Orbital Debris Environment for Spacecraft in Low Earth Orbit

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The results of measurements and modeling have been combined to describe an orbital debris environment model that can be used to evaluate spacecraft reliability vs shielding issues. Recent measurements by ground radars and telescopes, combined with analysis of recovered spacecraft surfaces, have provided some measurements of the environment over most of the size spectrum from micron size to the size of spacecraft. These measurements are consistent with models that assumed that smaller debris resulted from the breakup of satellites. Recent efforts to minimize satellite breakups will reduce the projected environment and delay the time period when satellite breakups from random collisions become important. However, there still remains a significant uncertainty in the current environment, and an even larger uncertainty in the projected environment. Uncertainties in the current environment will be reduced as a result of planned measurements. The future environment will mostly depend on future debris control measures taken and, to a lesser extent, on the amount of traffic to orbit.

Introduction

THE natural meteoroid environment has historically been a design consideration for spacecraft. Sizes smaller than about 1 cm in diameter were the major concern. Meteoroids are part of the interplanetary environment and pass through Earth orbital space.[1] Earth orbiting payloads and spent rocket stages act as sources of orbiting objects smaller than 1 cm. Mathematical models have predicted, and measurements have confirmed, that a small but significant fraction of the Earth orbiting mass is found in sizes smaller than 1 cm. This paper will review modeling and measurement results that have been used to formulate an environment model that can be used for the engineering design of spacecraft. Even though our understanding of the current environment has been improving somewhat, and is expected to improve even more in the near future, a very large uncertainty exists in the projected environment.

Analysis of Earth-Based Sensors

Early in the space program, there was a general perception that the North American Aerospace Defense Command (NORAD) was tracking "all man-made objects." However, during tests with NORAD's Perimeter Acquisition and Attack Characterization System (PARCS) radar, in 1976 and 1978, NORAD detected between 7 and 18% more objects than were being tracked.[2] Although this was not a large number, it did change the general perception. The new perception was that NORAD was tracking most objects in low Earth orbit larger than 10 cm. NORAD's exact limitations have never been released to the general public; however, the limitation of 10 cm was based on the fact that most NORAD radars operated at 70 cm wavelength; consequently, objects smaller than 10 cm would have very small radar cross sections. In addition, very few tracked objects at low altitudes had radar cross sections corresponding to objects smaller than 10 cm, and this limiting size increased with increasing altitude. These three considerations lead to the capabilities illustrated in Fig. 1.

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The responsibility for maintaining orbital element sets has been transferred from NORAD to U.S. Space Command. These element sets can be used to calculate flux as a function of altitude,[3] as shown in Fig. 2, where both the total tracked population and only the catalogued population are plotted for January 1987. The large peaks at 800, 1000, and 1500 km are the results of a combination of satellite breakups and heavy usage at these altitudes.

The effects of satellite breakups can be modeled to predict an uncatalogued population, if the nature of the breakup is understood. Figure 3 illustrates two breakup mass distributions from two different types of breakups. These two distributions are compared to an upper limit, which assumes that all of the fragment mass goes into some preferred size. This comparison shows that most of the mass from the Atlas missile explosion went into fragments slightly larger than 10 cm, with a very small amount of mass going into 1 mm to 1 cm fragments. The hypervelocity test also shows that most of the mass went into larger fragments; however, a significant fraction of the mass also went into 1 mm to 1 cm fragments. By fitting these types of distributions to known satellite breakups, the uncatalogued population can be predicted. An analysis in 1981[4] assumed that most of the satellite breakups followed the Atlas missile explosion data, and predicted a 10-cm population that was about twice the catalogued population. This analysis was inconsistent with the PARC's radar tests,

