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Short-Term Debris Risk to Large Satellite Constellations

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A debris collision hazard analysis is carried out on a large 800-satellite constellation, representative of the initial Teledesic configuration, using the Space Debris Simulation (SDS) software. Usage of the software focuses on the short- to medium-term effects of explosive and collision-induced breakups. Two potentially constellation-threatening scenarios are considered: 1) constellation member fragmentation and 2) constellation launch-vehicle breakup. The constellation collision probability and the debris impact-energy to target-mass ratio are used as indicators of the severity of the risk posed to the constellation. It is found that, in the case investigated, the collisional risk to the constellation is low in the short term. Of the scenarios examined, it is the collision-induced breakup of a constellation satellite that poses the greatest danger, in terms of the possibility of a secondary fragmentation. The SDS software is proven to be a useful tool in the analysis of the short-term, relative threat posed by debris impact to large constellation systems.

Introduction

THE orbital implementation of large low-Earth-orbit satellite constellations, principally for mobile communications purposes, represents a new and significant factor tending to increase the projected orbital debris density, with the consequent impact on the future operations of manned and unmanned space systems. This new chapter also represents a significant challenge to the space-environment modeling community to estimate the potential growth of the debris threat to future space activity.[1,2]

Some systems, in particular Orbcomm (36 satellites in 775-km-altitude orbits, inclined at 45 deg to the equator) and Iridium (66 satellites at 780-km height and 86-deg inclination) are being implemented. These systems will operate at a height where there already exists a peak in the debris density distribution,[1] and so, there is scope not only for the debris background population to affect the constellation satellites, but also for the satellites themselves to contribute to a further buildup in the severity of the environment. The latter would inevitably occur through the mechanisms of launch and operational activity (although the orbital implementation is planned with debris mitigation in mind), as well as the potential for constellation satellite fragmentations.

Another constellation that is receiving attention in terms of its potential impact on the projected debris environment is the Teledesic system, which in its original form was proposed to comprise 840 satellites (excluding spares) in 700-km-altitude orbits inclined at 98.2 deg. Both this system and Iridium occupy near-polar orbits, which further intensify the potential constellation–environment interaction. Currently, the projected Teledesic configuration has been scaled down to 288 spacecraft in near-polar orbits at 1400-km altitude,[§] a height that nevertheless again corresponds to a peak in the debris population. This proposal is certainly more manageable in terms of launch and operations, as well as in terms of the potential future impact upon debris environmental issues.

A case study is presented that attempts to quantify the debris threat to a large satellite constellation similar to the original Teledesic configuration, using the Space Debris Simulation (SDS) software suite. This is conducted because it is still important to understand the constellation–debris environment interactions involved in the operation of such a large system. The study is carried out with emphasis on realistic requirements and constraints, so that the study conclusions offer a useful picture of the threat posed in the short term. Several constellation-related fragmentation scenarios are examined.

Software

The SDS software[3] was developed at Southampton University, under contract to the Defence Evaluation and Research Agency (DERA) to assess the risk to operational spacecraft posed by debris clouds emanating from orbital fragmentation events. The software is best suited to short- to medium-term analysis (hours to months after the initial breakup), and so complements the long-term analysis IDES computer program,[4,5] also developed at DERA. Both explosive and collision-induced breakups can be simulated by the SDS software, and the dynamical model includes Earth gravity and aerodynamic perturbations.

The risk assessment is based on the target-oriented approach implicit in the probabilistic continuum dynamics (PCD) technique. This was first developed and discussed by Heard[6] and Housen.[7] Subsequently, Jenkin[8] adopted the phrase “probabilistic continuum dynamics” and was the first to apply the method to assess collision probability and potential damage for spacecraft in perturbed Keplerian orbits. The PCD method involves multiple solutions of the classical Gauss problem (of the determination of an orbital trajectory from two position vectors and a time of flight between them). The first position vector is that of the breakup event, and the second is that giving the current position of the target spacecraft. If there is a Gauss solution, then debris from the breakup can reach the target. By an appropriate transform, the velocity-space distribution at the breakup event can be mapped to a debris density in position space at the target spacecraft. A fairly sophisticated algorithm is required in the SDS suite to solve the Gauss problem because the trajectories are not ideal, but are perturbed. There is also a novel treatment of the breakup distribution in the program to take account of nonisotropic fragmentations. The reader is referred to Barrows et al.[9] for more detail. The PCD method is particular powerful because it generally avoids the need to make too many simplifying assumptions, as is sometimes the case with other methods.

