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Orbital Debris Hazard Assessment Methodologies for Satellite Constellations

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The expected proliferation of satellite constellations in the near future will tax the space environment in several ways. The many steps used to assess hazards posed to or by a satellite constellation are illustrated. Two categories of environmental impacts are examined: the effects of the constellations on the space debris environment and the effects of the environment on the satellite constellations. Issues such as intersatellite collision hazards for both controlled and uncontrolled spacecraft, intrasatellite constellation collision hazard (collision risks between members of a constellation), and collision risk between constellation members and the cataloged and uncataloged space population are included. Additional analysis of compliance issues with national space policy, voluntary national debris mitigation guidelines, and international concerns are also addressed.

Nomenclature

P_{exp} = probability of accidental explosion
P_{imp} = probability of impact with debris $\geq$10 cm

Introduction

IN the next decade, many large and small satellite constellations are likely to be deployed. Two issues that will have to be faced with each of these constellations are the effects of the space debris environment on the constellation and the effects of the constellation on the space debris environment. Constellation designers and operators should keep these two issues in mind when developing design and operational procedures.

For demonstration purposes, this paper shows results of an assessment process for a hypothetical large constellation by examining the process a satellite designer could take in quantifying the space debris risk. The primary focus of this paper is on the methodology used to define the debris hazard and the identified areas of the life cycle that each assessment step affects. Figure 1 shows this process flow. The column on the left shows the phase of the system life cycle impacted by each step of the debris assessment. Note that this is a closed-loop design process, in that the results of the assessment are used to modify the design of the system, if needed. Because the focus is on the process rather than specific mathematical models, the various models used were chosen based on their availability to the Air Force Research Laboratory's Space Debris Research Program. The Aerospace Corporation developed most of these models over the last decade for the U.S. Air Force. Other models that perform the same functions could be substituted and would likely produce different results due to the differences in the assumptions and limitations of the specific models. However, the process undertaken in the debris hazard assessment will remain unchanged.

The first objective is to define and assess key system-level issues. First, however, a specific satellite design must be developed. Launch hazards are primarily associated with the reliability of the launch vehicle system and are not covered in any detail in this paper. The breakup and survivability assessment is system and component dependent and also will not be covered in this paper due to the large variety of hardware components and materials used in satellites. The models are updated based on relevant design, launch, and survivability characteristics. Next, the long- and short-term effects on the environment, the constellation system, and other users of space are assessed. The assessment begins with an analysis of the background hazard. When the breakup characteristics of the system are taken into account, the long-term projections with and without the constellation are made. Once the environment is quantified, estimates of the probabilities of collision for spacecraft and components are made. After the long-term hazard is determined, the short-term hazard is assessed. This short-term hazard assessment involves estimating the effects of collisions and nearby explosions on the constellation. A strong consideration posed here is lethality. For example, a 1-cm object traveling at a relative velocity of 10 km/s will damage a spacecraft much more than the same size object traveling at a relative velocity of 2 km/s. Thus, it is not only necessary to assess the collision risk, but the lethality risk as well.

Then, the intersatellite collision hazard is determined during normal constellation operations and during both controlled and uncontrolled deorbit. First, normal operations are studied. Here, the satellites are controlled, and it is assumed that active collision avoidance will be performed (if needed). The second and more stressing case examines the uncontrolled deorbit phase in the operation of the constellation. This phase would occur if some or all control of the satellite were lost and a controlled reentry could not be undertaken. The satellite lifetimes are estimated at varying times through the mission, and the probability of collision for a decaying satellite is determined. The controlled deorbit scenario is studied, and various considerations dealing with this phase are also addressed.

Finally, an assessment is performed to examine compliance approaches with appropriate policy and guidelines. Applicable guidelines for individual programs are developed by the owner/operator/

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Table 1 Study objectives

Key questions	Study tasks	Application of results
What effect will the background debris environment have on the constellation?	Review of existing debris policy and mitigation guidelines	Assess hazard predictions against mitigation options
	Long-term hazard assessment	Preliminary design guidelines
What effect will the constellation have on other users?	Short-term hazard assessment	Identify key areas for more in-depth analysis
What effect will the constellation have on itself?	Intersatellite collision hazard assessment	

Table 2 Guidelines applicable to a constellation[1]

Debris source	Published NASA guidelines
Released during normal operations	<0.1 m^2/yr and <100 obj/yr for $\geq$ 1-mm debris
Generated by accidental explosions	Probability of accidental explosion, $P_{\text{exp}} \leq 0.0001$
Collisions with large objects	Probability of impact with debris $\geq$10 cm, $P_{\text{imp}} \leq 0.001$
Postmission disposal	Decay with lifetime < 25 years, or retrieve within 25 years or transfer to a storage orbit above LEO
Control of reentry risk	Controlled reentry away from land masses, uncontrolled total casualty area ≤ 8 m^2

