SATELLITE CONSTELLATIONS AND THEIR LONG TERM IMPACT ON THE DEBRIS ENVIRONMENT IN LOW EARTH ORBIT

R. Walker, R. Crowther, V. Marsh, P.H. Stokes

Space Department, Defence Research Agency, Farnborough, Hants., GU14 0LX, UK

G.G. Swinerd

Department of Aeronautics & Astronautics, University of Southampton, Hants., SO17 1BJ, UK

ABSTRACT

An increasing number of multiple satellite constellations providing global mobile telecommunications will be launched into low Earth orbit (LEO) within the next decade. These systems could be utilised for many years in a growing debris environment that presents a significant long term collision hazard. Most LEO constellations will be deployed in the regions of peak debris density at polar inclinations where the debris collision risk is the greatest. In this paper, we use the IDES long term evolution model to predict the impact of multiple satellite constellations on future collision rates and debris growth in LEO. Collision coupling between these constellations and background debris is investigated. System vulnerability to catastrophic debris is analysed by modelling constellation fatality rates and long term risk variations.

1. INTRODUCTION

The modern day concept of satellite constellations that provide continuous multiple whole Earth or 'global' coverage for communications purposes was first proposed by Walker (ref. 1). Walker suggested a design for satellites operating in a number of equally spaced near-polar circular orbit planes. The phasing strategy within the planes was later developed by Adams and Rider (ref. 2). The constellations to be deployed in the next few years are mostly based on this design, but they vary widely in size, operational orbits and function. For example, Globalstar comprises 48 satellites at 1400 km and provides mobile narrowband voice communications (ref. 3), whereas Teledesic has an 840 satellite configuration to be operated at 700 km altitude and offering high rate broadband data transmission for services such as video-conferencing or high performance Internet access (ref. 4).

To date, orbital debris research associated with constellations has mainly been concerned with short term and long term collision cascading within the system itself (ref. 5). Only a limited study has previously been performed with IDES to model the potential long term collision interactions between constellations and the background debris environment (ref. 6). This suggested that a large generic constellation placed in a region of high debris density will suffer a number of fatalities, resulting in a larger debris population in the next 20 years. There has been concern that the large increase in mass and area at critical altitudes due to constellations may accelerate long term debris growth in LEO (ref. 7) and trigger collision cascading in the background debris environment much earlier than previously estimated.

The extent of accelerated population growth due to constellations depends upon the level of collision interactions between the constellations and the background debris environment. A constellation system may suffer a number of satellite fatalities from collisions with debris fragments in the long term. A fatality is defined as a collision event that has enough energy to cause a catastrophic fragmentation of the target object. Each of these breakup events will spread more fragments into the environment local to the constellation, thus increasing the collision risk to both the constellation and large background objects, such as spacecraft, rocket upper stages and operational debris. This increase in risk may produce more collisions for large background objects near the constellation altitude, which would further enhance the risk to produce more constellation collisions and so on. This localised effect can be considered as a *long term collision coupling* between constellation and background debris. The IDES model is used to study this phenomenon.

2. THE IDES APPROACH

The Defence Research Agency's Integrated Debris Evolution Suite (IDES) has been developed in order to model the current and possible future orbital debris environments in LEO, and to provide directional collision risk assessments for individual orbiting satellites. The debris sources modelled by IDES are; low intensity explosions, high intensity explosions, catastrophic collisions, payloads, rocket upper stages, operational debris, secondary ejecta and paint flaking from meteoroid/debris impacts. IDES is capable of modelling all the major orbit perturbations for debris

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larger than 10 microns, which include geopotential, atmospheric drag, luni-solar and solar radiation pressure effects. Ref. 8 provides more specific information on the IDES modelling techniques. IDES has been formally developed and tested to ESA PSS-05 Software Engineering Standards.

The debris environment on 1st January 1996 is characterised by simulating each of the past 133 recorded fragmentation events in space and predicting the orbital evolution of the generated fragments to the reference epoch. Launch-related objects such as payloads, rocket upper stages, and operational debris from the USSPACECOM catalog are then added to the 1996 fragment population of greater than 1 mm in size.

This debris population constitutes the initial conditions which are used along with detailed future launch and explosion models for predicting debris evolution over the next 50 years. IDES has been designed with the capability to assess the complex long term collision interactions in the debris environment, including the involvement of satellite constellations. Snapshots of the debris flux environment are output from the model at 4 month time intervals so that satellite risk assessments can be performed at any future epoch, and long term encountered flux variations can be predicted.

The development of novel techniques for debris flux determination and future collision event prediction allows IDES to model collision interactions in detail. The size-dependent debris flux environment at a particular epoch is efficiently determined using analytical methods and represented in high resolution, with directionality, whilst retaining low data storage requirements. This enables the target-centred approach for collision event prediction to make rapid and accurate collision risk assessments, hence statistically predicting collisions for specific target objects such as constellation satellites or larger background debris.

2.1 Debris Flux Determination

The determination of debris flux for discrete sectors of the LEO regime is an essential component of the IDES model. The debris flux environment is represented by a three-dimensional inertial control volume divided into cells by the spherical co-ordinate parameters of Earth radius, declination and right ascension. By transforming the orbital state of the debris population into spatial density and intersection velocity vectors for each of the volume cells in the control volume, it becomes possible to determine the fluxes encountered by a single target orbit from different mass ranges. The method of flux determination in IDES uses a technique similar to Klinkrad (ref. 9).

