DEBRIS ENVIRONMENT INTERACTIONS WITH LOW EARTH ORBIT CONSTELLATIONS

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ABSTRACT

Several low Earth orbit (LEO) constellations for world-wide telecommunication services are being planned for deployment in the near future. Because of their size and complexity, these constellations have the potential for contributing to the orbital debris environment at a significant level. In this paper we present the results of a parametric assessment of the impact of LEO constellations on the orbital debris environment. The increase in loss rate of non-constellation spacecraft is considered in this analysis as well as the increase in loss rate or replacement rate of constellation satellites as a result of debris impact. Primary parameters in the analysis are the number, size, and altitude of the constellation. Parameters are also defined for the vulnerable area for loss of spacecraft and disposition of constellation spacecraft at the end of life. The analysis is performed using CONSTELL, a new model for calculating orbital debris effects in the presence of constellations.

1. INTRODUCTION

LEO communication constellations bring a new element into space operations. These programs, with a few 10's to a few 100's of active spacecraft may constitute a large amount of area and mass in orbit at any time. Because the total area of LEO constellations can be large, there may be a significant probability that impacts with debris will damage or catastrophically fragment constellation spacecraft. Conversely, the presence of one or more large constellations could affect other users of space by significantly increasing the orbital debris environment, either in localized altitude regions or over larger altitude ranges depending on the constellation characteristics and the source of the debris. If the region where there is significant buildup of constellation debris is the altitude of the constellation itself, then the constellation may be vulnerable to self-induced collisional damage.

To better understand this complex problem, a model for analyzing the interaction among LEO constellations, other space programs, and the orbital debris environment was developed at NASA Johnson Space Center (JSC). The model is written in a FORTRAN program called CONSTELL and was developed for the specific purpose of performing parametric studies of LEO constellation / orbital debris environment interactions.

2. DISCUSSION

2.1 Background

A cartoon of the parts of a LEO satellite constellation that are important in considering debris environment effects on constellations is presented in Figure 1. Constellation/debris interactions are characterized by many constellation architecture parameters. Some of these play a major role and some are of lesser but non-negligible importance. A synopsis of these parameters and the roles they play are presented in Table 1.

Since CONSTELL is to be used for parametric studies, some methodology needs to be defined to replace the detailed design information that is required to quantify debris environment effects on constellation spacecraft. This is done through the concept of an effective debris size. Effective debris size is associated with a particular type of event on board the spacecraft, for example a size to cause damage preventing re-orbit. For a given design one can calculate in theory the average rate, R_χ at which failures of a given type χ will occur on a given spacecraft, expressed analytically as

$$R_\chi = \int\int\int \Phi(\Omega,s,v)\, A_\Omega^{(\chi)}(s,v)\, v^2\, dv\, d\Omega\, ds \qquad (1)$$

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Table 1. Constellation Architecture Parameters Affecting Constellation / Debris Interactions

	COMMENTS
MAJOR PARAMETERS	
Constellation Altitude	Keep altitude as low as possible. Higher altitude generally leads to higher background debris fluxes, leads to longer lifetimes for debris generated by constellation.
Number of Operational Spacecraft	More operational s/c leads to greater feedback of constellation debris with the constellation
Size (Mass) of Spacecraft and Upper Stages	Increased collision cross-section leads to greater collisional interaction; more mass leads to more debris generated in catastrophic breakup
Size of Debris Causing Loss of Operational Spacecraft	Determines the importance of debris impact relative to design failures
Spacecraft Operational Lifetime	Controls the amount of constellation support traffic and the number of inactive spacecraft in the environment
Technology Replacement Cycle Time	Controls the amount of constellation support traffic and the number of inactive spacecraft in the environment
Constellation Lifetime	More or less important depending on the constellation altitude
Disposal Orbit Perigee Altitude	For both upper stages and inactive spacecraft; controls the amount of time inactive spacecraft and upper stages remain in the environment; can lead to localized increase in spatial densities that affect other programs
SECONDARY PARAMETERS	
Mission Orbit Inclination	Higher inclinations yield higher average relative velocities on impact, more spatial density enhancement at peak latitudes
Spacecraft Disposal Option	Re-Orbit or abandon; will become more important the higher the constellation altitude
Probability of Accidental Explosion of Upper Stage	Secondary because probability will always be small
(Planned) Probability of Spacecraft Design Failure	Loss of function or loss of control; contributes to number of inactive spacecraft in environment
Number of Spacecraft Delivered per Upper Stage	Controls the number of spent upper stages in the environment; may be different for constellation deployment and spacecraft replacement

