulatory focus of the FCC on the provision of telecommunication services would continue to be distinguished from DOT's focus on the safety and transportation components of the launch of vehicles and spacecraft.

In 1990, DOD, NASA, and DOT completed an Orbital Debris Research Plan designed to coordinate the research efforts of the respective agencies. The results are reported in chapters 1 through 7. Discussions continue between the agencies on an approach that best facilitates completion of identified research tasks. Safety research of DOT, therefore, will be used to identify the regulatory options and standards that may guide future industry practices.

II. Department of Transportation Approach

DOT evaluates space debris issues consistent with its congressional authorization to license and regulate commercial launch activities in a manner that ensures protection of public health and safety, safety of property and other U.S. interests. These issues are addressed through ongoing regulatory action in the following areas: (a) licensing and enforcement, (b) safety and regulatory research and standards development, and (c) financial responsibility/insurance requirements and risk allocation regimes.

A. Licensing and Enforcement

Through the license application review process, DOT examines proposed commercial launch activities. Safety Review and Mission Review procedures address, among other things, issues of orbital safety and, by implication, orbital debris in the following manner:

- Review of ELV staging and maneuvering hardware reliability, including safety impacts of vehicle operational performance statistics on previous failures and the failure mode and effect analysis.
- Review of elements involved with proposed mission planning and design, including the proposed trajectory, separation maneuvers, orbital

insertion, orbital life of proposed geo-transfer and parking orbits, and the potential for on-orbit collisions.

- Review of the license application to ensure that operational plans are consistent with U.S. Government recognized safe practices or otherwise address orbital safety concerns (i.e., venting of propellants and pressurants in orbiting spent stages to preclude explosions, separation maneuvers to avoid collisions, and satellite position management for end-of-life disposal).

Through its review of mission planning and design, DOT considers an applicant's proposal for minimizing risks to public safety. DOT requires that launch operators consider and address orbital debris issues through such means as on-orbit risk analysis. DOT has observed a growing understanding and heightened appreciation of orbital debris among U.S. commercial launch services providers.

As part of the mission review process, DOT coordinates with other government agencies to determine whether a launch proposal would present a threat to U.S. interests or public safety. A 1991 agreement between DOT and the USSPACECOM, which calls for the mutual exchange of data, contributes to the DOD's efforts to track objects in Earth orbit. Under the Commercial Space Transportation Licensing Regulations, 14 CFR chapter III, commercial launch operators are required to provide information on U.S. objects in space as a result of a launch event. The information is then relayed to the United Nations via the Department of State in accordance with the Convention on Registration of Objects Launched into Outer Space.

B. Regulatory and Safety Research and Standards Development

Under Executive Order 12866, "Regulatory Planning and Review," agencies are directed to consider the economic impacts of available regulatory alternatives through quantitative and qualitative measures of costs and benefits. In compliance with this established federal guideline, proposed commercial space transportation safety regulatory measures are extensively examined by DOT.

The DOT research program addresses a wide array of safety issues involving commercial launch ranges and launch service operations, as well as methods to evaluate the safety of reentries of objects from space, both normal and accidental, as well as natural and controlled. To date, research has focused on the impact of commercial launch operations on public safety, i.e., prelaunch vehicle preparation, vehicle stage separation, and payload orbit insertion, as well as the methodologies for identifying and analyzing risks. For example, research programs have evaluated how licensed commercial launch vehicles may affect proposed low Earth orbit constellations, as well as reentry risks resulting from commercial launch events. Future research efforts may examine the relative effectiveness, cost, and benefit of various proposed debris prevention and control options involving vehicle and operational practices.

C. Financial Responsibility and Insurance Requirements

DOT has the authority to require that a license applicant demonstrate financial responsibility as a condition of a licensed launch. The purpose of safety standards is to reduce the incidence of accidents, whereas insurance is a mechanism designed to compensate for the consequences of accidents. DOT expects to issue a notice of proposed rule making in the near future which addresses financial responsibility and allocation of risk requirements and establishes the basic mechanisms whereby companies may be required to carry insurance. In the meantime, such requirements continue to be imposed case by case pending issuance of the rule.

III. The Regulatory Environment

The National Space Policy requires that orbital debris mitigation measures be "consistent with mission requirements and cost effectiveness." This same principle should extend to the commercial sector.

Debris mitigation design solutions will result in some added cost or payload penalty. By implementing these solutions during the system design process, these 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 these commercial regulations on the domestic launch and satellite industries. Unlike the two governmental sectors (civilian and defense), the private, non-governmental sector functions in a highly competitive environment. The cost of orbital debris measures are passed on to the customer. If the same launch requirements are not imposed on foreign competitors in the launch industry, U.S. launch firms may have to operate at a distinct 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).