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§Teledesic Corp., World Wide Web Home Page, http://www.teledesic.com.

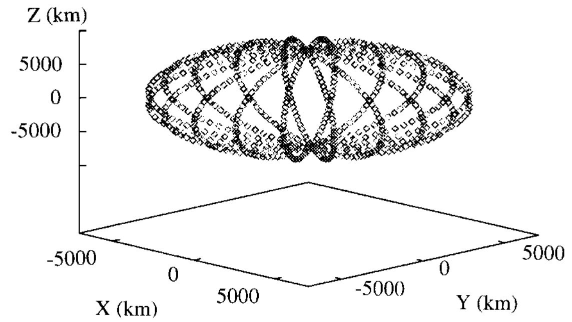

Fig. 1 Schematic of the 800-satellite constellation configuration.

As part of the software development, considerable time and effort was invested in the validation of the SDS suite.[10] The trajectory models were extensively compared with appropriate flight data. The debris-cloud evolution aspects were checked against published results of other software simulations, and also with real on-orbit fragmentation events by comparison of event Gabbard diagrams. A theoretical validation of the risk assessment methods used in this study has been given by Jenkin.[11] The SDS software also has been applied previously to numerous case studies, including a risk assessment of Envisat-1 (Ref. 12) and the threat to manned vehicles posed by the Clementine/Titan II breakup[13] that occurred in 1994.

Constellation Configuration

The constellation considered in this study is a configuration of 800 satellites, which is representative of, but not identical to, the original Teledesic proposal. The satellites are distributed with 80 spacecraft in each of 10 equally spaced orbit planes, as shown schematically in Fig. 1. Each satellite, of 500-kg mass, is in a near-circular, polar orbit (inclination 89 deg) at an altitude of 700 km. The intraplane satellite phasing is as given by Adams and Rider.[14]

Simulation Approach

The breakup scenarios are modeled using the SDS programs BREAKUP4.0 and TARGET4.0. The former is used to simulate the fragmentations in each case, with debris of 0.1 mm and greater in size being considered. When used for the risk assessment, TARGET4.0 considers each satellite in the constellation individually. Although computationally intensive, this approach gives information about which satellites are at risk and when. Collision probabilities then are summed for the whole constellation, by postprocessing using an auxiliary program. The collision-probability time histories are obtained by summing the contributions from all satellites during that time step. Similarly, the distributions made over satellite number are obtained by summing, for each satellite in turn, the collision probabilities registered over the whole duration of the simulation.

Satellite number increases with true anomaly, starting with the breakup satellite, and with orbit plane number. In the case of a satellite breakup, for example, satellites 1–80 reside in the breakup plane (with satellite 1 being the breakup satellite and plane 1 being the breakup plane), satellites 81–160 occupy the next orbital plane (plane 2 is 18° East in right ascension of the breakup plane), and so on. Satellites with numbers that have a difference of 80 are therefore closest to being in phase. For the case of a launch vehicle breakup, satellite 1 is taken as the constellation member closest to the booster at the fragmentation epoch.

Because the simulations are computationally intensive, the computer runs are performed typically for half a day of simulation time postbreakup, with a time step of 1 min. Also for reasons of computational efficiency, the orbital propagation method includes the effects of gravity (J_2) but not of drag. However, debris fragments reaching altitudes of less than 100 km are removed from the simulation. The values of collision probability quoted are per square meter of target.

The detail of the breakup models used are given by Barrows.[10] For more detail of the simulation models and input data, the reader is advised to contact the principal author.

Satellite Breakup

Active debris control, particularly with regard to battery design and end-of-life deorbit, should reduce the likelihood of a breakup of one of the constellation satellites. Despite these and other measures, the possibility of an explosive breakup will still exist. However, perhaps the greatest threat comes from an interaction with debris from the background population. By virtue of coverage requirements, numerous constellations have been proposed to fly in near-polar orbits in the altitude region (700–1000 km), where the background density is particularly high and the collisional threat is ever-present. Shielding can be used to guard against small particles but an interaction with larger-mass debris (around 1 kg and above) poses the prospect of major damage to, or complete fragmentation of, the constellation member.