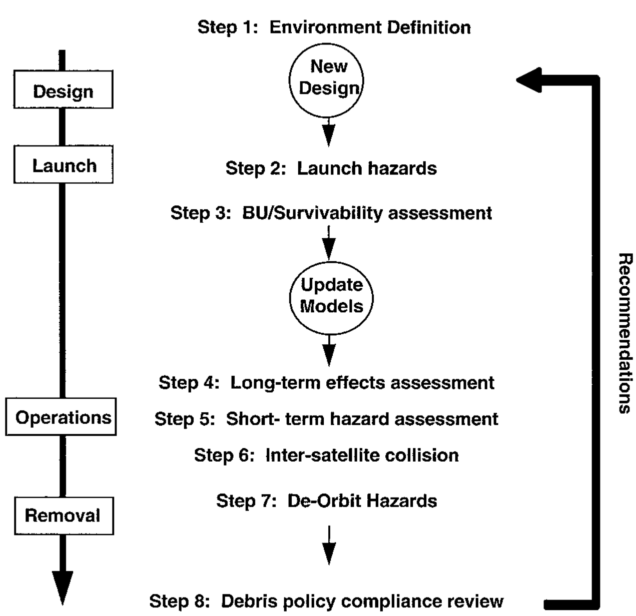


Fig. 1 Process summary related to system lifecycle.

customer of the system. The objectives for this assessment are summarized in Table 1.

For demonstration sake, we will assess the compliance of the hypothetical satellite constellation used in this paper to published NASA guidelines to illustrate the assessment process. These guidelines and hypothetical constellation design goals are presented in Table 2 (see Ref. 1).

The methods by which a constellation designer plans to accomplish debris mitigation objectives are typically determined in the final design and operational planning stages. However, it is possible for the designer to perform a preliminary debris hazard assessment for the constellation in the preliminary or critical design review phase. Some of the areas for mitigation and example goals to meet the Table 2 guidelines are presented in Table 3.

Table 3 Areas of debris mitigation

Areas for mitigation	Potential example debris mitigation goals
Released during normal operations	Goal of zero operational debris
Generated by accidental explosions	Goal of zero explosive potential Nonexplosive thrusters Assess battery risk
Collision with large objects ($\geq$10 cm)	Autonomous control, orbit management, stationkeeping Collision avoidance maneuvers
Collision due to loss of control	Maintenance of critical functions (redundancy, hardening)
Postmission disposal	Deorbit all mission hardware Highly reliable, fault-tolerant control and propulsion systems Options for deorbit of disabled satellites
Control of reentry risk	Design for complete burn-up on reentry

Table 4 Satellite size and mass properties

Component	Average cross-sectional area, m^2	Mass, kg
Entire satellite	94.9	1000
Solar array	58.4	100
Antenna	34	75
Electronics boxes	0.3	200

Hazard Assessment for a Large Satellite Constellation

A hypothetical large satellite constellation is now examined. An 800-satellite constellation is used (similar to the constellation used by Walker et al.[2,3]). We assume that these satellites are designed for a 10-year lifespan, common for many systems, and will begin operations starting in 2001. The constellation is to be placed in 20 orbital planes with 40 satellites per plane. The orbits are circular and sun-synchronous at 700-km altitude. The ascending nodes of adjacent planes are spaced at 18 deg around the equator. Whereas a real-world constellation would have variations in some of the orbital elements (noncircular orbits, slight differences in altitude, and inclinations), this case is a nominal design. Small variations in these orbital elements would further disperse the constellation, thus reducing the probability of intersatellite collisions. For simplicity, these variations are not included in this study.

The environmental interactions of major components along with the entire spacecraft of a representative communications satellite are analyzed next. Satellite size and mass properties for the major components of an example spacecraft are shown in Table 4. The resulting probabilities scale linearly with the size of the component. We assume that the constellation has an attitude control and stationkeeping capability.

The long-term hazard assessment was done using several computer models. The program EVOLVE-D[4] was used to estimate the current and future low-Earth-orbit (LEO) debris environments, based on modeled historical launches and breakups and anticipated sources and sinks. The assessment uses two different breakup models: IMPACT[5] and EVOLVE.[6] To estimate the current and future LEO debris environments based on measurement data the NASA Engineering Model (in ORDEM96; Ref. 6) was employed. Another model, DENSITY,[7] was used to determine the long-term spatial density distributions of orbital objects (satellites, upper stages, and debris) and to estimate the current and future LEO debris environments based on the Air Force Space Command (AFSPC) catalog and proposed spacecraft systems including commercial satellite constellations. Finally, LIFETIME[8] estimates orbital lifetimes of objects and includes the option of maintaining attitude variation effects (pointing of the solar panels). LIFETIME was also used to determine how long fragments remain in orbit following a breakup.

