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NEWS

A Decade of Growth

P. Anz-Meador

This article will examine changes in the low Earth orbit (LEO) environment over the period 1990-2000. Two US Space Surveillance Network (SSN) catalogs form the basis of our comparison. Included are all unclassified cataloged and uncataloged objects in both data sets, but objects whose epoch times are "older" than 30 days were excluded from further consideration. Moreover, the components of the Mir orbital station are "collectivized" into one object so as not to depict a plethora of independently-orbiting objects at Mir's altitude; the International Space Station (ISS) is afforded the same treatment in the year 2000 data set. Figure 1 depicts the spatial density [1/km^3] over the altitude range 100-2000 km and in 10 km altitude bands.

Figure 1 possesses several salient features. Perhaps the most prominent are the "spikes" located between 770-780 and 1410-1420 km altitude. These correspond to the Iridium and Globalstar commercial communication spacecraft constellations, respectively. Given the uncertain future of the Iridium constellation, the spike between 770 and 780 km may change drastically or even disappear over the next several years. Less prominent is the Orbcomm commercial constellation, with a primary concentration between 810 and 820 km altitude (peak "A" in Figure 1). Smaller series of satellites may also result in local enhancements of the population. For example, consider the peak between 840-850 km (Figure 1's peak "B"). This volume is populated by the Commonwealth of Independent State's *Tselina-2* spacecraft constellation, several US Defense Meteorological Support Program (DMSP) spacecraft, and their associated rocket bodies and debris. While the region is traversed by many other space objects, including debris, these satellites and rocket boosters are in near circular orbits. Thus, any group of spacecraft whose orbits are tightly maintained are capable of producing a spike similar to that observed with the commercial constellations. Not coincidentally, the NASA EVOLVE 4.0 long-term debris evolution computer model predicts that this region is sensitive to the collision hazard. This result appears driven by the large size and mass of the spacecraft resident there, particularly the *Tselina-2* constellation.

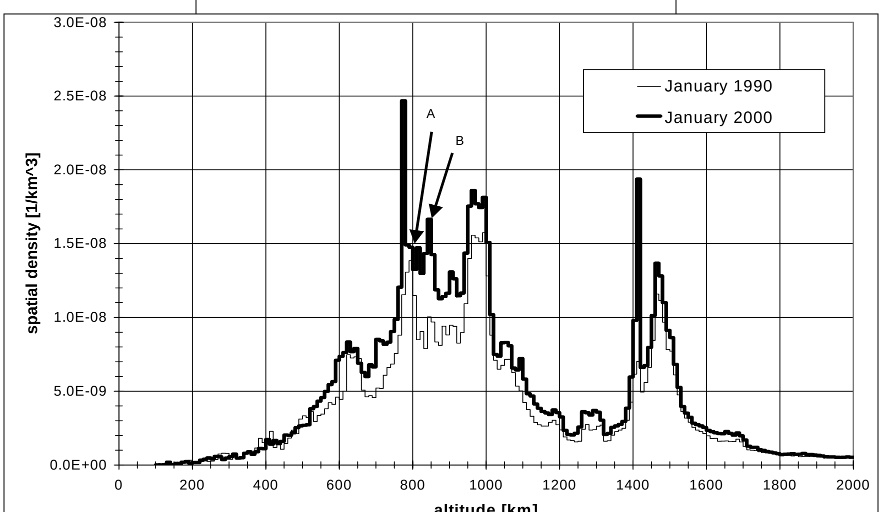

Figure 1. The LEO spatial density in 1990 and 2000.

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A Decade of Growth, Continued

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Note that both data sets presented are at or near Solar maximum. One may expect the low altitudes (< 600 km) to increase by up to a factor of two over the next five years, given decreasing Solar activity and assuming the historical fragmentation rate. Such behavior is historically evident when comparing a 1987 SSN catalog with the 1990 data set.

The spatial density chart averages over inclination; hence, collision rates won't be linearly related to the spatial density at any given altitude. Indeed, collision rates will vary not only with the spatial density but also with the inclination-dependent relative velocity. Altitudes dominated by high inclination (70-110°) orbits are expected to yield a significantly higher collision rate as compared to those populated by lower inclination orbits. The exception to this general rule returns us to our starting point: the commercial constellations. Because these constellations are maintained in precise orbital planes, their expected collision rate would be versus the "background" population only. Hence, the spikes representing the Iridium and Globalstar constellations do not present the inordinate collision risk implied by a casual examination. ❖

September Breakup is 22nd in Series

The year 2000's third fragmentation event occurred in early September with the fragmentation of a Russian *Proton* rocket's SOZ ullage motor. Naval Space Operations Center personnel discovered the event on 7 September 2000 when 57 debris penetrated the Navy's electronic fence, which spans the southern United States. Operational debris from the Gorizont 29 geosynchronous Earth orbit (GEO) launch on 18 November 1993, the unit (Satellite Number 22925, International Designator 1993-072E) was in an orbit of 140 km by 11,215 km with an inclination of 46.7 degrees at the time of the event. This was the 22nd known breakup of a *Proton* SOZ ullage motor since the first one exploded in 1984. This event occurred after approximately 2480 days on-orbit.

The SOZ ullage motors consist of hypergolic propellant (Nitrogen Tetroxide/ UDMH) spheres, associated support structure, and a multi-chamber thruster assembly for three-axis attitude control and for *Proton* fourth stage ullage (propellant settling). The *Proton* Block DM fourth stage carries two SOZ units. Each unit has a dry mass of approximately 56 kg but may contain up to 40 kg of unused propellant (Johnson *et al*., History of Soviet/ Russian Satellite Fragmentations, October 1995, Kaman). Russian officials have made design changes to prevent accidental explosions of the SOZ unit, although the date of full implementation is unknown. Newer versions of the Block DM stage do not eject the SOZ units following their ullage burn, though some Russian domestic launches continue to eject the units.