Collision-Induced Fragmentation

The cumulative collision probability vs time for the constellation following the breakup of one of its members is shown in Fig. 2. In the simulation, the breakup is the result of a collision with a debris fragment from the background population. The impact with a 1-kg fragment traveling at a relative speed of 10 km/s results in the complete breakup of the satellite. The breakup is modeled as an isotropic event by BREAKUP4.0, with resulting fragment delta-velocity increments (delta-vs) of up to 2 km/s considered by TARGET4.0.

Figure 3 shows the corresponding distribution of collision probability over satellite number. The satellites in the breakup plane experience a significantly higher risk of collision than the remainder of the constellation. This is due to the high values of debris density encountered by the breakup-plane satellites, particularly close to the cloud's pinch locations. Over a longer period of time, this

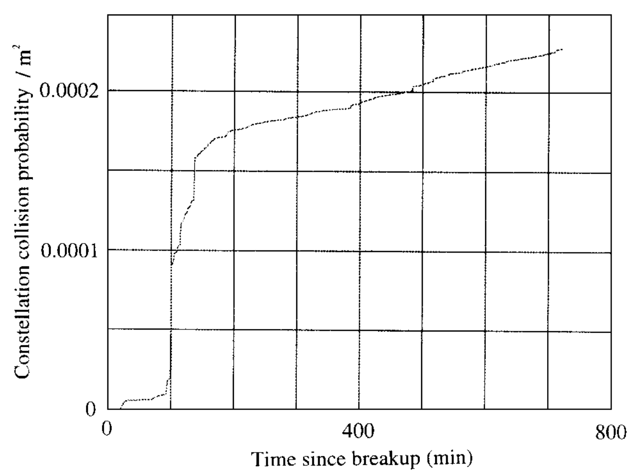

Fig. 2 Constellation collision probability over time, following the collision-induced breakup of a constellation satellite.

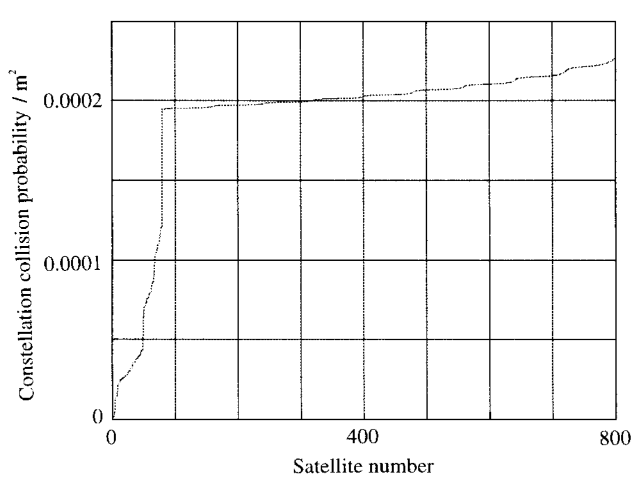

Fig. 3 Constellation collision probability relative to satellite number, following the collision-induced breakup of a constellation satellite.

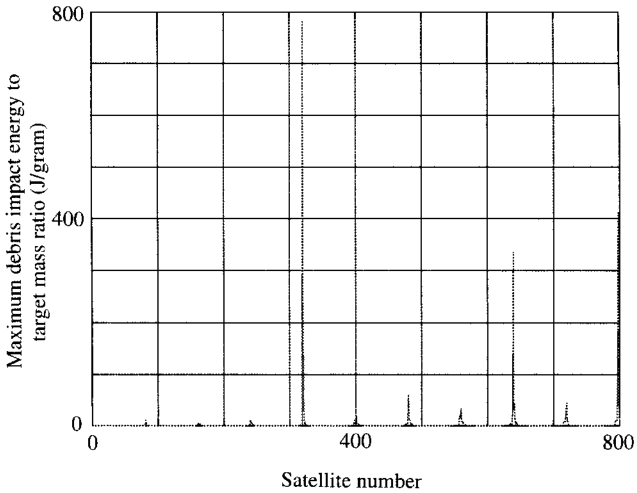

Fig. 4 Maximum debris impact-energy to target-mass ratio relative to satellite number, following the collision-induced breakup of a constellation satellite.