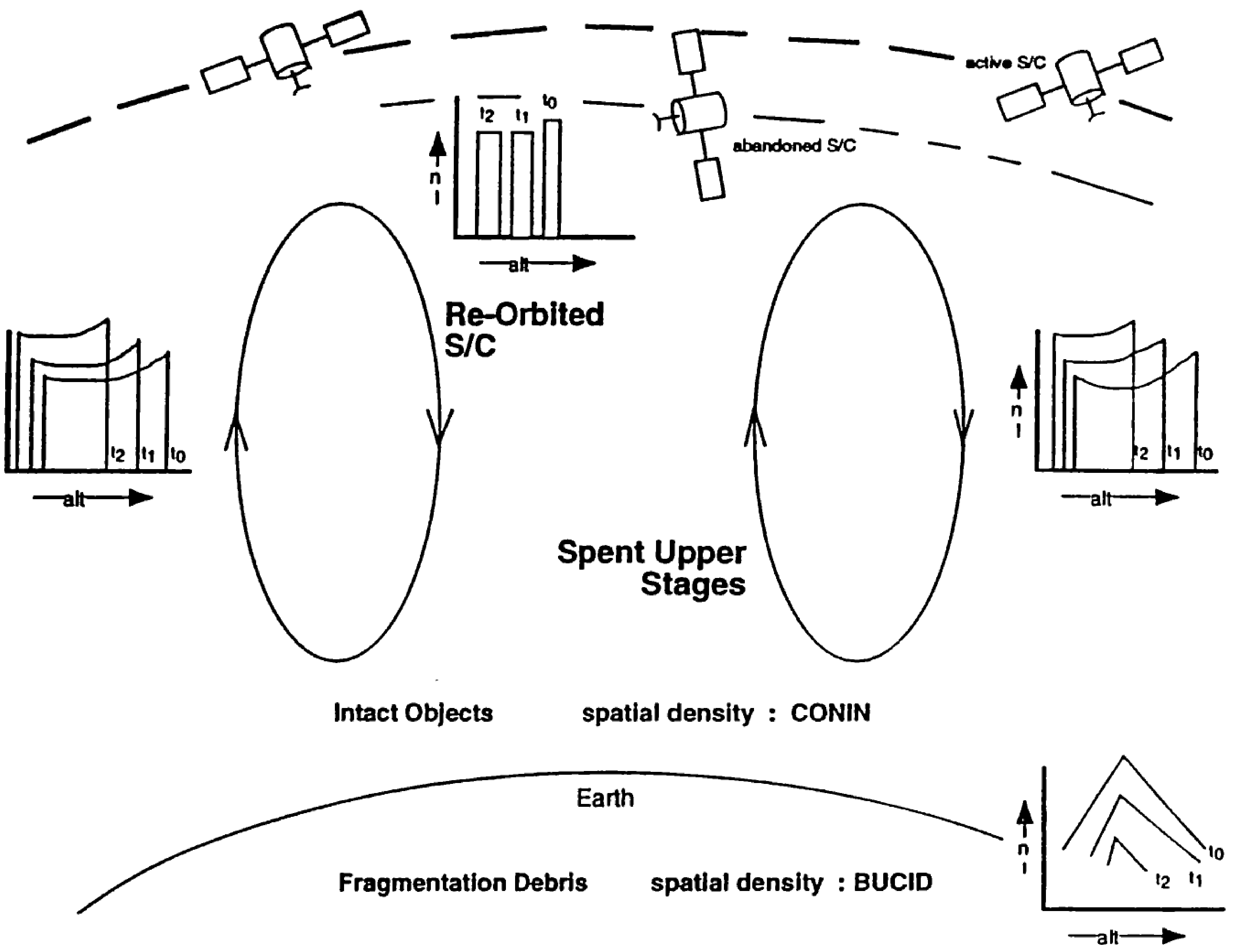

Figure 1. A Constellation from the Orbital Debris Perspective.

where $A_\Omega^{(\chi)}(s,v)$ is the vulnerable area for failure type χ for a spacecraft hit from direction Ω by debris of size s having impact speed of v, and $\Phi(\Omega,s,v)$ is the flux density of the orbital debris environment coming from direction Ω in a solid angle of $d\Omega$ steradians and in a velocity interval v to v + dv in the co-moving reference frame of the spacecraft. The effective debris diameter causing loss of control preventing re-orbit, d_{eff}^{ab}, would then be defined by

$$F(d_{eff}^{ab})\, A_X \equiv R_{lc} \qquad (2)$$

where

R_{lc} = rate of failures causing loss of control

$F(s_0)$ = is the cross-sectional area flux to a limiting debris diameter $= \int_{4\pi} \int_0^\infty \Phi(\Omega,s_0,v)\, v^2\, dv\, d\Omega$

A_X = average cross-sectional area of the spacecraft

The diameter d_{eff}^{ab} depends on both the design characteristics of the constellation spacecraft and on the orbital debris environment flux. The "ab" in the variable definition denotes the spacecraft is abandoned in the mission orbit, i.e., it cannot be maneuvered out of that orbit because control of the spacecraft has been lost. This diameter is basically the characteristic size of debris that would be expected to cause, in this case, failure not allowing re-orbit of the spacecraft. The benefit of the above transformation is that it replaces missing design information with environment data. It could be argued that one unknown has been replaced by another, but this is not really germane, since d_{eff}^{ab} will be a parameter and it spans a relatively narrow size range - probably greater than 1 mm and smaller than 1 cm. Similarly, an effective diameter, d_{eff}^{re}, causing failures requiring replacement but not preventing re-orbit could be defined. If the architecture plan is to abandon all spacecraft in the event of spacecraft failures or at the end of their operational life, the distinction between re-orbit and abandonment disappears.

