# 3: The Current and Future Environment: An Overall Assessement

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**SUMMARY**

Orbital debris is of a concern in primarily two regions of Earth orbital space: low Earth orbit and geosynchronous orbit. The hazard to spacecraft from orbital debris in low Earth orbit has already exceeded the hazard from natural meteoroids. This was predicted by models published over 10 years ago, and had been verified by measurements over the last few years. These same models also predict that certain altitudes are at, or near a "critical density," where the debris hazard will increase as a result of random collision breakups, independent of future spacecraft operational practices. Consequently, there is a need to make immediate changes in operational practices.

The current hazard in geosynchronous orbit has not likely exceeded the hazard from meteoroids. However, models and measurements of the environment in geosynchronous orbit are inadequate; therefore there is currently not an adequate long-term environment management strategy for geosynchronous orbit. A long-term strategy is required because of the increasing use of geosynchronous orbit plus the fact that objects remain in orbit essentially forever at this altitude. There is a need to understand various strategy options before making significant operational changes.

## INTRODUCTION

The unlimited bounds of space could lead one to conclude that we would be incapable of causing an environmental issue in this new frontier. This may be the case for most of space; however, Earth orbital space is finite, and past spacecraft operational practices have already produced an orbital debris environment that will likely affect the design of most future spacecraft operating in near-Earth orbital space. If left unchecked, this environment could increase within the next century to the point that some operations either become too expensive or too risky. In order to effectively manage the environment, we need to understand the environment which we have already produced and the potential sources for future orbital debris. With such an understanding, we may preserve near-Earth space for future generations without significantly altering the current planned activities in space.

There are two major regions of Earth orbit where orbital debris is of concern: 1. Low Earth Orbit (LEO), usually thought of as being below 2000 km altitude. 2. Geosynchronous orbit (GEO), at an altitude of about 35,800 km. The orbital debris issues and solutions in these two regions require different approaches, so it is best to discuss them separately. Therefore this paper will be divided in two parts.

## PART I – LOW EARTH ORBIT

A comparison of the hazards caused by orbital debris and natural meteoroids provides a threshold by which levels of concern can be measured. In low Earth orbit, this comparison is fairly straight forward, and provides some insight to orbital debris issues. Therefore, it is desirable to first understand the meteoroid environment.

### Meteoroids

Meteoroids are part of the interplanetary environment and result from the disintegration and fragmentation of comets and asteroids which orbit the sun. Meteoroids pass through Earth orbital space, rather than orbit the Earth, with a velocity distribution averaging about 16 km/sec (Kessler, 1969). At any one instant, about 200 kg of meteoroid mass is within 2000 km of the Earth's surface. The largest fraction of this mass is in meteoroids with diameters of about 0.1 mm. A lesser fraction of the mass is between meteoroid diameters of 1 mm and 1 cm...the size interval responsible for the "falling stars" or meteors observed at night. This distribution of mass and velocity is sufficient to require shielding on some spacecraft, depending on the spacecraft size and desired reliability. Figure 1 describes the cumulative flux as a function of meteoroid diameter (Grün, et al., 1985). The average number of impacts on any surface is calculated by multiplying this flux by the product of time and average cross-sectional area of that surface exposed to the environment.

Protection against this environment requires a background in the field of hypervelocity impacts, and can become complex when unique materials and geometric properties are taken into consideration. However, as a rule of thumb, aluminum bumper shields can be constructed to have a total added aluminum thickness equal to the meteoroid diameter to be protected against; a single sheet of aluminum would have to be about 5 times more massive than an aluminum bumper, while some "multi-shock" shielding protection techniques are about half as light as an aluminum bumper.

Historically, shielding as light as thermal insulation blankets are usually sufficient for protecting vulnerable areas, such as wiring bundles, and pressurized containers, on small, unmanned spacecraft over their lifetime. This results from the fact, as can be concluded from Figure 1, that only meteoroids smaller than 1 mm in diameter are likely to hit these vulnerable areas over the spacecraft lifetime. Larger, longer duration and high reliability spacecraft, such as the planned Space Station Freedom, would require much more protection against meteoroids. Shielding weights totaling several thousand kilograms would be required to protect the vulnerable areas such as the habitation modules and fuel storage tanks. These higher weights result from the fact, as also can be concluded from Figure 1, that shielding is required to protect against meteoroids of about 0.5 cm over the hundreds of square meters of Space Station vulnerable areas in order to obtain about one chance in 10 that these areas will not be penetrated over the Space Stations planned 30 year lifetime (Christiansen, et al., 1990).

**Fundamentals of orbital debris in Leo**

Within the same 2000 km above the Earth are approximately 7000 man-made orbiting objects which have been cataloged by the US Space Command with a total mass of about 3,000,000 kg. Many of these objects are in near polar orbit, so that their velocities relative to one another can be as high as twice their orbital velocity, or around 15 km/sec. The average collision velocity between any particular spacecraft orbiting in near-Earth orbital space and the cataloged objects are a function of that spacecraft's inclination and ranges from about 10 km/sec for low inclination spacecraft, to about 13 km/sec for near polar orbits. Because these velocities are not too different that for meteoroids, a comparable amount of orbital debris mass in any particular size interval will produce a comparable collision probability, and the damage resulting from a collision will be similar for meteoroids and orbital debris of about the same size. Since, most of the orbiting mass is in intact spacecraft or rocket bodies...objects several meters in diameter, the hazard created by these objects is more than 4 orders of magnitude larger than the hazard from meteoroids which are several meters in diameter. However, this alone is not necessarily significant since meteoroids of this size are not a problem for spacecraft. However, when combined with other data, two issues become obvious which have both short and long term implications to the environment:

1. If only 0.01% of the orbiting mass, or less mass than in a single average spacecraft were converted into a size distribution similar to the size distribution of meteoroids, it would create a hazard similar to the hazard from meteoroids. There have been about 100 satellite breakups due to explosions in Earth orbit...more than enough fragmentation mass to create such a hazard, but the degree of the hazard depends on the fragment size distribution resulting from these breakups. These breakups are the major concern for short term orbital debris considerations.
2. Random hypervelocity collisions will soon begin to convert the orbiting mass of satellites into a size distribution that is not too different than the meteoroid size distribution. Hypervelocity laboratory tests indicate that a hypervelocity collision between an average spacecraft and a several kilogram fragment can be expected to produce a large number of fragments in the 1 mm to 1 cm size interval.

Figure 2 gives the calculated flux (Kessler, 1981-B) of catalogued objects as a function of altitude for an orbiting spacecraft for 1987, when solar activity was low, and for 1991, when solar activity was high. Note that the high solar activity has increased the atmospheric density and reduced the flux below 600 km...this has occurred during previous high solar activity periods. By 1997, when solar activity is expected to be lower, the flux below 600 km should return to about its 1987 values. Figure 2 is averaged over inclination; the flux for spacecraft with low inclinations will be slightly lower (by about 10%) than given in the figure, while some inclinations (e.g., 80 degrees and 100 degrees), will experience twice the flux given in the figure (Kessler, et al., 1989-A). The collision rate for small spacecraft would be small against the catalogued population; however spacecraft larger than about 100 meters in diameter begin to have a significant probability of colliding with a cataloged object. It is for this reason that collision avoidance maneuvers are planned for the Space Station. Just as significantly, the total area of all cataloged objects is larger than the area of a 100 meter diameter spacecraft; consequently, since collision avoidance between all 7000 catalogued objects is impractical, there is a near certainty that two catalogued objects will collide in the relatively near future. Random collisions are the major concern for long term orbital debris considerations.

**Early predictions**

The earliest orbital debris studies by NASA were mostly concerned with calculating the collision probabilities between objects large enough to be catalogued by NORAD (Donahoo, 1970; Brooks, et al., 1975). All catalogued objects are larger than 10 cm in diameter. Fragmentation data from ground explosions and hypervelocity tests gathered by NASA Langley Research Center suggested that a much larger population of uncatalogued objects must exist in Earth orbit (Bess, 1975). NASA, Johnson Space Center (JSC) used the Langley data to predict a future uncatalogued population from random collisions, even if such an uncatalogued population did not currently exist (Kessler, et al., 1978). These predictions were later