In performing the short-term hazard assessment, IMPACT was utilized to estimate fragment characteristics (mass, size, and velocity distribution) for spacecraft explosions and hypervelocity collisions. Program DEBRIS[9] estimates the short-term (first few orbital revolutions) hazard to operational satellites from breakup debris cloud(s). In assessing the intersatellite collision hazard, the AFSPC program COMBO can be used to calculate close approach occurrences. Although not a debris issue, errors in orbit propagation and determination can make collision avoidance an issue of concern for satellite operators, and, should a collision occur, it then becomes a debris issue. Programs LIFETIME and DENSITY were also used in evaluating the intersatellite collision hazard.

Results

The preliminary results are categorized into three components: 1) long-term hazard assessment, 2) short-term hazard assessment, and 3) intersatellite collision hazard assessment.

Long-Term Hazard Assessment

There are several considerations in assessing the long-term hazard. It is necessary to determine the background hazard from the debris environment, both current and projected. From the background determination, we estimate the collision probabilities for satellites and components. Looking at the assessment from another viewpoint, we can also examine the long-term hazard of satellite components on the background environment.

The current debris environment is based on several models. There are some inherent uncertainties in the measured and modeled debris environment in the 1–10-cm-size range because the Space Surveillance Network typically tracks few objects smaller than 10 cm. At the example constellation's nominal operating regime, the debris flux based on several models is shown in Fig. 2. Figure 2 shows the level of uncertainty in various models, demonstrating that due to the extreme lack of measurement data it is very difficult to determine which is the right model to use. The curve associated with EVOLVE-D (I) shows the results using the IMPACT breakup model with the EVOLVE-D software. EVOLVE-D (E) shows results using the breakup model in the NASA EVOLVE model instead of IMPACT. For comparison, the meteoroid environment flux is included. Although these models have been and are continuing to be updated, the analyst is advised to use the most current and/or most readily available models. The models used in this assessment were the most readily available when the study was conducted. Because the focus of this paper is the assessment process, the models are used for demonstration purposes only.

Based on the proposed addition of the constellation to the space environment, the flux increases only near the operating altitude, as shown in Fig. 3. Figure 3 assumes a 5% per year growth (extrapolated from historical growth rates) from July 1994 to 2006 (midpoint of 10-year mission) in the satellite catalog. Use of different growth rates will cause the results to change, but the methodology will not.

Next, an estimate of the collision probabilities for both the entire spacecraft and the main components are made. The individual component impact likelihood is determined by vehicle design and is proportional to the cross-sectional area. Because of the relatively large area of the solar panels, these are the most likely components to be involved in collisions. Although the panels would be hit more frequently, there is a relatively low probability of a full solar panel breakup due to the particulars of many solar panel designs. For these

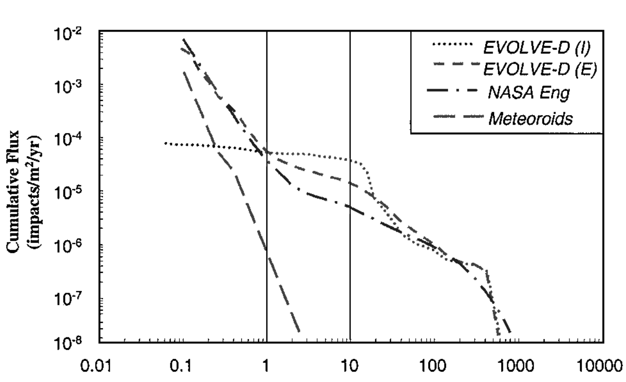


Fig. 2 Flux vs mean fragment diameter for different models (1994, 700 km, inclination = 98 deg).

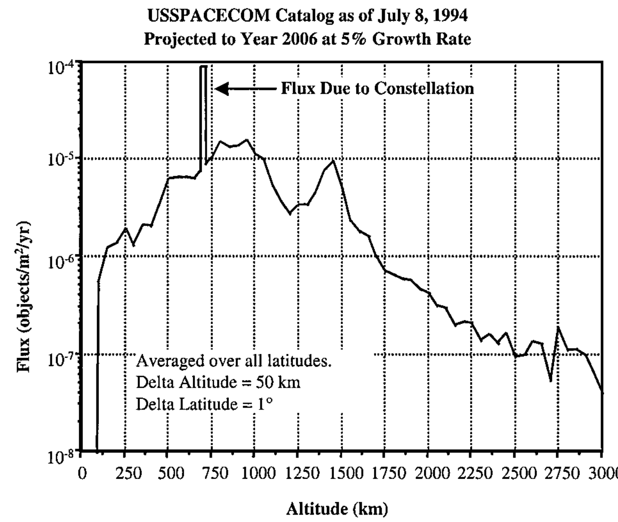


Fig. 3 Flux vs altitude.