For each large debris object >10 cm with individual orbital elements of semi-major axis, a, eccentricity, e, inclination, i, right ascension of ascending node, Ω, and argument of perigee, ω, the method determines the true anomalies, θ, of the orbit which intersect the respective cells of the inertial control volume. These are defined by borders of radius, r, declination, δ, and right ascension, α. The method uses the following equations derived by Hauptmann:

$$\theta(r) = \cos^{-1}\left(\frac{a(1-e^2)/r - 1}{e}\right) \tag{1}$$

$$\theta(\delta) = \sin^{-1}\left(\frac{\sin\delta}{\sin i}\right) - \omega \tag{2}$$

$$\theta(\alpha) = \sin^{-1}\left(\frac{\sin(\alpha - \Omega)}{\sqrt{1-\sin^2 i \cos^2(\alpha - \Omega)}}\right) - \omega \tag{3}$$

Each of the true anomalies are converted to an intersection time and then the intersections are sorted in ascending time order. The time between these intersections (t_2 - t_1) is used to determine the residential probability, P_{res} (given orbital period T), and hence the spatial density, S, of the object during passage through the respective cell volume, V. The velocity vector is defined at the mid-point of cell passage by the velocity magnitude, v, azimuth, A_z, and elevation, h:

$$P_{res} = \frac{t_2 - t_1}{T}, \quad S = \frac{P_{res}}{V}, \quad v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)} \tag{4}$$

$$A_z(\theta) = -\cos^{-1}\left(\frac{\sin i \cos(\omega + \theta)}{1 - \sin^2 i \cos^2(\omega + \theta)}\right) \tag{5}$$

$$h(\theta) = \cos^{-1}\left(\frac{-e\sin\theta}{\sqrt{1 + e^2 + 2e\cos\theta}}\right) - \frac{\pi}{2} \tag{6}$$

The flux magnitude of each debris intersection in the cell is the spatial density multiplied by the velocity magnitude. Overall debris flux in each cell is then defined as the summation of all such flux magnitudes. Instead of recording every flux vector of every cell intersection of every debris orbit, the data storage and processing requirements are significantly reduced by computing average vectors in each cell. For each cell intersection, the velocity, azimuth and elevation values are weighted by the residential probability and added to their respective running totals. The residential probability is simply accumulated. The mean vector for each cell after all debris intersections is then derived by dividing each of the running totals by the total residential probability. The spatial density for each cell is then simply the total residential probability divided by the volume of the cell. However, one mean vector per cell is not sufficient to represent the wide variation in directionality. In fact, 8 mean vectors are required per cell to cover this variation. The 8 vectors come from the combinations of 4 sectors in azimuth angle from -180 to 180 degrees and 2 sectors in elevation angle from -90 to 90 degrees.

The mass-binned contributions to the debris flux matrix from the small-size debris population are derived from a fragment orbit matrix which bins the population by perigee radius, eccentricity, inclination, and mass. For each orbit-mass bin of the fragment orbit matrix, the number of particles in the bin and the orbit bin centroid co-ordinate in perigee radius-eccentricity-inclination space, are used to determine the *group* spatial density and velocity vector in a particular mass bin of each volume cell. Again, the theory is used in the same way as described for large debris objects. However, all debris objects within a particular orbit bin of the fragment orbit matrix are assumed to traverse the centroid orbital path and so the *unit* spatial density (due to one object) can be scaled by the number of objects in the orbit-mass bin for the group spatial density.

2.2 Collision Event Prediction

Collision event prediction is treated in the simulation by a 'target-centred' approach. It combines individual collision risk analysis of large object targets relative to smaller mass debris fluxes with a statistical Monte Carlo prediction of events. The lethality of each predicted collision event is assessed. This method triggers catastrophic collision breakups as well as non-lethal damaging impacts that produce secondary fragments. Each member of the debris population with mass greater than 50 kg is considered as a target which encounters a relative flux from debris of lower mass ranges. The Klinkrad method (ref. 9) of determining relative flux to a target orbit is used. Firstly, the cell intersections of the target orbit are found by employing the same technique as for the debris flux calculations. For each cell intersection, the target velocity components in *x,y,z* cartesian co-ordinates, the target declination and right ascension, and residential probability are computed. Then, for each mass bin of the intersected cell, each of the 8 debris flux vectors is taken in turn and the velocity components of the debris flux vector relative to the target are derived from:

$$\begin{pmatrix} \Delta\dot{x}_{n.m} \\ \Delta\dot{y}_{n.m} \\ \Delta\dot{z}_{n.m} \end{pmatrix} = v_n \begin{pmatrix} c\alpha_m\left(-s\delta_m ch_n cA_n + c\delta_m sh_n\right) - s\alpha_m sA_n \\ s\alpha_m\left(-s\delta_m ch_n cA_n + c\delta_m sh_n\right) + c\alpha_m sA_n \\ c\delta_m ch_n cA_n + s\delta_m sh_n \end{pmatrix} - \begin{pmatrix} \dot{x}_m \\ \dot{y}_m \\ \dot{z}_m \end{pmatrix} \quad (7)$$

In this matrix, *c=cos*, *s=sin*, *n* denotes the debris (from a particular mass bin) and *m* denotes the target. In order to express this relative velocity vector in the target-centred moving reference frame, the target right ascension of ascending node, inclination and argument of true latitude, u_m, are used in a matrix transformation:

$$\vec{v} = \begin{pmatrix} cu_m c\Omega - su_m s\Omega ci & cu_m s\Omega + su_m c\Omega ci & su_m si \\ -su_m c\Omega - cu_m s\Omega ci & -su_m s\Omega + cu_m c\Omega ci & cu_m si \\ s\Omega si & -c\Omega si & ci \end{pmatrix} \begin{pmatrix} \Delta\dot{x}_{n.m} \\ \Delta\dot{y}_{n.m} \\ \Delta\dot{z}_{n.m} \end{pmatrix} \quad (8)$$

The relative velocity vector has 3 component directions; *u,v*, and *w*, where *u* denotes radial direction, *v* denotes along track direction, and *w* denotes out-of-plane direction. The relative velocity *magnitude* between the debris vector and the target is then simply:

$$v_{rel} = \left|\vec{v}_{n.m}\right| = \sqrt{\left(v^u_{n.m}\right)^2 + \left(v^v_{n.m}\right)^2 + \left(v^w_{n.m}\right)^2} \quad (9)$$

Finally, the relative flux magnitude between debris flux vector and target is given by the debris vector's spatial density multiplied by this relative velocity. The orbit-integrated mean relative flux to the target, F_t, is then a summation of each of the relative flux magnitudes encountered in each of the target cell intersections weighted by the respective target residential probability.