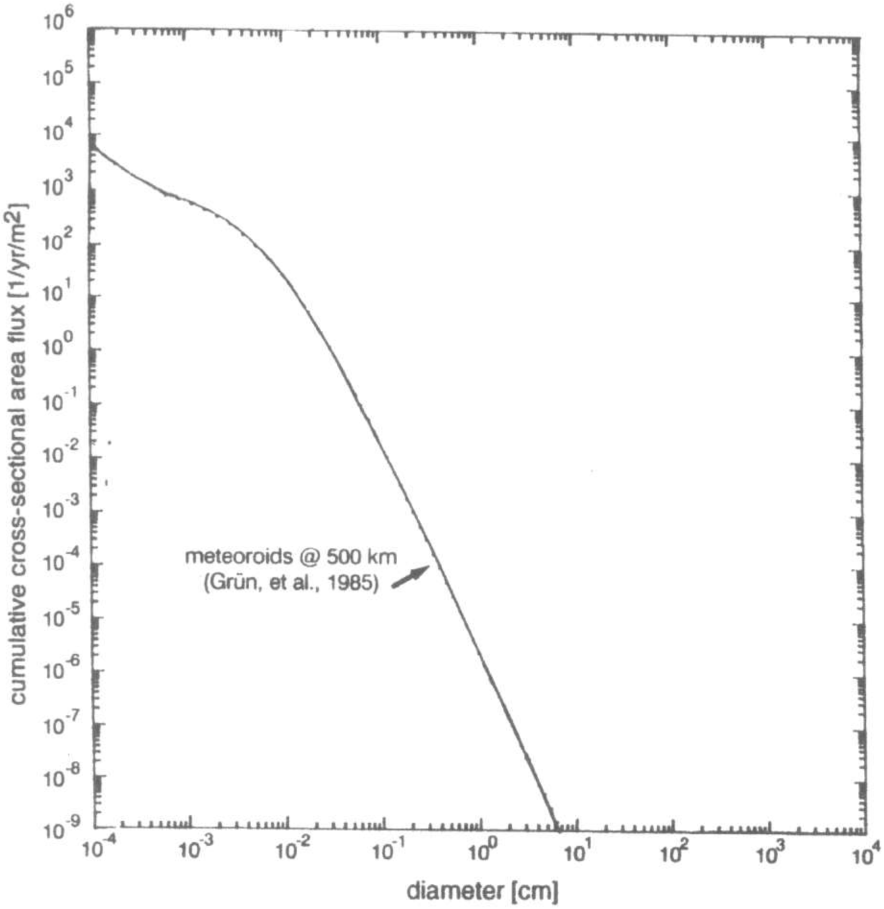


**Figure 1:** Meteroid environment at 500 km altitude.

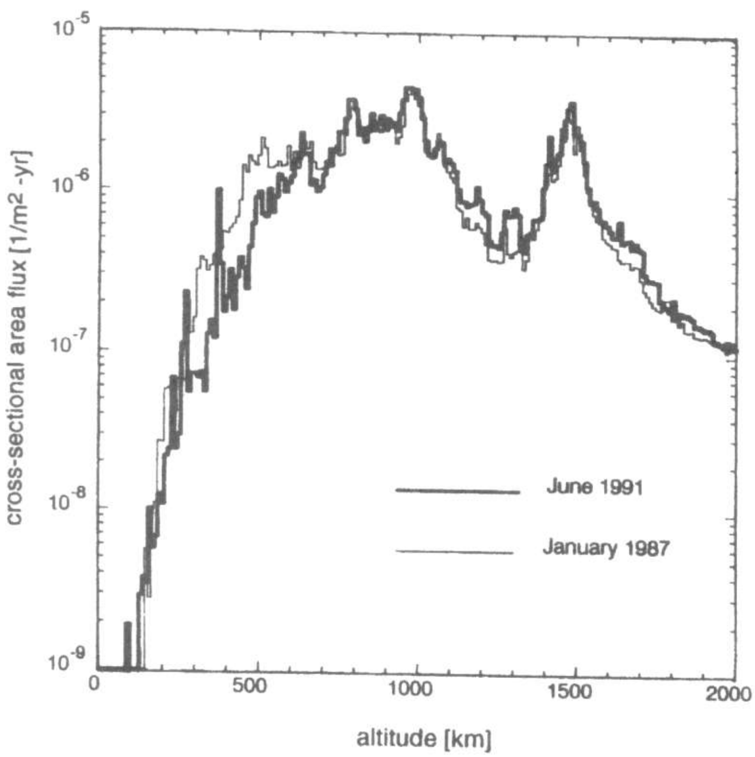


**Figure 2:** Average flux resulting from US Space Command cataloged population.

expanded to include an estimate of the uncatalogued population in 1978 (Kessler, 1981).

Until 1984, there were no measurements of debris in orbit, other than what could be cataloged by NORAD. Predictions of smaller debris had to be based on models which described the process of satellite breakups in terms of number and velocity of breakup fragments, and models which predicted the rate that debris was removed from the environment through atmospheric drag. To predict future environments then, as now, assumptions had to be made concerning future traffic into space and the rate that future satellites will breakup. A measure of the ability of these models to predict the future environment can be obtained by comparing these early model predictions with today's measurements.

Figure 3 shows a published prediction (Kessler, 1981), based on 1978 data, when the catalogue contained about 4500 objects. The 1978 Debris "Observed" line represents the catalogued population between 600 km and 1100 km; the "Corrected" line is a model prediction of the 1978 environment based on a comparison of the size distribution measured from explosions on the ground and the size distribution of catalogued orbiting fragments. Note that this analysis predicted that there were about twice as many objects in orbit that were larger than 10 cm than is reflected in the catalogue, and more than three times as many objects larger than 4 cm. The analysis also predicted that by 1995 there would have been 3 satellite breakups caused by random collisions, producing a population of smaller debris that produced a debris flux which exceed the meteoroid flux for sizes larger than about 1 mm. Since debris in these size ranges have now been measured, and 1995 is less than 3 years away, these predictions can be compared with recent measurements.

**Measurements of uncatalogued population**

The number of orbiting objects increases with decreasing size. If one were to try to catalogue all orbiting objects, eventually, the catalogue would become so large that only a statistical interpretation of the population would be meaningful. Consequently, there is a debris size where statistical measurements become more cost effective. Statistical measurements sample a fraction of the population and do not require that the each detected object be tracked so that it can be observed again.

Sampling of objects in Earth orbit is a less difficult problem than the cataloging of objects; however, the detection of uncatalogued objects requires either different sensors, or that these sensors be operated in a different mode than the sensors used to catalogue. Remote sensors are required for debris larger than about 1 mm, simply because the population of this size debris is sufficiently sparse that a large collection area is required in order to obtain a statistically meaningful sample. Below 1 mm, the population is sufficiently dense that direct impact on spacecraft will obtain a statistically meaningful sample. The least expensive remote sensors are Earth based; consequently, these sensors have provided the best data to date. The measurements to date have been obtained using ground telescopes, ground radar, and returned spacecraft surfaces.

*Ground telescopes*

A 1 cm diameter metal sphere in sun light at 900 km distance would appear as a 16th magnitude star. Since telescopes larger than about 30 inches can detect stars of this magnitude, in 1983 NASA Johnson Space Center (JSC) contracted MIT Lincoln Labs to use their Experimental Test Site (ETS) to look for 1 cm debris. An advantage of the ETS was that it contained two 31 inch telescopes which could look at the same area of the sky to use parallax to determine altitude. It was felt that this feature would be essential to discriminate against the luminosity caused by much smaller meteoroids hitting the Earth's atmosphere (meteors) at about 100 km altitude. The telescopes were operated just after sunset and just before sunrise, when the debris was in sun light and the telescopes were in darkness. The telescopes were pointed vertically, and debris was observed to pass through the field of view. Nine hours of data were recorded on video tape and analyzed by Lincoln Labs. Published results (Taft, et al., 1985) concluded that the ETS detection rate was 8 times the rate expected from objects in the catalogue. However, two errors were found in the analysis, plus one of the assumptions proved to be wrong.

NASA, JSC reanalyzed the ETS data and found parallax errors which placed a larger number of the objects detected into the category of meteors. This reduced the detected orbital debris to between 2 and 5 times the catalogue rate, depending atmospheric seeing conditions. A calibration error placed the limiting magnitude of the telescopes at 13.5 for debris with the typical angular velocity of 0.5 deg/sec. Finally, independent measurements using radar, infrared wavelengths and optical wavelengths determined that the assumption that debris fragments would reflect light similar to a metal sphere was wrong. Debris fragments reflect much less light than a metal sphere...typically only about 10% of the light is reflected, although some objects reflect a larger fraction. Consequently, the limiting size measured by these telescopes was about 8 to 10 cm.

Since then, NASA has worked closely with the US Space Command to use their Ground Electro-Optical Deep Space Sensors (GEODSS), which are telescopes, similar to Lincoln Lab's ETS, except they are slightly less sensitive (limiting magnitude of about 13 at 0.5 deg/sec.), and have twice the field of view. Over a hundred hours of data have been analyzed by NASA which produced nearly a thousand orbiting objects. The US Space Command catalogue was used to predict which of the detected objects were already in the catalogue. Only about half of these objects can be identified as being catalogued objects (Henize, 1990). Consequently, these telescopic measurements have provided convincing data to NASA that at about the 10 cm threshold, the low Earth orbit catalogue is only about 50% complete. The exact limiting size measured by

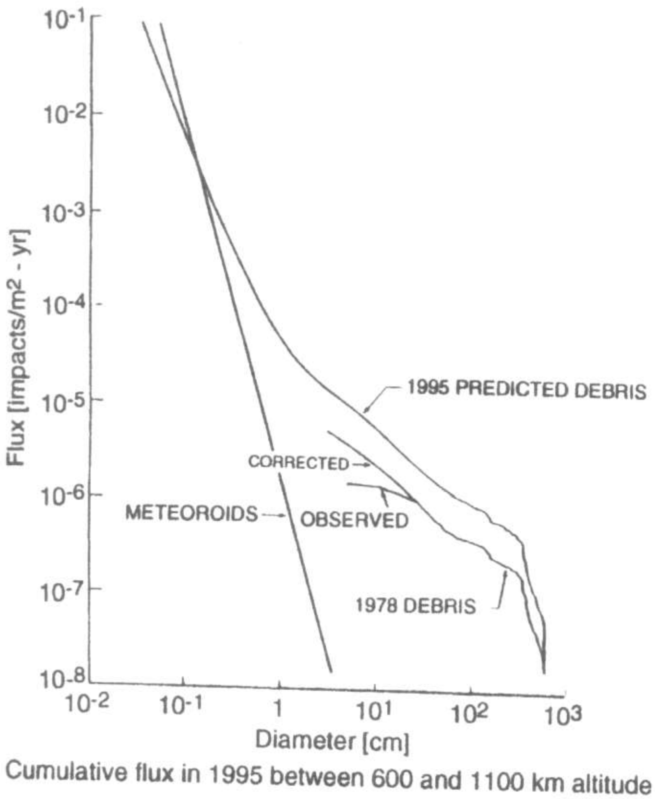


**Figure 3:** Early model predictions of orbital debris environment. (Published in 1981)

each of these two different types of sensors is a function of two different distributions relating signal return to size, and also a function of the rate of increase in the number of smaller debris with decreasing size. When these distributions are taken into account, the "average" limiting size of the telescopes can be shown to be slightly smaller than the "average" limiting size for the catalogue. The DOD has a program to better understand the size and orbits of these uncatalogued objects by tracking them with radar and ground telescopes. However, because NASA requires data on smaller debris, its program has been expanded to obtain measurements using the Haystack ground radar. This radar is now detecting a smaller population at a rate that is more than 60 times the catalogue rate.