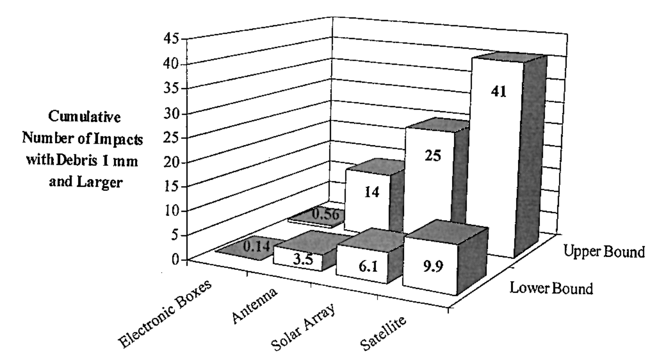


Fig. 4 Average number of impacts on representative spacecraft over 10-year mission.

designs, there is a higher likelihood of a punch through collision, which would produce small secondary debris that would be unlikely to create further breakups. However, the solar panel response to impact is not well understood and is highly dependent on the type of array.

Other likely possibilities include collisions between debris and antennas. Less likely would be collisions between debris and electronic boxes. Finally, the least likely scenario, as well as the worst-case scenario, would be a satellite-to-satellite collision.

Based on the results of the study, the number of impacts from debris greater than 1 mm over a 10-year mission lifespan is presented in Fig. 4. Notice that the graphs are plotted for both an upper and lower bound. These graphs are based on a Monte Carlo analysis of many simulations. The large number of impacts of smaller debris will require designs to preclude exposed wires, cables, or other parts vulnerable to millimeter-sized debris. For a single satellite, collision probabilities for various larger debris over the 10-year mission lifetime are shown in Fig. 5.

Based on these results, the collision probability with objects greater than 10 cm exceeds the NASA guidelines, even with today's catalog. The majority of impacts on individual components will be on solar arrays, and the lethality of debris hits on these panels would need to be studied further once a solar panel component design is chosen. The most lethal collision points on the satellite are the electronic boxes. Should one of these boxes be hit by a piece of debris, the satellite has a strong likelihood that loss of control will occur.

The results of this study found that the large constellation can expect a large number of impacts of smaller debris. Design actions could be recommended to protect wires, cables, or other parts vulnerable to millimeter-sized debris. The functionality of the satellites can be assured by proper hardening, for example, shielding and redundancy. The generation of secondary debris requires further study, including investigation of mitigation techniques.

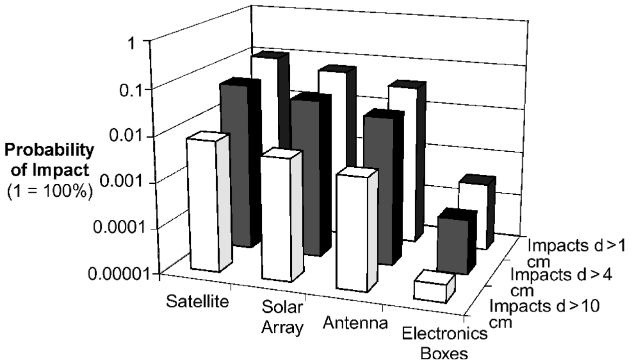


Fig. 5 Collision probabilities for satellite and components.

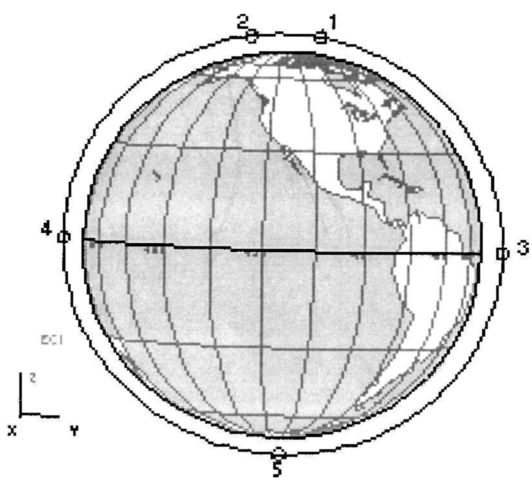


Fig. 6a Coplanar satellite.