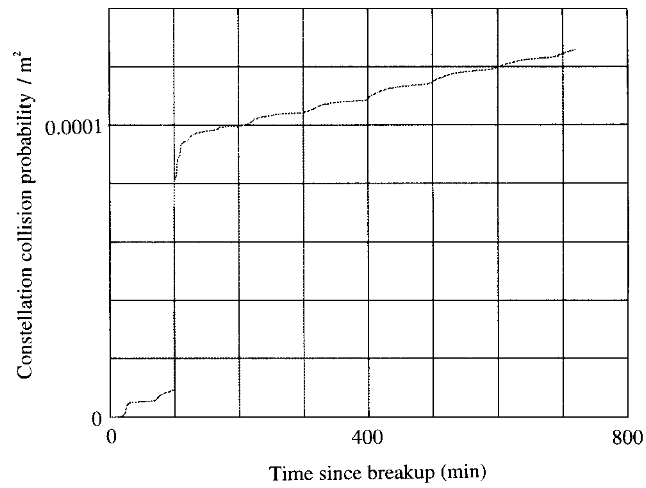

Fig. 5 Constellation collision probability over time, following the explosive breakup of a constellation satellite.

effect would be lessened because of orbital perturbations. However, although the risk of collision is highest in the breakup plane, the risk of a damaging event is small because debris encounters occur at low relative speeds. Figure 4 shows that the most potentially damaging events occur in orbital planes where relative speeds are high, in particular, plane 10, where head-on encounters are possible at nearly twice orbital speed (~15 km/s). Figure 4 gives the maximum impact-energy to target-mass ratio λ, where a value of the order of 35–45 J/g has been observed empirically to correspond to the threshold of complete satellite fragmentation.[15] Even in the short simulation presented here, several satellites are exposed to potentially lethal debris encounters. These occur when satellites close to being in phase with the breakup satellite, but located in other orbital planes, intersect the debris cloud's orbit close to its centroid.

In the long term, the collision probability will decrease because of the expansion of the cloud and the corresponding fall in debris density. However, over the period of this short-term simulation, damaging events can occur at any time and, in fact, in this example the most potentially dangerous of these are clustered toward the end of the simulation, several hours after the breakup event.

Explosive Fragmentation

In the second case examined, a low-intensity explosion of a constellation satellite is simulated using BREAKUP4.0, with maximum ejection speeds of 500 m/s being considered by TARGET4.0. The physical mechanisms that can produce such an event are many and varied (bipropellant mixing, battery explosion, pressure-vessel burst, etc.). However, in the simulation, a generic, isotropic breakup is modeled without reference to a particular mechanism because the SDS breakup model is insufficiently detailed to allow such a characterization. The resulting distribution of constellation collision probability over time and satellite number is similar to that manifested by the collision-induced satellite breakup scenario, although the level of collision probability is lower because of the reduced debris density in the explosion cloud. Figure 5, which gives the constellation collision probability over time, shows that the level of risk is reduced by a factor of around 2 for the explosive case.

Further analysis shows that the distribution of impact-energy to target-mass ratio λ with satellite number for the explosive case is essentially identical to that given in Fig. 4. This is because the peak values attained in each case correspond to the passage of a satellite through the debris cloud's central region. The two clouds differ in spatial density and size but both contain large fragments close to their centroids. The relative speeds of debris with respect to the satellites are primarily a function of orbital geometry, and so are common to both fragmentation scenarios, particularly for the large, lower-velocity fragments that produce the highest λ values.

Launch Vehicle Breakup

A launch strategy and debris mitigation policy similar to that proposed for Motorola's Iridium constellation is assumed for the 800-satellite constellation case study considered here. Iridium is due to commence operations in 1998 and Motorola has included debris mitigation as a major mission design driver from the outset. The multiple launches that will be used to build the modeled constellation similarly should be devoid of operational debris. Initial parking orbits below the constellation altitude are proposed, with the satellites boosting themselves up to operational height after separation. It also is proposed that the rocket second stages will be deorbited after use and vented of residual propellants to lessen the risk of explosive fragmentation.