*Ground radars*

The failure of ground telescopes to detect 1 cm orbiting debris forced NASA to reexamine the use of radar to detect uncatalogued objects. A major reason that US Space Command radars do not detect smaller objects is that most of their radars operate at a 70 cm wavelength; consequently, objects as small as a few centimeters in diameter are well into the Rayleigh scattering region and reflect a very small fraction of the radar signal. A shorter wavelength radar, in principle, could detect smaller objects. However, another factor in the limiting size of catalogued objects is in the method of the operation of radars to catalogue objects. In order to catalogue an object, the object must first be found within a large volume of space, then the object must be tracked by several radars over an extended period of time. This process requires a larger threshold size than a process which only required detection within a smaller volume when the object is closest to the sensor.

In 1987, NASA, JSC developed a technique of using a radar in a "beam park" mode, where the radar stares in a fixed direction (preferably vertically) and debris randomly passes through the field-of-view. In this mode, using a relatively inexpensive, high powered, moderate size X-band radar (3 cm wavelength), objects as small as 1 cm could be detected at a 500 km altitude. In 1987, interest in the hazards of orbital debris to the Space Station produced a series of events which resulted in an agreement between NASA/JSC and the US Space Command to operate the Haystack radar, located near Boston, in the beam park mode, and to develop the necessary computer programs to analyze the data. However, the Haystack radar is not optimally designed (the antenna beam width is small, consequently more time is required to obtain the necessary data), nor optimally placed (its too far north, and cannot see low inclination debris). Therefore, a Haystack auxiliary radar is being built next to the Haystack radar. In addition, another radar near the equator is to be built, although the detail of this radar has not yet been resolved. As a result of this series of events, a significant amount of ground radar data has been obtained using the Arecibo, Goldstone, and Haystack radars.

To test the concept of obtaining orbital debris data in a beam park mode, in 1989, NASA, Jet Propulsion Laboratory (JPL) used the Arecibo Observatory's high-power S-band radar, and the Goldstone Deep Space Communications Complex X-band radar to obtain orbital debris data. Neither radar was optimally configured to obtain data in this mode, although both radars were predicted to detect small debris, if it existed. In 18 hours of operation, the Arecibo experiment detected nearly 100 objects larger than an estimated 0.5 cm in diameter (Thompson, et al., 1992). The predicted number from the catalogue alone was about one. In 48 hours of observation, the Goldstone radar detected about 150 objects larger than about 0.2 cm in diameter (Goldstein, et al., 1990). The probability that at least one catalogued object would pass through the field of view during the 48 hours was about 0.13, indicating a population which is slightly more than 1000 times the catalogued population. Because little effort was made to accurately define these radars field of view, and to properly calibrate the radars, this data has fairly large uncertainties. Even so, these two experiments did demonstrate that data could be obtained is this mode of operation, and that there was a large population to be detected.

After testing the concept, NASA committed to a program of using the Haystack radar to obtain orbital debris data. The program included calibration of fragment size using a radar range and fragments from ground tests, calibration of the antenna pattern, development of a real-time Processing and Control System to process and record detections, and establishment of a data processing facility at JSC. In order to ensure that NASA was properly acquiring and analyzing the data, a peer review panel was established. The chairman was Dr. David K. Barton and included other well known experts from the radar community. The panel concluded that "the Orbital Debris Radar Measurements Project is fundamentally sound and is based on good science and engineering." They also made a number of recommendations to improve efficiency or accuracy of the data. Many of those recommendations have been implemented.

To date, over 1000 hours of data have been collected, of which over 800 hours has been analyzed, and more than 2000 objects have been detected passing through the radar beam (Stansbery, et al., 1992). Figure 4 gives the altitude of each detection when the radar beam is parked in its most sensitive position of looking vertically, compared to the detection rate expected for the catalogue alone and the rate predicted by the model given by Kessler et al., 1989. At the lowest altitudes (350 km), objects larger than 0.3 cm are detected. At the highest latitude (1400 km), objects larger than 0.6 cm are detected. The detection rate averaged over all altitudes is about 65 times the rate predicted by the catalogue alone. In the altitude band between 850 km and 1000 km, the rate is 100 times the rate predicted by the catalogue alone.

*Recovered samples*

Objects returned from space usually contain pits or holes from hypervelocity impacts with meteoroids or orbital debris. Outside the laboratory, these are the only two possible sources which can impact surfaces with sufficient velocity to cause melting of the surface in the impacted area. One technique to determine which of these sources caused the impact pit or hole is to use the scanning electron microscope (SEM) dispersive X-Ray analysis to determine the chemistry of material melted into the surface. This analysis has been completed for some of the pits found on Space Shuttle windows, impacts into surfaces returned from the Solar Max repair mission in 1984, surfaces on the returned Palapa satellite, and some of the Long Duration Exposure Facility (LDEF) surfaces, returned to Earth in 1991. Because LDEF was a controlled experiment, was in space for nearly 6 years, had a large surface area, and was always oriented in the same direction with respect to the orbital velocity vector, these surfaces are providing the best data to date. Analysis of LDEF surfaces is still continuing, however the data analyzed thus far exceeds the quality of the earlier data.

The largest impact crater predicted and found on LDEF was slightly larger than 5 mm in diameter, likely due to an impact by an object 1 mm in diameter The number of impact craters increased rapidly with decreasing size, with more than 3000 craters larger than 0.5 mm. The most complete chemical analysis has been conducted by Fred Hörz, the Principal Investigator for the Chemistry of Micrometeroids Experiment (Hörz, et al., 1991; Bernhard, et al., 1992). The analysis to date indicates that about 15% of the impacts in the gold surfaces, facing in the rear direction, are orbital debris. The most common orbital debris impacts are aluminum; however, copper, stainless steel, paint flecks, and silver were also found. Orbital debris impacts on rear surfaces was a surprising result because a very small set of elliptical orbital debris orbits are capable of hitting the rear surfaces (Kessler, 1992). The most probable direction for orbital debris to impact is the front and side surfaces; the surfaces facing in this direction are made of aluminum, and aluminum impacts cannot be identified. Even so, 14% of the impacts on these surfaces were identified as orbital debris; the origin of 55% of the impacts could not be identified because only aluminum was detected. If the ratio of aluminum to other orbital debris compositions found on the gold surfaces is also on the aluminum surfaces, then most of the impacts on aluminum surfaces that could not be identified would have been caused by an aluminum impact. This would increase the orbital debris impacts on the aluminum surfaces. When averaged over all orientations, the average number of orbital debris craters to meteoroid craters may be about the same, or slightly higher, as the results obtained from the Solar Max Satellite (Barrett, et al., 1988). Analysis of the LDEF surfaces is not complete.

Perhaps the most surprising result on LDEF came from the Interplanetary Dust Experiment (Mulholland, et al., 1991). This was the only experiment on LDEF which measured the time of impact. Six detectors were on orthogonal surfaces, and sensitive to impacts smaller than 1 micron. The surprising result was that most impacts could be associated with "orbital debris swarms." That is, the sensors would detect a large

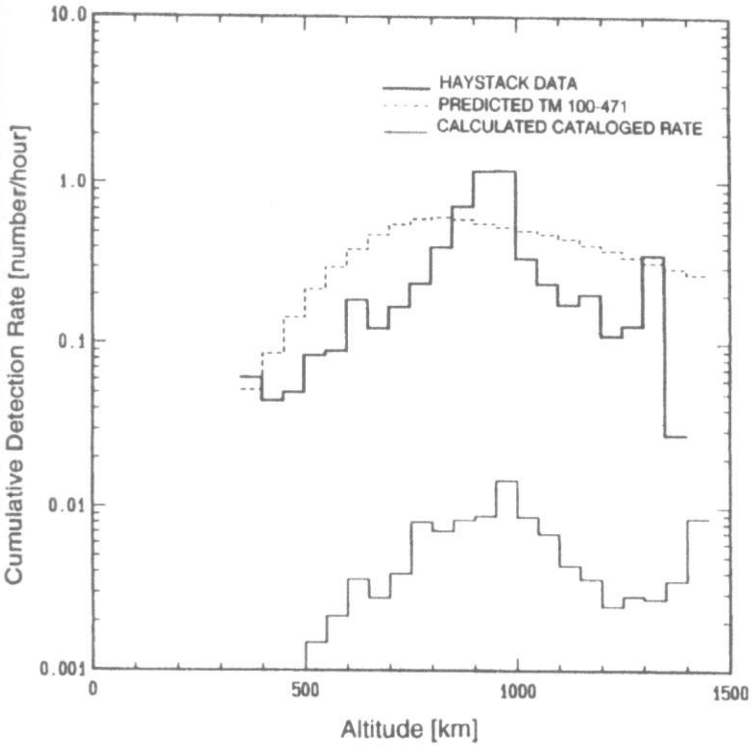


**Figure 4:** Rate of detection by the Haystack Radar, vertically pointed for 188 hours.

increase in flux, lasting for a few minutes, at the same points in the LDEF orbit, and these points would slowly change with time...characteristics of orbital precession rates. However, in retrospect, these results should not have been such a surprise.