2.2 Approach

The conflicting demands to understand constellation / environment interactions in general with the highly detailed knowledge required to properly characterize the problem in any particular case would indicate that a parametric modeling approach should be used. Such a model must be able to support all parameters that might be considered for the constellation architecture and be able to calculate single cases relatively rapidly so that parameter ranges can be spanned with some resolution.

The CONSTELL model was developed for this purpose. CONSTELL uses an approach to calculating debris environments in the presence of collisional sources using a technique best described as recursion to convergence. A multi-component initial environment is modelled, consisting of a background environment without any constellations and N components from N constellations. The initial background environment in this paper is the new NASA engineering model, ORDEM96 (Ref 1). The other initial environment components are the constellations, defined without collisional interactions. That is, the initial constellation population will consist of: (1) active constellation spacecraft and on-orbit spares, (2) inactive constellation spacecraft that have reached end of life or have failed for reasons other than by debris impact (design failures), (3) upper stages used to place constellation spacecraft in orbit, (4) orbital debris released during constellation deployment operations, and (5) explosion fragments created by accidental (not collision-induced) explosions. This initial state is modified recursively via the outer-most (environmental update) loop by calculating the modified environment. Notionally, we have

$$E^{(K+1)}=E^{(K)} + S_C(E^{(K)}) - S_C(E^{(K-1)}) \equiv E^{(K)}+\delta S_C^{(K)} \qquad (3)$$

where $E^{(n)}$ is the nth environmental iteration and S_C is the collisional source term based on the indicated environment iteration. The recursive process continues until the change in environments between iterations is sufficiently small. The convergence criterion may be derived from the recursive relationship

$$E^{(K+1)} - E^{(K)} = \delta S_C^{(K-1)} \leq \varepsilon\, S_C^{(K)} \qquad (4)$$

where the first equality follows from the recursion condition and ε is some small positive quantity. Note that spatial densities from successive environment iterations are strictly increasing.

The issue of collisional cascading has been addressed in previous papers (Ref 2). The benefit of this approach is that it clearly delineates the role of successive generations of collision fragments in contributing to the environment. On iteration K, the contribution from generation (K-1) debris fragments is calculated (that is collisions between generation (K-1) fragments and all generations up to and including (K-1)).

2.3 Illustrative Results for a Test Case

To illustrate the output of the model, more detailed results will be presented for a single constellation case. This sample case is for a constellation of 1000 spacecraft at an altitude of 1000 km. The spacecraft have a 4-year lifetime, there is a 10-year technology replacement cycle, and the size of debris that will cause loss of a spacecraft will be 5 mm. During the time of constellation operations there will be 100 spares in orbit. The constellation lifetime is 20 years. Whenever possible, spacecraft are re-orbited to a 1000 km x 400 km disposed orbit once they become inactive through damage, design failure, or reaching end of life.

A spatial density plot is shown for this case in Figure 2 for objects of size larger than 1 mm. It can be seen from the figure that for ≥ 1 mm debris the constellation debris falls considerable below the background environment even at the constellation altitude. However, even 10 years after the constellation has been removed, there is a significant reduction on the spatial densities only at altitudes below ~600 km. The ≥ 1 cm debris results, not shown, are somewhat more complicated. Over most of the LEO altitude range the constellation debris spatial densities fall well below the background, but in this size range the contribution of re-orbited systems is comparable to the background. Given that this is in the altitude region for the International Space Station, these results illustrate the undesirability of having the re-orbit perigee altitude for a constellation being in the region of an important spacecraft or program.