The expected number of collisions for each mass bin over the timestep is then computed from the orbit-integrated mean relative flux, the target cross sectional area, σ_t, the average debris cross sectional area for the mass bin, σ_p, and the time interval, Δt:

$$\lambda = F_t \sqrt{\sigma_t^2 + \sigma_p^2}.\Delta t \quad (10)$$

The *predicted* number of collisions from a particular mass range over Δt can be statistically derived using a Poisson distribution from n = 0 to N events to obtain N event probabilities, P_n, as performed in refs. 10 and 11:

$$P_n = \frac{\lambda^n}{n!} e^{-\lambda} \quad (11)$$

Values of P_n are accumulated to give a total probability, then each event probability is normalised by this value. All normalised event probabilities lie in the range from 0 to 1. A high precision uniform random number is generated and the predicted number of events corresponds to which normalised event probability has been exceeded by the random number.

Name	Year	Alt.(km)	Inc.(°)	Total	Area(m^2)	Mass(kg)
CONSTEL1	2000	700	98	924	40	700
CONSTEL2	1998	780	86	72	40	700
CONSTEL3	1999	1400	52	56	36	450
CONSTEL4	1998	775	45	28	14	45

Table 1. Generic Constellation Design Data Modelled in IDES

If one or more collisions are predicted for the target, then the lethality is assessed by calculating the impactor energy-to-target mass ratio (*EMR*) from parameters of target mass, M_t, projectile mass from the mass bin, M_p, and the relative velocity at the peak encountered flux as the impact velocity, v_{imp}:

$$EMR = \frac{\frac{1}{2} M_p \, v_{imp}^2}{M_t} \qquad (12)$$

If the *EMR* is greater than the lethality ratio of the target (default of 40 J/g), a catastrophic collision is executed by the breakup model, with true anomaly of the breakup set to the value where the peak relative flux is encountered. However, if the *EMR* is less than the target's lethality ratio then a damaging impact producing secondary ejecta is simulated by the breakup model.

2.3 Future Traffic Modelling

In order to obtain a realistic orbit distribution, the launch traffic model has an 'object-oriented' approach which uses over 450 different families of objects. Each object family has representative attributes, such as injection orbital elements, mass and area. The model then makes associations between a primary object family and any number of secondary object families to characterise the launch of a particular payload with a given rocket body and a number of other launch-related objects. Object families (or *classes*) are classified by nationality, orbit type, inclination band, object type, and family name. Object class data and associations are derived from analysis of historical launch activity. Object types include payloads, rocket bodies, boosters, kick motors, payload related objects (eg. lens covers) and launch vehicle related objects (eg. shrouds).

3. SCENARIO DEFINITION

Due to the statistical nature of modelling future collisions, IDES is used in a Monte Carlo mode to represent different statistical permutations. In order to obtain a reasonable statistical average of the impact of constellation operations on long term debris evolution, 10 Monte Carlo simulations are run for each of two distinct cases. The 'no constellations' case uses the pre-generated 1996 debris population and a 'business as usual' future traffic model to predict long term evolution from 1996 to 2050 in 4 month time intervals. Only *catastrophic* collisions are assessed at every timestep. The 'all constellations' case is identical to the 'no constellations' case except that 4 generic constellations are included in the simulations. Table 1 shows their design data which is used as input into the IDES model. Their configurations represent the wide variation in design parameters currently being proposed.

Besides the consideration of collisions, factors such as the future launch rate and future explosion rate can influence the long term evolution of the LEO debris environment over the next 50 years. In both cases, the future launch rate remains constant at around 80 per year and the future explosion rate is set to 4 per year. These rates are called the 'Business As Usual' (BAU) rates and have been derived from the average of the last 8 years of LEO activity. This assumes that future activity will continue at the same level as the recent past, hence the term 'Business As Usual'. Since both cases have the same average launch and explosion rates, then the differences in the future collision rate and hence population growth will be exclusively due to the operation of the constellations.

Geopotential and atmospheric drag perturbation models are used to propagate the debris population in these scenarios. Debris mitigation measures (eg. de-orbiting of rocket bodies and payloads) that reduce the long term risk to the operational satellite population are *not* modelled by IDES in this study.

4. ASSUMPTIONS

The launch and possible explosions of launch vehicle upper stages associated with the deployment of these constellations have not been included. This is because many of the launch contracts and upper stage orbits are unknown. The constellations are assumed to be operational throughout the 54 year time span with expended satellites de-orbited and replaced by ground spares on demand. Any constellation satellites fragmented by a collision are assumed to be replaced in a similar way, so that the operational configuration is maintained.

5. RESULTS

Most of the presented results are based upon the averages of various quantities from the analysis of the 10 statistical Monte Carlo runs performed for each case; future 'business as usual' (BAU) evolution with and without the constellations defined in Table 1. These average values can be considered as the most likely evolution trends of the orbital debris environment in LEO, as predicted by IDES. Averages from both cases are compared with each other in order to determine the average impact of all the constellations on the long term debris evolution and vice versa.

Figure 1 shows how the long term operation of all four considered constellation systems can affect the overall collision rate in LEO for the 'business as usual' traffic scenario.