The small amount of mass required to produce a large flux of less than 1 micron debris in Earth orbit, coupled with their short orbital lifetime would predict that a large number of particles could be found in orbits close to the orbit of their source. If the source is paint being removed by atomic oxygen erosion, then less than 10 grams of paint is needed to be removed from each orbiting spacecraft per year to explain these results. If the source orbit is highly elliptical, then less than 1 gram of paint need is needed. These are rates consistent with the rates expected from atomic oxygen erosion.

Other sources are possible, such as the large amount of aluminum oxide dust that each solid rocket motor expels when fired. This dust is expelled at a velocity of 3.5 km/sec, and over a range of directions, most of which would cause the dust to immediately reenter the Earth's atmosphere. Although some dust would remain in orbit, most should reenter quickly and not product swarms lasting for several months, as observed. However, this is not to say that a spent rocket stage might not slowly release sufficient dust to produce the long lasting swarms. These are possible areas of future research.

*Summary environment*

A summary of the best measurements to date is shown in Figure 5, compared to the natural meteoroid environment. When compared to the 1995 model predictions shown in Figure 1, there is a general agreement (within a factor of 2) over nearly the entire size range, even though some of the measurements were made at altitudes of 600 km, or lower, where debris was predicted by some analysis to be much less than the environment between 600 and 1100 km. This could be interpreted as an indication that the environment was under predicted for sizes smaller than about 5 mm, and this may be the case. However, some of this data is indicating that elliptical orbits are important in this size range and at these lower altitudes. Elliptical orbits will produce an environment that is less altitude dependent than circular orbits. Until all of these parameters are understood, or until small debris measurements are made at higher altitudes, there will be an uncertainty in extrapolating these measurements to higher altitudes.

What should have been the easiest prediction is the catalogued population. The prediction was that would be slightly over 11000 catalogued objects in orbit by 1995. There are currently 7000, and this number might increase to 8000 by 1995, but not 11000. There are three important reasons for under predicting the catalogued population: 1. Rather than a slight increase in the amount of material launched into space, the rate of launches world wide has remained constant. 2. Two of the three highest solar activities in 200 years of record keeping occurred between 1978 and 1992. High solar activity increases the atmospheric density, causing more objects to reenter from orbit. 3. Since 1981, the US has lead an effort to minimize on-

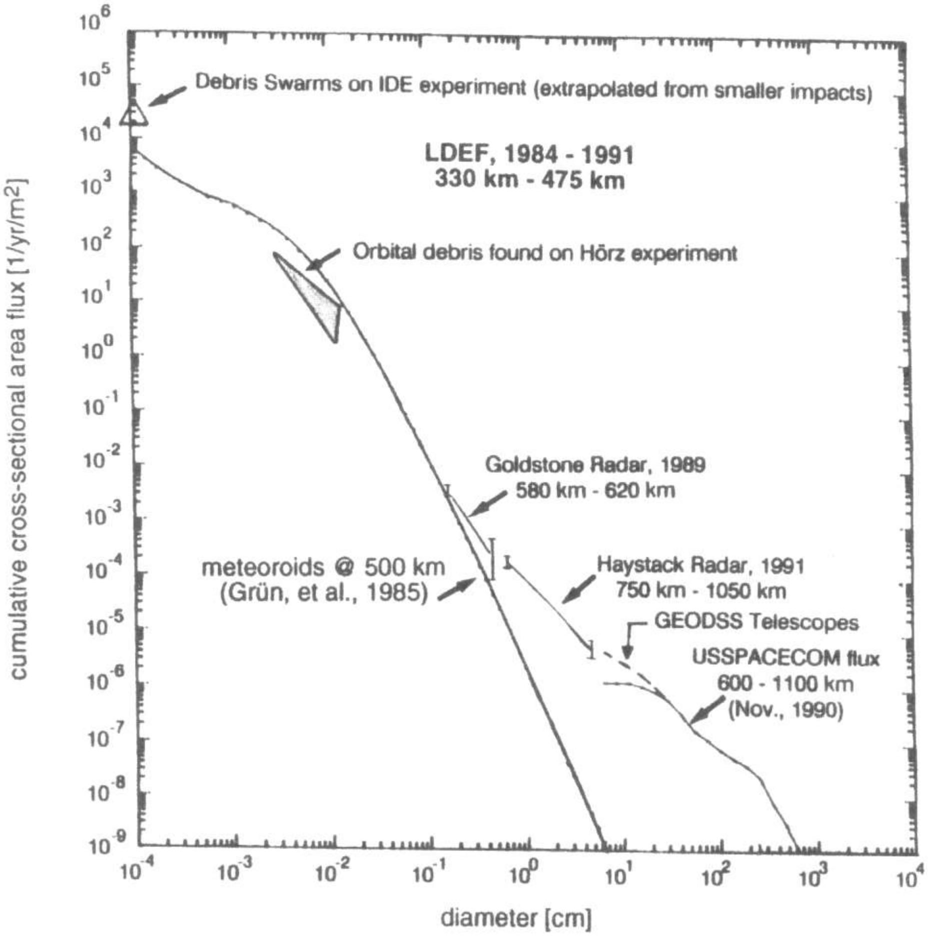


**Figure 5:** Meteoroid environment compared to recent measurements of orbital debris environment.

orbit explosion. As a result, fewer US, ESA and Japanese upper stages have exploded in orbit than would have occurred if this effort had not been undertaken.

For the above three reasons, the 1995 prediction of the uncatalogued population should have also been high. That is, as a result of fewer large objects in orbit, there should be fewer random collisions to generate small debris; also as a result of fewer on-orbit explosions, there should have been less small debris. The implications are that either the current breakup models are under predicting the amount of small debris which is generated and remains in orbit, or there are unmodeled sources of debris. The most likely cause is the breakup models, and that these models are under predicting the fraction of mass which goes into smaller debris. This should not be surprising since smaller fragments are more likely to be lost during ground experiments to determine breakup characteristics. The possible tendency of current breakup models to under predict should be keep in mind as similar models are again used to predict the future environment.

**Future environment**

The most important parameters in predicting the future orbital debris environment is the rate and consequences of satellite breakups. The major issue is the size and velocity distribution of fragments produced as a function of the amount of fragmentation energy by various fragmentation energy sources. In the past and near term, the energy sources have mostly been chemical, and we can see that this source has already produced a hazardous environment for most spacecraft. Chemical explosions can easily be controlled; so our near term environment will be a function of our efforts toward eliminating these past sources of explosions in orbit. However, in the future, the major energy source could be kinetic energy; this source is not as easily controlled. The amount of kinetic energy represented by an object as small as 1 kg, traveling 10 km/sec is not too different than the amount of chemical energy which caused past chemical explosions in orbit.

Like most chemical explosions, most of the mass of fragments from a hypervelocity collision is in the larger fragments; however, because the energy source is concentrated in a smaller amount of mass, higher temperatures are reached and melting of the impacted spacecraft occurs, which results in a small, but significant fraction of the mass being distributed in smaller fragments. These characteristics of hypervelocity collisions, combined with the increasing rate that they could occur if no changes in current practices are made within the next few years, make them important to the future orbital debris environment in low Earth orbit.

The Defense Nuclear Agency (DNA) has a program to define better breakup models (Tedneschi, et al., 1991). The analysis of hypervelocity tests by DNA are not yet complete; however, a gross characterization would be that they are in general agreement with the assumptions of earlier models; that is, at 10 km/sec, a 1 kg fragment can completely fragment a 1000 kg spacecraft, producing hundreds of 1 kg fragments, each of which could fragment another spacecraft, and also producing millions of smaller hazardous fragments, each capable of damaging an operational spacecraft. Some masses catalogued by the US Space Command are smaller than 1 kg, while there is undoubtedly some uncatalogued fragments which exceed 1 kg. The rate that catalogued objects can be expected to collide with one another is a fairly easily calculation. Based on the current population, the rate is about one collision every 20 years (Kessler, 1991A); however, to date, such an event has not been observed to occur. Estimates of the mass of uncatalogued debris predict that the current rate of satellite breakups from hypervelocity collisions is about once every 8 years (Kessler, 1991B); there is data and analysis (Johnson, et al., 1991; Johnson, 1992; McKnight, 1991) to suggest that such events have occurred. Because these rates are proportional to the square of the number density of objects in orbit, these collisional fragmentation rates can become much more frequent in the relatively near future if objects continue to accumulate at past rates.