If the rocket bodies are successfully made safe after satellite release, then the risk they pose to the constellation will be negligible. However, if a system malfunction occurs that prevents the deorbit maneuver, the presence of the spent stage will heighten the debris risk to the constellation. In the event of a collision between the stage and a member of the background debris population, or indeed if it were to suffer explosive breakup, then the additional debris cloud formed may impinge upon the constellation altitude. These two scenarios are modeled for the 800-satellite constellation considered here.

In particular, the effects on the constellation of the fragmentation of a 900-kg Delta-2 rocket body are simulated and examined. The rocket body is assumed to be in a circular orbit at 500-km altitude, with its inclination and ascending node position both equal to that of one of the constellation planes. The breakup occurs on the equator, in phase with the passage of constellation satellite 1. Further, the constellation is assumed to be complete to enable a worst-case scenario to be examined. Such a situation would occur during the launch of replacement or redundant satellites.

Collision-Induced Breakup

The breakup of a Delta-2 rocket body is simulated using BREAKUP4.0, following a collision with a 1-kg debris object at 10 km/s. Fragment ejection velocities of up to 2 km/s are considered by TARGET4.0 in the subsequent collision hazard analysis. The resulting constellation collision probability is shown over time and satellite number in Figs. 6 and 7, respectively. The estimated collision probabilities are of the same order of magnitude, but nevertheless less than those for the satellite breakup scenarios.

Figure 8 shows the distribution of debris impact-energy to target-mass ratio over satellite number. This is around three orders of magnitude less than those found in the constellation-satellite breakup case, however, indicating that the collision-induced launch-vehicle breakup is less effective in spreading relatively large debris fragments up to constellation altitude. The effect of varying the launch-vehicle parking altitude is examined later.

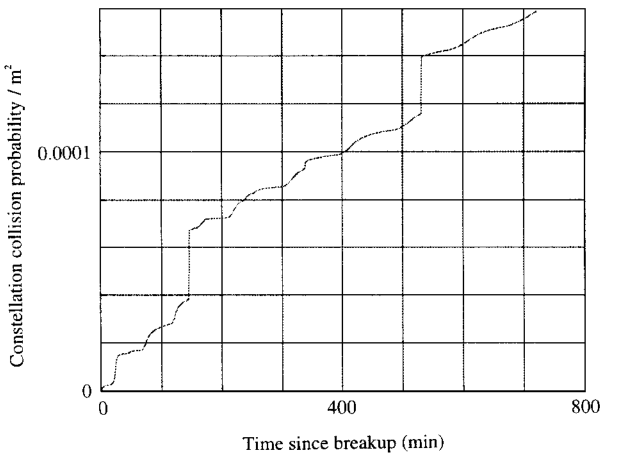

Fig. 6 Constellation collision probability over time, following the collision-induced breakup of a launch vehicle.

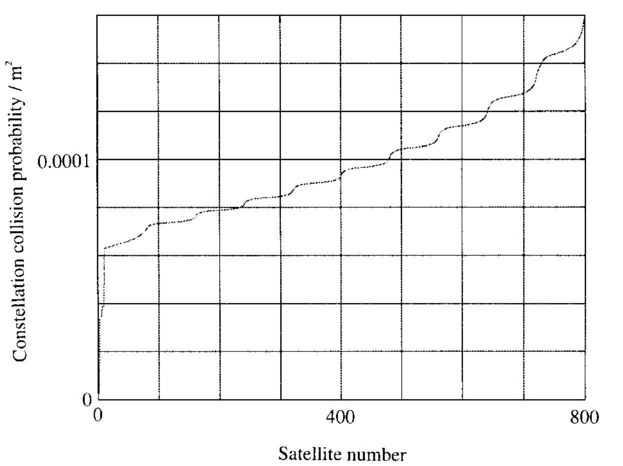

Fig. 7 Constellation collision probability relative to satellite number, following the collision-induced breakup of a launch vehicle.