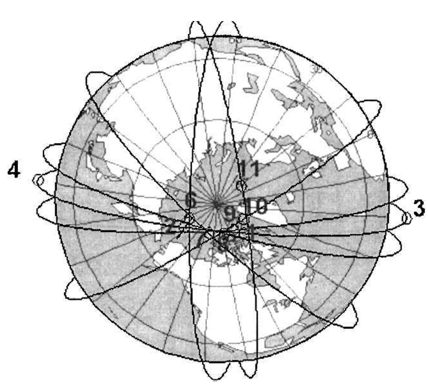
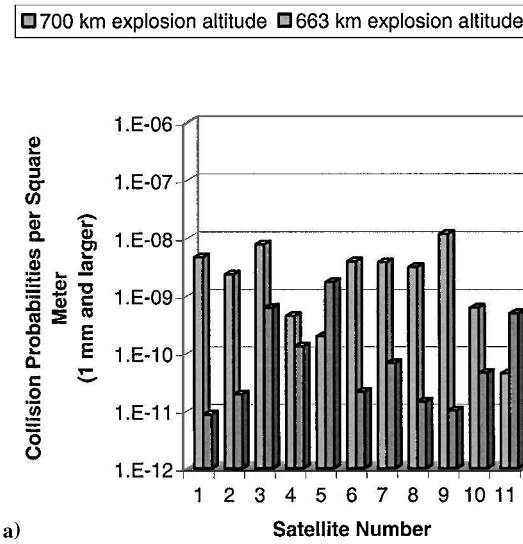
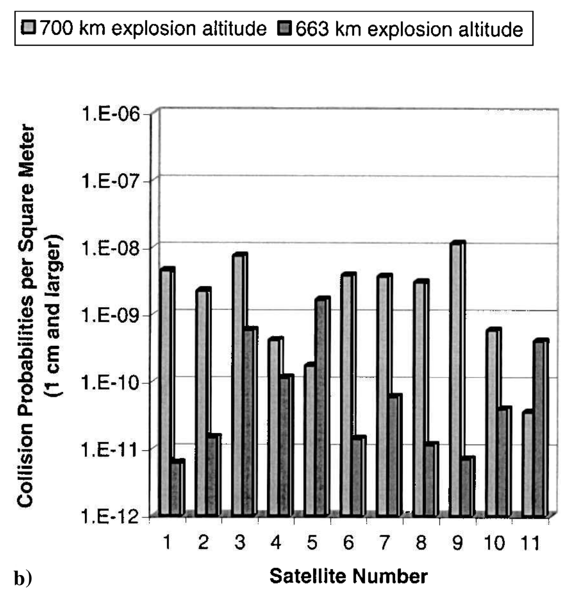


Fig. 6b Noncoplanar satellites.



a)



b)

Fig. 7 Collision probabilities for nearby explosions.

Short-Term Hazard

The next area examined is the short-term hazard posed to the constellation members due to breakup debris, both nearby explosions and component collisions. Figures 6a and 6b show the sample constellation members used in the short-term analysis. The numbers refer to arbitrary satellite numbers. Figure 6a shows several members of an individual orbital plane, whereas Fig. 6b shows member satellites in different planes.

First, examples of nearby explosions are modeled. One occurs at the same altitude as the satellite constellation (700 km), and a second one occurs at an altitude lower than the satellite constellation (663 km). For both breakup altitudes, the collision probabilities for 1-mm and larger fragments (Fig. 7a) and 1-cm and larger fragments (Fig. 7b) 24 h after breakup occurs are plotted. Note that the 663-km explosion adds virtually nothing to the collision probability from the background. The collision probabilities are generally orders of magnitude lower than the collision probabilities of the same altitude explosion case. The added effect of an explosion at the constellation's altitude does, however, affect the collision probability of satellites in the constellation for the first several hours following the explosion. The IMPACT explosion model was used in these cases. Had the EVOLVE explosion model been used, the impact probabilities for debris 1 mm and larger in size would have been approximately 60 times larger.

