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ORBITAL DEBRIS ENVIRONMENT

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ABSTRACT

Until recently, the definition of the orbital debris environment depended upon mathematical models and limited data which had been obtained as a side product of other space related operations. Measurements to specifically determine the orbital debris environment in low Earth orbit have now been conducted. These measurements are decreasing the uncertainty in how the number of Earth orbiting objects increases with decreasing size and providing data on the altitude and inclination distributions of smaller debris. Sufficient data now exist to remove some simplifying assumptions and update these earlier models. However, in geosynchronous orbit, fewer mathematical models have been used to predict the evolution of small debris, and no measurements of small debris have been conducted. An estimate of the current hazard in geosynchronous orbit indicates that currently the meteoroid environment likely represents the greater hazard; however, the long orbital lifetime and rapid growth in the population suggests that the orbital debris environment will eventually dominate unless a debris environment management strategy is formulated and adopted.

1. INTRODUCTION

Past operational practices are producing an orbital debris environment which causes a greater hazard to future spacecraft than the hazard from the natural meteoroid environment. In order to effectively manage the environment, we need to understand the environment that we have already produced and the potential sources of future orbital debris. It is the purpose of the paper to describe what is known about the current environment and suggest probable sources for future debris.

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 these two regions will be discussed separately. 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; however, in geosynchronous orbit this comparison is more complicated by differences in velocity.

2. 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 (Ref. 1). Figure 1 describes the cumulative flux as a function of meteoroid diameter (Ref. 2). The hazard from this environment will be used as representing a threshold of concern for the orbital debris environment in both low Earth orbit and Geosynchronous orbit.

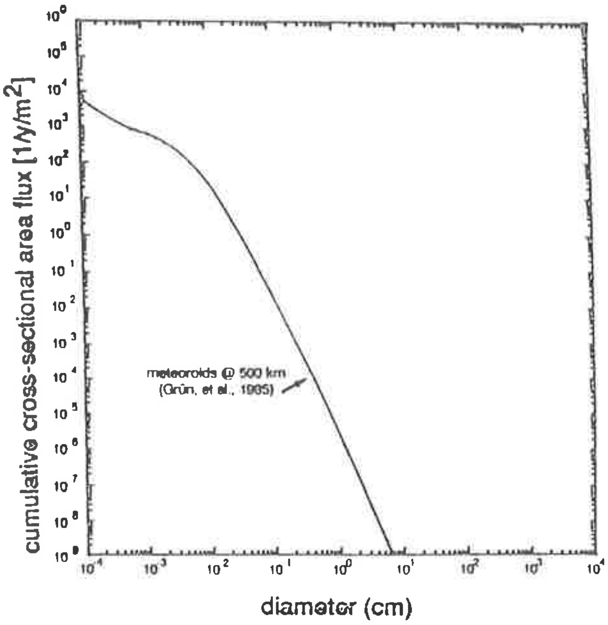

Figure 1. Meteoroid Environment at 500 km Altitude

3. LOW EARTH ORBIT

The average collision velocity between any particular spacecraft orbiting in near-Earth orbital space and orbital debris objects is 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 (Ref. 3). 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.

Low Earth orbital objects must be larger than about 10 cm in order to be maintained in a catalogue by the US Space Command. Figure 2 gives the calculated flux (Ref. 4) 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 (Ref. 3). Note that for most altitudes, the flux from catalogued objects is about the same as the flux from 1 to 2 cm meteoroids.