An analysis of the event, conducted the day the Orbital Debris Program Office was notified of the fragmentation, indicates that the long-term environmental consequences are minimal, as the parent object was in a catastrophic decay from the original GEO transfer orbit. This lessens the spatial density in low Earth orbit because of the large eccentricity and low perigee of the parent's orbit. ❖

Reentry Survivability Analysis of Extreme Ultraviolet Explorer (EUVE)

R. O'Hara

A reentry analysis of the Extreme Ultraviolet Explorer (EUVE) spacecraft was performed using the Object Reentry Survival Analysis Tool (ORSAT) - Version 5.0. The analysis was done in response to a request by NASA Headquarters and Goddard Space Flight Center (GSFC) after a preliminary assessment had shown that the EUVE reentry may produce a debris area greater than the limit set within the NASA Safety Standard 1740.14 guidelines.

NASA's 3243 kilogram EUVE spacecraft was launched on June 7, 1992 from Cape Canaveral Air Station on board a Delta II launch vehicle into a 528 kilometer, 28.5 degree inclined orbit. With the spacecraft nearing its end of mission and a possible reentry into the Earth's atmosphere expected as early as October 2001, personnel at Goddard Space Flight Center performed a reentry analysis using the NASA Johnson Space Center Debris Assessment Software (DAS) - Version 1.0, in accordance with NASA Policy Directive 8710.3. In the GSFC analysis, there were 18 individual objects predicted to survive. The total casualty area calculated for these surviving objects was 12.41 m^2, which exceeds the 8 m^2 limit set in the NASA safety standard. The EUVE spacecraft was not designed with a propulsion system and therefore cannot perform a controlled reentry. In order to mitigate the potential risk to human safety from an uncontrolled reentry of the EUVE spacecraft, a retrieval of the spacecraft using the Space Shuttle was considered. However, since DAS is a lower fidelity model and tends to produce a more conservative result, the Orbital Debris Program Office at JSC was asked to perform a more detailed reentry study using the higher fidelity NASA-Lockheed Martin ORSAT model to determine if taking such a measure would be necessary.

Several sophisticated material and thermal properties are included in ORSAT but do not exist in the DAS code. These enhancements tend to result in fewer objects surviving reentry when using ORSAT as opposed to DAS for a reentry analysis. For example, the emissivity is set to 1.0 for all materials available in DAS, implying blackbody radiation for each component analyzed. Thus, objects in DAS tend to lose heat faster and are more likely to survive. In ORSAT, however, the emissivity can be adjusted based upon what type of material the object is composed of. ORSAT also considers heat of oxidation during reentry, which means that the object gains heat faster and will demise more readily. Heat of oxidation is not considered in DAS. ORSAT also allows for thermal conductivity. With this enhancement and using a layered approach to modeling the fragments, ORSAT can reduce the overall debris area by allowing for objects to partially ablate. In contrast to this method, DAS will allow the entire fragment to surive. And finally, ORSAT enables the user to supply a wall thickness for an object, making it easier to model hollow objects. DAS treats all objects as solid and therefore requires a workaround to approximate the reentry heating to a hollow object. This workaround has been validated

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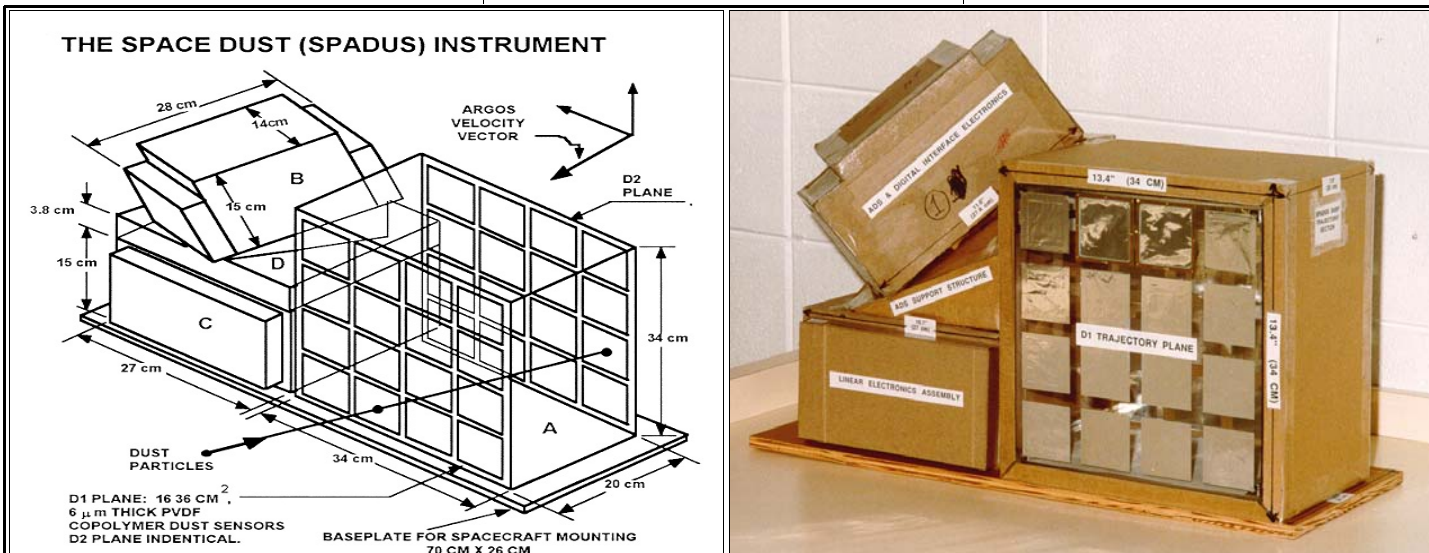
In Situ Detections of a Satellite Breakup

J. Opiela, N. Johnson

For the first time, a particle detector in Earth orbit has provided evidence to directly link sub-millimeter orbital debris to a specific satellite breakup. The University of Chicago's Space Dust instrument (SPADUS), on the U.S. Air Force's Advanced Research and Global Observation Satellite (ARGOS), has been operating in a nearly polar orbit at an altitude of about 830 km since soon after its launch on 23 February 1999. The experiment was designed primarily to detect small natural and man-made particles less than 100 microns in diameter.