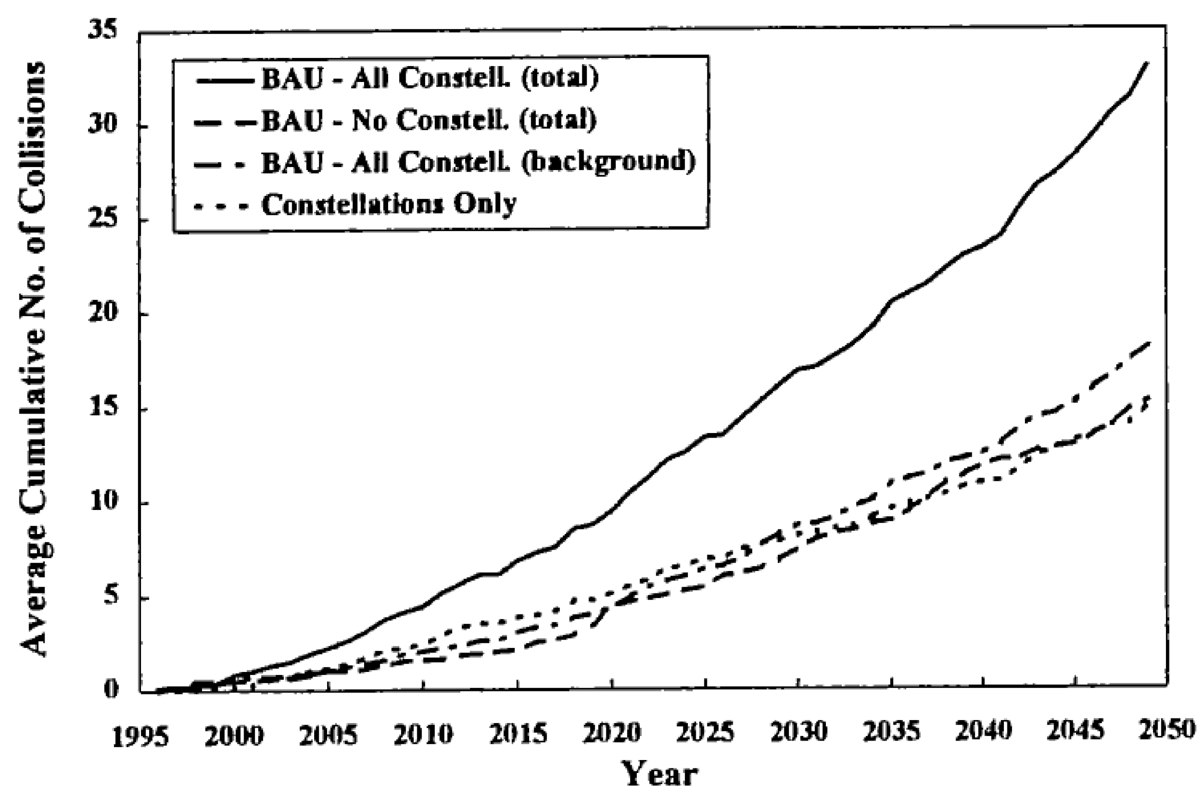

Figure 1. The average impact of all constellations on collision rates in LEO

The overall impact of the constellations is a factor of 2.2 increase in the collision rate over time. This large rise is mainly due to the collisions predicted for constellation satellites. This is because the collision rate for 'constellations only' is comparable to the total collision rate in the 'no constellations' case (where collisions are predicted for 'background' objects). This can account for a factor of 2 increase, but the factor of 2.2 also includes a background object collision rate that is 20% higher for the 'all constellations' case. This rise can only be attributed to the collision-induced breakups of constellation satellites, since the average explosion rate is the same in both BAU cases. If the constellation collisions were not predicted, then the background object collision rate would be the same in both cases. The fact that there is an increase in the background object collision rate due to the constellation collisions implies that there *is* a long term collision coupling between constellations and the background debris environment.

The 20% increase in background object collisions due to constellations covers the whole LEO region. However, what are the enhancements in collision rates at altitudes local to the constellations? Figure 2 gives us a breakdown of the average cumulative number of collisions up to the year 2050 in 50 km altitude bands for the critical altitude range of 700 to 1000 km.