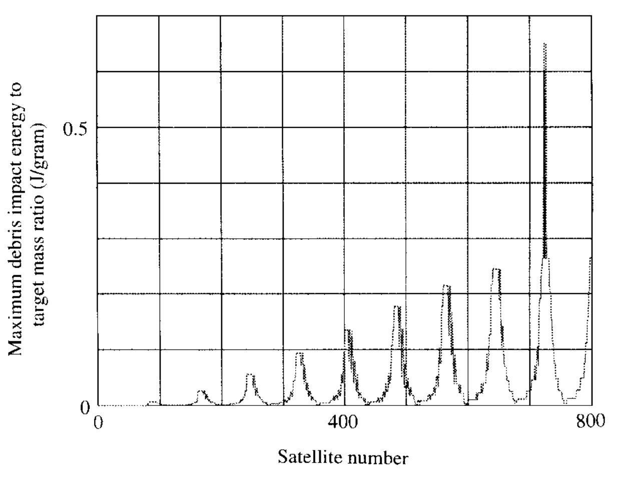

Fig. 8 Maximum debris impact-energy to target-mass ratio relative to satellite number, following a collision-induced breakup of a launch vehicle.

Explosive Breakup

The low-intensity explosion of a Delta-2 upper stage is simulated using BREAKUP4.0. TARGET4.0 is used to assess the collision risk to the constellation from debris ejected from the breakup, with delta-vs of up to 500 m/s considered. The constellation collision probability over time is shown in Fig. 9, where the values predicted are around two orders of magnitude less than those found for a constellation satellite breakup. However, an assessment of the debris impact energy to target mass ratio in this case reveals that lethal values up to 900 J/g are possible, as shown in Fig. 10, indicating

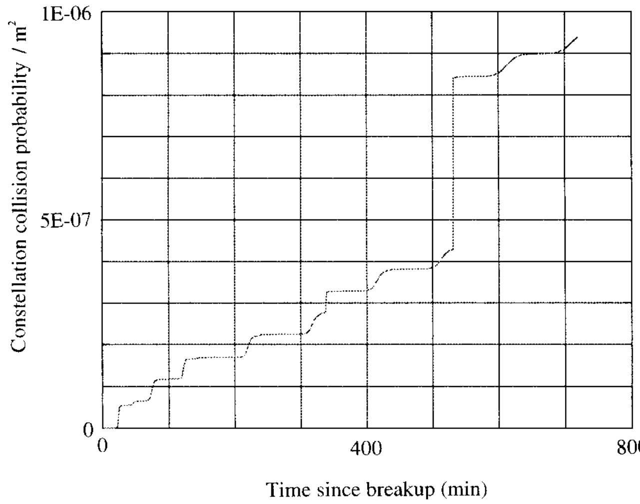

Fig. 9 Constellation collision probability over time, following the explosive breakup of a launch vehicle.

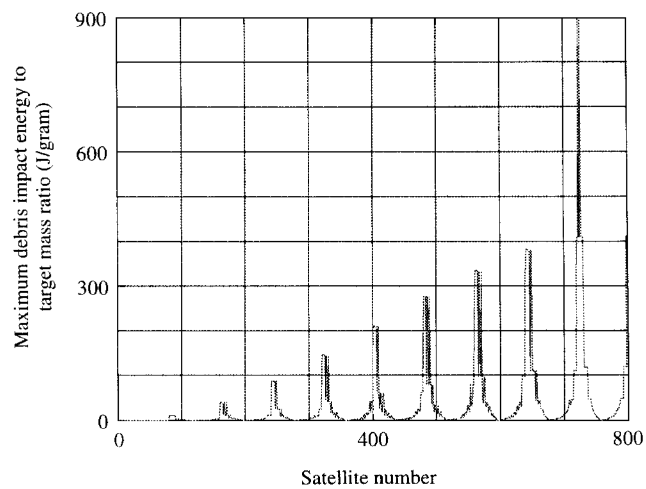

Fig. 10 Maximum debris impact-energy to target-mass ratio relative to satellite number, following the explosive breakup of a launch vehicle.

that debris large enough to fragment a constellation satellite can be encountered at constellation altitude. So, although the probability of an event is relatively low, the consequences of such an event are severe. That potentially damaging fragments are ejected from 500 km to 700 km would seem at first a surprising result. However, a simple calculation shows that the delta-v required to do this is a moderate ~55 m/s. The relationship used in the SDS software to relate fragment size to ejection delta-v is that due to Reynolds.[16] This, in combination with the moderate delta-v requirement, shows that indeed trackable fragments will reach the constellation and with potentially damaging energies. The most severe cases, as indicated in Fig. 10, correspond to satellites that are counter-rotating with respect to the fragments, where typical impact speeds are of the order ~15 km/s.