A robust and economically viable commercial satellite and launch sector is a necessary component of the National Space Policy strategy to assure the continuance of U.S. leadership in space. Consistent with this objective, DOT's mission under 49 United States Code subtitle IX, chapter 701 (formerly the Commercial Space Launch Act) (the Act) is to promote and encourage a commercial launch industry. While the Act authorizes regulation of commercial launch activities, DOT's regulatory authority is limited to the extent necessary to ensure compliance with U.S. international obligations and to protect public health and safety, safety of property, and U.S. national security and foreign policy interests.

Part Four:

Findings and Recommendations

Findings and Recommendations

The section focuses on the essential findings of this 1995 revision of the interagency study on orbital debris. These findings highlight changes that have occured since the publication of the 1989 Report on Obital Debris. In addition five specific recommendations are proposed to address the issues raised by this report.

Summary of Findings

The 1989 Report on Orbital Debris noted the lack of definitive measurements on the debris environment. Since that time NASA, with the assistance of DOD, has conducted an extensive program to measure the LEO debris environment. There has now emerged a comprehensive picture of the orbital debris environment in LEO. The current Haystack measurements indicate populations a factor of two lower than predicted in 1989 at Space Station altitudes and a factor of two higher at the 1000 km altitude. In GEO, however, NASA has only conducted an exploratory campaign to measure the debris environment. Both of these efforts should continue in order to refine our understanding of the current environment as well as to monitor changes in the environment with time.

Contributions to the current debris environment continue to be essentially proportional to the level of space activity by a given spacefaring nation. Of particular concern is the sustained rate of fragmentation events since 1989 despite the active efforts of the spacefaring nations to reduce the probability of such occurrences.

The orbital debris environment in LEO continues to present problems for space operations that involve large spacecraft in orbit for long periods of time. Taking note of all that has been learned since 1989, the International Space Station Program has taken steps to maximize protection from debris penetration by implementing state-of-the-art shielding; utilizing existing ground radars to track and avoid larger debris; and actively developing operational and design options which will minimize the risk to the crew and the Station.

Since release of the 1989 Report, there have been a series of proposals to develop large LEO satellite constellations. These constellations could present a significant new concern for the orbital debris environment. For those constellations which have a large aggregate area, the collision probabilities are sufficiently high that additional means of protection need be considered. The problem is particularly acute because the high inclination of their orbits lead to high spatial density over the poles.

The development and utilization of predictive models has improved significantly since 1989. This improved predictive capability when combined with our increased knowledge of the debris environment, leads to the conclusion that failure to take any mitigation action could lead to significant increase in orbital debris in the coming years. Assuming a continuation of launch activity at the same average rate as over the last ten years, average future solar cycles, and future operational practices that will minimize but not eliminate the possibility of explosions in orbit, most models predict that an increasing fraction of future debris will originate from breakups due to random collisions between orbiting objects. The use of operational practices to limit the orbital lifetime of spent upper stages and payloads have the potential to mitigate the growth of orbital debris.

In 1989 National Space Policy Directive-1 (NSPD-1) was approved. NSPD-1 called for agencies to "seek to minimize the creation of space debris." Since that time orbital debris concerns have caused changes in the plans and activities of some agencies, particularly NASA. NASA has issued a comprehensive agency policy concerning orbital debris. The Department of Defense (in particular the Air Force and the U.S. Space Command) have adopted broad policies concerning orbital debris. Beyond the general statement in NSPD-1, there remains no comprehensive statement of USG policy on orbital debris.

The 1989 Report called for NASA and the DOD to develop a plan to monitor the orbital debris environment. Since that time NASA, utilizing many DOD assets and NASA's own capabilities, has expended considerable effort to accomplish this recommendation. The modification of the Haystack Radar for orbital debris measurements has greatly enhanced our ability to monitor the LEO debris environment. Today, data measurements as well as data management limitations significantly affect the capability of the Space Surveillance Network to detect and track smaller debris objects. Statistical techniques are being utilized to characterize the current debris population.

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Since the publication of the 1989 Report, the United States and a number of national and international spacefaring organizations have begun to address orbital debris concerns. As a result of the recommendations set out in the 1989 Report, the United States and other spacefaring nations have taken voluntary design measures (i.e., tethering of operational debris such as lens caps and the use of debris free devices for separation and release) as well as operational procedures to prevent the generation of orbital debris. More than ever, it is clear that closer international cooperation is necessary for dealing effectively with orbital debris. It is in the broad interest of the United States to continue to maintain a leadership role in international considerations relating to orbital debris. The United States considers the development of technical cooperation and consensus to be a prerequisite for any potential international agreements, regulatory regimes or other measures relating to orbital debris. The unilateral application of debris mitigation measures could put U.S. satellite and launch vehicle industries at a competitive disadvantage.

Recommendations

In light of the findings contained in this revision of the 1989 Report on Orbital Debris, and noting the progress that has been made in our understanding of the debris environment, the following recommendations should be implemented.