During its first year in orbit, SPADUS recorded 195 impacts, about one impact every two days. In late March 2000 the instrument detection rate soared by over an order of magnitude, suggesting a potential encounter with a cloud or stream of debris. Principal Investigator Dr. Anthony Tuzzolino of the University of Chicago contacted the NASA Orbital Debris Program Office at JSC to seek assistance in identifying the source of the particles. A review by NASA of the impact times and ARGOS orbital characteristics indicated that most of the detections occurred at multiples of half-revolution intervals deep in the northern and southern hemispheres, with a clear majority of impacts found in the latter.

Since a major satellite breakup had occurred on 11 March with the fragmentation of a Long March 4B third stage (see *Orbital Debris Quarterly News*, "The First Satellite Breakup of 2000", Volume 5, Issue 2), NASA examined the orbital plane intersections of ARGOS and the Chinese orbital stage and found a close correlation. Approximately 40 of the SPADUS detections during the period 25 March – 1 April could be associated with the postulated Chinese debris cloud. A joint paper by the University of Chicago and NASA detailing this investigation is in work and will be presented early next year. ❖



A photo of SPADUS, along with a diagram where:
A: dust trajectory system consisting of two identical arrays (D1 plane and D2 plane) of polyvinylidene fluoride (PVDF) copolymer dust sensors
B: digital electronics
C: analog electronics box
D: power supply box

Liquid Mirror Telescope Observations of the 1999 Leonid Meteors

J. Pawlowski

The November 1999 Leonid Meteor Shower was observed and videotaped using a Liquid Mirror Telescope (LMT) located at the Johnson Space Center (JSC) Observatory near Cloudcroft New Mexico. This is the largest aperture optical instrument ever used for meteor studies. The sensitivity of the LMT along with its automated meteor detection software enabled detection of Leonid meteors in the 5 to 12 magnitude range. Leonids of such faint magnitudes were unable to be seen using our low light level video camera which was operating concurrently at the same location. Our purpose was to use the data from both sources to validate the Leonid Mass Distribution Model derived at JSC by Dr. Mark Matney. This model along with other meteor and orbital debris models is used for meteoroid and orbital debris risk assessment performed prior to every Space Shuttle Mission.

A total of 151 Leonids were detected by the LMT over 3 nights of observations (November 17, 18 & 19). Their masses were estimated to be between 10^{-4} and 10^{-8} grams using meteor analysis software also developed at JSC. A mass distribution of these lightweight Leonids was calculated, and the slope of their mass distribution was compared to the slope of mass distribution of the Leonid Meteor Mass Distribution Model. There was excellent agreement over the 0.002 to 0.02 milligram range. This agreement along with the agreement in the 0.02 to 0.2 gram range based on data from our low light level cameras reported in the April issue of this publication supports our continued use of the model. ❖

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The New NASA Orbital Debris Engineering Model ORDEM2000

J.-C. Liou, P. Anz-Meador, M. Matney, D. Kessler, J. Theall, and N. Johnson

The Low Earth Orbit (LEO, between 200 and 2000 km altitudes) debris environment has been constantly measured by NASA Johnson Space Center's Liquid Mirror Telescope (LMT) since 1996 and by Haystack and Haystack Auxiliary (HAX) radars at MIT Lincoln Laboratory since 1990. Debris particles as small as 3 mm can be detected by the radars and as small as 3 cm can be measured by LMT. Objects about 10 cm in diameter and greater are tracked and catalogued by the US Space Surveillance Network (SSN). Much smaller (down to several micrometers) debris particles can be estimated based on in situ measurements, such as Long Duration Exposure Facility (LDEF), and based on analyses of returned surfaces, such as Hubble Space Telescope solar arrays (HST-SA), European Retrievable Carrier (Eureca), and Space Shuttles. To increase our understanding of the current LEO debris environment, the Orbital Debris Program Office at NASA JSC has initiated an effort to improve and update the Orbital Debris Engineering Model ORDEM96 utilizing the recently available data. This article gives an overview of the new model, ORDEM2000.

An orbital debris engineering model is different from a dynamical model in that it provides a mathematical description of the debris environment (spatial density, flux, etc.) regardless of the origin or dynamical history of the debris particles. It is a useful tool for debris observers and spacecraft designers. In 1996, NASA released the first computer-based orbital debris engineering model, ORDEM96. Over the years ORDEM96 has become a standard model widely used by the international space community to evaluate the debris environment.

The motivation to build a new debris engineering model to replace ORDEM96 is twofold. First, the LEO debris environment is an evolving environment. It is essential to update an engineering model, such as ORDEM, on a regular basis. Secondly, more LEO debris observations and measurements are available now than when ORDEM96 was developed. One should certainly take advantage of the newly available data to improve the fidelity of the model. In addition, computers are much faster now than they were 5 years ago. Faster computers allow us to develop a more rigorous and more computer CPU intensive method to derive debris populations from observations and to build a better debris environment model.