Two additional collision cases are examined next. In these cases, a component of one of the constellation spacecraft (either an antenna or an electronics box) breaks up due to a collision with a 4-cm piece of debris impacting at a relative closing velocity of 15 km/s. In this assessment, it is assumed that the satellite breakup is located midway in the plane behind satellite 2 and in front of satellite 1; thus, these are the two closest in-plane satellites. Satellites 1 and 2 are separated by 18 deg. Satellite 5 is 180 deg away from the breakup, whereas satellites 3 and 4 are 90 deg behind and ahead of the breakup, respectively. The location of the satellite breaking up was chosen to be at the nodal crossing of the orbital planes, the worst-case scenario. Satellites 6–11 are located near the nodal crossing in different orbital planes. This scenario provides a representative sample of various relative positions for which collision hazards are assessed. The same process could be repeated for the remaining satellites in the constellation and probably should be done for the detailed design process. The maximum closing velocity is 15 km/s, which allows for studying the worst-case scenario. For a breakup of a satellite component, the cumulative collision probabilities for one day after an antenna and an electronics box breakup are presented in Figs. 8a and 8b. Similar to Fig. 7, the graphs are for debris larger than 1 mm and larger than 1 cm, respectively. The highest collision probability was found for satellite 1 (directly behind the breakup by 9 deg). A time history of the debris impact probability for the case of antenna breakup for 1-mm debris is presented in Fig. 9.

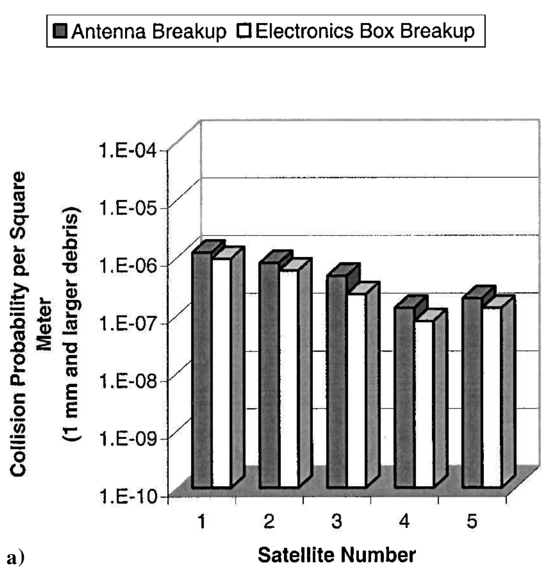
The study found that the overall maximum collision probability was less than the background. Small encounter velocities lowered the lethality. The hazard grows rapidly during the first day and then diminishes. The collision probability is highest for coplanar satellites and is highest (but still low) for satellite 1. The highest coplanar encounter velocity occurs for satellite 5, which is diametrically opposed to the breakup point. The lethality is also small, with fragments smaller than 1 cm dominating the risk. The possibility of additional debris generated by interfragment collisions was not assessed.

Intersatellite Collision Hazard Assessments

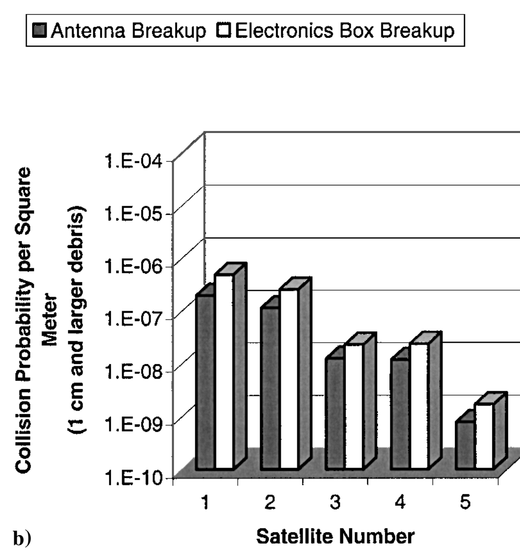
The risk of intersatellite collisions during constellation operations was addressed next. Three time frames were examined. First, normal operations were assessed. Here the satellites are controlled, and active collision avoidance is performed. The second case examines the uncontrolled deorbit phase of constellation operations. This scenario would occur if all control of a satellite were lost and a controlled reentry could not be undertaken. Satellite lifetimes were estimated at varying times through the mission, and the probability of collision for a decaying satellite was determined. Finally, the controlled deorbit scenario was studied. In this case, the orbital lifetimes were estimated, and a simulation of close approach between the deorbiting satellite and a projected satellite catalog, including the constellation, was examined.

For an uncontrolled satellite, the collision probability of that satellite, in a given plane, colliding with any fellow constellation satellite was assessed. The variation in collision probability over time is related to the solar cycle. When solar activity is low, the uncontrolled spacecraft takes longer to traverse the constellation and vice versa.

The results of our simulation showed that during the controlled deorbit of a satellite using low-thrust propulsion, the time duration of the deorbit process can be as little as 8 months and as much as 5 years, depending on the phase of the solar cycle. The time to



a)



b)

Fig. 8 Collision probabilities for component breakups.