1. Continue and Enhance Debris Measurement, Modeling and Monitoring Capabilities

Our ability to fully understand the orbital debris problem will depend upon our continuing capabilities to measure, model and monitor the debris environment. NASA and DOD should continue current investments in their debris research programs and, as resources permit, seek to expand existing measurement capabilities (both radars and optical systems) and bring new systems now under development on line as soon as possible. NASA should continue its program of returned material analysis and seek additional opportunities to exchange samples with other spacefaring nations. DOD and NASA should closely coordinate their laboratory studies of breakups from explosions and collisions. Particular attention should be given to those orbits where critical national security payloads may be located, where permanent presence is planned (i.e., the Space Station orbit), in geosynchronous orbits, and in the economically and scientifically critical sun-synchronous orbits.

2. Conduct a Focused Study on Debris and Emerging LEO Systems

To date, government involvement has focused primarily on the frequency licensing issues associated with these systems. To ensure that other considerations pertinent to these systems are adequately understood and reviewed, NASA, with the participation of DOD, DOT, DOC, and other relevant federal agencies should convene a workshop with U.S. industry on debris mitigation and LEO systems. The workshop should serve as a first step in identifying possible measures for debris mitigation that LEO operators could incorporate in the design of future systems. The workshop could also identify possible mitigation measures for launch vehicle operators contemplating service for LEO systems. This effort should include appropriate analysis of the economic impacts that specific mitigation measures could have on the satellite and launch vehicle communities. NASA should document the results from this workshop in a report and factor these results into government/industry efforts to develop guidelines on debris mitigation (see Recommendation 3).

3. Develop Government/Industry Design Guidelines on Orbital Debris

NASA has made substantial progress in documenting and defining specific design measures that can be taken into account during the development of spacecraft and launch vehicles in order to minimize or eliminate debris generation. Using this initial work, NASA and DOD should jointly develop draft design guidelines that could serve as a baseline for agency requirements for future spacecraft and launch vehicle/service procurements. Upon completion of the draft guidelines, NASA and DOD should disseminate the draft to industry for comment and convene a workshop to discuss industry and government concerns. This workshop should also seek to identify design guidelines which would require international consensus in order to ensure a fair and level playing field. The goal of the exercise would be the development of Government/Industry guidelines that both sectors could use in the design and development of future systems.

4. Develop a Strategy for International Discussions

Since the 1989 report was issued, three important international developments related to debris have taken place. First, through NASA's efforts, an international agency-level organization (the Inter-Agency Space Debris Coordination Committee) has been formed to facilitate the exchange of technical research and information related to debris. The United States, Japan, ESA, Russia, and China currently have agency-level representation on the committee. Planning for membership of other spacefaring nations is underway. Second, the United States introduced detailed analysis on the problem of the safing and disposal of geostationary satellites to relevant working groups in the International Telecommunication Union. Third, the United States joined consensus with other members of the Scientific and Technical Subcommittee of the United Nations Committee on Peaceful Uses of Outer Space to take up the subject of space debris as a formal agenda item.

The United States should maintain its leadership role in these forums, but seek to do so in a more coordinated and comprehensive way. The Department of State and NASA, with the participation of other relevant agencies, should co-chair a review to develop a strategy outlining how the United States should seek to encourage other spacefaring nations to adopt debris policies and practices and how current bilateral and multilateral discussions can be better coordinated. In developing this strategy the United States government should take into account the need to ensure that a level playing field is created in the application of international orbital debris mitigation policies and practices.

5. Review and Update U.S. Government Policy on Debris*

National Space Policy Directive-1 (NSPD-1), signed in 1989, includes an Intersector Policy guideline calling on agencies to "seek to minimize the creation of space debris." Under NSPD-1, design and operation of space tests, experiments, and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. NSPD-1 calls on the government to encourage other spacefaring nations to adopt policies and practices aimed at debris mitigation and minimization.

On June 2, 1995, the President directed the OSTP and NSC to lead a comprehensive review of National Space Policy, including policies affecting the civil, commercial, and national security space sectors. As part of this review, the Administration should seek to translate the recommendations contained in this report, as appropriate, into national policy concerning agency programs and activities related to orbital debris.

