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NEWS

Publication of the "History of On-Orbit Satellite Fragmentations"

E. Cizek

The 12th Edition of the History of On-Orbit Satellite Fragmentations (JSC-29517) has recently been completed. This release contains all known satellite fragmentations prior to May 30, 2001. Expanded topics include descriptions of Information Sources, Environment Overview, On-orbit Spatial Density, Population Disposition, and A 1990s Fragmentation Retrospective. Numerous tables and color diagrams have been added to illustrate information related to these topics and others within the document. A new section, Event Master List, provides a quick reference for the reader to identify an event by the international designator and its associated color-coded event type.

The first page of the two page format for the breakups consists of information pertinent to the breakup; parent identity, satellite number, event date and time, breakup orbital parameters, the number of pieces detected, the number remaining in orbit and the assessed cause. The second page consists of a Gabbard diagram of the debris cloud if sufficient orbital data were collected.

The 12th Edition will be available in Adobe PDF format on the Orbital Debris website at http://www.orbitaldebris.jsc.nasa.gov/measure/sat_frag_update.html. A free copy of Adobe Reader may be obtained from the Adobe website. If you wish to obtain a printed copy of the document, please send your request to marie.e.cizek1@jsc.nasa.gov. For shipping purposes, include a street mailing address (PO box numbers are not acceptable) and a business phone number. ❖

New Satellite Breakups Detected

P. Anz-Meador

The year 2001's fourth and fifth fragmentation events occurred in June and July with two fragmentations of the Russian *Proton* rocket's SOZ ullage motors. These represent the 24th and 25th known breakups of a *Proton* SOZ ullage motor since the first one exploded in 1984. An inventory of remaining SOZ units on-orbit, as well as an analysis of historic SOZ-related fragmentations, will be the subject of a future Quarterly article.

The first fragmentation, that of a Cosmos 2139-2141 ullage motor (21226, 1991-025G) occurred 16 June 2001. The motor was in a 18960 x 300 km, 64.5° inclination middle Earth orbit (Russian *GLONASS* navigation satellite constellation) transfer orbit. The second object was associated with the launch of *Gorizont 27* (22250, 1992-082F). The fragmentation occurred on 14 July 2001 while the object was in a decaying Geosynchronous transfer orbit of 5340 x 140 km altitude, 46.5° inclination orbit. While both orbit profiles are difficult for the US Space Command to acquire and track, 31 and 14 large debris objects had been detected in the Cosmos and Gorizont clouds, respectively. However, these object counts may increase significantly over time.

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.

Analyses of these events indicate that the long-term environmental consequences are minimal, due to the relatively large eccentricity and low perigee of the parent's orbit. These orbital characteristics yield a consequently low spatial density in low Earth orbit. ❖

Inside...

NEWS

Publication of the CCD Debris Telescope Report

K. Jarvis

NASA has published the report, "CCD Debris Telescope Observations of the Geosynchronous Orbital Debris Environment. Observing Year:1998. #JSC-29537".

The CCD Debris Telescope (CDT) observes the Geosynchronous Earth Orbit (GEO) debris environment. It is an automated 32-cm aperture, portable Schmidt telescope presently co-located with the NASA's Liquid Mirror Telescope (LMT) at Cloudcroft, NM. The CDT is equipped with a CCD camera capable of detecting 17th magnitude (~0.8-meter, albedo~0.10) objects at 36,000 km. The CDT is currently conducting systematic searches of the GEO environment as part of an international measurement campaign under the auspices of the Inter-Agency Space Debris Coordination Committee (IADC). The objectives for this survey are to determine the extent and character of debris in GEO, specifically by obtaining distributions for the brightness, inclination, RA of ascending node, and mean motion for the debris. Initial tests using the CDT for this campaign took place in late 1997 and data collection began in January, 1998. This report describes the collection and analysis of 58 nights (~420 hours) of data collected in 1998.

Results show that for objects tracked by US Space Command, the CDT is seeing most objects that crossed its field of view; there are potential explanations for most satellites predicted to cross the field of view but which were not seen. The total number of detections was 4900. Approximately 3900 of these objects are tracked by US Space Command. The remaining 1000 objects are untracked debris. The peak of the absolute magnitude distribution for these untracked objects corresponds to a size of 1.1 m diameter (assuming 0.10 albedo at 36,000 km) and then starts to roll off due to sensor limitations. ❖

Project Reviews

The 2001 Leonids: A Major Test for Meteor Stream Forecasting

Bill Cooke, CSC/ED44 Marshall Space Flight Center

November of each year brings the annual Leonid shower, and, given that parent comet's nodal crossing was some three years ago, there is the possibility of a meteor storm *(In this article, a meteor storm is defined as a shower whose Zenith Hourly Rate (ZHR) exceeds 1000 meteors per hour)*. Indeed, the three major groups (David Asher/Rob McNaught, Esko Lyytinen/Tom Van Flandern, and Peter Brown/Bill Cooke) that do meteor stream forecasting are all predicting a storm with a fluence (integrated flux) exceeding that of the 1999 Leonids on November 18th, which is not pleasant news for spacecraft operators, who hoped this Leonid business was over with the 1999 storm. However, from the forecasting viewpoint, the 2001 Leonids will provide the "acid test" of the various stream models used by these groups; simply put, whatever happens, at least one group is going to be wrong.