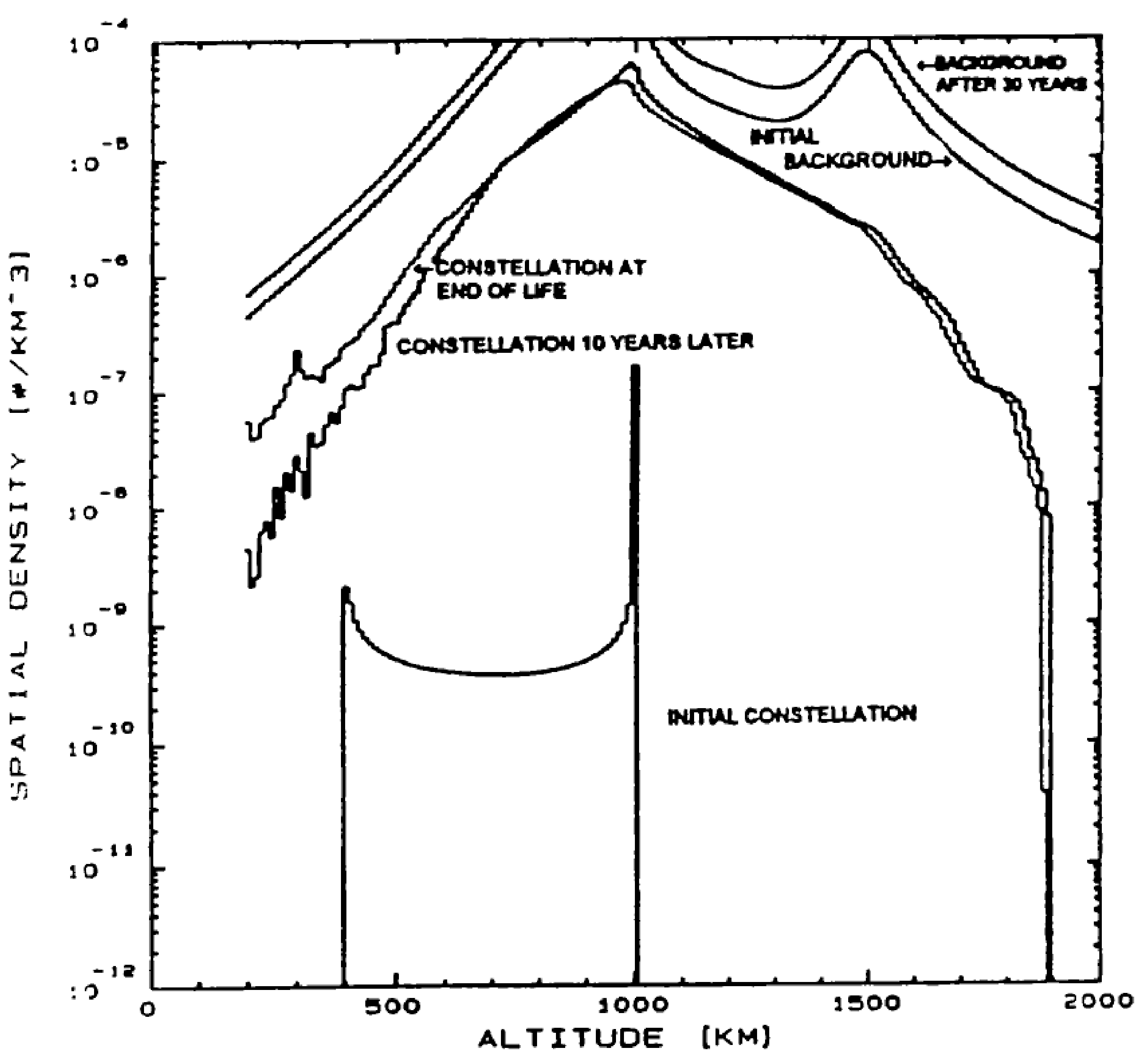

Figure 2. Spatial Densities Associated with the Background Environment and with the Constellation.

2.4 Debris Effects as a Function of Constellation Size and Operational Altitude

The constellation model is simplified for the parameter sweep calculations. It is assumed for these cases that there is a single deployment of the constellation in the year 2000 and that the number of active spacecraft remains constant for the 30 year period of the calculation. The constellation is also assumed to keep an additional 10% of the active satellites available as on-orbit spares. Constellation spacecraft are assumed to experience damage requiring replacement if hit by a 1 cm or larger debris object over any part of a 10 m^2 cross-sectional area and preventing re-orbit if hit by a 5 mm or larger projectile over 5 m^2 cross-sectional area.

The two parameters that are varied in these calculations are the operational altitude and number of active spacecraft. The number of active spacecraft ranges from 100 to 2,000 for operational altitudes of 500 km (Case 500), 700 km (Case 700), and 1000 km (Case 1000). In each of these cases it will be assumed that damaged spacecraft will be re-orbited whenever possible. The 1000 km altitude constellation is also run assuming all damaged or failed spacecraft are abandoned in their mission orbit rather than re-orbited to a decay orbit (Case 1000A). This last case illustrates the potential importance of not just planning to re-orbit spacecraft but the need to perform this maneuver with a high probability of success (i.e., the design should have a very low probability of failure to perform re-orbit with or without damage from debris impact). Not having such a plan would be inadvisable for some constellation architectures, and choosing a high altitude constellation as the test case demonstrates this on the short time scale of 30 years.