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* The findings and recommendations contained in this report were transmitted to the Interagency Working Group for Space Policy in November 1995

Appendices

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Appendix

History of On-Orbit Fragmentations*

Common Name	International Designator	Catalog Number	Launch Date	Event Date	Cataloged Upon Breakup	Currently Tracked In Orbit	Apogee (km)	Perigee (km)	Incl. (°)	Probable Cause	Comments
TRANSIT 4A R/B	1961-OMI 3	118	29-Jun-61	29-Jun-61	298	200	995	880	66.8	PROPULSION	ABLESTAR STAGE
SPUTNIK 29	1962-B I0T 1	443	24-Oct-62	29-0ct-62	24	0	260	200	65.1	PROPULSION	SL-6 FINAL STAGE
ATLAS CENTAUR 2	1963-47A	694	27-Nov-63	27-Nov-63	19	9	1785	475	30.3	PROPULSION	CENTAUR STAGE
COSMOS 50	1964-70A	919	28-Oct-64	05-Nov-64	96	0	220	175	51.2	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 57	1965-12A	1093	22-Feb-65	22-Feb-65	167	0	425	165	64.8	COMMAND	INADVERTENT DESTRUCTION
COSMOS 61-63 R/B	1965-20D	1270	15-Mar-65	15-Mar-65	147	22	1825	260	56.1	UNKNOWN	SL-8 FINAL STAGE
OV2-1/LCS 2 R/B	1965-82B	1640	15-Oct-65	15-Oct-65	470	55	790	710	32.2	PROPULSION	TITAN 3C-4 TRANSTAGE
OPS 3031	1966-12C	2015	15-Feb-66	15-Feb-66	38	0	270	150	96.5	UNKNOWN	
GEMINI 9 ATDA R/B	1966-46B	2188	01-Jun-66	Mid-Jun-66	51	0	275	240	28.8	UNKNOWN	ATLAS CORE STAGE
AS-203	1966-59A	2289	05-Jul-66	05-Jul-66	34	0	215	185	32.0	DELIBERATE	SATURN SIVB STAGE
USSR UNKNOWN 1	1966-88A	2437	17-Sep-66	17-Sep-66	53	0	855	140	49.6	UNKNOWN	
USSR UNKNOWN 2	1966-101A	2536	02-Nov-66	02-Nov-66	41	0	885	145	49.6	UNKNOWN	
APOLLO 6 R/B (S4B)	1968-25B	3171	04-Apr-68	13-Apr-68	16	0	360	200	32.6	PROPULSION	SATURN SIVB STAGE
COSMOS 249	1968-91A	3504	20-Oct-68	20-Oct-68	109	55	2165	490	62.3	DELIBERATE	TEST
COSMOS 248	1968-90A	3503	19-Oct-68	01-Nov-68	5	0	545	475	62.2	DELIBERATE	TEST
COSMOS 252	1968-97A	3530	01-Nov-68	01-Nov-68	140	53	2140	535	62.3	DELIBERATE	TEST
METEOR 1-1 R/B	1969-29B	3836	26-Mar-69	28-Mar-69	37	0	850	460	81.2	UNKNOWN	SL-3 FINAL STAGE

Common Name	International Designator	Catalog Number	Launch Date	Event Date	Cataloged Upon Breakup	Currently Tracked In Orbit	Apogee (km)	Perigee (km)	Incl. (°)	Probable Cause	Comments
INTELSAT 3 F-5 R/B	1969-64B	4052	26-Jul-69	26-Jul-69	26	1	5445	270	30.4	PROPULSION	TE 364-4 STAGE
OPS 7613 R/B	1969-82AB	4159	30-Sep-69	04-Oct-69	260	97	940	905	70.0	UNKNOWN	AGENDA D STAGE
NIMBUS 4 R/B	1970-25C	4367	08-Apr-70	17-Oct-70	372	278	1085	1065	99.9	UNKNOWN	AGENDA D STAGE
		4601	23-Jan-85							UNKNOWN	
		4649	17-Dec-85							UNKNOWN	3 ADDITIONAL OBJECTS
		4610	02-Sep-86							UNKNOWN	2 ADDITIONAL OBJECTS
		4601	23-Dec-91							UNKNOWN	5 ADDITIONAL OBJECTS
COSMOS 374	1970-89A	4594	23-Oct-70	23-Oct-70	102	36	2130	530	62.9	DELIBERATE	TEST
COSMOS 375	1970-91A	4598	30-Oct-70	30-Oct-70	47	27	2100	525	62.8	DELIBERATE	TEST
COSMOS 397	1971-15A	4964	25-Feb-71	25-Feb-71	116	59	2200	575	65.8	DELIBERATE	TEST
COSMOS 462	1971-106A	5646	03-Dec-71	03-Dec-71	25	0	1800	230	65.7	DELIBERATE	TEST
SALYUT 2 R/B	1973-17B	6399	03-Apr-73	03-Apr-73	25	0	245	195	51.5	PROPULSION	SL-13 FINAL STAGE
COSMOS 554	1973-21A	6432	19-Apr-73	06-May-73	195	0	350	170	72.9	DELIBERATE	PAYLOAD RECOVERY FAILURE
NOAA 3 R/B	1973-86B	6921	06-Nov-73	28-Dec-73	197	180	1510	1500	102.1	PROPULSION	DELTA SECOND STAGE
COSMOS 699	1974-103A	7587	24-Dec-74	17-Apr-75	50	0	445	425	65.0	DELIBERATE	FIRST OF COSMOS 699 CLASS
			02-Aug-75				440	415	65.0	DELIBERATE	
LANDSAT 1 R/B	1972-58B	6127	23-Jul-72	22-May-75	226	52	910	635	98.3	PROPULSION	DELTA SECOND STAGE
PAGEOS	1966-56A	2253	24-Jun-66	12-Jul-75	79	3	5170	3200	85.3	UNKNOWN	NUMEROUS OTHER EVENTS
			20-Jan-76				5425	2935	85.1	UNKNOWN	
			10-Sep-76							UNKNOWN	
			MID-Jun-78							UNKNOWN	
			MID-Sep-84							UNKNOWN	
			MID-Dec-85							UNKNOWN	
NOAA 4 R/B	1974-89D	7532	15-Nov-74	20-Aug-75	148	129	1460	1445	101.7	PROPULSION	DELTA SECOND STAGE
COSMOS 758	1975-80A	8191	05-Sep-75	06-Sep-75	76	0	325	175	67.1	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 777	1975-102A	8416	29-Oct-75	25-Jan-76	62	0	440	430	65.0	DELIBERATE	COSMOS 699 CLASS