The data sources used in building and testing ORDEM2000 include: SSN catalogue, Haystack, HAX, and LMT data, LDEF, Eureca, HST-SA, and Space Flyer Unit measurements, the Goldstone radar, Shuttle, and Mir data. The eleven data sources are utilized in two different ways. Major data sources, including the SSN catalogue, Haystack radar measurements, and LDEF data, are used to build the debris environment. The remaining data sets are used to adjust the debris populations or to compare with the model. The 10 cm and greater debris population is derived from the SSN catalog while the 1 cm and greater debris population is derived from the Haystack observations. The LDEF impact data are used to build debris particles smaller than 100 μm. The Goldstone data are used to bridge the gap between 1 cm and 100 μm particles. All data are used to test and validate the model output.

One of the difficulties in dealing with measurement data of the orbital debris environment is that the desired information is often incomplete. Data from Haystack, for instance, gives good flux information at a particular altitude, but in general does not give good orbit eccentricities. Returned surfaces give information on cratering fluxes, but do not indicate whether the particle was a small object traveling quickly or a larger object traveling more slowly.

The actual number of craters on a given oriented surface or in a radar range/range-rate bin due to a particular orbit is determined by the unknown number of objects in that particular orbit. However, the ratio of detected objects in one measurement bin to another measurement bin is a function of the geometry of the orbit and the physics of the detection process (e.g., cratering). The expected ratios among the various measurement bins can be computed for all allowed types of debris populations. If the populations are chosen carefully, then the "fingerprints" for each orbit population are linearly independent.

The measured data represent a convolution of these data "fingerprints" for the actual debris populations in orbit. A Maximum Likelihood Estimator can be used to solve this "inversion" problem. It is used to derive debris populations from the Haystack radar measurements and LDEF surface impact data sets.

Once debris populations are derived from observations/measurements, a new method is developed to build the debris environment. Template files are created to describe the spatial density, velocity distribution, and inclination distribution of debris particles of a given size and greater at a given latitude and at a given altitude. They form the basis of the new engineering model. Two options are available from the model. The first one is for a telescope/radar observer while the other is for an orbiting spacecraft.

For a ground-based telescope or radar observer, the only input parameter needed is the geographic latitude of the instrument. Once defined, the model selects the spatial density, velocity distribution, and inclination distribution templates and outputs them to the user. They can be combined to obtain the surface area flux measured by the instrument.

To calculate the potential debris flux on an orbiting spacecraft, the required input parameters are the five orbital elements (semimajor axis, eccentricity, inclination, argument of perigee, longitude of the ascending node) of the spacecraft. Once the orbit of the spacecraft is determined, the model "flys" the spacecraft through the environment and picks up the templates along the orbit. The debris flux on the spacecraft is calculated by combining the debris spatial density with the relative velocities between debris particles and the spacecraft.

Because a spacecraft program can span a couple of decades from planning to end-of-life, a future projection function (1991 to 2030) is implemented in the model. It is based on the spatial density variation at each altitude bin between 1991 and 2030 from the NASA orbital debris dynamical model EVOLVE 4.0. A business-as-usual future launch traffic that repeats the 1992 through 1999 traffic and the NOAA solar activity projection are used in the future projection mode in EVOLVE.

ORDEM2000 will be released by the NASA Orbital Debris Program Office for external review in early November 2000. Once the reviewing process is completed, it is expected that ORDEM2000 will be designated as the official NASA orbital debris engineering model.

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GEO_EVOLVE 1.0: A Long-Term Debris Evolution Model for the Geosynchronous Belt

P. Anz-Meador, P. Krisko, M. Matney

Introduction

The low Earth orbit (LEO) long-term debris environment evolution code EVOLVE 4.0 has been modified to model the deep space environment, specifically the Geosynchronous Earth Orbit (GEO), creating the independent computer model GEO_EVOLVE 1.0. The major differences between the two codes reside in the fragmentation model and the manner in which the collision rate is calculated. We introduce these topics to the reader and illustrate GEO_EVOLVE results by examining the long-term consequences of a post-mission disposal (i.e., collection) orbit 300 km above the nominal Geosynchronous altitude.

GEO_EVOLVE 1.0 Fragmentation Model

△v Distribution

Low-speed impacts are defined as those occurring at or below the speed of sound in the target material; since aluminum forms a large percentage of a typical satellite's mass, a threshold velocity of 5 km/s was chosen. Based on simulations involving the current Space Surveillance Network (SSN) catalog, the maximum collision velocity in GEO is on the order of 1.5 km/s. Thus, all collisions in GEO fall into the low speed category.

This model normalizes the velocity distribution to both projectile velocity and energy using a formulation first derived within the group in the mid-1980s and formulated specifically for low speed impacts by Hanada *et al.*[1] The model's functional form is given by:

$$\log_{10}(v/v_p) = 0.1139 - 0.1117[\log(L/L_m)]^2,\ L \geq L_m$$

and (1)

$$\log_{10}(v/v_p) = 0.1139,\ L < L_m$$

where L denotes characteristic length, and v denotes fragment velocity [km/s], v_p is the projectile velocity [km/s], and L_m [m] is an energy dependent threshold parameter. This parameter is defined by:

$$L_m = (E_p)^{0.33}/k \qquad (2)$$

where k is equal to $9.17\times\times10^4$ [$J^{0.33}/m$] and E_p is the projectile kinetic energy [J].

Collisions

The cumulative number of objects of mass M and greater has been explored by Hanada *et al.*[1] and is based upon laboratory impact tests conducted at 150 m/s. GEO_EVOLVE 1.0 uses a modified Hanada *et al.* relationship and the Satellite Orbital Debris Characterization Impact Test (SOCIT) results to convert between mass m and characteristic length L. The cumulative number N as a function of size L and larger is given by:

$$N(L) = 0.39\cdot(m_e)^{0.62}\cdot L^{-1.62}, \qquad (3)$$

where m_e is the ejecta mass (the mass going into the debris cloud, in [kg]) liberated during the collision event and L is the characteristic length [m] of the debris object.