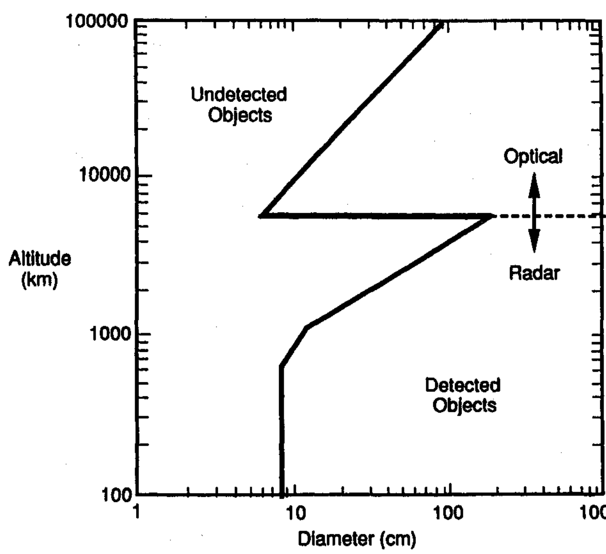

Fig. 1 U.S. Space Command sensor altitude limitations.

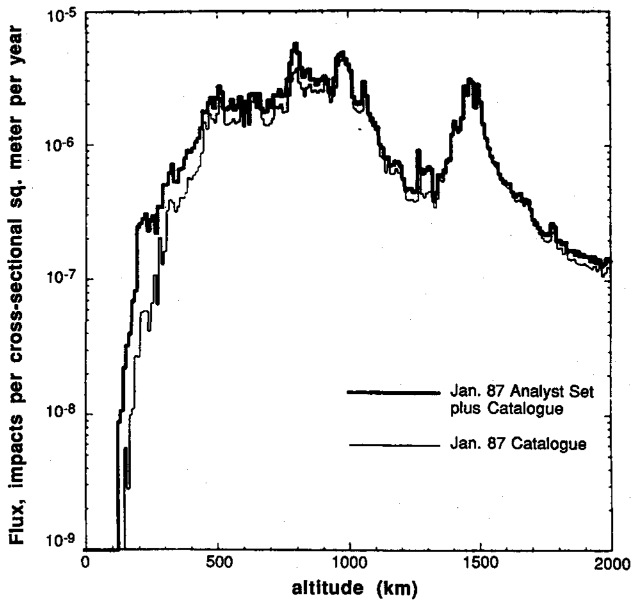

Fig. 2 Comparison of the flux arising from the January 1987 tracked population (Analyst Set plus catalogue) and the January 1987 catalogue.

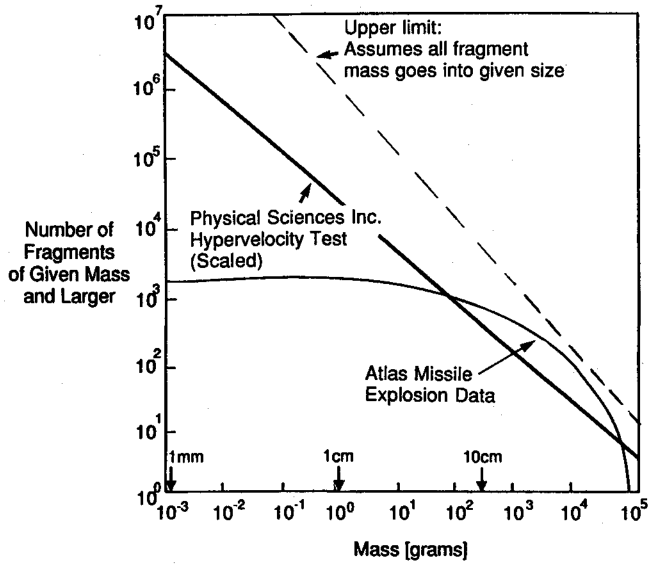

Fig. 3 Expected number of fragments from the breakup of a 1400 kg satellite.