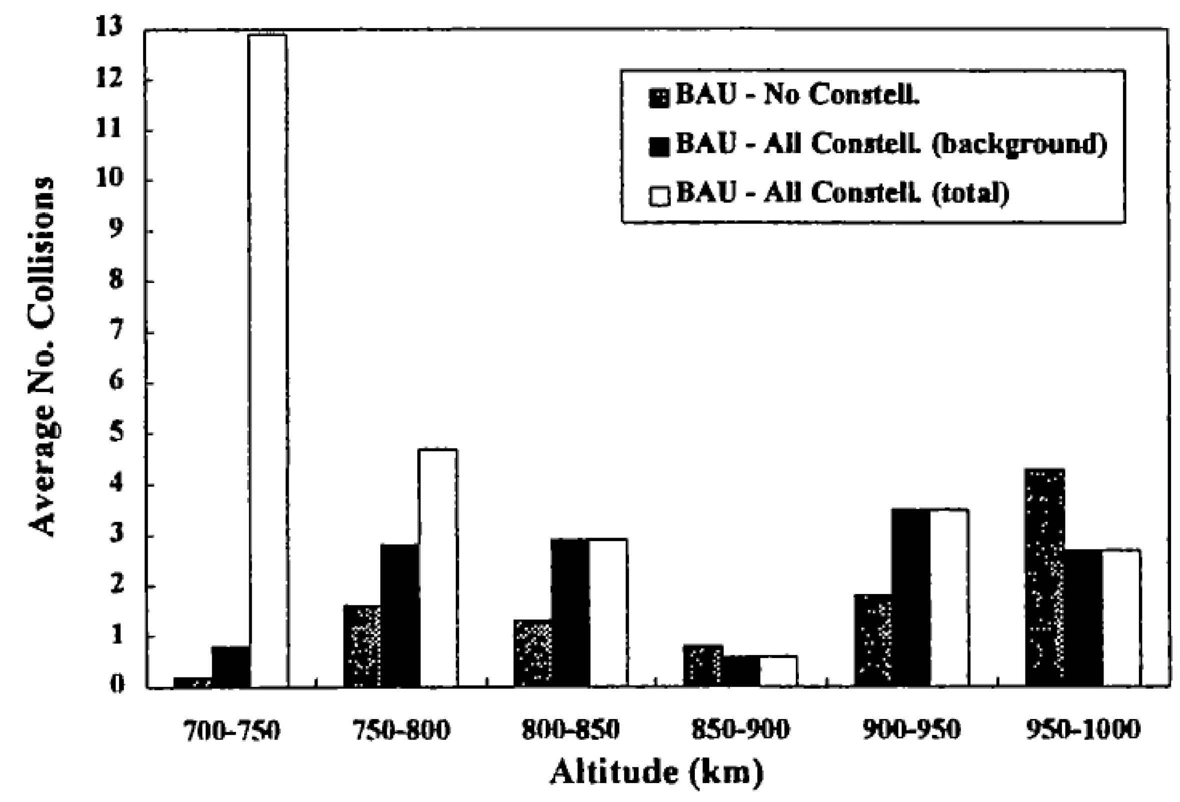

Figure 2. The average number of collisions up to the year 2050 in various altitude bands

In the 700 to 750 km altitude band, the average collision rate is a factor of 65 higher for the 'all constellations' case (12.9 collisions) compared to the 'no constellations' case (0.2 collisions). This is mainly due to the average 12.1 collisions predicted for CONSTEL1 operating at 700 km. There is also a contribution from the background object collision rate in the 'all constellations' case (0.8 collisions) which shows a factor of 4 increase over the 'no constellations' case. This factor of 4 increase is probably induced by the large number of collisions for CONSTEL1.

There is a factor of 3 increase in the collision rate between 750 and 800 km where CONSTEL2 and CONSTEL4 are operating. Here, the background object collision rate is almost a factor of 2 higher in the 'all constellations' case. This difference could be partially due to the average 1.9 collisions for CONSTEL2, but more likely as a result of the large numbers of debris fragments dispersed from the average 12.1 collisions for CONSTEL1.

This is certainly true for the 800 to 850 km altitude band where no constellations will be operating, but the background object (and therefore total) collision rate is a factor of 2 larger for the 'all constellations' case, when compared to the 'no constellations' case. This represents an absolute increase of 1.6 average collisions which is much larger than the corresponding increase of 0.6 in background object collisions at the CONSTEL1 700 to 750 km band. The difference can be explained by reduced atmospheric density and therefore drag decay of debris fragments at 800 km, leading to a higher accumulation of debris and hence collision risk for background objects in the long term.

In Figures 1 and 2, it was seen that constellations can be responsible for increases in overall and local collision rates and have a long term collision coupling with background objects in the local debris population. Table 2 compares the initial risk and predicted catastrophic collisions for each constellation system.

Constell. Name	Initial Flux >10cm (#/m^2/yr)	Av. # of Catastrophic Collisions up to 2050	Percentage of Catastrophic Constell. Collisions
CONSTEL1	3.4×10^{-3}	12.1	81%
CONSTEL2	5.6×10^{-4}	1.9	13%
CONSTEL3	1.6×10^{-4}	0.9	6%
CONSTEL4	1.3×10^{-4}	0	0%

Table 2. Risk and catastrophic collisions for various generic constellations

The initial risk for debris larger than 10 cm is a first order *indication* of system vulnerability to catastrophic debris, since the impact energies of 10 cm debris in LEO are sufficient to cause the catastrophic breakup of most objects. In this case, the overall relative *flux* of debris larger than 10 cm initially encountered by a constellation is a direct measure of this risk. The values have been derived from the summation of the flux relative to each of the constellation satellites in the operational configuration. As expected, the 924 satellite CONSTEL1 design is the most at risk from catastrophic debris of larger than 10 cm. The initial flux is 6 times higher than for CONSTEL2, and consequently the number of fatalities after 54 years is also a factor of 6 higher.

However, the initial flux cannot be used to directly infer a particular system vulnerability to catastrophic debris. This depends upon the future growth of the debris population and therefore collision risk at the constellation altitudes. Factors such as the rate and proximity of breakup events to the constellation altitude, atmospheric drag, and the solar cycle will influence the growth of the constellation collision risk. Prediction of the long term catastrophic collision risk and hence constellation *fatalities* also requires accurate modelling of second order effects such as the long term collision coupling (feedback) between all constellations and background objects. From Table 2 we can see that CONSTEL1, with the highest initial risk is predicted to suffer 81% of all constellation fatalities. Note that these constellation *fatality* rates do not represent the *failure* rates of the systems, because the failure of a satellite may also be induced by a debris impact that would only damage the satellite, but still render it non-functional. Failure rates will be much higher than the fatality rates presented here because of the higher risk of collision with smaller centimetre-sized debris. Although not considered in this study, the IDES model does have the capability to predict damaging impacts and therefore the failure rates for specific constellations.

A long term risk assessment for the CONSTEL2 constellation in both cases of future debris evolution is given in Figure 3. The difference between the two cases highlights a factor of 2 increase in the collision risk to debris larger than 1 cm due to constellation system fatalities and long term collision coupling. In both BAU evolution cases, the average collision risk is generally growing exponentially over time. By 2050, the collision risk for the 'all constellations' case is a factor of 4.4 higher than the initial collision risk.