Explosions

The number-size distribution for explosions in deep space is the same as that utilized in LEO. The sole difference lies in the explosion probabilities assigned to classes of deep space objects. The cumulative number of objects of size L and greater is given by:

$$N(L) = S\cdot 6\cdot L^{-1.6}, \qquad (4)$$

where S is a unitless scaling factor. The scaling factor may either be assigned automatically, based on exploding object class, or assigned by an analyst after a given event. For all classes of explodable GEO ring satellites, rocket bodies (propellant explosion), and spacecraft (battery explosion), the scaling factors are currently set to 1.0.

Collision Probability

All objects resident in GEO are not considered candidates for collision in GEO_EVOLVE 1.0. Active payloads are not allowed to interact with each other. Active payloads may, however, collide with inactive intacts (*i.e.*, abandoned intacts) and fragmentation debris. Abandoned objects and debris may collide as these orbits are not maintained.

Orbital evolution at and near GEO is qualitatively different than that in LEO. Most objects start in near-circular, near-zero inclination orbits. The orbital inclination of these objects increases over a period of time, then cycles back to the starting inclination. One of the byproducts of this evolution is that the ascending node of the evolving orbit is a direct function of the inclination and is not random with respect to it. This is because the orbit behaves as if it were precessing about a stable plane fixed in inclination and ascending node. The time scale of the change in the inclination, ascending node, and argument of perigee of GEO and near-GEO orbits is of the order of years to decades. Unlike the ascending node, there is no direct relation between the argument of perigee of an orbit and its inclination or ascending node. Consequently, the argument of perigee can be assumed to be randomized with respect to the other orbital parameters. The EVOLVE 4.0 yearly space traffic files have been modified to incorporate estimates of initial ascending node and argument of perigee.

Generally collision rates in LEO are computed using the assumption that the argument of perigee and the ascending node of an orbit are thoroughly randomized and the inclination, perigee, and apogee are fixed over the computation interval. Because the precession of the argument of perigee and ascending node are not directly linked to one another, this assumption is (in general) valid over a scale of years or decades, even for orbits where the ascending node varies slowly. Only for the special case of *Molniya*-type orbits where the argument of perigee behaves in special ways does this assumption break down.

In GEO, however, the majority of objects will display the stable plane behavior described above or something similar to it. Consequently, a different collision computation method must be used than that for LEO. The method chosen for GEO_EVOLVE 1.0 is to calculate a detailed collision rate of each object versus every other object at a snapshot in time. The number of separate collision rate calculations required for an ensemble of N objects is N·(N-1)/2. Fortunately, the methods chosen are fast enough to make this number of calculations feasible.

Using the assumption that two objects have fixed inclination and ascending node over the calculation period and that the argument of perigee is randomized, then each orbit plane spatial density distribution has the appearance of a flat ring with the outer edge at the apogee radius and the inner "hole" edge at the perigee radius. The two orbit planes are tilted to one another by an angle α given by

$$\cos\alpha = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 (\cos \Omega_1 \cos\Omega_2 + \sin \Omega_1 \sin \Omega_2)\ , \qquad (5)$$

where i is the inclination, Ω is the right ascension of ascending node, and the subscripts refer to the two orbits being computed. This geometry is equivalent to having one orbit (it does not matter which) having pseudo-inclination αa and the other having pseudo-inclination of zero. In this pseudo-inclination construction, there is no preferred pseudo-

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ascending node, so the spatial densities used by Kessler[2] can be used with α substituted for inclination.

$$\rho_1 = \frac{1}{2\pi^3 r a_1 \sqrt{\sin^2\alpha - \sin^2\lambda}\sqrt{(r_{A1}-r)(r-r_{P1})}} \quad [\text{km}^{-3}], \ (6)$$

where λ is the latitude [deg], r is the distance from the center of the Earth [km], and r_{A1}, r_{P1}, and a_1 are the apogee, perigee, and semi-major axis of the orbit [km].

The spatial density of the orbit plane at zero pseudo-inclination must be constructed separately because Kessler's equations break down for zero inclination. The formula is

$$\rho_2 = \frac{\delta(\lambda)}{2\pi^2 r a_2 \sqrt{(r_{A2}-r)(r-r_{P2})}} \quad [\text{km}^{-3}], \ (7)$$

where δ(λ) is the Dirac delta function of latitude.

The collision rate X for these two orbits can now be computed by integrating over the volume V and using the relative velocity between the two orbits where they overlap v_{REL} and the collision cross section between the two objects σ_{12}

$$X = \iiint_V dV \sigma_{12}\rho_1\rho_2 v_{REL} \quad [\text{sec}^{-1}] \quad (8)$$

$$= \frac{\sigma_{12}}{2\pi^4 a_1 a_2 \sin\alpha}\int_{r_a}^{r_b}\frac{v_{REL}\,dr}{\sqrt{(r_{A1}-r)(r-r_{P1})}\sqrt{(r_{A2}-r)(r-r_{P2})}}$$

The integration limits r_a and r_b are the overlap interval of the two orbits in radius. This one dimensional integral is computed numerically by the program. For cases where α equals zero or 180 degrees or where two perigees and/or apogees overlap, this integral can become infinite. In the real world, the orbits are not perfect Keplerian orbits, so these cases never actually occur. In practice, when the program detects that the perigees/apogees come within a few meters of one another or if α gets too close to zero or 180 degrees, it simply resets them to a reasonable value near the critical value.