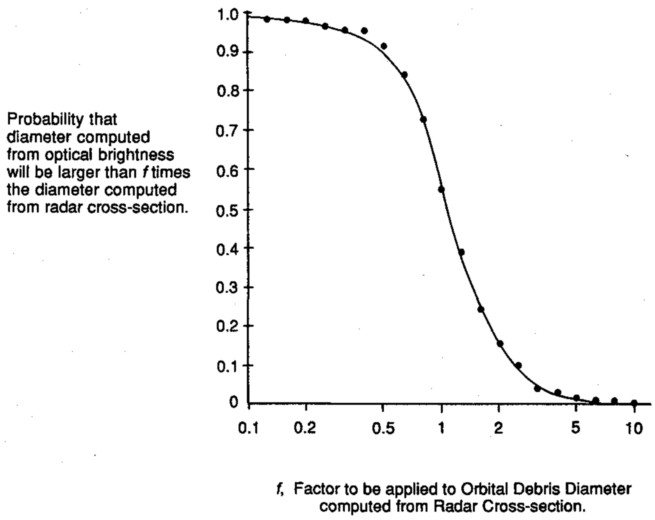

Fig. 4 Probability that an optically measured size will be larger than its radar measured size.

which detected a much lower uncatalogued population. Consequently, the model in NASA TM-100-471[5] assumed that the U.S. Space Command tracked population is essentially complete to 10-cm diam.

In 1984, NASA began sponsoring a program of telescopic observations of orbital debris. The first of these was by the Massachusetts Institute of Technology (MIT),[6] which concluded that the 1 cm orbital debris population was eight times the U.S. Space Command tracked population. A reanalysis of the data at the Johnson Space Center (JSC) concluded that an improper parallax measurement had tagged some meteors as being orbiting objects, and concluded that the correct ratio was five times the tracked population during periods of excellent seeing conditions, and twice the catalogued population during average seeing conditions. In addition, radar, optical, and infrared measurements[7] of known orbital debris lead to the conclusion that orbital fragments are much darker than previously believed, meaning that the debris that MIT detected was larger than 1 cm, being closer to 2–5 cm. This detection size was assumed in TM 100-471. However, recent calibration of the MIT telescopes at JSC has shown that the telescopes were not as sensitive as previously believed; therefore, the objects detected by MIT were larger than 5 cm.

A more complete analysis of telescopic data is given by Henize and Stanley[8] using the slightly less sensitive telescopes of the U.S. Space Command. These telescopic data indicate that there are twice as many objects in orbit larger than 10 cm than are catalogued, and that some 1-m-diam objects are not catalogued. This again appears to conflict with the PARC's radar tests. A possible explanation might be that some fraction of smaller debris might happen to appear brighter as it goes through the telescope field a view, and thus be described as a larger object. Fluctuations in brightness can be expected due to distributions in albedo, phase functions, and orientation as the object goes through the field of view. However, we have measures of these distributions when satellites with known radar cross sections went through the field of view. That is, from the distribution of measured brightness as satellites of a given radar cross section went through the telescope field of view, we can determine the probability that a given radar cross section will appear as an optically larger object.

Using the distribution of optically determined diameters for objects of known radar cross section, as given by Henize and Stanley,[8] the probability that an optically measured size would be larger than its radar measured size was determined, and is given in Fig. 4. Consider, for example, an object 20 cm in diameter, as determined by its radar cross section. Multiplying f in Fig. 4 by 20 cm, the figure shows there is about a 50% probability that any optically determined diameter would be 20 cm or greater, as one would expect if the proper average albedo and phase function had been assumed. There is also a 2% probability that the same size object would appear as a 100 cm ($f=5$) optical object, or larger. Since over 300 unknown objects were detected, most between 10 and 30 cm, chances are that several of the 10–30 cm objects would appear to be optically 1 m in diameter or larger, and this is what was observed. Therefore, without a more complete analysis, it would be premature to conclude from the telescopic observations that there are objects with radar cross sections as large as 1 m that are not catalogued.