The Earth's atmosphere will remove fragments from low Earth orbit. If fragments are removed faster than they are generated, then an equilibrium environment will be established, and this environment will not increase unless new material is added to Earth orbit. However, if collisions are producing fragments at rate faster than they can be removed by the atmosphere, then the orbital debris environment will continue to increase even without adding new material to orbit. The satellite population density which will produce collision fragments at the same rate they are removed has been defined as a "critical density." To attempt to maintain a satellite population above the critical density means that debris will increase as a result of random collisions alone. Objects nearer the Earth are removed at a faster rate. The rate that fragments are generated is not only a function of number density, but satellite size and inclination of the orbits.

Figure 6 compares the 1989 catalogue with a calculated critical density as a function of altitudes (Kessler, 1991). The figure shows that below 800 km, atmospheric drag removes fragments at a sufficiently large rate and that this region is well below the critical density line. Between 800 km and 1000 km, the current population density is above the critical density line. Above 1000 km the physical size of satellites is smaller, reducing the fragment generation rate; even so this rate exceeds the removal rate again above 1400 km. The uncertainty in this critical density line is about a factor of 3; consequently, within this uncertainty is the possibility that a critical density has not yet been reached. However, even if it has not been reached, the population of these two altitude bands might be expected to exceed the critical density within the next few years.

Similar conclusions have been independently reached by other researchers using different modeling approaches (Eichler, et al., 1990, Talent, 1991; Farinella, et al., 1991; Lee, et al., 1990). An evolutionary model (EVOL) developed by NASA, JSC (Reynolds, et al., 1990) illustrates the same trends and is being used to evaluate the consequences of various possible operational practices. In Figure 7, this model is used to plot the 1 cm population at 400 km and 1000 km as a function of time for several operational conditions. The "case 1" curves assume "business as usual, keeping the world launch rate at the current 100 launches per year, with all objects allowed to accumulate in orbit at the end of their life, and no reductions in the rate objects explode in orbit. At the end of 100 years, the environment is a factor of 10 larger than the current environment at 1000 km altitude. At 400 km altitude, the flux varies due to the varying atmospheric density due to solar activity; even so, the flux has a general upward trend with time. The "case 2" curves assume the same conditions, except all chemical explosions are eliminated in the year 2000. Note that the rate of increase of 1 cm debris immediately begins to decrease when explosions are eliminated, especially at 400 km. However, by the year 2030, there are sufficient old rocket bodies and payloads in orbit that the satellite break up rate from random collision causes the 1 cm flux to begin to increase again. By the end of the century at 1000 km the fact that explosions were eliminated is of minor importance. Under these conditions, kinetic energy has become the most important source of energy causing satellites to break up in orbit.

Kinetic energy can be eliminated by eliminating mass in orbit. The bottom curve assumes the same conditions as the 2nd curve, except that after the year 2000, rocket bodies are required to reenter after delivering their payload, and after the year 2030, payloads are required to be removed from orbit at the end of their operational life (assumed to be 10 years). Under these conditions, the 1 cm environment continues to decline. Consequently, this model, as well as other models, is predicting that future payloads and rocket bodies must be reentered in the relatively near future in order to keep the future small debris population from increasing.

**Environment management of low Earth orbit**

In the short term, management of the low Earth orbit orbital debris environment is concerned with the control of explosions in orbit. Users of space are already adopting new operational procedures which are designed to accomplish this. This includes depleting the unused fuel from orbiting upper stages after payload orbit insertion and conducting military tests at low altitudes to ensure that all fragments reenter. However, it now seems clear that in the long term, these changes will make

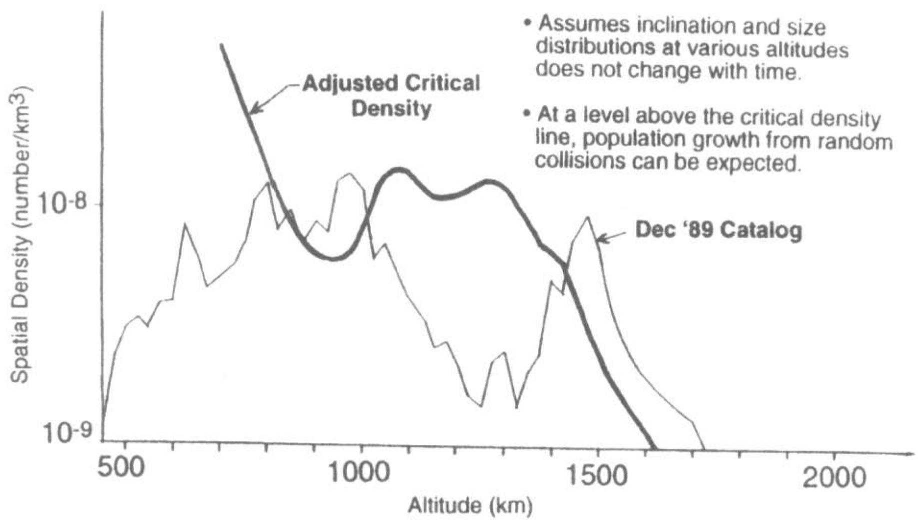


**Figure 6:** Critical density compared to 1989 cataloged population where the catalog is maintained.

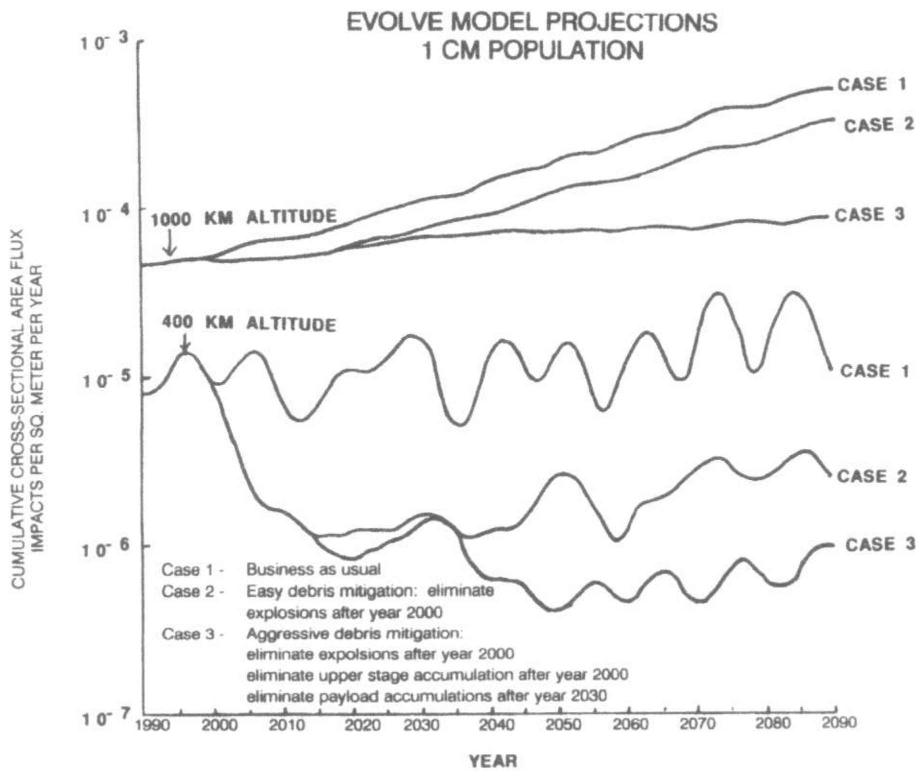


**Figure 7:** Predicted 1 cm flux for three possible operational practices, all assuming a continuation of current launch rates.

little difference and new, more costly changes must be made. Some of these changes should begin now.

The design process should begin now which would prevent mass from continuing to accumulate in certain regions of low Earth orbit. Various techniques have been studied which could accomplish this (Loftus, et al., 1991). These techniques include the planned reentry of rocket stages, payloads, self disposal options, retrieval, and the use of drag devices. An option which could begin very soon is the planned reentry of certain rocket stages. With a minor amount of additional fuel and an extended battery life, many of the currently used upper stages could be left in orbits with much shorter lifetimes after delivering their payloads.

Upper stages left in transfer orbits from low Earth orbit to geosynchronous orbit can cause a significant problem to altitudes below about 500 km (Kessler, 1989). This is because at these lower altitudes, the orbital lifetime of these high energy orbits can be very long. However, the lifetime of these stages can be shortened considerably by a very small change in velocity at the apogee of the transfer orbit. The required change in velocity is so small that lunar and solar gravity can be used, if the original orbit has the proper orientation with respect to the sun (Mueller, 1985), to cause the upper stage to reenter within a year.

The reentry of payloads is more difficult because payloads do not usually have the potential propulsive capability of upper stages. Alternatives include the use drag devices (i.e., deploy a large surface area, such as a balloon, so that the atmosphere will drag the object out of orbit more quickly), or tethers. The cost of alternatives such as these and others need to be evaluated against the cost of simply increasing payload propulsion capability.