Common Name	International Designator	Catalog Number	Launch Date	Event Date	Cataloged Upon Breakup	Currently Tracked In Orbit	Apogee (km)	Perigee (km)	Incl. (°)	Probable Cause	Comments
LANDSAT 2 R/B	1975-04B	7616	22-Jan-75 19-Jun-76	09-Feb-76	207	39	915 910	740 745	97.8 97.7	UNKNOWN PROPULSION	DELTA SECOND STAGE
COSMOS 844	1976-72A	9046	22-Jul-76	25-Jul-76	248	0	355	170	67.1	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 886	1976-126A	9634	27-Dec-76	27-Dec-76	76	63	2295	595	65.8	DELIBERATE	TEST
COSMOS 862	1976-105A	9495	22-Oct-76	15-Mar-77	11	11	39645	765	63.2	PROPULSION	FIRST OF COSMOS 862 CLASS
COSMOS 838	1976-63A	8932	02-Jul-76	17-May-77	40	0	445	415	65.1	DELIBERATE	COSMOS 699 CLASS
HIMAWARI 1 R/B	1977-65B	10144	14-Jul-77	14-Jul-77	169	79	2025	535	29.0	PROPULSION	DELTA SECOND STAGE
COSMOS 839	1976-67A	9011	08-Jul-76	29-Sep-77	70	67	2100	980	65.9	UNKNOWN	FIRST OF COSMOS 839 CLASS
COSMOS 931	1977-68A	10150	20-Jul-77	24-Oct-77	6	5	39665	680	62.9	PROPULSION	COSMOS 862 CLASS
COSMOS 970	1977-121A	10531	21-Dec-77	21-Dec-77	70	67	1140	945	65.8	DELIBERATE	TEST
NOAA 5 R/B	1976-77B	9063	29-Jul-76	24-Dec-77	159	154	1520	1505	102.0	PROPULSION	DELTA SECOND STAGE
COSMOS 903	1977-27A	9911	11-Apr-77	08-Jun-78	2	2	39035	1325	63.2	PROPULSION	COSMOS 862 CLASS
EKRAN 2	1977-92A	10365	20-Sep-77	25-Jun-78	1	1	35798	35786	0.1	ELECTRICAL MALFUNCTION	NI H2 BATTERY
COSMOS 1030	1978-83A	11015	06-Sep-78	10-Oct-78	4	4	39760	665	62.8	PROPULSION	COSMOS 862 CLASS
COSMOS 880	1976-120A	9601	09-Dec-76	27-Nov-78	49	2	620	550	65.8	UNKNOWN	COSMOS 839 CLASS
COSMOS 917	1977-47A	10059	16-Jun-77	30-Mar-79	1	1	38725	1645	62.9	PROPULSION	COSMOS 862 CLASS
COSMOS 1124	1979-77A	11509	28-Aug-79	09-Sep-79	5	5	39795	570	63.0	PROPULSION	COSMOS 862 CLASS
COSMOS 1094	1979-33A	11333	18-Apr-79	17-Sep-79	1	0	405	380	65.0	DELIBERATE	COSMOS 699 CLASS
COSMOS 1109	1979-58A	11417	27-Jun-79	Mid-Feb-80	6	6	39425	960	63.3	PROPULSION	COSMOS 862 CLASS
CAT R/B	1979-104B	11659	24-Dec-79	Apr-80	1	0	33140	180	17.9	UNKNOWN	ARIANE 1 FINAL STAGE