The results of the calculations are presented in terms of two types of debris impacts on the constellation:

(1) the fraction of the constellation replaced in 30 years of constellation operations; if this parameter is not constant as the number of constellation spacecraft increases then collision processes associated with the constellation must be contributing small debris that cause a noticeable number of losses.

(2) the number of collisions involving a constellation system per constellation spacecraft; if this parameter is not independent of the number of constellation spacecraft then collision processes associated with the constellation must be contributing large debris that cause an increase in the number of catastrophic collisions.

The fraction of the constellation replaced in 30 years is presented for the four cases in Figure 3. Extrapolating the curves to the y-axis indicates the number of spacecraft that would be lost strictly from interactions with the background environment; the reason for the different limit point values is, of course, due to the difference in background flux levels at the different altitudes. Although the zero point loss for the constellation at 1000 km is much higher than for the two lower altitude constellations, it would be a factor of 2 higher still if the constellation were 100 km lower so that it was operating near the 900 km altitude peak in the small particle environment.

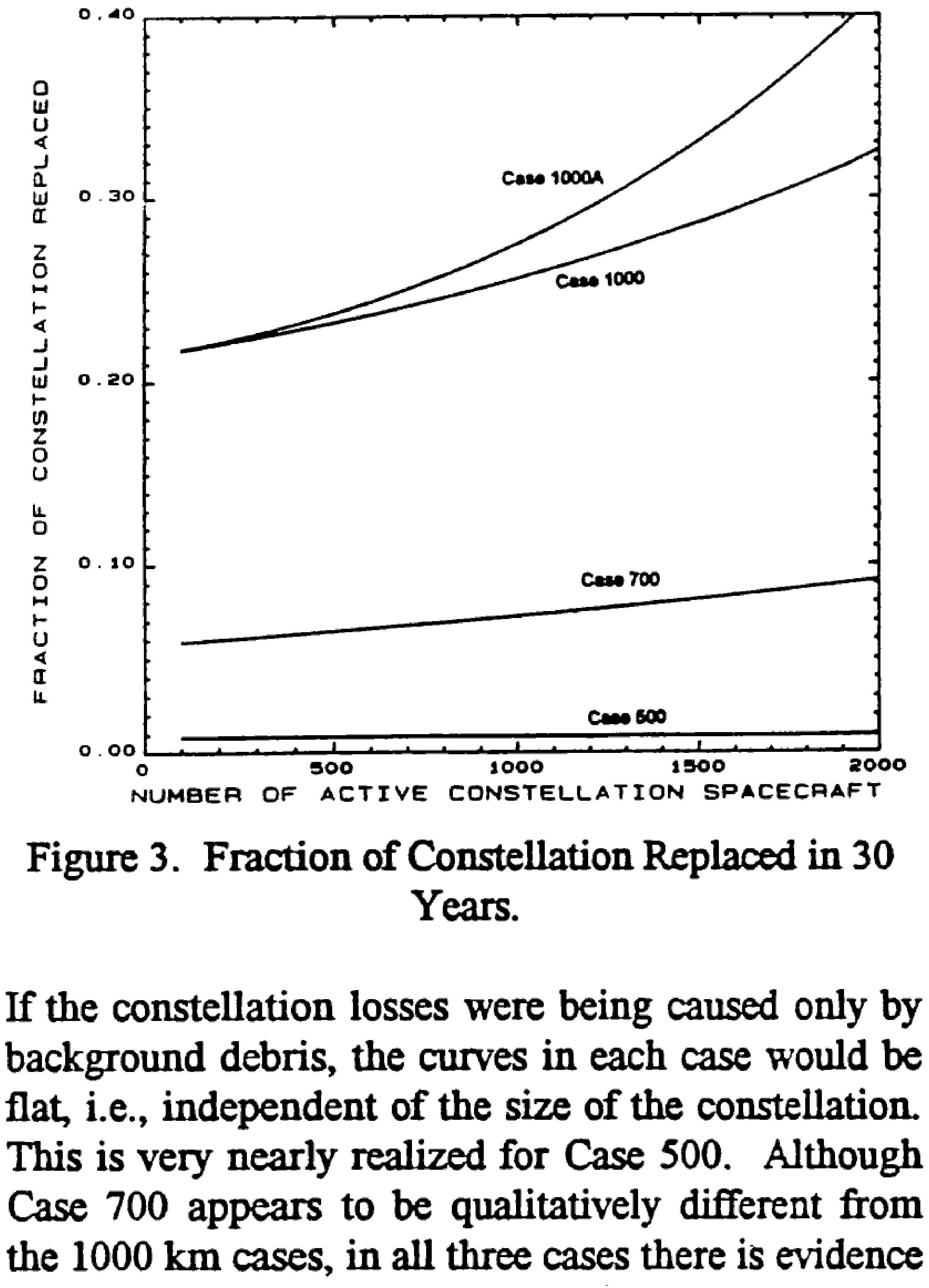

Figure 3. Fraction of Constellation Replaced in 30 Years.