The cost of the retrieval of objects in orbit using current technology is very high, and this is a major reason for designing removal options into future rockets and payloads. However, this is not to say that future technology could not provide a dedicated retrieval system that would be inexpensive to operate. If so, such a system might then relieve some future design requirements. However, the need to not leave dead rocket stages and payloads in low Earth orbit is immediate, and should become a design consideration for all new programs.

## PART II – GEOSYNCHRONOUS ORBIT

Orbital debris studies concerning geosynchronous orbit are slightly more than 10 years old (Hechler, et al. 1980). Most of the studies to date have been concerned with the larger, cataloged objects (Chobotov, 1990; Flury, 1991). No models have been developed to predict the population of small debris, nor how this population might vary with time. No measurements have been conducted to determine the orbital debris population to sizes smaller than about 1 meter in diameter.

The reasons for the lack of modeling and data are twofold: 1. The higher collision velocities in low Earth orbit cause the consequences of collisions to be more dramatic than in geosynchronous orbit. For some time there has been sufficient data to show that the environment in low Earth orbit affected the design of planned NASA missions, resulting in more resources being devoted to understanding and controlling this environment. 2. Geosynchronous orbit is farther away from Earth. While this distance has kept traffic to geosynchronous orbit smaller than to low Earth orbit, it has also made observational data more difficult to obtain; consequently, more resources may be required to obtain the necessary data than have been devoted to low Earth orbit research. Despite the lack of data, some users are unilaterally adopting a policy of moving their dead payloads to higher altitudes, "grave-yard" orbits. While this may provide some operational convenience, it may be totally inappropriate to long-term environment management.

### Fundamentals of orbital characteristics in geosynchronous orbit

The orbital period of an object in geosynchronous orbit is the same as the time required for the Earth to spin one revolution, or about 23 hours and 56 minutes. If the orbit has zero eccentricity and inclination, the object will appear to be stationary (hence the orbit is sometimes referred to as geostationary orbit) over a location on the Earth's equator, and because its altitude is about 35,786 km, it can be seen by nearly an entire hemisphere. However, this orbit is sufficiently far from the Earth that the forces produced by the sun and moon will not allow the orbit to naturally maintain a zero eccentricity and inclination. Eccentricity is typically less than 0.001, keeping perigee minus apogee distances to less than 100 km. This is sufficiently small that it does not cause a ground tracking problem. However, inclination will naturally oscillate between zero and 15 degrees over a 53 year cycle. This can cause a ground tracking problem, so that a significant fuel budget is usually required for "North-South station keeping."

Without "East-West station keeping," another ground tracking problem would exist. The fact that the Earth is not a perfect sphere also causes an oscillation in the longitude of an uncontrolled satellite. This oscillation is about the nearest "stable point," located over longitudes of 75 degrees East, and 105 degrees West. If the desired position of the satellite is far away from the stable points, the satellite would oscillate nearly halfway around the Earth before returning about 3 years later. Fortunately, East-West station keeping fuel requirements are small, requiring less than 5% of the fuel budget required for North-South station keeping (Flury, 1991).

### The orbital debris problem

The orbital debris problem results from the accumulation of satellites, fragments of satellites, and operational debris in orbits which pass through the paths of operational geosynchronous satellites. Any of these objects could collide with an operational spacecraft, damaging it and reducing its operational life. If a large number of objects accumulate, the hazard could significantly add to the hazards from other sources, such as collisions with natural meteoroids. Figure 8 is an expansion of Figure 2 for 1991, and compares the flux of catalogued objects in low Earth orbit with geosynchronous orbit.

At geosynchronous altitudes, there is only one natural process which will eventually eliminate a satellite from this altitude. Over extended periods of time, spacecraft and fragments of spacecraft will break up from collisions with other objects which are either in or pass through the geosynchronous region. The smallest fragments (less than about 10 microns) are affected by solar radiation, which both increases the orbital eccentricity and decreases the orbital semi-major axis, resulting in the smallest fragments being removed from orbit by hitting the Earth's atmosphere within a few months (Mueller, et al., 1985; Friesen, et al., 1992-B). If this process acted quickly to remove fragments of all sizes, then the accumulation of

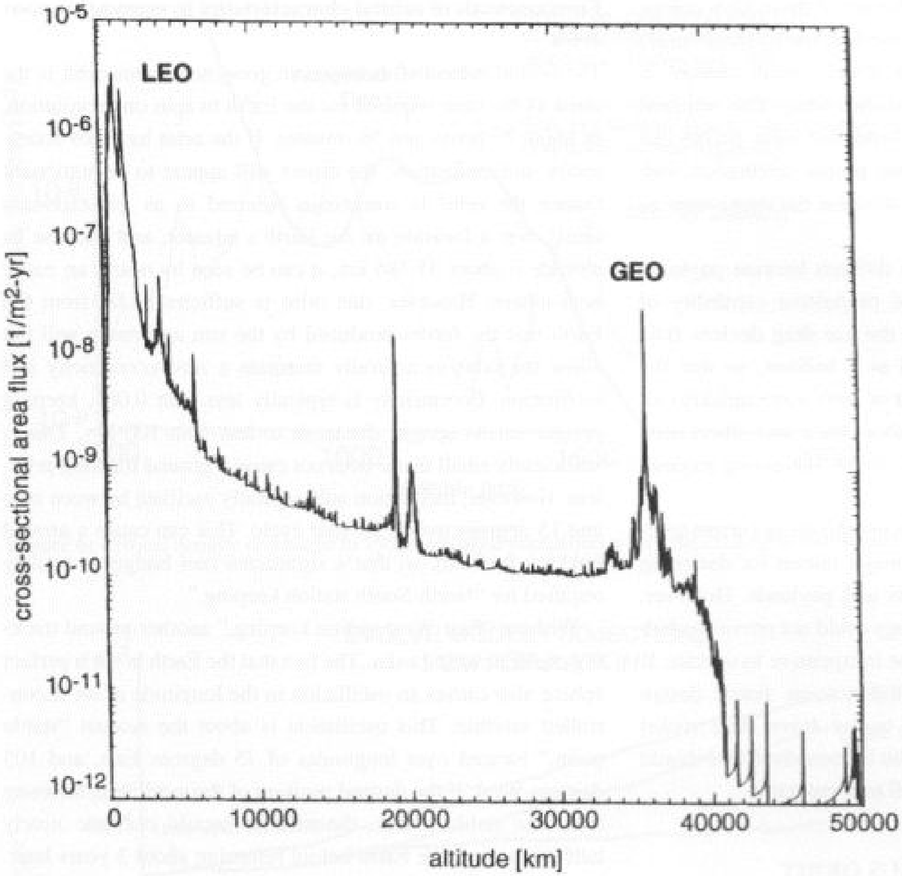


**Figure 8:** Average flux resulting from US Space Command cataloged population.

debris at geosynchronous altitudes problem would be minimal; however, this is not the case. If the rate of fragment generation were small, the hazard would not be significant for a long period of time. As will be developed in the following sections, collisional fragmentation rates are likely to be small; however, the rates that satellites fragment for operational or design failures are probably much larger.

**Time scale for the orbital debris problem**

The time required for an object to be removed from the geosynchronous altitude from solar radiation forces alone is very long. Objects smaller than about 1 cm require about 60,000 years for the orbit to decay sufficiently so that no part of the solar radiation pressure induced eccentricity causes the orbit to cross geosynchronous altitude (Friesen, et al., 1992-A). When eccentricity is induced by other forces, the time is longer. Lunar and solar gravity control the eccentricity of objects larger than 1 cm, while collisional forces are likely to control the eccentricity of collisional fragments of all sizes. Consequently, most debris is likely to cross geosynchronous orbit for periods much longer than 60,000 years, perhaps 100,000 to 1,000,000 years. An even longer period of time is required for the debris to be removed from Earth orbit, unless object is very small, less than about 10 microns. Solar radiation pressure increases the eccentricity of very small debris to such a large value that the debris collides with the Earth within a few months (Mueller, et al., 1985; Friesen, et al., 1992-B).

The rate that collisional fragments are generated in geosynchronous orbit is not so clear. This rate is a function of three parameters: 1. The rate of collisions. 2. The velocity of collisions. 3. The efficiency with which the collisional energy produces fragments of various sizes and velocities. None of these parameters are well defined at this time, although a few attempts have been made to determine them.

**Rate of collisions**

The rate of collisions for any particular object (i.e., a measure of the hazard to that object) is proportional to the area of that object and the number of other uncontrolled objects in orbit. The rate at which any two objects collide (i.e., a measure of the rate of debris production) is proportional to the rate for a typical uncontrolled object and the number of uncontrolled objects. Consequently, debris production from collisions increases as the square of the number of uncontrolled satellites in orbit. The relationship between orbital elements and collision rates has been developed by a number of investigators.

A simple approach for obtaining the collision rate was introduced by Perek (1978). Perek calculated the collision rate by first taking the ratio of the collisional cross-sectional area of active satellites to the area of the geosynchronous ring. Inactive satellites, which would generally have an inclination of several degrees, would pass through the geosynchronous ring twice a day. The collision rate per 12 hours is then this ratio times the number of inactive satellites. A more accurate, but more complex approach was developed by Kessler (Kessler, 1981). Both approaches assume an even distribution of satellites around the geosynchronous ring. Perek's approach can be shown to be equivalent to Kessler's approach as long as orbital inclinations of uncontrolled debris are between about 0.1 degrees and 20 degrees, and orbital eccentricities are small, which is the case for most debris in geosynchronous orbit.