Now consider an object 5 cm in diameter, as determined by its radar cross section. Such an object would have a near zero chance of being detected by U.S. Space Command's 70 cm radar wavelength. However, Fig. 4 shows that there is a 15% probability that such an object would appear optically as a 10 cm object or larger, and a 4% probability that the object would appear as a 30 cm object or larger. If there were about as many 5 cm objects as 10–30 cm objects, then one would expect between 15% and 4% of the unknown objects to actually be 5 cm objects that appeared brighter in the telescope; this is a small fraction of the unknowns. There would have to be 7–25 times as many 5 cm objects as 10–30 cm objects to account for the unknowns observed by these telescopes. Although such a large number of 5 cm objects is highly unlikely, it cannot be ruled out. Similarly, since there is a 0.3% probability that a 1 cm object would appear as bright as a 10 cm object, there would have to be 300 times as many 1 cm objects as 10 cm objects to account for the unknowns observed by these telescopes. Again, such a large number is highly unlikely, but cannot be ruled out. Consequently, there are two possible conclusions: 1) there are twice as many 10 cm objects and larger in orbit than are catalogued by U.S. Space Command; or 2) there are many times the number of catalogued objects in orbit with sizes slightly smaller than 10 cm. The more probable conclusion is the first one, although there is certainly a small fraction of smaller than 10 cm objects that were detected because they appeared to be larger than 10 cm. Therefore, we are faced with question of why the U.S. Space Command radars are not tracking these objects. To answer this question will require further research.

Analysis of Space-Based Sensors

The first orbital debris measurements of very small debris resulted from examining the Skylab IV/Apollo windows,[9] which revealed aluminum-lined pits in about half of the hypervelocity pits found on the window. Other experiments, such as Skylab's S149 Micrometeoroid experiment and the Explorer 46 Meteoroid Bumper Experiment, also showed indications of measuring the orbital debris population of debris smaller than 0.1 mm. The Shuttle windows are examined after every flight for pitting, and some windows have been replaced to ensure an adequate safety margin when the Shuttle is relaunched. The largest pit found to date has a diameter of about 4 mm, and was first noticed on the third day of the STS-7 mission. This was the only pit analyzed today to determine the origin of the impacting particle; this origin was concluded to be orbital debris.

By far, the best data to date have been recovered from the Solar-Max surfaces.[10] Both the thermal insulation blankets and aluminum louvers contained a significant number of holes caused by hypervelocity impact. Even though there is a problem of calibrating the penetration hole size to the impacting particle size, the analysis of data has determined the relative contributions from meteoroids and orbital debris. The analysis indicates that the orbital debris flux dominated the particle flux for sizes smaller than about 0.01 mm, although some secondary impacts likely contributed to this flux. Meteoroids dominated the flux between about 0.03 and 0.2 mm particle impacts by about a factor of 4. An extrapolation of the data would predict that the orbital debris flux would also dominate for particle sizes larger than about 1 mm. A particle production rate of about 100 kg/yr is required to maintain the measured orbital debris flux, if the particles were in circular orbits; less mass is required if the orbits are elliptical.[11]

The Long Duration Exposure Facility (LDEF) was exposed to space for a longer time and has a much larger area than the solar-max surfaces. It is expected that analysis of the impacts found on LDEF will improve and expand the measurements of the orbital debris flux in this size range.[12]

1 mm to 10 cm Flux

Until very recently, the flux between 1 mm and 10 cm was unmeasured. Estimates of this flux were obtained by a combination of modeling and an extrapolation of Solar-Max and ground telescope data. Such an extrapolation was the basis of the environment given in TM 100-471. The extrapolation was reasonable since only a small fraction of the past satellite breakup mass would be required to be in this size region. In 1989, two tests were performed by the Jet Propulsion Lab (JPL) that would partially measure the flux in this size range.[13] One test was with the Arecibo radar, which measured the flux between 2 and 0.5 cm, and the other used the Goldstone radar, measuring the flux between 0.5 and 0.2 cm. Within the errors of the measurements, both tests agreed with the environment in TM 100-471.