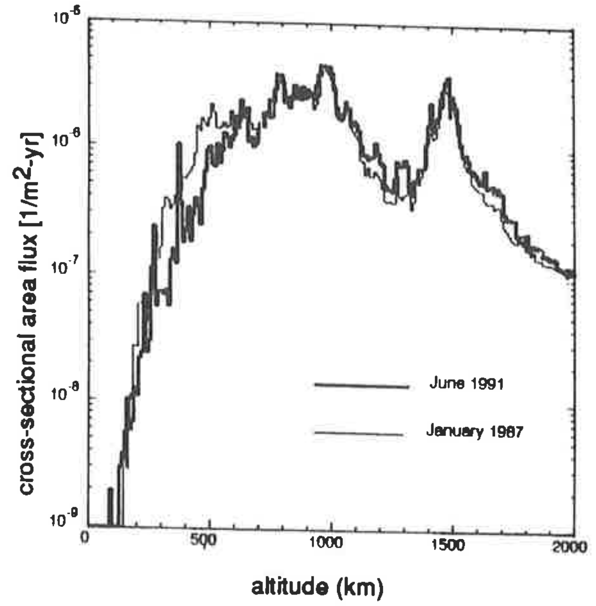

Figure 2. Average Flux Resulting from US Space Command Catalogued Population

The earliest orbital debris studies by NASA were mostly concerned with calculating the collision probabilities from these catalogued objects (Ref. 5 and 6). 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 (Ref. 7). 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 (Ref. 8). These predictions were later expanded to include an estimate of the uncatalogued population in 1978 (Ref. 9).

Before 1984, there were no measurements of uncatalogued orbital debris; consequently, these early predictions were based on models which described the number of objects generated when an object fragmented in orbit, and the orbital lifetime of these fragments based on atmospheric drag. The model described in Ref. 9 predicted that the catalogue was incomplete for orbital debris sizes smaller than 20 cm, and that by 1995, the orbital debris hazard for sizes larger than 1 mm would exceed the natural meteoroid environment hazard. Current measurements of the uncatalogued orbital debris population are confirming these predictions.

3.1 MEASUREMENTS OF UNCATALOGUED POPULATION

Sampling of objects in Earth orbit requires less resources than cataloging objects; however care must be taken to ensure that any sampling bias is properly taken into account. Remote sensors are required to sample 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.

3.1.1 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 meteors at about 100 km altitude. Nine hours of data were recorded on video tape and analyzed by Lincoln Labs. Published results (Ref. 10) 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, an "average" limiting size measured by these telescopes is about 8 to 10 cm. However, as will be discussed later, the exact average depends on other parameters.

Since 1986, 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 (Ref. 11). 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. However, the exact limiting size measured by 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 10 cm. This is because of the long wave-length used to catalogue debris. This longer wave-length results in a larger probability that smaller debris will happen to reflect a larger fraction of light to the telescope than to happen to reflect a larger fraction of radar signal to the radar. As a result, the "average" size detected by the telescope is biased toward the more numerous smaller debris with an albedo larger than the typical 10%.

3.1.2 Ground Radars

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 wave-length), 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.

3.1.2.1 Arecibo and Goldstone Radar Tests

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 (Ref. 12). 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 (Ref. 13). 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.

3.1.2.2 Haystack Radar

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. Since 1990, over 1400 hours of data have been collected and analyzed (Ref. 14). This data contains information on the size, altitude, eccentricity and inclination distribution of centimeter sized orbital debris. The following is a discussion of these distributions.

3.1.2.2.1 Size Distribution

The size distribution measured by Haystack clearly demonstrates that flux significantly increases with decreasing orbital debris size. The radar range calibration of irregular fragments has provided valuable insight into the relationship between radar return signal and "average" debris size. This type of calibration is also providing a better understanding in the actual sizes of larger, catalogued orbital debris. As pointed out in Ref. 14, an accurate understanding of the size distribution requires integration over the probability of radar return functions for a given size object. When the data is analyzed in this manner, the measured size distribution even more clearly shows an increasing flux with decreasing size.

3.1.2.2.2 Altitude Distribution

Figure 3 gives the distribution of altitudes for detected objects 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 Ref. 3. 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.

While there is some agreement between the model prediction and the measurements, there are some obvious differences. The most obvious difference is in the sharp peak in the measured environment between

850 km and 1000 km, and its rapid fall-off with altitude. A large number of satellite breakups have occurred within this altitude band. Previous models have assumed that the small fragments from these explosions would be ejected at sufficiently high velocity to be spread out more in altitude. The Haystack measurements suggest that the ejection velocity of small fragments may not be too different that the larger, catalogued fragments, meaning that most of the fragments are in near circular orbits. This would be necessary to explain the decreasing count rate with increasing altitude above 1000 km. However, below 900 km, atmospheric drag must also be playing a role. The near record solar activity during the period when the Haystack measurement were made, combined with an increased number of near circular orbits of small fragments, would cause an even larger decrease in the environment at lower altitudes than predicted by previous models. This may be responsible for the differences between model predictions and the measurements for altitudes between 400 km and 800 km. As solar activity decreases over the next few years, the environment could significantly increase in this region, depending on the rate the future small debris is generated. However, below 400 km, the environment could still be dominated by highly elliptical orbits, as suggested by the distribution of impacts around the LDEF satellite. If so, these orbits would not be as sensitive to solar activity. Some of these other Haystack measured parameters can help to resolve this issue.