If the constellation losses were being caused only by background debris, the curves in each case would be flat, i.e., independent of the size of the constellation. This is very nearly realized for Case 500. Although Case 700 appears to be qualitatively different from the 1000 km cases, in all three cases there is evidence of constellation debris causing some of the losses. This can be seen from the form of the equation for collisional loss of constellation spacecraft:

$$\Delta N = N_0 \left[C_{bg} f_{bg} + C_{con} f_{con} \right] \qquad (5)$$

where N_0 is the number of spacecraft in the constellation, f_{bg} and f_{con} are fluxes from the background and constellation respectively , and C_{bg} and C_{con} are proportionality constants that account for collision cross-section and time over which the losses accumulate. $\Delta N/N_0$ is plotted in Figure 3. When the constellation contributions to loss are small compared to the background, $\Delta N/N_0$ is independent of N_0. The constellation flux component is proportional to the number of catastrophic breakup events, which is proportional to N_0 for constellation-background catastrophic collisions and to N_0^2 for constellation-constellation collisions. Therefore, over the 30 year period for the calculation, the 500 km case shows no appreciable contribution from collisions for constellation sizes up to 2000 spacecraft, but the higher altitude constellations do show such a contribution. The source of these additional losses for the 700 km case is background-constellation collisions, but for the 1000 km altitude cases constellation-constellation collisions are already contributing within the 30-year projection time. Case 700 would show the same quadratic upward turn if a longer projection time was used. These results depend on the collisional breakup model used for the projection, and one focus for future work is to determine the sensitivity of the results to variations in the breakup model.

The results show a strong dependence on the operational altitude of the constellation. There are two reasons for this, both related to the efficiency of aerodynamic drag to remove objects from the environment. As the altitude of the constellation increases, (1) debris clouds that are created either by explosions of the upper stages or collisions will occur at higher altitudes, leaving fragments from those events in the environment for a longer time, and (2) spacecraft which are abandoned at the operational altitude of the constellation remain in the altitude range of the constellation for a longer time and therefore have more time to interact collisionally with the constellation. The importance of this latter effect is illustrated in the difference between cases 1000 and 1000A.

The number of catastrophic collisions per constellation spacecraft is presented in Figure 4. This parameter should show the same behavior as for spacecraft losses, i.e., in the absence of contribution from collisions involving constellation members the number should be independent of the number of constellation spacecraft. Figure 4 shows the influence of large debris fragments created by catastrophic collision, whereas Figure 3 shows the contribution of small debris created by these events. Figure 4 shows the same feedback effects as did Figure 3. The number of collisions in each case can be determined by multiplying the plotted value by the number of spacecraft. One observation to make from Figure 4 is that in many cases the number of collisions involved is not large. The effects that are observed involve a rather few events that, while correctly modeled for the rate of occurrence leading to fractional events in the CONSTELL average rate approach, conceal the large variance that would be found if a Monte Carlo model was adopted instead. Since CONSTELL deals only with average effects, another measure of the likelihood that a constellation would experience measurable debris consequences that perhaps should be considered would be to weigh the collision rate (or probability), which can be calculated within CONSTELL, by some "severity parameter" for a collision event either to the constellation or to background spacecraft. Once the average rate leads to several collisions, this measure would be less interesting because the uncertainty in this number of events would be significantly smaller.