Uncertainty in the Current Environment

Based on the measurements to date, an estimate of the uncertainty in the current environment can be made. Figure 5 compares the uncertainty with the environment in TM 100-471

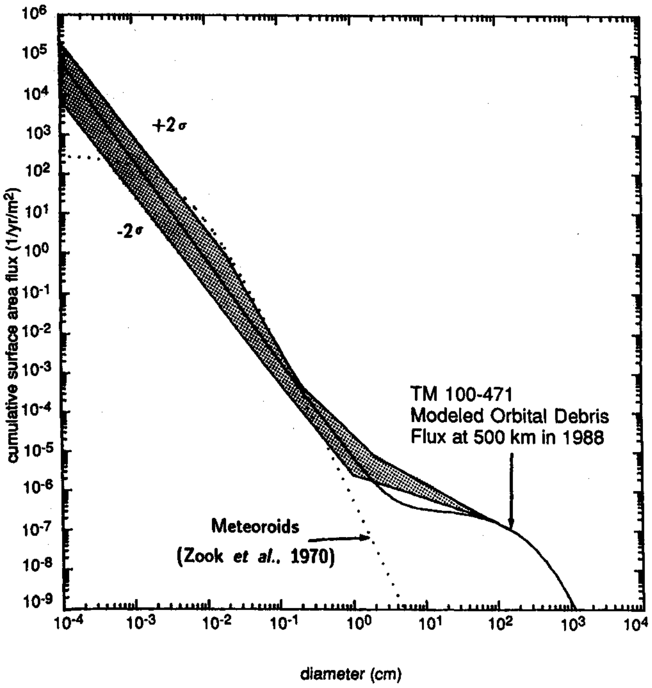

Fig. 5 Uncertainty in current environment at 500 km compared to NASA TM-100-471 environment and meteoroids.

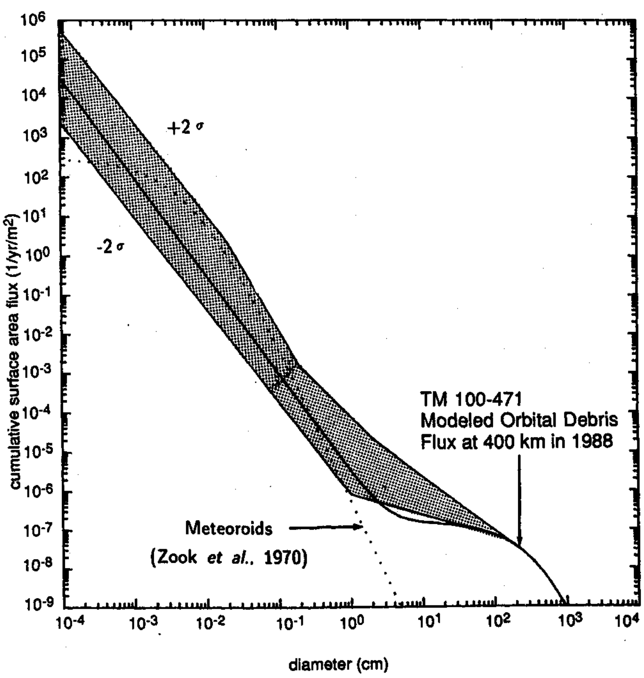

Fig. 6 Uncertainty in current environment at 400 km compared to NASA TM-100-471 environment and meteoroids.

and the meteoroid environment.[14] Except for the size interval between about 2 cm and 1 m, the modeled environment is a good representation of existing measurements; however, it is likely that the model does underestimate the 2 cm to 1 m population. Data that will better define the flux in this region are expected in late 1990 and early 1991.[15]

All of the measurements were near 500 km altitude or higher. How the flux changes with altitude is a function of the types of orbits contributing to the flux. If all orbits are circular and the source of debris is above the altitudes of interest, then the flux will vary as the inverse of the atmospheric density. The reduction in flux of U.S. Space Command tracked objects with decreasing altitude is a reflection of this. However, the flux of tracked objects does not exactly follow this relationship. This is because there are sources of debris within the altitude of interest; in addition, elliptical orbits contribute to the flux. Both of these factors contribute to the flux being more constant with altitude. If there were a large number of elliptical orbits passing through low altitudes, or if there were large sources of debris at low altitudes, it would be possible for the orbital debris environment to be larger at lower altitudes than higher altitudes. Consequently, unless the orbits and sources are known, an additional uncertainty is introduced at altitudes different from 500 km. Figure 6 compares the uncertainty at 400 km with the environment model in TM 100-471. Again, the modeled environment is a good representation of existing data; however, the existing data are highly uncertain when extrapolated to 400 km.