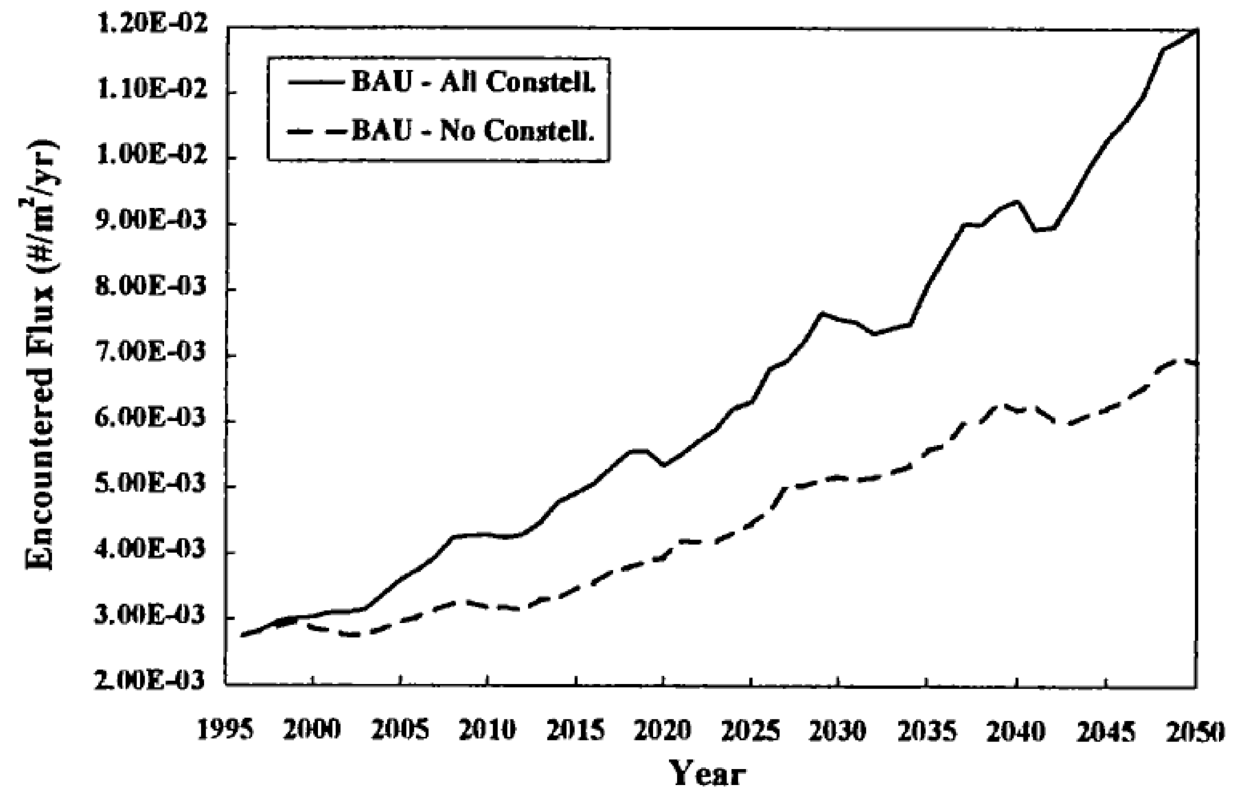

Figure 3. The influence of constellation-background debris collision interactions on the >1cm long term flux for CONSTEL2

The influence of the solar cycle on the relative flux is clearly evident by periodic modulation of the exponential trend. During periods of high solar activity the atmosphere will be heated, resulting in a higher atmospheric density and drag decay at 780 km altitude, thus removing some of the 1 cm debris population from that altitude. This has the effect of lowering the flux encountered by CONSTEL2. Correspondingly during solar minimum, atmospheric density and drag are at a minimum which allows debris objects to accumulate, hence producing an increase in the encountered flux. Since the solar cycle will affect all Monte Carlo runs of future evolution in this way, then it is also evident for the average evolution.

Figure 4 shows the growth in the >1cm LEO debris population under the 'business as usual' - 'no constellations' case for all of the 10 Monte Carlo runs predicted by IDES. The general average trend is a shallow exponential growth from 145,000 in 1996 to 245,000 in 2050. This is an increase of 70% over 54 years. Throughout the period of evolution, the maximum and minimum deviation from the average number of objects in or intersecting LEO does not exceed 25%.

This can be considered as a very reasonable error margin for modelling the debris environment over such a long time interval.