Because of the fundamental and critical nature of this calculation, an independent method was derived to check the collision rates of the method just described. The independent method utilizes an ideal gas collision rate approximation within three-dimensional cells distributed in right ascension, declination, and altitude. A comparison of collision rates among the six unique collision partners indicates good agreement between the two quite dissimilar methods. Therefore, the high speed analytical technique described above is accepted as providing a high speed, yet high quality, estimate of the GEO collision rate.

The probability of an actual collision in GEO over any small time interval is very small. It is preferable therefore to estimate a limiting maximum probability of a collision over the time interval to compare to the random number draw. A much faster algorithm has been developed that approximates the above formulae. It is used to compute a preliminary probability of collision for the ensemble that is guaranteed to be greater than that derived from the true collision rate. If the random number draw exceeds this value, then there is no need to do the detailed calculation because no collision could have occurred during that Monte Carlo step. If the random number draw is below the limiting maximum probability of collision, then a collision may have occurred in that Monte Carlo step. The program then computes the more accurate (and more time consuming) collision probability to determine the true probability to compare to the random number draw. During this step, if a collision has been computed to occur beteen two objects, both greater than 10 cm in size, the conditions (location and velocities) are computed. This information is used to determine the characteristics of the breakup cloud.

Collection Orbit Comparisons

In order to demonstrate the operation of GEO_EVOLVE 1.0, we present the results of a comparative study. This short study compared a nominal case with a case in which all spacecraft were re-orbited to a collection orbit located 300 km above GEO altitude (35788 km) at end of life. Spacecraft were assumed to have a 10 year lifetime, and the cases were projected a century into the future. Launch traffic was assumed to mimic the 1992-1999 traffic, and this historical traffic was repeated in a cyclic fashion over the projection period. Ten (10) Monte Carlo trials were conducted for each scenario. The results are presented in Table 1.

Table 1. Test matrix scenarios with means and standard deviations.

TEST	Objects ≥ 10 cm	Explosions	Collisions
Baseline	6489 (±260)	11.6 (±3.4)	0.2 (+0.4 -0.2)
300 km collection orbit (±10km)	6323 (±179)	11.6 (±3.4)	0

Table 1 illustrates the relatively benign GEO environment at the end of the 100 year-long projection period. The explosion rate may be somewhat high, as doubt now exists about an alleged Titan Transtage fragmentation used to compute the explosion probability. The collision rate appears consistent with previous estimates[3,4] of the time required to generate a single collision. Note, however, that the implementation of a collection orbit strategy for satellites at end of life reduces the projected number of collisions to zero. Not readily apparent however is the spatial behavior of the environment. Figures 1 and 2 depict, in each case, the number of objects ≥ 10 cm in characteristic size as a function of both altitude (50 km bins) and time (1 year bins) for the collection orbit case. Clearly evident is the growth of the collection orbit population beginning 10 years into the projection. The slight growth exhibited by the GEO ring population is due to explosions of the relatively small rocket body population and previously abandoned spacecraft in GEO. Figure 2, in particular, reveals the behavior of this pseudo-spatial density on a yearly basis. Each contour corresponds to 30 objects. Cross-contamination in altitude is evident from the GEO ring population; spreading at the collection orbit altitude is limited due to the relatively tight orbit insertion dispersion (± 10 km). Over the long term, such cross-contamination could lead to the case in which a fragmentation in one orbit influences the collisional behavior of the other orbit. This result could argue either for higher or lower collection orbit or increased efforts towards the abolition of on-orbit explosions *via* guidelines such as NASA Safety Standard (NSS) 1740.14 or similar policy initiatives.

Conclusions

It is reasonable to assume that explosions will continue to contribute to the GEO

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environment over the next century. The explosion rates are approximately linear and proportional to the number of objects in the GEO ring population. In both cases, the production rate (explosions) and orbital perturbations tend to spread debris over increasingly larger spatial volumes over the duration of the projection. The collection orbit is subject to contamination by GEO ring debris. Collisions do not currently constitute a threat to the GEO environment under the assumptions and criteria employed by GEO_EVOLVE 1.0. This conclusion is applicable to the environment over the course of the next century, and is consistent with previous analyses.

A significant delimitation implicit in the current study is that model results have not been validated against observational data. Recent observations made by the NASA CCD Debris Telescope (CDT) indicate a population of uncorrelated target satellites in or near the Geosynchronous Orbit (GEO) ring.[5] These objects, observed to a limiting size of approximately 0.6 m in characteristic length, constitute an on-orbit population 20% larger than the cataloged population. The majority of these objects are likely debris. Other observations performed by the European Space Agency (ESA) using larger optics indicate that the GEO population, to a limiting diameter of approximately 0.1-0.2 m, exceeds the cataloged population by a factor of four.[6] Such a comparison between the GEO environment and GEO_EVOLVE, of course, constitutes an important and necessary future task.

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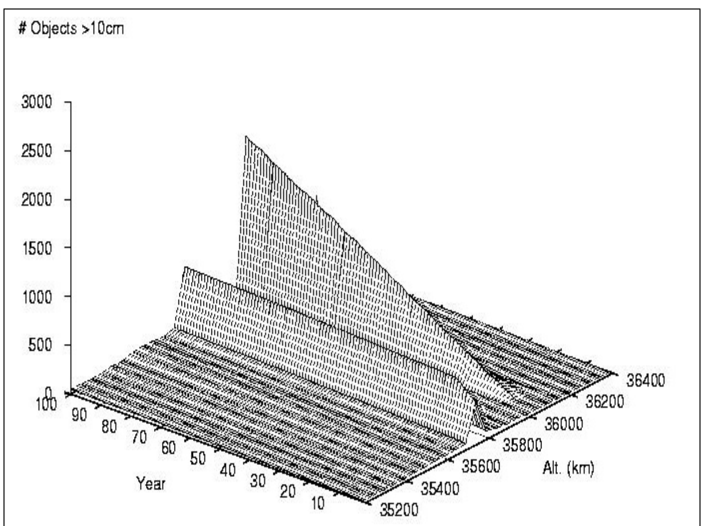

Figure 1. GEO_EVOLVE 1.0 number-altitude-time history for the GEO + 300 km collection orbit.