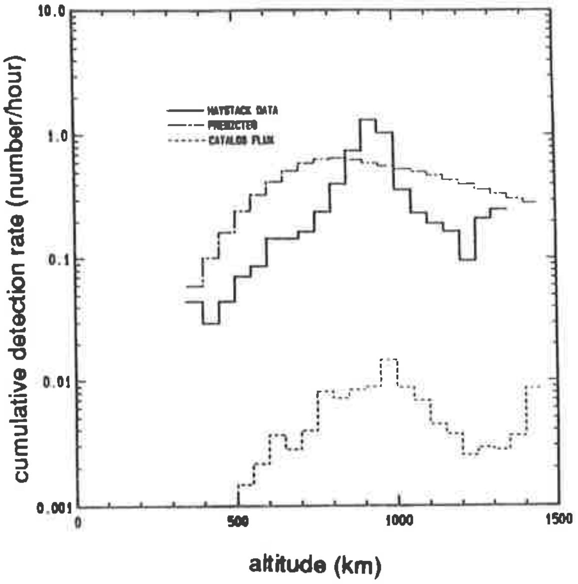

Figure 3. Measured and Predicted Altitude Distribution for all Objects Detected by Haystack at the 90° Elevation Beampark in the 346 Hours of Data Collection

3.1.2.2.3 Eccentricity and Inclination Distributions

Both eccentricity and inclination are two orbital parameters that the Haystack measures directly very poorly. However, there are related measurements that are of value. The radar measures the radial velocity very accurately. When vertically pointed, all objects in circular orbits, or objects detected near their perigee, will have zero radial velocity. If altitudes below 400 km are dominated by highly elliptical orbits, these objects will also be detected at higher altitudes with a radial velocity up to 3 km/sec. Figure 4 shows the measured radial velocity distribution for all objected detected above 600 km altitude. Some of the measured radial velocities are too large to be from an object permanently be in Earth orbit. These signals could be false signals, or from either meteoroids or larger objects detected in the radar beam sidelobe. For the purposes of analysis, these signals were assumed to be a noise that is equally distributed in radial velocity. This noise was subtracted from the data set. The resulting measured distribution can be summarized as follows: 2.2% of the objects detected above 600 km had radial velocities between 0.6 and 1 km/sec, 0.9% had radial velocities between 1 km/sec and 2 km/sec, and less than 0.3% had radial velocities between 2 km/sec and 3 km/sec. The question now becomes, what do various models predict?

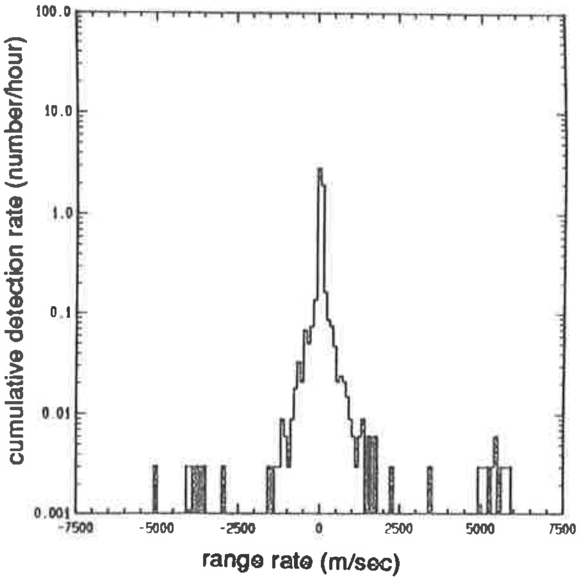

Figure 4. Range Rate Distribution Measured by Haystack at 90 Degrees Elevation and Altitudes above 600 km