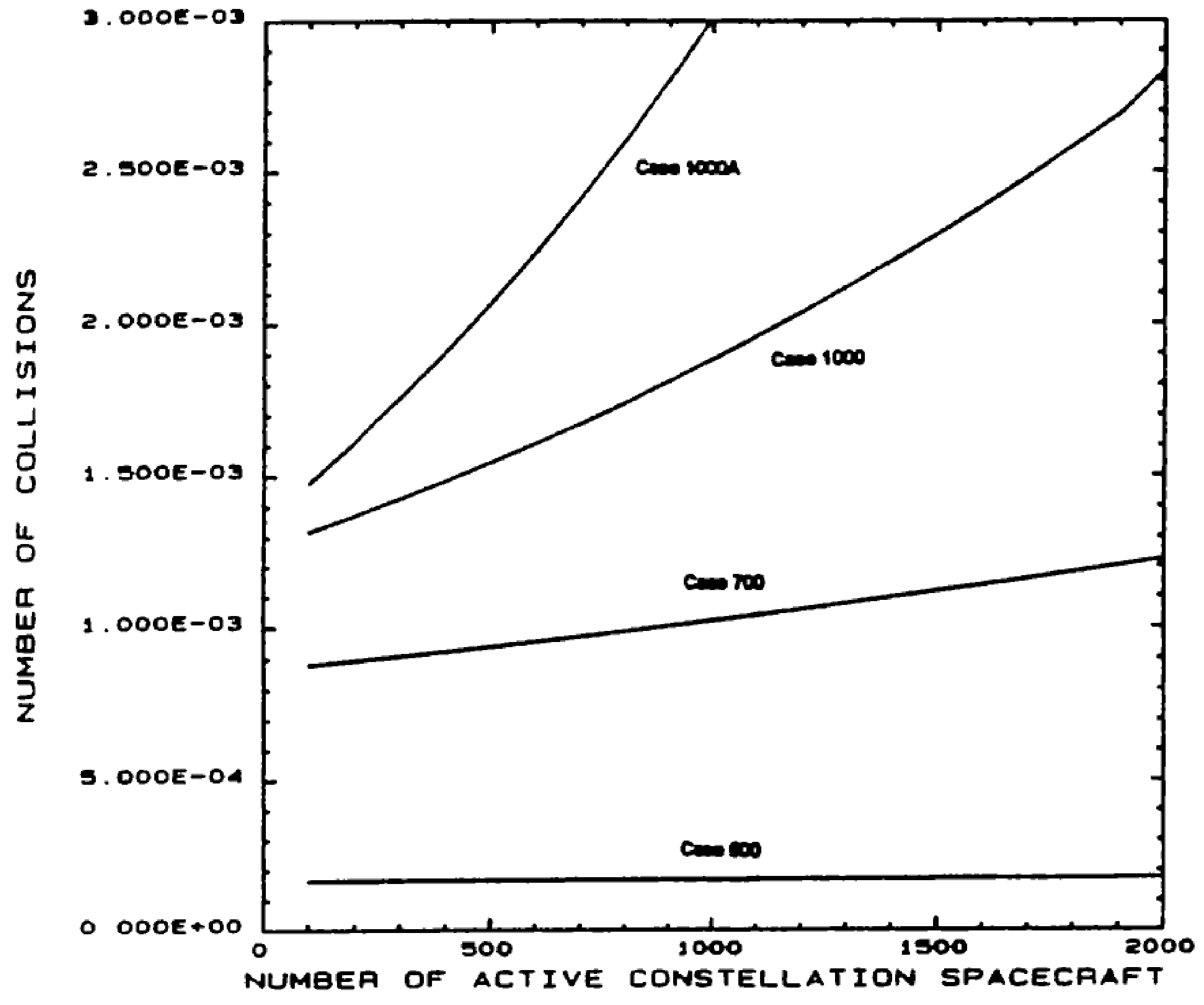

Figure 4. Number of Catastrophic Collisions Involving Constellation Elements.

Spacecraft losses (Figure 3) measure the number of collisions between small but lethal debris, in this case in the 5 mm to 1 cm size range. The debris source that directly contributes a large amount of debris into the environment are catastrophic collisions involving constellation systems, and that is measured by Figure 4. The non-linearity in Figure 3 is a measure of the importance of small debris fragments causing loss of spacecraft which increases the likelihood of additional collisions. The non-linearity in the Figure 4 curves shows the immediate effect of constellation fragmentations causing additional collisional breakups and is more indicative of debris environment instabilities that might be introduced by large, high altitude constellations.

2.5 A Simple Predictive Risk Parameter

Since some of these constellation cases are being driven by interactions with the background orbital debris environment, a simple predictive risk parameter normalizing the fractional loss rate by the effective background debris flux for losses, $[\Delta N/N_0]/f_{bg}$, was defined. This parameter is plotted against the number of constellation spacecraft in Figure 5. For the two higher altitudes, the losses were dominated by the 5 mm and larger flux, so that value was used for the normalizing flux, while for the 500 km constellation the two types of losses contributed comparably, so an intermediate size of 7 mm was used. If this parameter would be used in designing a constellation architecture, the predicted number of spacecraft losses would be calculated knowing only the number of constellation spacecraft and the predicted background flux. Alternatively, if an acceptable loss rate could be defined, then, given the number of constellation spacecraft, a limit to the size of debris that would cause a constellation spacecraft to be damaged could be defined via the maximum allowed background debris flux.