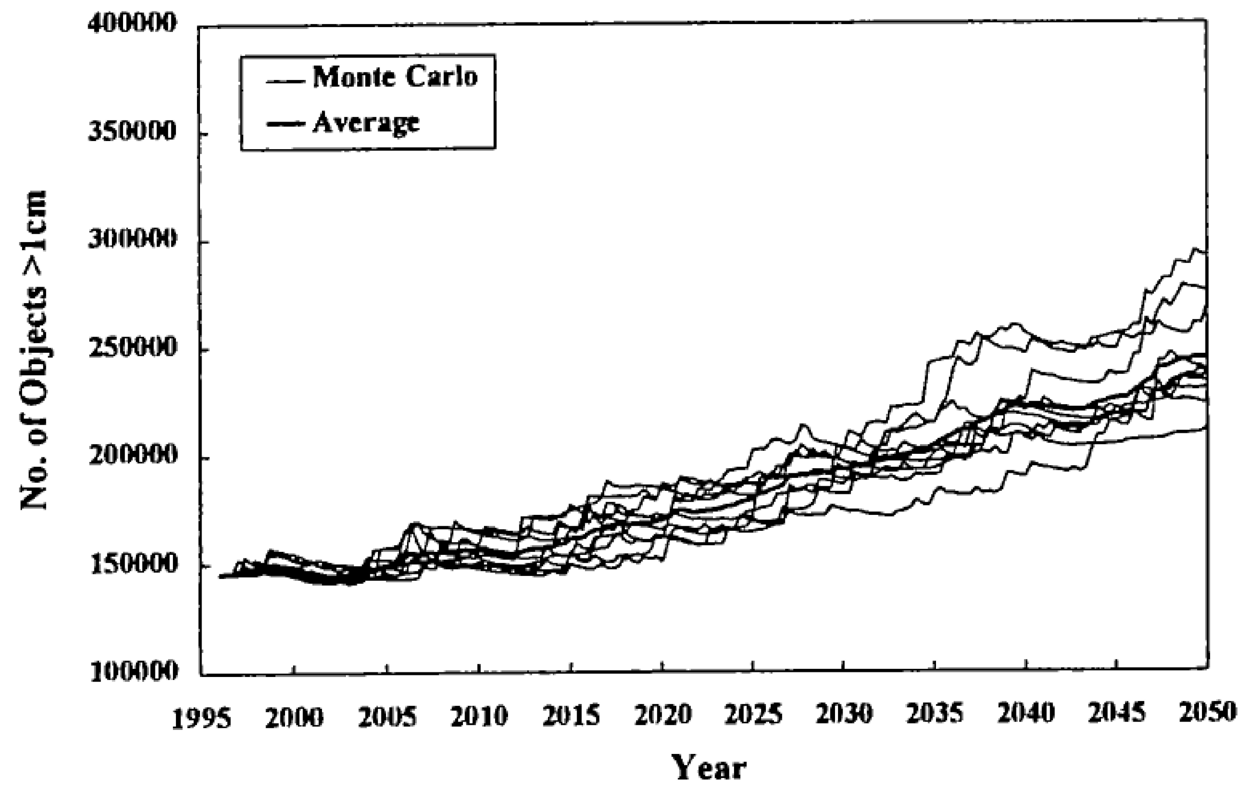

Figure 4. Future BAU evolution for debris >1cm in LEO - no constellations case (10 Monte Carlo runs)

In comparison, Figure 5 presents a distinct increase in the exponential growth for all 10 Monte Carlo runs of the 'business as usual' - 'all constellations' case. The general average trend for this case starts at 145,000 in 1996, as in Figure 4, and rises to 320,000 in 2050 which is a 120% (factor of 2.2) increase over the 54 years of evolution. As with the 'no constellations' case, the maximum and minimum deviation of the 10 Monte Carlo runs from the average population growth does not exceed 25%.

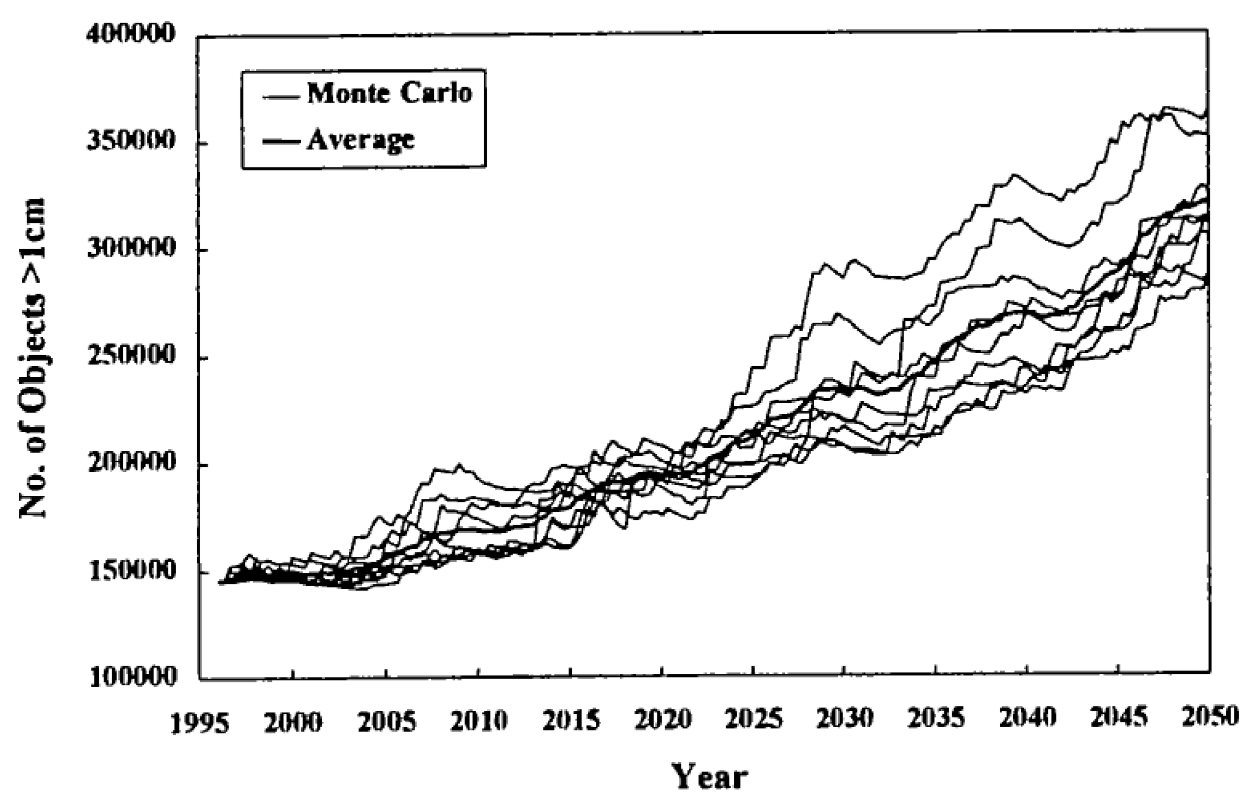

Figure 5. Future BAU evolution for debris >1cm in LEO - all constellations case (10 Monte Carlo runs)

If we directly compare the average LEO population growth trends for the two BAU cases (see Figure 6), the difference between the two curves presents the average impact of all the modelled LEO constellations on the orbital debris environment for debris larger than 1 cm. In fact, this impact is predicted to be an increase of 30% in the population over time. According to ref. 12, collision cascading in LEO could commence in 30 to 60 years time. The number of objects >1 cm in 30 years (2027) for the BAU - 'no constellations' case is predicted to be 190,000. However, this population level is reached in the BAU - 'all constellations' case by the year 2017, which is 10 years earlier than expected. By 2050, this gap increases to 15 years. Again, note the periodic influence of the solar cycle on the exponential population growth in both cases.