The equations in Ref. 4 were applied to the orbits contained the US Space Command catalogue to predict the measured radial velocity from these orbits. However, it was assumed that Molniya-types of orbits could not be detected by Haystack, since their perigee is located in the Southern hemisphere. The results from the calculation using the catalogue were that a smaller than measured fraction of the population would have higher radial velocities. The catalogue alone would predict the above percentages to be 1.6%, 0.4% and 0.09%, respectively. Consequently, Haystack is measuring a more elliptical orbit distribution than predicted by the catalogue. The LDEF data suggested that catalogued orbits with an apogee greater than 10,000 km could be weighted by a factor of 30. This assumption would predict a larger than measured fraction of the population with higher radial velocities...the above percentages would become 2.0%, 1.9%, and 2.3% respectively. Consequently, the relative number of highly elliptical orbits measured by Haystack in this mode is not as large as suggested by LDEF. The best fit to the observed data is obtained by weighting the catalogued objects with an apogee above 2500 by a factor of 3, where the predicted percentages become 2.1%, 1.1%, and 0.3%. This result would suggest that while elliptical orbits are more frequent in the centimeter size range than in the catalogue, they do not dominate the low altitude environment. However, these results can only be applied to orbits with inclinations above 42 degrees, since lower inclination orbits cannot be observed when Haystack is vertically pointed.

A measure of other inclinations requires that the radar be pointed toward the Southern horizon. Pointed 10 degrees above the horizon, the radar is detecting objects with inclinations below 28 degrees, and altitudes above 500 km. At this pointing angle, the detection rate is exceeding model predictions, and showing less altitude dependency than the model. This is consistent with a large population of low inclination, highly elliptical orbits, like that measured by LDEF as developed in the next section. However, this Haystack data has not yet been critically examined, and more analysis is required. Ideally, vertical observations from lower latitudes would leave less uncertainty concerning these orbits.

3.1.3 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 (Ref. 15), 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 (Ref. 16 and 17). 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. 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 Hörz's side facing aluminum surfaces to more than 50%.

Orbital debris impacts on the rear surfaces of LDEF were a surprising result because only highly elliptical orbits with low inclinations are capable of hitting the rear surface. Figure 5 if from Ref. 18, where the crater distribution from orbital debris on LDEF's side and rear surfaces are compared with the crater distribution expected from the orbital distribution represented by the US Space Command Catalogue. As can be seen, this orbital distribution does not contain a sufficient number of the type of orbits necessary to impact the rear surfaces of LDEF. The relative number of high eccentricity, low inclination orbits must be increased by a factor of 20 in order to be consistent with the orbital debris crater distribution measured around LDEF.

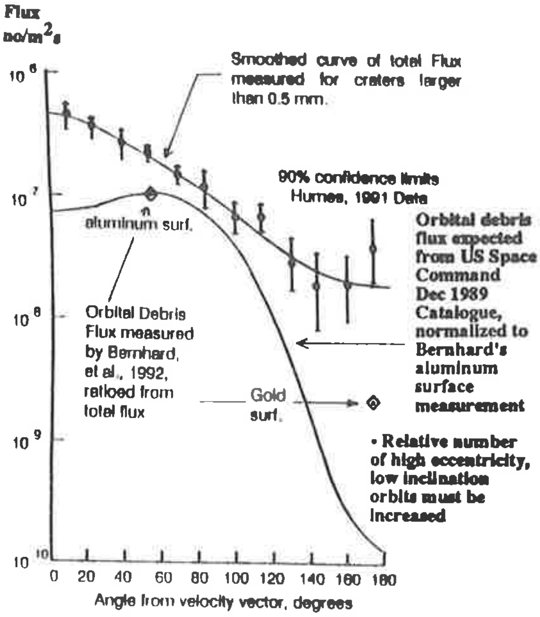

Figure 5. Crater Distribution Measured by LDEF Compared to that Predicted by the Orbit Distribution in the US Space Command Catalogue

Perhaps the most surprising result on LDEF came from the Interplanetary Dust Experiment (Ref. 19). 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 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 from objects in near circular orbits, then less than 10 grams of paint is needed to be removed from each orbiting spacecraft per year to explain these results. If the orbits of the source objects were in circular orbits, then the swarms should have been observed twice per orbit; however, most were only observed once per orbit. This would indicate that the swarms were in elliptical orbits. If the source orbit is highly elliptical, then less than 1 gram per year 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.