The simplicity of Perek's approach provides some additional insight; namely, that collision probability in geosynchronous orbit is approximately independent of orbital inclination. Consequently, this approach can be used to obtain the collision rate between any two inactive satellites if the differences in inclination are between 0.1 and 20 degrees, which is generally true for most pairs of uncontrolled satellites. If N is the number of uncontrolled satellites, then the average rate of collisions between any pair would be N(N-1)/2 times the rate of collisions between a single pair.

There are currently about 250 objects known to be in geosynchronous orbit, with average linear dimensions of about 5 meters (Royal Aircraft Establishment). Most of these objects are in orbits which confine their motion to a 100 km band, centered at the geosynchronous altitude. Assuming all of these objects become uncontrolled and are randomly distributed within this band gives an average collision rate of once every 15,000 years. This is about the same rate if one assumed an average flux of $7 \times 10^{-9}/\mathrm{m}^2 - \mathrm{yr}$. From Figure 8, this flux might be an appropriate average within the geosynchronous band, although it is likely that the appropriate average could be slightly higher due to the non-uniform distribution within the geosynchronous altitude band. Even so, the collision, rate is low compared to the rate in low Earth orbit; however, like low Earth orbit, it is high compared to the rate that objects are removed by natural forces. Also like low Earth orbit, this rate increases as the square of the number of objects in orbit; consequently, if the rate of accumulation of objects in geosynchronous orbit continues at its current level of 25 objects per year, then there is a 50% probability that there will be at least one collision in geosynchronous orbit in the next 140 years.

These rates are smaller than other published rates… in some cases, significantly smaller. Part of the reason is in the assumption that the satellites are randomly distributed within the geosynchronous altitude band...they are not. Some researchers have obtained significantly higher collision rates at certain longitudes (Guermonprez, 1990). However, these higher rates may not be representative of the generic hazard, but result from the desire to maintain the satellite over the same longitude. These higher rates are reduced significantly simply by terminating station keeping. Once station keeping is terminated, the satellite begins to drift in longitude, and the distribution of satellites approaches a more uniform distribution. Researchers who assume that the satellites are simply abandoned (Hechler, 1985) obtain collision rates that are less than a factor of two different than the collision rates obtained by assuming a uniform distribution. Consequently, the long-term error in assuming a uniform distribution is probably small, although this assumption should be carefully examined.

When the size and number of satellites in geosynchronous orbit is assumed to be large, the collision rate will also be large. For example, a rate of one collision every 400 years to 600 years, and a 0.16 probability of a collision over a 20 year period was calculated by Hechler (1985), and is frequently quoted by others (ESA, 1988; Flury, 1991). This appears to be very different than the one collision every 15,000 years previously calculated. The primary reason for these large differences is in the very large size and larger number of objects in geosynchronous orbit assumed by other authors. These authors sometimes assumed 200 satellites with linear dimensions of 50 meters, and as many as 10,000 one cm orbiting fragments in geosynchronous orbit. Existing satellites in geosynchronous orbit are much smaller, and there is no hard data describing the number of small fragments in geosynchronous orbit. Even so, a comparison with the natural hazard reduces the ambiguity introduced with these assumptions.

Collision rates are proportional to area for both meteoroids and debris; consequently the relative collision rates from meteoroids and debris are the same for any assumed satellite size. The collision rate from meteoroids increases with decreasing meteoroid size; however, the damage resulting from a collision decreases with decreasing size. Consequently, a high collision rate with small debris may not be significant to the over-all hazard of the spacecraft when compared to the meteoroid hazard. A key parameter in comparing the debris hazard to the meteoroid hazard is the collisional velocity.

**Collision velocity: meteoroids and satellite breakup rates**

If all station keeping in geosynchronous orbit was terminated so that orbital inclinations could reach their natural long-term distribution, then the collision velocity that an average satellite would experience would range for zero to about 0.8 km/sec, and have an average of about 0.5 km/sec. The average meteoroid velocity is 16 km/sec. Therefore, for a given mass, meteoroids will collide with geosynchronous satellites at about 32 times more momentum and 1000 times more kinetic energy than a collision with another object in geosynchronous orbit. At 16 km/sec, a 0.7 kg a meteoroid would breakup the average 2000 kg spacecraft. The rate that a 0.7 kg meteoroid can be expected to collide with any one of the 250 satellites, each 5 meters in diameter, is about once every 100,000 years (Zook, 1992). Consequently, the current rate of satellite collisional breakups is probably controlled by the current number of satellites in geosynchronous orbit, rather than meteoroids; however, the time scale is very long before a satellite will break up due to either type of collision.

Satellites in geosynchronous orbit may break up more frequently for other reasons. In low Earth orbit, nearly half of the catalogued population is fragments of satellites, resulting from more than 100 explosions in low Earth orbit. Most of these explosions were due to the failure of an energy storage device, such as the tanks of upper stage which contained residual fuel, or batteries on a spacecraft. These same potential sources are equally common in geosynchronous orbit. At the rate that explosions have occurred in low Earth orbit, one should expect about 10 explosions to have occurred in geosynchronous orbit (Kessler, 1989-B)...yet, none have been officially recorded (Johnson, et al., 1991). However, there have been two reports of an observer witnessing an object exploding in geosynchronous orbit. One report was from Russia, made in February, 1992, reporting that in June, 1978, a USSR Ekran satellite was photographed as it exploded from what was believed to be a Nickel-Hydrogen battery failure (Johnson, 1992). The other was on Feb. 21, 1992, when a Titan upper stage, launched on Sept. 26, 1968, was video taped just after it appeared to explode (Bruck, 1992). However, as yet, no fragments have been catalogued from either of these events, which may not be surprising since fragments smaller than about 1 meter in diameter are difficult to detect from the ground with sufficient regularity to catalogue. Given the improbability that such events would be recorded, other, unrecorded explosions are likely to have occurred. Consequently, a satellite breakup rate due to current operational practices is likely to range between once every 1 to 10 years...a rate much higher than the highest predicted rate based on collisions. The final step in evaluating the significance of these breakup rates is in understanding the number, size, and velocity of fragments generated as a result of breakups and how the resulting debris hazard compares to the natural environment.

### Consequences of breakup in geosynchronous orbit

A breakup in geosynchronous orbit has 2 possible consequences: 1. A breakup produces fragments large enough to break up another intact satellite. These fragments contribute to collisional cascading, or "a chain reaction" if an average of more than 1 large fragment per satellite breakup is generated which stays in the geosynchronous ring. If the number of large fragments is significantly larger than one, the contribution to collisional cascading will be greater. 2. A breakup produces small fragments that can collide with and damage operational spacecraft. A key question becomes how this hazard compares to the natural hazard.

Although some data is available on the number, size and velocity of fragments generated as a result of breakups, most of that data was generated under conditions very different than needed to understand the consequences of breakups in geosynchronous orbit. Missing is data from collisions at about 0.5 km/sec, and complete data on explosion fragments smaller than 10 cm. Because satellite construction is more important at the lower collision velocities expected in geosynchronous orbit, any extrapolation of tests results leads to large uncertainties in predictions.

A "worst case" environment can be predicted by assuming that only the ratio of target mass to projectile mass, as determined by hypervelocity tests, is important in predicting the projectile mass causing catastrophic breakup at 0.5 km/sec. In this case, a 5 kg projectile could catastrophically break up the 2000 kg satellite. Ground explosions and explosions in space suggest that the largest fraction (about half) of the satellite mass goes into about this size fragment (Kessler, 1991-B), so that about 200 fragments of this size would likely be produced. The same data also suggest that these fragments would be ejected in all directions with an average velocity of about 50 meters/sec relative to the center of mass. This velocity is sufficient to spread the fragments over thousands of kilometers of altitude, so that at any one time, only about 20 of the 200 fragments would be found within the 100 km altitude band where geosynchronous satellites are located. Consequently, with this extreme assumption, collisional cascading in geosynchronous orbit is possible; but with only 20 fragments per satellite breakup to contribute to the cascading and with the first collision not expected for 140 years, the cascading would be very slow, requiring thousands of years to be noticeable.

An equally important conclusion from this extreme assumption concerns the "safe" distance to place inactive satellites outside of the geosynchronous orbit. A satellite breakup which occurred within a few thousand kilometers above or below the geosynchronous altitude would eject 5 kg fragments into orbits which passed through geosynchronous orbit. If the breakup were within a few hundred kilometers, the contribution to the hazard to geosynchronous orbit would almost be as great as if the breakup had occurred within geosynchronous orbit (Friesen, et al., 1992-B). Consequently, if the energy of future breakups in geosynchronous orbit is not too different than past breakups in low Earth orbit, the safe distance to place inactive satellites must be measured in thousands of kilometers from geosynchronous orbit in order to be effective.

### Hazard resulting from explosions

Since collisions are not likely to be a significant source of debris in the near future, a more important issue might well be the consequence of past explosions in, or near, geosynchronous orbit. Two objects have been observed to explode; it is not unreasonable that 10 times this number, or 20 explosions have occurred. Assuming the same size and ejection velocity relationships as before, we should expect an average of 400 additional objects, with masses of 5 kg or larger, to be in the geosynchronous altitude band at any one time. If these fragments are capable of catastrophic breakup of any of the 250 geosynchronous satellites known to be in geosynchronous orbit, they would increase the catastrophic collision rate from once every 15,000 years to once every 8,300 years...i.e., the explosion fragments would be as important as the known satellites in geosynchronous orbit in contributing toward collisional cascading.