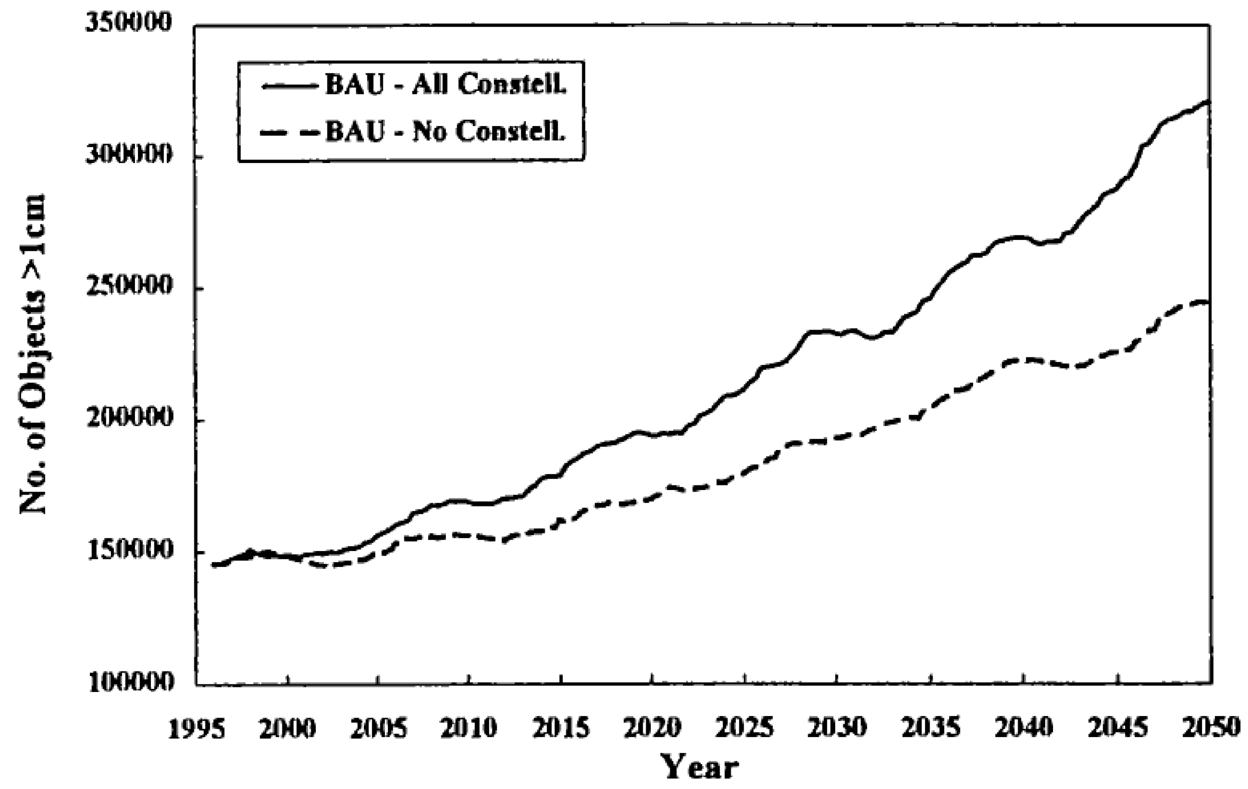

Figure 6. The average impact of all constellations on the long term evolution of debris >1cm in LEO

An acceleration in collision cascading can also be confirmed from the comparison of the total collision rates in Figure 1. By the year 2050, the average number of collisions is predicted to reach 15.2 for the BAU - 'no constellations' case. However, this number is estimated to be reached by the year 2028 in the BAU - 'all constellations' case which is 22 years earlier resulting from constellation activity. For the year 2027, the gap in time is predicted to be 14 years.

6. CONCLUSIONS

The long term impact of the LEO satellite constellations on the orbital debris environment over the next 50 years, as predicted by the IDES model for a 'business as usual' traffic scenario, can be summarised as follows:

1.) Constellation activity would more than double the overall collision rate in LEO. Most of this increase is due to collisions predicted for constellation satellites. The constellation collision rate matches the background object collision rate when no constellations are operating. A smaller fraction of this increase results from a 20% rise in the background object collision rate when constellations are present.

2.) Localised background object collision rates between 700 and 850 km altitude typically increase by a factor of 2 when the constellations are deployed, even in the 800 to 850 km band which does not contain any constellations. This demonstrates that there would be a long term collision coupling process between constellations and the background debris environment in that region.

3.) An assessment of system vulnerability to catastrophic debris indicates that the number of satellite fatalities varies by an order of magnitude for different constellation designs. The fragments generated from constellation collisions would cause a factor of 4 increase in the number of collisions for background objects between 700 and 750 km. Constellation collisions and extra background object collisions could result in a factor of 65 increase in the total number of collisions occurring between 700 and 750 km altitude.

4.) Debris fragments dispersed from the collisions associated with constellations and their collision coupling with background debris are predicted to be the major cause of a factor of 2 increase in the >1 cm long term collision risk to constellations operating between 700 and 800 km altitude. Under these conditions, the >1 cm long term risk may be over 4 times higher after 50 years, when compared to the initial risk.

5.) The constellation activity in LEO considered in this analysis is likely to cause a 30% long term increase in the debris population larger than 1 cm in size. Constellation operations are predicted to accelerate the start of collision cascading in LEO by between 10 and 20 years, depending upon the timescales of current estimates for collision cascading.

This study of future evolution predictions is based upon a 'business as usual' future traffic scenario. However, further research would be appropriate to estimate the role of constellations in other scenarios, such as the growth of spaceflight activities or the implementation of debris mitigation measures, including explosion suppression and routine de-orbiting of spacecraft and rocket bodies.

7. ACKNOWLEDGEMENTS

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