Future Environment

Many assumptions are required in order to estimate the future environment. These include the future traffic model, satellite fragmentation rate, and solar activity. Even if these were known, there may be some unmodeled source of debris that may be important. However, some bounds can be put on the future environment. Since 1960, the rate of catalogued objects has accumulated at the rate of 240 objects per year.[16] However, this has been during two periods of much higher than average peak solar activity, and also includes the period before the world launch rate reached its current value of about 120 per year. If one assumes that future solar cycles are likely to be average, then the period between 1966 and 1977 would be more representative of future growth, if there were no changes in current traffic and satellite fragmentation rates. The accumulation rate during this period was about 300 catalogued objects per year, or about 4% of the current population per year.

However, the U.S., European Space Agency (ESA), China, and other nations plan to increase their activities in space. If these planned traffic models are exercised, they will lead to between 5 and 10% per year increases in the accumulation of mass in low Earth orbit,[17] not including an SDI deployment. Such an increase in traffic could lead to satellite fragmentation rates caused by random collisions to become the major source of debris, perhaps within the next 10 years.

The rate of random collisions was computed from an altitude distribution of catalogued objects in 1989, similar to the altitude distribution shown in Fig. 2. It was assumed that half of the catalogued objects were 10 cm in diameter (explosion fragments), and the other half were 3 m in diameter (payloads, rocket bodies, etc.). It was also assumed that the catalogued population, limited to a size of 10 cm, should be doubled, and that all of these uncatalogued objects were 10 cm in diameter. Finally, it was assumed that a catastrophic collision would result from either the collision between two objects 3 m in diameter, or between 10 cm and 3 m diameter objects. The equations for this type of calculation are given by Kessler.[18] The results of this calculation were 0.12 catastrophic collisions per year, or one every eight years.

This is significantly higher than a previous calculation based on the 1976 population,[19] which was 0.013 per year. There are several reasons for this: The catalogued population has nearly

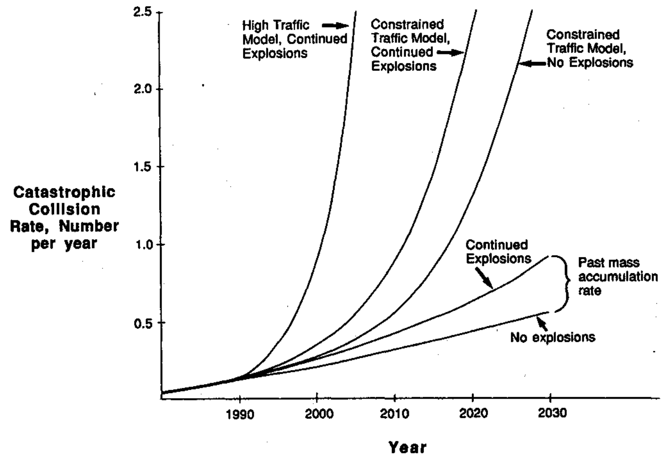

Fig. 7 Rate that payloads, spent rocket stages can be expected to catastrophically break up as a result of random collisions.

doubled since 1976, which alone would quadruple the rate. The introduction of an uncatalogued 10 cm population increased the rate by nearly a factor of two. Finally, using these two sizes to represent the true size distribution will give a slightly higher collision rate. However, by averaging over inclination, and not using the measured inclination distribution (which includes a large number of high inclination orbits that have relatively high collision probabilities) to calculate the collision rates, the calculated collision rate is too low. These last two factors should about cancel one another, so that a rate of 0.12 per year is a realistic number for today's population. Integration over the last 30 years indicates that an average of about 1 catastrophic collision should have occurred to date. That is, from Poisson statistics, there is about a 63% chance that one or more of the 100 catastrophic satellite breakups of the past was due to a collision, based on collision probability alone.