Common Name	International Designator	Catalog Number	Launch Date	Event Date	Cataloged Upon Breakup	Currently Tracked In Orbit	Apogee (km)	Perigee (km)	Incl. (°)	Probable Cause	Comments
COSMOS 1174	1980-30A	11765	18-Apr-80	18-Apr-80	46	11	1660	380	66.1	DELIBERATE	TEST
LANDSAT 3 R/B	1978-26C	10704	05-Mar-78	27-Jan-81	209	147	910	900	98.8	PROPULSION	DELTA SECOND STAGE
COSMOS 1261	1981-31A	12376	31-Mar-81	APR/May-81	4	4	39765	610	63.0	PROPULSION	COSMOS 862 CLASS
COSMOS 1191	1980-57A	11871	02-Jul-80	14-May-81	2	2	39255	1110	62.6	PROPULSION	COSMOS 862 CLASS
COSMOS 1167	1980-21A	11729	14-Mar-80	15-Jul-81	12	0	450	355	65.0	DELIBERATE	COSMOS 699 CLASS
COSMOS 1275	1981-53A	12504	04-Jun-81	24-Jul-81	306	275	1015	960	83.0	UNKNOWN	POSSIBLE IMPACT?
COSMOS 1305 R/B	1981-88F	12827	11-Sep-81	11-Sep-81	3	3	13795	605	62.8	POPULSION	SL-6 FINAL STAGE
COSMOS 1247	1981-16A	12303	19-Feb-81	20-Oct-81	4	4	39390	970	63.0	PROPULSION	COSMOS 862 CLASS
COSMOS 1285	1981-71A	12627	04-Aug-81	21-Nov-81	3	3	40100	720	63.1	PROPULSION	COSMOS 862 CLASS
NIMBUS 7 R/B	1978-98B	11081	24-Oct-78	26-Dec-81	1	1	955	935	99.3	UNKNOWN	DELTA SECOND STAGE
COSMOS 1260	1981-28A	12364	20-Mar-81	08-May-82	68	1	750	450	65.0	DELIBERATE	COSMOS 699 CLASS
			10-Aug-82				750	445	65.0	DELIBERATE	
COSMOS 1220	1980-89A	12054	04-Nov-80	20-Jun-82	78	1	885	570	65.0	DELIBERATE	COSMOS 699 CLASS
			25-Aug-82				885	565	65.0	DELIBERATE	
COSMOS 1306	1981-89A	12828	14-Sep-81	12-Jul-82	8	0	405	380	64.9	DELIBERATE	COSMOS 699 CLASS
			18-Sep-82				370	370	64.9	DELIBERATE	
COSMOS 1286	1981-72A	12631	04-Aug-81	29-Sep-82	2	0	325	300	65.0	DELIBERATE	COSMOS 699 CLASS
COSMOS 1423 R/B	1982-115E	13696	08-Dec-82	08-Dec-82	29	0	427	235	62.9	PROPULSION	SL-6 FINAL STAGE
COSMOS 1481	1983-70A	14182	08-Jul-83	09-Jul-83	3	3	39225	625	62.9	PROPULSION	COSMOS 862 CLASS
COSMOS 1355	1982-38A	13150	29-Apr-82	08-Aug-83	29	0	395	360	65.1	DELIBERATE	COSMOS 699 CLASS
			01-Feb-84				320	305	65.0	DELIBERATE	
			20-Feb-84				290	270	65.0	DELIBERATE	
COSMOS 1456	1983-38A	14034	25-Apr-83	13-Aug-83	4	4	39630	730	63.3	PROPULSION	COSMOS 862 CLASS
COSMOS 1405	1982-88A	13508	04-Sep-82	20-Dec-83	32	0	340	310	65.0	DELIBERATE	COSMOS 699 CLASS