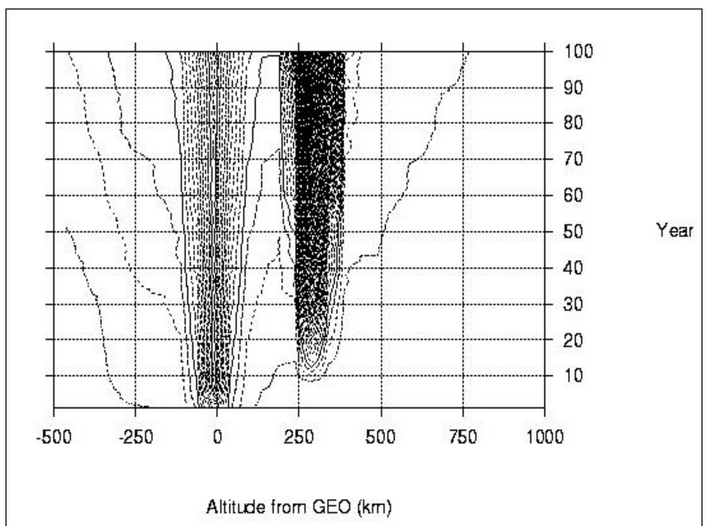

Figure 2. GEO_EVOLVE 1.0 population contours (≥ 10cm) for GEO + 300 km collection orbit.

Abstracts from Papers

Updating the NASA LEO Orbital Debris Environment Model with Recent Radar and Optical Observations and in Situ Measurements
51st International Astronautical Congress (IAF)

J.-C. Liou, et al

The Low Earth Orbit (LEO, between 200 and 2000 km altitudes) debris environment has been constantly measured by NASA Johnson Space Center's Liquid Mirror Telescope (LMT) since 1996 (Africano et al. 1999, NASA JSC-28826) and by Haystack and Haystack Auxiliary radars at MIT Lincoln Laboratory since 1990 (Settecerri et al. 1999, NASA JSC-28744). Debris particles as small as 3 mm can be detected by the radars and as small as 3 cm can be measured by LMT. Objects about 10 cm in diameter and greater are tracked and catalogued by the US Space Surveillance Network. Much smaller (down to several micrometers) natural and debris particle populations can be estimated based on in situ measurements, such as Long Duration Exposure Facility, and based on analyses of returned surfaces, such as Hubble Space Telescope solar arrays, European Retrievable Carrier, and Space Shuttles. To increase our understanding of the current LEO debris environment, the Orbital Debris Program Office at NASA JSC has initiated an effort to improve and update the ORDEM96 model (Kessler et al. 1996, NASA TM-104825) utilizing the recently available data. This paper describes the LEO debris environment based on all relevant available data. It serves as the foundation for the upcoming NASA orbital debris environment model, ORDEM2000. ❖

Calculation of Collision Probabilities for Space Tethers
51st International Astronautical Congress (IAF)

M. Matney, D. Kessler, N. Johnson

Space tethers represent a new technology to increase the capabilities and versatility of Earth-orbiting spacecraft. However, tethers also present a new type of collision hazard for spacecraft. In addition, space tethers themselves are especially susceptible to severing by orbital debris collisions. Traditional mathematical models that are used to compute collision rates between orbiting objects are based on the assumption that the spacecraft themselves are much smaller in size than the scale of their orbits (i.e., the spacecraft are treated as mathematical points). This assumption begins to break down for tethers, which can be many kilometers in length. In this paper, a mathematical procedure is introduced that allows for collision rate calculations for extended structures such as tethers. These equations are then applied to several current and planned tether missions to determine their mean sever lifetime and their risk of collision with other orbiting bodies. ❖

A New Approach To Computing Micrometeoroid Fluxes On Spacecraft
51st International Astronautical Congress (IAF)

M. Matney

Neil Divine in his "Five Populations of Interplanetary Meteoroids" (JGR, Vol. 98, E9, pp. 17,029-17,048) introduced a method of defining the interplanetary meteoroid environment in terms of orbit families. For this work, a new method is introduced to apply Divine's populations to spacecraft in interplanetary space and to spacecraft within the gravitational field of a planet or moon. The flux on the target is defined per unit solid angle per unit speed. This differential flux can be related to that outside the gravitational field by use of Liouville's theorem. Integration is performed over bins in solid angle (defining the direction of the meteoroids) and in meteoroid speed. This formulation computes the directional gravitational lensing while avoiding numerical problems in the integration calculation. It is also relatively easy to account for the shadowing of the planet body. In addition, for near-Earth space, a meteor shower model is included to assess short-term risks for spacecraft. For spacecraft in planetary orbit, the model can integrate over true anomaly to average the flux over the entire orbit. This paper includes a series of examples to compare the new model results against previous models, and demonstrates how it can be used to assess spacecraft risk. ❖