3.2 Summary Environment

A summary of the best measurements to date is shown in Figure 6, compared to the natural meteoroid environment. When compared to the model predictions given 10 to 15 years ago, there is a general agreement 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.

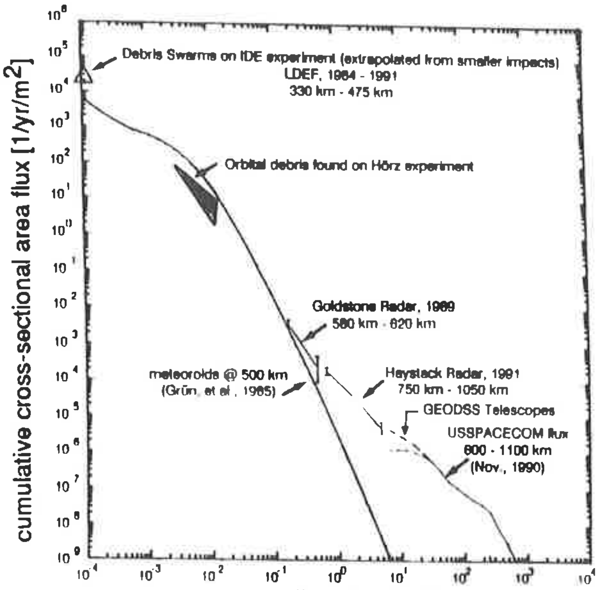

Figure 6. Meteoroid Environment Compared to Recent Measurements of Orbital Debris Environment

3.3 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 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 (Ref. 20); 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 (Ref. 21); there is data and analysis (Ref. 22, 23, and 24) 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. A predicted future environment for low Earth orbit has been given by a number of additional papers (Ref. 25, 26, 27, 28, and 29).

4. GEOSYNCHRONOUS ORBIT

Orbital debris studies concerning geosynchronous orbit are slightly more than 10 years old, where one of the first serious studies was conducted by Hechler, et al in 1980 (Ref. 30). Most of the studies to date, like the early low Earth orbit studies, have been concerned with the larger, cataloged objects (Ref. 31 and 32). 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 inappropriate to long-term environment management.

Figure 7 is an expansion of Figure 2 for 1991, and compares the flux of catalogued objects in low Earth orbit with geosynchronous orbit. Note that the average flux in geosynchronous orbit is much lower than in low Earth orbit. However, 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. If this process acted quickly to remove fragments of all sizes, then the accumulation of 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.

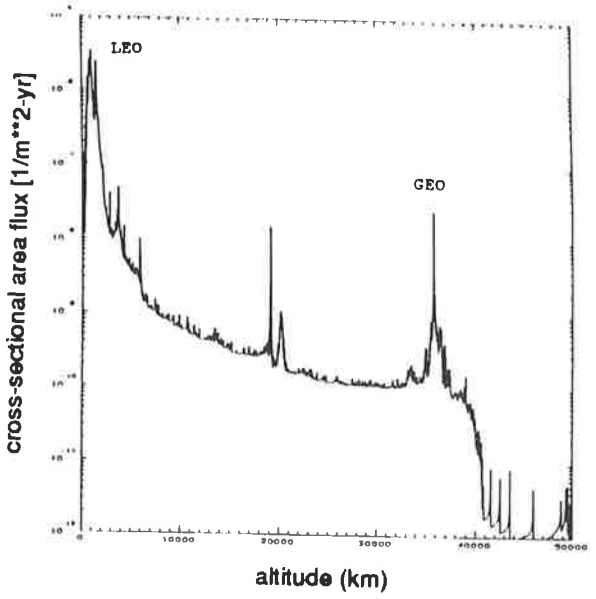

Figure 7. Average Flux Resulting from US Space Command Catalogued Population

4.1 <u>Time Scale for the Orbital Debris Problem</u>

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 (Ref. 33). 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 larger debris is likely to cross geosynchronous orbit for periods much longer than 60,000 years, perhaps 100,000 to 1,000,000 years. For very small debris (less than about 10 microns), solar radiation pressure increases the eccentricity to such a large value that the debris collides with the Earth within a few months (Ref. 34 and 35).