Common Name	International Designator	Catalog Number	Launch Date	Event Date	Cataloged Upon Breakup	Currently Tracked In Orbit	Apogee (km)	Perigee (km)	Incl. (°)	Probable Cause	Comments
COSMOS 1317	1981-108A	12933	31-Oct-81	LATE-Jan-84	4	4	39055	1315	62.8	PROPULSION	COSMOS 862 CLASS
WESTAR 6 R/B	1984-11F	14694	03-Feb-84	03-Feb-84	14	1	310	305	28.5	PROPULSION	PAM-D UPPER STAGE
PALAPA B2 R/B	1984-11E	14693	03-Feb-84	06-Feb-84	3	1	285	275	28.5	PROPULSION	PAM-D UPPER STAGE
ASTRON DEB	1983-20B	13902	23-Mar-83	03-Sep-84	1	0	1230	220	51.5	PROPULSION	SL-12 FINAL STAGE DEBRIS
COSMOS 1461	1983-44A	14064	07-May-83 13-May-85	11-Mar-83	158	3	890 885	570 570	65.0 65.0	DELIBERATE DELIBERATE	COSMOS 699 CLASS
COSMOS 1654	1985-39A	15734	23-May-85	21-Jun-85	18	0	300	185	64.9	DELIBERATE	PAYLOAD RECOVERY FAILURE
P-78 (SOLWIND)	1979-17A	11278	24-Feb-79	13-Sep-85	285	9	545	515	97.6	DELIBERATE	TEST
COSMOS 1375	1982-55A	13259	06-Jun-82	21-Oct-85	58	57	1000	990	65.8	UNKNOWN	COSMOS 839 CLASS
COSMOS 1691	1985-94B	16139	09-Oct-85	22-Nov-85	14	11	1415	1410	82.6	ELECTRICAL	NI H2 BATTERY MALFUNCTION
NOAA 8	1983-22A	13923	28-Mar-83	30-Dec-85	7	1	830	805	98.6	ELECTRICAL	BATTERY MALFUNCTION
COSMOS 1588	1984-83A	15167	07-Aug-84	23-Feb-86	45	0	440	410	65.0	DELIBERATE	COSMOS 699 CLASS
USA 19	1986-69A	16937	05-Sep-86	05-Sep-86	13	0	745	210	39.1	DELIBERATE	TEST (SEE ALSO USA 19 R/B)
USA 19 R/B	1986-69B	16938	05-Sep-86	05-Sep-86	5	0	610	220	22.8	DELIBERATE	TEST (SEE ALSO USA 19)
SPOT 1 R/B	1986-19C	16615	22-Feb-86	13-Nov-86	489	59	835	805	98.7	UNKNOWN	ARIANE 1 FINAL STAGE
COSMOS 1278	1981-58A	12547	19-Jun-81	Early-Dec-86	2	2	37690	2665	67.1	PROPULSION	COSMOS 862 CLASS
COSMOS 1682	1985-82A	16054	19-Sep-85	18-Dec-86	23	0	475	385	65.0	DELIBERATE	COSMOS 699 CLASS
COSMOS 1813	1987-04A	17297	15-Jan-87	29-Jan-87	194	0	415	360	72.8	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 1866	1987-59A	18184	09-Jul-87	26-Jul-87	9	0	255	155	67.1	DELIBERATE	PAYLOAD RECOVERY FAILURE
AUSSAT/ECS R/B	1987-78C	18352	16-Sep-87	Mid-Sep-87	2	1	36515	245	6.9	UNKNOWN	ARIANE 3 FINAL STAGE
COSMOS 1769	1986-59A	16895	04-Aug-86	21-Sep-87	4	0	445	310	65.0	DELIBERATE	COSMOS 699 CLASS

Common Name	International Designator	Catalog Number	Launch Date	Event Date	Cataloged Upon Breakup	Currently Tracked In Orbit	Apogee (km)	Perigee (km)	Incl. (°)	Probable Cause	Comments
COSMOS 1646	1985-30A	15653	18-Apr-85	20-Nov-87	24	0	410	385	65.0	DELIBERATE	COSMOS 699 CLASS
COSMOS 1823	1987-20A	17535	20-Feb-87	17-Dec-87	110	46	1525	1480	73.6	ELECTRICAL	NI H2 BATTERY MALFUNCTION
COSMOS 1656 DEB	1985-42E	15773	30-May-85	05-Jan-88	6	6	860	810	66.6	PROPULSION	SL-12 FINAL STAGE DEBRIS
COSMOS 1906	1987-108A	18713	26-Dec-87	31-Jan-88	37	0	265	245	82.6	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 1916	1988-07A	18823	03-Feb-88	27-Feb-88	1	0	230	150	64.8	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 1045 R/B	1978-100D	11087	26-Oct-78	09-May-88	45	42	1705	1685	82.6	UNKNOWN	SL-14 FINAL STAGE
COSMOS 2030	1989-54A	20124	12-Jul-89	28-Jul-89	1	0	215	150	67.1	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 2031	1989-56A	20136	18-Jul-89	31-Aug-89	9	0	365	240	50.5	DELIBERATE	PAYLOAD RECOVERY FAILURE
FENGYUN 1-2 R/B	1990-81D	20791	03-Sep-90	04-Oct-90	73	69	895	880	98.9	UNKNOWN	CZ-4A FINAL STAGE
COSMOS 2101	1990-87A	20828	01-Oct-90	30-Nov-90	4	0	280	195	64.8	DELIBERATE	PAYLOAD RECOVERY FAILURE
USA 68	1990-105A	20978	01-Dec-90	01-Dec-90	29	5	850	610	98.9	PROPULSION	TE-M-364-15-UPPER STAGE
COSMOS 1519-21 DEB	1983-127H	14608	29-Dec-83	04-Feb-91	5	4	18805	340	51.9	PROPULSION	SL-12 FINAL STAGE DEBRIS
COSMOS 2125-32 R/B	1991-09J	21108	12-Feb-91	05-Mar-91	73	73	1725	1460	74.0	UNKNOWN	SL-8 FINAL STAGE; UP TO 9 SEPARATE EVENTS
NIMBUS 6 R/B	1975-52B	7946	12-Jun-75	01-May-91	236	190	1103	1093	99.6	PROPULSION	DELTA SECOND STAGE
COSMOS 2163	1991-71A	21741	09-Oct-91	06-Dec-91	1	0	259	187	64.8	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 1710-2 DEB	1985-118L	16446	24-Dec-85	29-Dec-91	2	2	18886	654	65.3	PROPULSION	SL-12 FINAL STAGE DEBRIS
OV2-5 R/B	1968-81E	3432	26-Sep-68	21-Feb-92	1	1	35812	35102	11.9	UNKNOWN	
COSMOS 2045 DEB	1989-101E	20399	27-Dec-89	Jul-92 (?)	2	2	27651	344	47.1	PROPULSION	SL-12 FINAL STAGE DEBRIS
COSMOS 1603 DEB	1984-106F	15338	28-Sep-84	05-Sep-92	22	1	845	836	66.6	PROPULSION	SL-12 FINAL STAGE DEBRIS
GORIZONT 17 DEB	1989-04E	19771	26-Jan-89	17/8-Dec-92	1	1	17577	197	46.7	PROPULSION	SL-12 FINAL STAGE DEBRIS