Meeting Report

33rd Scientific Assembly of COSPAR
16-23 July 2000 Warsaw, Poland

The 33rd Scientific Assembly of COSPAR was held in Warsaw, Poland, 16-23 July 2000. The four sessions on orbital debris and meteoroids, which were jointly organized by Commission B and the Panel on Potentially Environmentally Detrimental Activities in Space, included thirty presented papers and three posters. Discussions covered such topics as radar, optical, and in situ measurements of orbital debris and meteoroids, results of orbital debris modeling, hypervelocity impact phenomenology, and debris mitigation practices. Aside from those dedicated sessions, orbital debris was also discussed in the Space Weather session (PSW1) of Commission C, and was the subject of one of four daily Interdisciplinary Lectures. ❖

INTERNATIONAL SPACE MISSIONS

July - September 2000

International Designator	Payloads	Country/ Organization	Perigee (KM)	Apogee (KM)	Inclination (DEG)	Earth Orbital Rocket Bodies	Other Cataloged Debris
2000-036A	COSMOS 2371	RUSSIA	35778	35802	1.2	2	3
2000-037A	ISS (ZVEZDA)	ISS	355	368	51.6	1	0
2000-038A	ECHOSTAR 6	USA	35782	35791	0.1	1	0
2000-039A	NINA (MITA-O)	ITALY	408	471	87.3	1	0
2000-039B	CHAMP	GERMANY	418	477	87.3		
2000-039C	BIRD-RUBIN (SL-8 R/B)	GERMANY	411	472	87.3		
2000-040A	NAVSTAR 48 (USA 151)	USA	20037	20326	55.1	2	0
2000-041A	CLUSTER II-FM6	ESA	17585	120187	90.6	1	0
2000-041B	CLUSTER II-FM7	ESA	17853	119920	90.6		
2000-042A	MIGHTYSAT II.1	USA	546	583	97.8	1	0
2000-043A	PAS 9	USA	35785	35790	0.0	1	0
2000-044A	PROGRESS M1-3	RUSSIA	376	386	51.6	1	0
2000-045A	CLUSTER II-FM5	RUSSIA	17782	119990	90.6	1	0
2000-045B	CLUSTER II-FM8	RUSSIA	17692	120082	90.5		
2000-046A	BRAZILSAT B4	BRAZIL	35835	35883	0.1	1	1
2000-046B	NILESAT 102	EGYPT	35769	35804	0.0		
2000-047A	USA 152	USA	ELEMENTS UNAVAILABLE			1	0
2000-048A	DM-F3	USA	185	20249	27.6	1	0
2000-049A	RADUGA 1-5	RUSSIA	35769	35801	1.4	2	4
2000-050A	ZIYUAN-2	CHINA	482	499	97.4	1	0
2000-051A	SIRIUS 2	USA	EN ROUTE TO OP. ORBIT			2	1
2000-052A	EUTELSAT W1	EUTELSAT	35774	35799	0.1	1	0
2000-053A	STS 106	USA	375	387	51.6	0	2
2000-054A	ASTRA 2B	LUXEM.	EN ROUTE TO OP. ORBIT			1	1
2000-054B	GE 7	USA	EN ROUTE TO OP. ORBIT				
2000-055A	NOAA 16	USA	850	863	98.8	0	0
2000-056A	COSMOS 2372	RUSSIA	211	335	64.8	1	5
2000-057A	TIUNGSAT-1	MALAYSIA	634	642	64.6	1	1
2000-057B	MEGSAT-1	ITALY	641	647	64.6		
2000-057C	UNISAT	ITALY	640	644	64.6		
2000-057D	SAUDISAT 1A	SAUDI AR.	640	654	64.6		
2000-057E	SAUDISAT IB	SAUDI AR.	640	661	64.6		
2000-058A	COSMOS 2373	RUSSIA	210	275	70.4	1	0

Upcoming Meetings

19-21 March 2000: *Third European Conference on Space Debris*, Darmstadt, Germany. This conference provides a forum for the presentation of results from research on space debris, to assist in defining future directions for research, to identify methods of debris control, reduction and protection, and to discuss international implications and policy issues. Deadline for abstracts is November 15, 2000. For more information contact W. Flury at wflury@esoc.esa.de

3-5 April 2001: *Space Control Conference*, MIT Lincoln Laboratory, Lexington, Massachusetts, USA. The conference is the 19th annual meeting hosted by MIT Lincoln Laboratory on space control issues, surveillance technology (including orbtial debris), and monitoring and identification. For further information contact Susan Andrews at scc@ll.mit.edu

ORBITAL BOX SCORE

(as of 27 September 2000, as catalogued by US SPACE COMMAND)

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	30	355	385
CIS	1335	2573	3908
ESA	28	237	265
INDIA	20	4	24
JAPAN	66	46	112
US	929	2897	3826
OTHER	298	22	320
TOTAL	2706	6134	8840

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EUVE, Continued

(Continued from page 2)

using comparisons with ORSAT runs, though the more direct approach used by ORSAT is more reliable.

In the ORSAT analysis, only the objects shown to survive with the DAS model were evaluated, and the high fidelity features of ORSAT were applied to the reentry analysis. Reentry of the EUVE spacecraft was considered to occur at an altitude of 122 kilometers with breakup occurring at 78 kilometers. All of the objects were considered exposed to reentry heating at this breakup altitude. Objects were also analyzed for possible shielding affects by other components. Any object shown to demise at the breakup altitude, but was considered shielded by other spacecraft components, was reanalyzed starting at the demise altitude for the object shielding it. This allowed for some conservatism since in reality these objects would have experienced some heating and possible ablation prior to the demise of the object shielding it. The final debris area calculated from the more sophisticated ORSAT analysis of the surviving fragments came to a total of approximately 6 m^2, which is well under the 8 m^2 NASA constraint.

The more detailed reentry study of the EUVE spacecraft done using ORSAT has shown the future uncontrolled reentry of EUVE to be of an acceptably low risk to human safety and therefore mitigation measures are unnecessary. ❖