The catastropic collision rate can then be projected into the future for different growth conditions. It is assumed that the "constrained" and "high" traffic models can be approximated by 5 and 10% per year growth rates in the amount of mass to orbit, respectively. (These two functions fit well until the year 2010.) It is also assumed that the ratio of the number of 10 cm to 3 m objects remain constrained under a "continued explosion" policy, and the absolute number of 10 cm remains constant under a "stop explosion" policy. Also considered is a traffic model that would result in an accumulation of 300 catalogued objects per year if explosions were continued, and an accumulation of 150 objects (all 3 m in diameter) per year if explosions were eliminated. Collision fragments were not added to the population since, initially, their number would be small. The results are shown in Fig. 7.

The catastrophic collisions that would take palce would nearly all be major in the sense that they would produce a large number of fragments at altitudes where the fragments would remain for a long period of time. Under this definition, there have only been five major satellite breakups during the past 10 years, or an average rate of 0.5 per year. Consequently, when the random catastrophic collision rate exceeded this value, it could represent a source of debris exceeding that of past explosions. This is important because the random collision rates are proportional to the square of the number of objects in space; consequently, the rate of growth of fragments will be twice the rate of intact objects, to a first approximation. With a high-traffic model or a constrained-traffic model, both with continued explosions, this could happen in either 1997 or 2005, respectively. By eliminating explosions, the constrained-traffic model could continue until 2009 before reaching a 0.5 rate. Maintaining a growth of 300 catalogued objects per year increases this time to the year 2014, and by eliminating explosions, to 2026. The uncertainty as to which

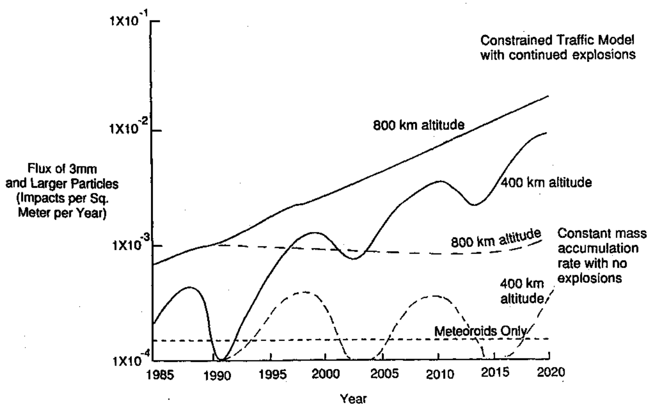

Fig. 8 Predicted future environments of debris 3 mm diameter and larger for two growth conditions.

of the conditions represents the future causes a very large uncertainty in the future population.

Figure 8 predicts the future 3 mm population under two possibilities: the constrained-traffic model with continued explosions (the recommended model in TM 100-471), and a continuation of the current accumulation of mass rate (i.e., 150 objects/yr, 3 m in diameter), but no explosions. By the year 2020, there is a factor of 10 difference in these two fluxes.

Because of the positive response from recent efforts by the U.S. to inform other nations about orbital debris, it is becoming less realistic to assume that explosions will continue at their past rate. In addition, future controls may be adopted so that even high traffic into space would result in a small accumulation rate of debris. If so, the environment 30 years from now may not be too different from today's environment.

Conclusions

Recent measurements tend to confirm the current orbital debris environment described in NASA TM-100-471, with one exception. The new telescopic data indicate that the model is too low for sizes slightly larger than 10 cm, and may be too low for sizes between 2 and 10 cm. However, there is still a significant uncertainty in the current environment, especially for sizes smaller than 10 cm, and at altitudes different from 500 km. There is an even larger uncertainty in the future environment that depends on the debris control measures taken and, to a lesser extent, on the amount of traffic to orbit.

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