Explosions will also produce smaller debris which will cause a hazard to other spacecraft. However, the type of explosions which are likely to have occurred are not likely to produce a large number of small debris. For example, a low intensity explosion is predicted to produce about 1000 fragments larger than 1 gm (Kessler, 1991-B). These fragments are likely to have velocities larger than the 50 meter/sec for the 5 kg fragments, consequently, spread over a larger volume of space...however, data sources giving the expected velocity is lacking. A conservative assumption would be that the velocities are the same, implying that about 100 of the 1000 fragments would be in the geosynchronous altitude band at any one time. A total of 20 explosions would mean that 2000 fragments of 1 gm and larger are in the geosynchronous altitude band at any one time, producing a flux of 1 impact every 18 million years per square meters of spacecraft cross sectional area. The meteoroid flux for this mass is 1 impact every 3 million years per square meters of spacecraft cross sectional area, which is more than 5 times larger than the debris flux resulting from these explosions. In addition, given the low velocity of 0.5 km/sec which debris is likely to collide with spacecraft in geosynchronous orbit, a debris mass between 5 and 25 times the meteoroid mass (Christiansen, 1992) depending on spacecraft construction, is required in order to do the same damage to the spacecraft as a meteoroid. Consequently, the meteoroid flux which is likely to do the same damage as a 1 gm debris fragment is between 1 impact per square meter every 120,000 to 600,000 years, or much higher than the possible debris flux resulting from 20 past explosions.

All current satellite breakup models predict that the fraction of satellite mass which goes into smaller sizes decreases with decreasing size. On the other hand, the amount of meteoroid mass increases with decreasing size. If the debris flux of 1 gm fragments is less than the meteoroid flux, then all satellite breakup models would predict that the meteoroid flux is also larger than the debris flux for sizes smaller than 1 gm. For the orbital debris hazard in geosynchronous orbit to exceed the meteoroid hazard, many times more than the assumed 20 satellites must breakup in geosynchronous orbit.

Therefore, the ability of breakups to produce an environment in geosynchronous orbit which is more hazardous than the meteoroid environment is much less than in low Earth orbit. This should not be interpreted that one should not be concerned, but rather that there is time to properly consider the total environmental management issue in geosynchronous orbit, and to address the major sources of debris in geosynchronous orbit.

**Environment management of geosynchronous orbit**

The only seriously considered technique to manage orbital debris in geosynchronous orbit has been the use of a "grave-yard" orbit (Suddeth, 1985; Chobotov, 1990; Flury, 1991). Most studies show that if an intact satellite is placed in a circular orbit about 200 to 300 km away from geosynchronous orbit, it will stay there. However, if one were to do nothing but move all objects from geosynchronous orbit into such a grave-yard orbit, the same orbital debris sources of explosions and collisions would be taking place in the grave-yard orbit. As developed earlier, with only a 200 to 300 km separation distance, the orbits of fragments generated in the grave-yard orbit would still cause an increase in the hazard in geosynchronous orbits that would be reduced by less than a factor of two compared to the hazard caused by the objects fragmenting in geosynchronous orbit. Several thousand kilometers of distance is required in order to prevent a significant fraction of satellite fragments from passing through geosynchronous orbit (Friesen, et al., 1992-B). Consequently, it is important that any long term environment management include other elements.

Perhaps the most important element is to minimize the possibility of accidental explosions in, or near, geosynchronous altitude. In low Earth orbit, this has been accomplished for upper stages by eliminating excess fuel after the upper stage has delivered its payload. Other energy storage devices, such as high pressure containers and batteries should also deplete their energy source. These actions are many orders of magnitude more effective at eliminating near-term sources of debris than is the use of a grave-yard orbit.

However, in the long term, the major energy source for satellite fragmentation is kinetic energy. This energy source can only be eliminated by either eliminating the satellite mass or by minimizing the relative collision velocity between objects in the geosynchronous region. To effectively eliminate the satellite mass, the satellite must be removed from Earth orbit; this is not operationally practical since it requires a delta velocity of more than 1 km/sec. Without station keeping, the relative collision velocity of objects in geostationary orbit will increase to an average of 0.5 km/sec. There is an orbit at geosynchronous altitude where much lower velocities can effectively be accomplished for uncontrolled satellites. The orbit has been referred to as "the stable plane orbit" (Friesen, et al., 1992-A).

**Use of the stable plane for environment management**

At geosynchronous altitude, the precession or "wobble" of the orbital plane occurs about a plane which is inclined 7.3 degrees to the Earth's equator. It is this precession which produces orbital paths which differ by as much as 14.6 degrees, and produce collision velocities as high as 0.8 km/sec. If a satellite is orbited in this "stable plane," it would have an orbital inclination of 7.3 degrees, and a right ascension of ascending node of zero degrees, and would not have any wobble. That is, without station keeping, all objects in the stable plane orbit will always be moving in the same direction, so that if collisions occur, the relative velocity will be very small...less than 0.005 km/sec. Satellites can easily be constructed to avoid fragmenting at this low collision velocity. Consequently, collisions between spacecraft are not likely to produce any fragments large enough to breakup another spacecraft, and collisional cascading is not possible.

The stable plane orbit is not a geostationary orbit. That is, from the ground, a satellite in this orbit will move 7.3 degrees North and South of the equator. For ground antennas without North-South tracking, or antennas which require a high signal strength, this may not be a desirable orbit. For those ground stations with North-South tracking, it can be a highly desirable orbit, since it requires only 5% of the station keeping fuel of a geostationary orbit. Many users have already adopted the practice of not using North-South station keeping in order to extend the satellite life; however, until recently, these users were prevented from launching into the stable plane because of a ruling by the International Frequency Registration Board which limited satellite inclinations to less than 5 degrees. In March, 1991, this limitation was rescinded. Consequently, in the future, both the stable plane orbit and geostationary orbit will have users driven by economic considerations. Therefore, environment management of the geosynchronous region needs to consider both types of orbits.

From an environmental management perspective, use of both the stable plane and the geostationary orbit is preferred to using only the geostationary orbit. Use of geostationary orbit alone, without station keeping, leads to higher collision velocities than using both. From an operational perspective, if both are used, it may be desirable to require the user of one of the orbits to maintain a slight eccentricity so that the two orbital paths cannot intersect. However, this should not be necessary for satellites which do not maintain station keeping since the collision probabilities are no different than for any uncontrolled satellites at geosynchronous altitudes.

If the stable plane is used for geosynchronous operations, then the use of a near-by grave-yard orbit becomes more practical. Objects could be placed only a few hundred kilometers above the geosynchronous stable plane, and still be very near, or in, a grave-yard stable plane which is inclined slightly more than 7.3 degrees. This means that collision velocities in the grave-yard orbit would also be less than 0.005 km/sec, so that if a collision occurred, the debris would not spread to geosynchronous altitude. However, if an object is originally launched into geostationary orbit, the delta velocity required to change to a stable geosynchronous or stable grave-yard orbit is prohibitively high...nearly 400 m/sec.

A final option of the stable plane is to use the two stable points at geosynchronous altitude located over 75 degrees East and 105 degrees West as a grave-yard orbit. These two points are considered desirable operational locations because East-West station keeping is not required. However, without proper environment management, these locations would suffer the highest orbital debris flux. The tendency of objects to move toward these two points make them an even more stable grave-yard location than any other location in the stable plane or in a higher grave-yard orbit. Collision velocities at the stable points would approach zero, and if any object had a collision velocity greater than zero, any collisions would damp out relative motion until the object came to rest at a stable point. The more mass placed in these stable points, the more stable they become. Consequently, they could represent a long term solution to management of the orbital debris in geosynchronous orbit.

**Concluding remarks concerning geosynchronous orbit**

An adequate environmental management strategy does not exist for orbital debris in geosynchronous orbit. The use of grave-yard orbits does not address the more serious short term sources of debris: the accidental explosions of upper stages and stored energy devices on satellites. Neither do these proposals significantly reduce the hazard caused by the long term sources of collisional fragmentation.

Current operational practices in or near geosynchronous altitudes combined with the long orbital life of debris generated as a result of these operations make an environmental management strategy desirable. Some geosynchronous operators are unilaterally performing maneuvers in the belief that they are contributing to proper environment management. With less operational expense, these operators might make a much larger contribution to environment management, once a strategy has been established.

The current hazard to spacecraft in geosynchronous orbit from orbital debris is low and is likely smaller than the hazard from natural meteoroids. However, future activities in the geosynchronous region may be on a scale much different than today's operations. We would be ill advised to preclude these operations because of poor environment management practices of today. Requiring operators to deplete excess fuel in upper stages left in geosynchronous orbit would be a much more effective management practice than requiring operators to maneuver to a grave-yard orbit.

Other options to manage orbital debris in geosynchronous orbit should be considered. Priorities based on the trade-off between operational expenses and an effective environment management strategy should be established. In order to do this, better models need to be developed. These models should be based on better data obtained from ground tests of satellite breakups, and the models should be validated with better observational data of the environment in geosynchronous orbit. Until an environmental management strategy is established which considers the cost effectiveness of all options, it is premature to establish policy adopting one option over another.

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