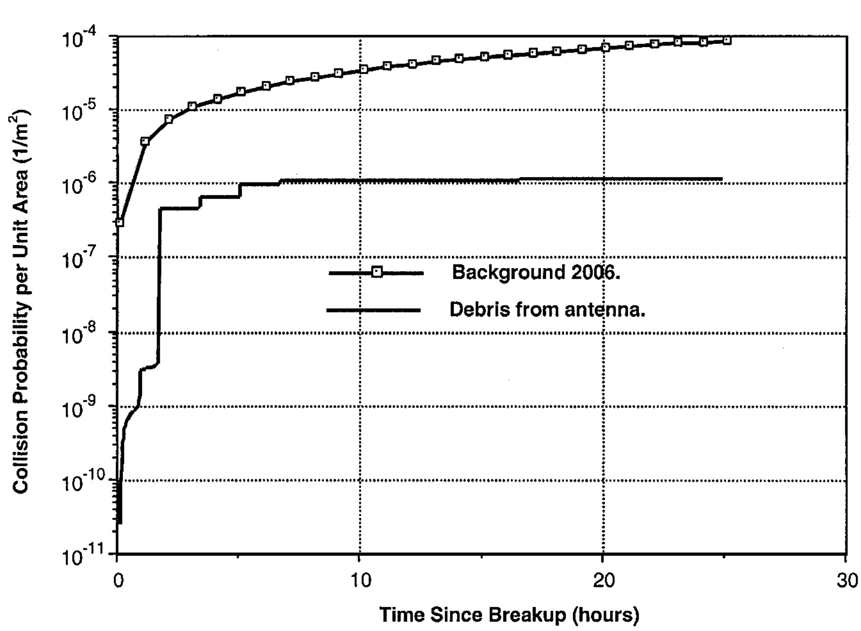


Fig. 9 Time history of cumulative collision probability for satellite 1; 1-mm fragments and larger.

descend through the constellation can be as much as 2 years. Additional considerations such as variations in orbital spacing (altitude, inclination, and eccentricity) can further reduce these occurrences and decrease the collision risk. Additionally, the risk assessment process for both controlled and uncontrolled reentry can be analyzed using methodologies presented by Patera and Ailor,[10] among others.

Debris Policy Review

The U.S. government policy on debris mitigation along with guidance for implementation of mitigation practices comes from several sources.[11–16] Additional mitigation considerations may include an operational close-approach detection and collision avoidance system (a traffic control system) and installing in situ laser corner cube detectors on satellites for more accurate tracking. Owners/operators/customers may have either more or less restrictive guidelines to be met, and these should be handled on a case-by-case basis.

Based on the example analyzed and using the models available, the NASA guideline is exceeded for collisions with large objects ($\geq$10 cm). In this example constellation, a given satellite has the probability of impact on average of 0.008 over the 10-year lifespan. This means that, on average, approximately 6 of the 800 satellites will be hit. The primary locations of any expected collisions are the solar arrays because they are the largest component of the example spacecraft. These collisions are not expected to be catastrophic but may significantly affect operating capability. The effects of collision warning and avoidance maneuvers need further study. The electronic boxes, which are the critical control elements, have impact probabilities on average of 0.00032 for debris greater than 1 cm. Assuming that a collision with a 1-cm fragment is the threshold giving loss of control, the probability that any of the 800 satellites could lose control is, on average, 26%.

Conclusions

This paper has developed a methodology to assess the risk posed to and by a large satellite constellation. The results for a hypothetical satellite constellation are presented, using representative computer models. This study found that the effects on the long-term background were relatively small except for a significant increase in the immediate vicinity of the satellite constellation, although the shorter-term effects on some users need to be evaluated further. It is anticipated that the small debris flux will require design practices to avoid exposure to vulnerable wires and cables. The mitigation issues involving the debris lethality for specific component designs and techniques to limit secondary debris will be dependent on the detailed system-level design of the spacecraft. A breakup of a constellation member poses the largest risk to coplanar satellites. However, the risk is still below that of the current and projected background. Collision avoidance strategies may be implemented; however, this decision would be based on the desired level of risk an operator is willing to take traded off against the operational costs of avoiding potentially catastrophic collisions. Should active collision avoidance be desired, a requirement for sufficient warning time needed to complete a maneuver must be developed. The present guidelines for collisions due to loss of control are currently met with the worst-case assumptions. Follow-on analysis is needed to examine the satellite failure modes and collision avoidance strategies in the context of a detailed system-level design of the spacecraft. The long-term hazard assessment found that there is a large probability of collisions with small particles. We also conclude that even a large constellation affects only users in the vicinity of the operational region of the constellation. The analysis performed for the short-term hazard assessment shows that the spacecraft are robust to short-term hazards from nearby explosion and component breakups within the constellation.