Effects of Launch-Vehicle Parking-Orbit Altitude

The height of the launch-vehicle parking orbit below the constellation altitude will affect the collision risk to which the constellation is exposed from a debris cloud generated by a launch-vehicle breakup. The risk to the constellation resulting from collision-induced launch-vehicle breakups is examined, as an example, at five parking-orbit altitudes in addition to the 500-km baseline case discussed in the preceding sections. The baseline corresponds to an altitude difference of 200 km between the parking- and mission-orbit altitudes. Figure 11 shows that, generally, the collision risk to the constellation reduces as the parking-orbit height is lowered with respect to the constellation altitude. The 50- to 300-km-curve labels refer to the height below the constellation altitude in each case. These data indicate that increasing the altitude difference from 50 km to

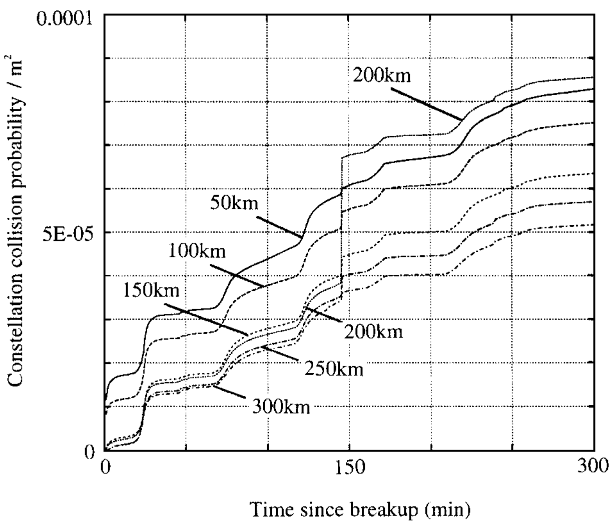

Fig. 11 Effect of launch-vehicle parking-orbit height on the constellation collision probability, for the case of a collision-induced launch-vehicle breakup. The labels correspond to the height difference between the parking orbit and the constellation orbit.

250 km produces a 40% to 50% decrease in collision probability. However, it should be observed from the step in the 200-km curve that, although the collision risk generally diminishes with increased height difference, lower parking orbits in fact can give rise to higher values of collision probability if the constellation-breakup geometry produces a particularly high-risk debris–target encounter. In this particular case, a step in the cumulative collision probability is observed in each case at around 145 min after the breakup event. This corresponds to approximately $\frac{3}{2}$ times the orbit period τ of the direct elliptical orbit between the breakup altitude and the constellation. This, in combination with appropriate phasing of the constellation members, means that an encounter with the debris cloud at a pinch-point location is likely, which would result in a significant rise in the risk at this time. Although this physical explanation helps to interpret the results, it nevertheless represents a simplification of what is a complex interplay of geometry and dynamics, which is fully modeled by the computational simulation.

An investigation of the debris impact energy shows that, even when the parking orbit is raised to within 50 km of the constellation altitude, debris from the collision-induced launch-vehicle breakup is unable to produce a catastrophic secondary fragmentation. The maximum value of λ in this case is around 6 J/g, and the value drops off rapidly with decreasing parking-orbit altitude. As expected, the lowering of the parking orbit not only reduces the chance of a secondary collision following a launch-vehicle breakup, but also tends to reduce the severity of any collisional event.

Conclusions

The potential hazards associated with constellation operations are numerous. Breakups of both constellation satellites and launch vehicles pose a threat to the constellation as a whole, and the orbital environment in general. Locating large constellations in or close to highly populated orbital regions heightens the probability of a collision between a constellation spacecraft and the background debris population.

This study shows that the probability of serious debris impact damage to the constellation is low in the short term. The reader is reminded that the probabilities stated in the study are per square meter of target. Consequently, an assumption that each constellation member has a cross-sectional area of the order of 10 m^2 increases the given probability estimates by an order of magnitude. Nevertheless, the conclusion remains that the risk of impact damage is low.