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.

4.2 <u>Rate of Collisions</u>

The relationship between orbital elements and collision rates for uncontrolled objects has been developed by a number of investigators. A simple approach for obtaining the collision rate was introduced by Perek in Ref. 36. Perek calculated the collision probability per day from twice the ratio of the collisional cross-sectional area of satellites to the area of the geosynchronous ring. A more accurate, but more complex approach is described in Ref. 4, and was used to generate figure 7. This approach assumes a random distribution of longitude of ascending node crossings, which is approximately the case when inclination is measured relative to the "stable plane", discussed later. The two approaches can be shown to be equivalent 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 directly provides the insight that collision probability in geosynchronous orbit is independent of orbital inclination, proportional to the area to the satellite, and inversely proportional to the altitude band that satellites will move. The lack of data on debris in geosynchronous orbit will cause a much larger uncertainty in the actual hazard in geosynchronous orbit than the uncertainty introduced by using Perek's approach to calculating collision rates; consequently his approach will be used here.

There are currently about 250 objects known to be in geosynchronous orbit, with average linear dimensions of about 5 meters (Ref. 37). 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 between catalogued objects of once every 15,000 years. This is about the same rate if one assumed an average flux of 7 x 10-9/m2 - yr. From

Figure 7, 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 (Ref. 38). 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 (Ref. 39) 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 in Ref. 39, and is frequently quoted by others. 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. 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.

4.3 Collision Velocity: Meteoroids and Satellite Breakup Rates

If all station keeping in geosynchronous orbit were terminated so that orbital inclinations could reach their natural long-term distribution, then the collision velocity that an average satellite would experience would range from 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 (Ref. 40). 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 (Ref. 41)...yet, none have been officially recorded (Ref. 22). 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 (Ref. 23). 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 (Ref. 42). 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.

4.3.1 Consequences of Breakups 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 (Ref. 43), 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 (Ref. 21), 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 (Ref. 34), 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 500 years, the cascading would be very slow, requiring thousands to tens of 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. 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.

4.3.2 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 (Ref. 21). 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 (Ref. 44) 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

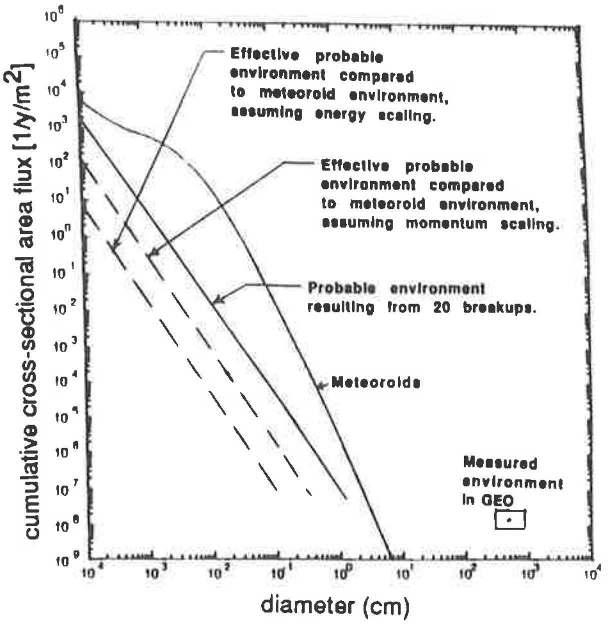

Figure 8. Probable Orbital Debris Environment in GEO Resulting from 20 Satellite Breakups

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. Figure 8 gives the expected orbital debris environment in geosynchronous orbit for sizes smaller than 1 gm, under the assumptions that 20 explosions have occurred and the resulting size distribution is the same as measured in low Earth orbit. Momentum and energy scaling of debris in geosynchronous orbit will reduce the hazard of orbital debris to an "effective size", also shown in figure 8, that will damage spacecraft to the same level as meteoroids. Consequently, 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.

4.4 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 (Ref. 31, 32, and 45). 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. 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. However, there is an orbit at geosynchronous altitude where collision velocities for uncontrolled satellites is only 0.005 km/sec. This orbit has been referred to as "the stable plane orbit" (Ref. 33).

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 canceled. 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 about 0.1 degree 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.

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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