The intersatellite collision hazard assessment showed that the orbit maintenance plan limits the risk of intersatellite collisions, consistent with the propulsion budget. The orbit lifetimes and reentry for the spacecraft studies found that deorbit occurs within the 25-year NASA guidelines. Collision avoidance and reentry hazards must be dealt with on a case-by-case basis; collision avoidance can be an issue if there is a large uncertainty in the orbit propagation and orbit determination. Reentry hazards can be issues depending on the size of the satellite and the materials used in the construction of the spacecraft. The results of the intersatellite collision hazard assessment can be used to manage the risk of intraconstellation collision within the current propulsion system budget for drag makeup.

The constellation design used in this study met all of the NASA guidelines with the exception of collision with large objects; this is due to the large cross-sectional area of the satellites and the large number of satellites. However, it was uncertain whether the NASA guideline number is applicable for large satellite constellations. Because many of these guidelines were developed before the creation of large satellite constellations, a reexamination of the guidelines and their applicability to large satellite constellations is necessary.

When assessing the debris hazard posed to and by a real constellation, other issues such as launch traffic, solar cycle, and international debris mitigation practices or requirements should also be taken into consideration. They were neglected for this example because this study demonstrates only the methodology.

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References

[1]"NASA Safety Standard: Guidelines and Assessment Procedures for Limiting Orbital Debris," NSS 1740.14, Office of Safety and Mission Assurance, NASA Headquarters, Aug. 1995.

[2]Walker, R., Crowther, R., Wilkinson, J., and Stokes, P. H., "Orbital Debris Collision Risks to Satellite Constellations," *Mission Design and Implementation of Satellite Constellations: Proceedings of an International Workshop*, edited by J. C. Van Der Ha, Kluwer Academic, Dordrecht, The Netherlands, 1997.

[3]Walker, R., Crowther, R., March, V., and Stokes, P. H., "Satellite Constellation and Their Long-Term Impact on the Debris Environment in Low-Earth Orbit," *Proceedings of the Second European Conference on Space Debris*, edited by W. Flury, ESA, SP-393, Noordwijk, The Netherlands, 1997, pp. 359–366.

[4]Yates, K. A., and Jonas, F. M., "Assessment of the NASA EVOLVE Long-Term Orbital Debris Evolution Model," U.S. Air Force Phillips Lab., PL-TR-92-1030, Albuquerque, NM, April 1993.

[5]Sorge, M. E., and Johnson, C. G., "Space Debris Hazard Software: Program IMPACT Version 3.0 User's Guide," The Aerospace Corp., Rept. TOR-93(3076)-3, El Segundo, CA, Aug. 1993.

[6]Johnson, N., Christiansen, E., Reynolds, R., Matney, M., Zhang, J.-C., Eichler, P., and Jackson, A., "NASA/JSC Orbital Debris Models," *Proceedings of the Second European Conference on Space Debris*, edited by W. Flury, ESA, SP-393, Noordwijk, The Netherlands, 1997, pp. 225–232.

[7]Herman, D. E., "Introduction to DENSITY, a FORTRAN Program that Computes Spatial Density," The Aerospace Corp., ATM 93(3019-24)-2, Los Angeles, March 1993.

[8]Chao, C. C., "Program LIFETIME User's Guide," The Aerospace Corp., ATR-95(5917)-1, Los Angeles, Sept. 1995.

[9]Jenkin, A. B., "DEBRIS: A Computer Program for Debris Cloud Modeling," International Astronautical Federation Paper IAA.6.3-93-746, Oct. 1993.

[10]Patera, R. P., and Ailor, W. H., "The Realities of Reentry Disposal," *Advances in the Astronautical Sciences*, Vol. 99, Pt. 2, 1998, pp. 1059–1071.

[11]"MEO/LEO Constellations: U.S. Laws, Policies, and Regulations on Orbital Debris Mitigation," AIAA Paper SP-016-2-1999, 1999.

[12]Loftus J. P., and Reynolds, R. C., "A Handbook to Support the NASA Policy to Limit Orbital Debris Generation," International Astronautical Federation Paper IAA.3.3-93-700, Oct. 1993.

[13]"Orbital Debris: A Technical Assessment," National Research Council, Washington, DC, 1995.

[14]"Interagency Report on Orbital Debris: 1995," Office of Science and Technology Policy, Washington, DC, 1995.

[15]"U.S. National Space Policy," National Science and Technology Council, Washington, DC, 19 Sept. 1996.

[16]Campbell, W. S., Sorge, M. E., Spencer, D. B., and Maethner, S. R., "Proposed Development of Department of Defense (DoD) Debris Mitigation Guidelines," American Astronautical Society, Paper 96-112, Feb. 1996.

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