A primary conclusion of the study is that a collision-induced breakup of a constellation satellite poses the greatest risk to the remainder of the constellation in terms of the possibility of a secondary fragmentation. In addition, it was found that the collision probabilities associated with explosive breakups are less than those from collision-induced events, but the abundance of large fragments produced by low-intensity explosions in particular means that lethal secondary impacts are possible, even from breakups of launch-vehicle stages 200 km below the constellation altitude. Further, the satellites closest to being in phase with the breakup body are found to be most at risk from collision. However, those in orbital planes farthest from the breakup orbital plane are most likely to undergo a catastrophic fragmentation as a result of a debris strike.

Finally, the SDS software has proven to be a useful tool in assessing the short-term debris risk to satellite constellations. The cases presented could have been extended in terms of simulation period (perhaps to several days), but at the expense of a significant increase in computational run time.

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References

[1]Levin, G. M., "Interagency Report on Orbital Debris," Committee on Transportation Research and Development, National Science and Technology Council, Washington, DC, Nov. 1995.

[2]*Proceedings of the Second European Conference on Space Debris,* (ESOC, Darmstadt, Germany), ESA SP-393, European Space Agency, Noordwijk, The Netherlands, 1997.

[3]Barrows, S. P., Swinerd, G. G., and Crowther, R., "Assessment of Target Survivability Following a Debris Cloud Encounter," *Space Forum,* Vol. 1, 1996, pp. 329–353.

[4]Walker, R. J., Hauptmann, S., Crowther, R., Stokes, H., and Cant, A., "Introducing IDES: Characterising the Orbital Environment in the Past, Present and Future," *Advances in the Astronautical Sciences,* Vol. 93, Part 1, 1996, pp. 201–220.

[5]Walker, R. J., Crowther, R., Marsh, V., Stokes, H., and Swinerd, G. G., "Satellite Constellations and Their Long Term Impact on the Debris Environment in Low Earth Orbit," *Proceedings of the Second European Conference on Space Debris,* (ESOC, Darmstadt, Germany), ESA SP-393, European Space Agency, Noordwijk, The Netherlands, 1997, pp. 359–366.

[6]Heard, W. B., "Dispersion of Ensembles of Non-Interacting Particles," *Astrophysics and Space Science,* Vol. 43, 1976, pp. 63–68.

[7]Housen, K. R., "The Short-Term Evolution of Orbital Debris Clouds," *Journal of the Astronautical Sciences,* Vol. 40, No. 2, 1992, pp. 203–213.

[8]Jenkin, A. B., "DEBRIS: A Computer Program for Debris Cloud Modelling," 44th Congress of the International Astronautical Federation, Paper IAA-6.3-93-746, Graz, Austria, Oct. 1993.

[9]Barrows, S. P., Swinerd, G. G., and Crowther, R., "Review of Debris-Cloud Modelling Techniques," *Journal of Spacecraft and Rockets,* Vol. 33, No. 4, 1996, pp. 550–555.

[10]Barrows, S. P., "Evolution of Artificial Space Debris Clouds," Ph.D. Thesis, Dept. of Aeronautics and Astronautics, Univ. of Southampton, Southampton, England, UK, March 1996.

[11]Jenkin, A. B., "Probability of Collision During the Early Evolution of Debris Clouds," *Acta Astronautica,* Vol. 38, Nos. 4–8, 1996, pp. 525–538.

[12]Barrows, S. P., Swinerd, G. G., and Crowther, R., "Debris-Cloud Collision Risk Analysis: Polar-Platform Case Study," *Journal of Spacecraft and Rockets,* Vol. 32, No. 5, 1995, pp. 905–911.

[13]Barrows, S. P., Swinerd, G. G., and Crowther, R., "A Computational Comparison of Debris Cloud Models," *Journal of Spacecraft and Rockets,* Vol. 34, No. 5, 1997, pp. 650–654.

[14]Adams, W. S., and Rider, L., "Circular Polar Constellations Providing Continuous Single or Multiple Coverage Above a Specified Latitude," *Journal of Astronautical Sciences,* Vol. 35, No. 2, 1987, pp. 155–192.

[15]Nagl, L., "Review of Data to Support Breakup Modelling," AIAA Paper 92-4440, 1992.

[16]Reynolds, R. C., "A Review of Orbital Debris Environmental Modelling at NASA/JSC," *Orbital Debris: Technical Issues and Future Directions,* edited by A. Potter, NASA CP-10077, NASA, Washington, DC, 1990, pp. 89–109.