Common Name	International Designator	Catalog Number	Launch Date	Event Date	Cataloged Upon Breakup	Currently Tracked In Orbit	Apogee (km)	Perigee (km)	Incl. (°)	Probable Cause	Comments
COSMOS 2227 R/B	1992-93B	22285	25-Dec-92 30-Dec-92	26-Dec-92	209	208	855 855	847 847	71.0 71.0	UNKNOWN UNKNOWN	SL-16 FINAL STAGE
GORIZONT 18 DEB	1989-52F	20116	05-Jul-89	12-Jan-93	1	1	36747	258	46.8	PROPULSION	SL-12 FINAL STAGE DEBRIS
COSMOS 2225	1992-91A	22280	22-Dec-92	18-Feb-93	6	0	279	227	64.9	DELIBERATE	PAYLOAD RECOVERY FAILURE
COSMOS 2237 R/B	1993-16B	22566	26-MAR-93	28-MAR-93	27	27	850	841	71.0	UNKNOWN	SL-16 FINAL STAGE
COSMOS 2243 R/B	1993-28B	22642	27-APR-93	27-APR-93	1	0	225	181	70.4	UNKNOWN	SL-4 FINAL STAGE (PAYLOAD?)
COSMOS 1484	1983-75A	14207	24-JUL-83	18-OCT-93	33	31	593	545	97.5	UNKNOWN	
COSMOS 2262	1993-57A	22789	07-SEP-93	18-DEC-93	1	0	316	180	64.9	DELIBERATE	PAYLOAD RECOVERY FAILURE
CLEMINTINE R/B	1994-04B	22974	25-JAN-94	07-FEB-94	0	0	297	240	67.0	UNKNOWN	
COSMOS 2133	1991-10D	21114	14-FEB-93	07-MAY-94	?	?	21805	225	46.6	UNKNOWN	SCZ MOTOR
ASTRA/MOP R/B (1)	1991-15C	21141	2-MAR-91	27-APR-94	3	3	28819	254	6.6	UNKNOWN	
COSMOS 2133 DEB	1991-010D	21114	12-FEB-91	7-MAY-94	1	1	21806	225	46.6	PROPULSION	SL-12 AUX MOTOR
COSMOSS 2204-06 DEB	1992-047H	22067	30-JUL-92	8-NOV-94	0	0	19033	479	64.6	PROPULSION	SL-12 AUX MOTOR
RS-15 R/B	1994-085B	23440	26-DEC-94	26-DEC-94	21	21	2199	1882	64.8	UNKNOWN	ROKOT FINAL STAGE
H-II R/B	1994-056B	23231	28-AUG-94	31-MAR-95	0	0	24209	129	28.6	UNKNOWN	FIRST JAPANESE R/B BREAKUP
ELEKTRO DEB	1994-069E	23338	31-OCT-94	11-MAY-95	0	0	35467	154	46.9	PROPULSION	SL-12 AUX MOTOR

* From: Teledyne Brown Engineering, Ninth Edition, July 1995

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Abstract

Taking into consideration the results of the National Research Council orbital debris technical assessment study funded by the National Aeronautics and Space Administration, an Interagency Working Group under the direction of the Office of Science and Technology Policy and the National Security Council revised and updated the 1989 Report on Orbital Debris. This 1995 Report contains an up-to-date portrait of our measurement, modeling, and mitigation efforts and a set of recommendations outlining specific steps we should pursue, both domestically and internationally, to minimize the potential hazards posed by orbital debris.

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