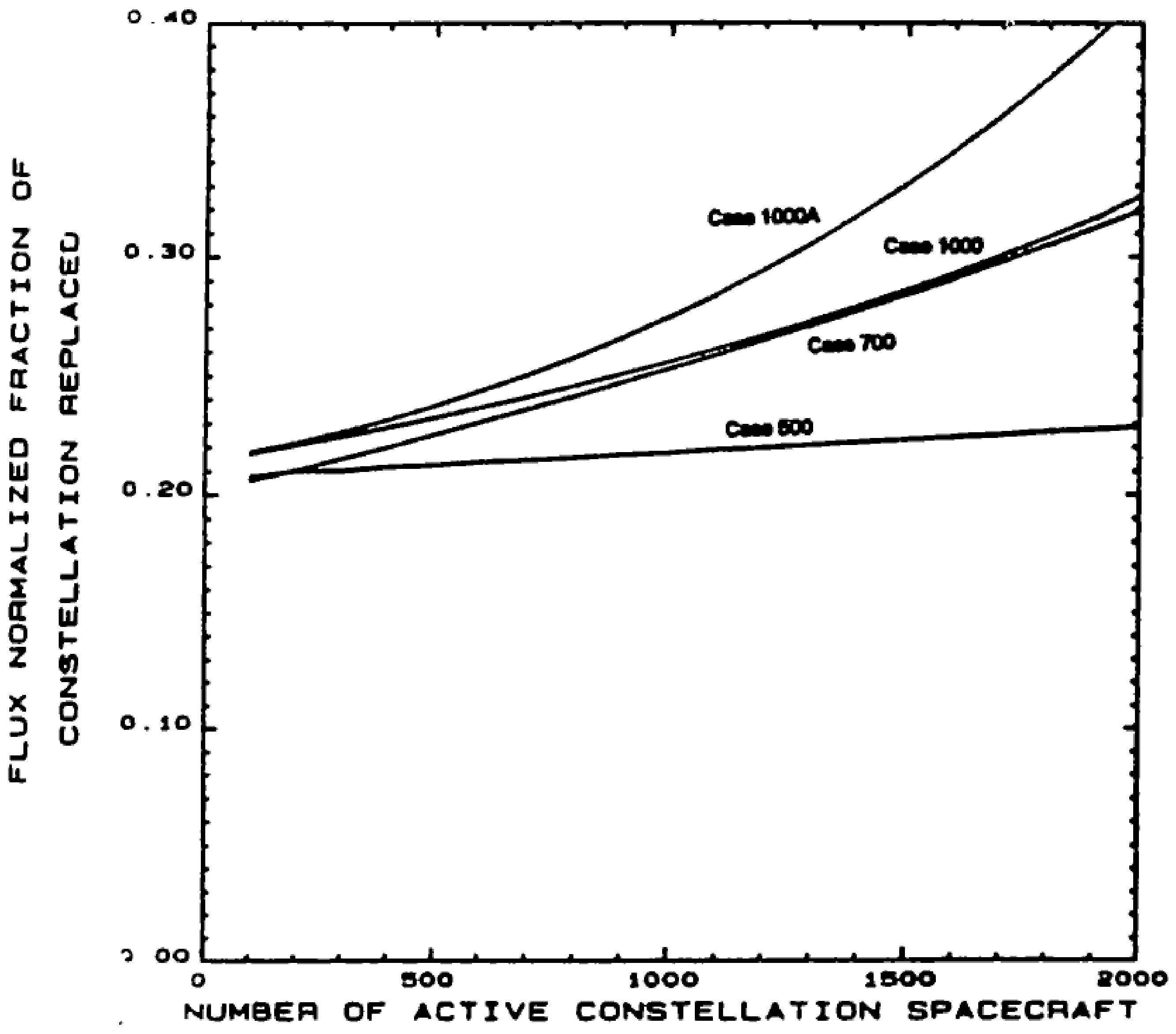

Figure 5. Behavior of a Simple Predictive Risk Parameter as a Function of Number of Constellation Spacecraft.

It can be seen from the figure that this parameter is reasonably consistent for constellation cases where interactions with constellation debris is least important. In the future more complex parameters will be derived.

3. CONCLUSIONS

A model for constellation interactions with an orbital debris environment has been developed at JSC. This model is able to simulate reasonable, complex constellation architectures but is designed primarily to perform parametric assessments to determine sensitivities of debris effects to constellation characteristics. Detailed model results were illustrated for a single architecture. This model is suitable for risk assessment of planned constellations.

Parametric assessment of constellations at altitudes of 500 km, 700 km, and 1000 km show the effects of constellation-induced damage events at altitudes of 700 km and above, even for small constellations, although the effect is small at the lower altitudes. In the case of 1000 km where re-orbit was not designed with the architecture, there was a much more rapid increase in loss with increasing constellation size. The constellations at 700 km show evidence of damage caused by fragmentation debris generated by constellation-background collisions, but the 1000 km constellations show evidence of damage caused by fragmentation debris generated by constellation-constellation collisions. These results should be viewed with some caution since they are dependent on the collisional breakup model, and assessments have not yet been made on the sensitivity of these results to uncertainties in this model.

A simple predictive risk parameter was used to illustrate the value of looking for such parameters in future studies. This parameter considered only the influence of the background environment on the constellation, and the correlation between the parameter prediction and calculated constellation losses was good for relatively small ($N_0 \leq 200$) constellations.

4. REFERENCES

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