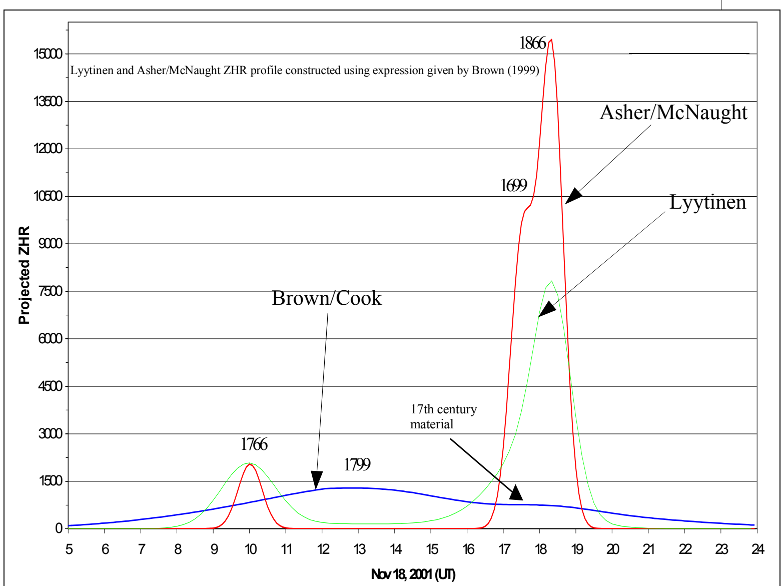

Figure 1. 2001 Leonid Forecasts. Creation year of streams are indicated over activity peaks.

There is generally good agreement between the Leonid forecasts of Asher/McNaught and Lyytinen/Van Flandern as to the level of activity in 2001; all predict a much larger storm than that seen in 1999, with ZHR's ranging from 7,500 to 15,000 at maximum. These models indicate a moderate peak (~2,500 ZHR) at 10:00 UT, and much higher levels of activity (7,500-15,500 ZHR) between 17 and 19 hours on November 18th. However, the Brown/Cooke forecast has changed substantially from a previous forecast issued 6 months ago, largely due to a) the incorporation of the recent Leonid observations into the fits, and b) the elimination of the extremely unreliable 18th and 19th century ZHR estimates from the fit data. As a result, they have lowered the maximum predicted ZHR by an order of magnitude, from approximately 13,000 to 1,300, and reduced the fluence by a factor of 4. The revised Brown/Cooke model has two very broad peaks, the first being at about 13 hours UT, predominately due to material from the 1799 trail. The second, smaller peak occurs near 17 hours UT and is produced by meteoroids ejected during the 17th century, with some contribution from the 1866 trail. A comparison of the stream center locations is shown in figure 2; note the discrepancies between the two models.

Despite the disagreement in rates, the forecasted fluences are not that disparate: 6 Leonids km^{-2} for Asher/McNaught, 9 Leonids km^{-2} for Lyytinen/Van Flandern, and 7 Leonids km^{-2} for Brown/Cooke. These numbers are about 5 to 8 times the fluence of the 1999 Leonid storm, so the risk per spacecraft (in LEO) should be correspondingly greater.

In order to reliably distinguish between the forecasts, the Space Environments Team at Marshall is leading an observation campaign involving some 20 low-light level meteor video systems and two meteor radars. The current deployment plan makes use of the all-weather capabilities of the University of Western Ontario's

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The 2001 Leonids: A Major Test for Meteor Stream Forecasting, Cont'd

(Continued from page 2)
3-frequency backscatter radar, located in London, Ontario, and the MSFC forward scatter system, located at Marshall. Both of these systems are automated and operate 24 hours per day, so they should give excellent coverage when the radiant is visible from their respective sites. The video systems will be dispersed to seven locales around the globe, chosen on the basis of a) climatology, b) coverage of anticipated shower activity, and c) team familiarity with the locale. These sites are:

1. Calar Alto, Spain
2. Marshall Space Flight Center, Alabama
3. Eglin AFB, Florida
4. Apache Point Observatory, New Mexico
5. AMOS site, Hawaii
6. Guam
7. Gobi Desert, Mongolia (manned by University of Western Ontario personnel)

Assuming all are clear (which is unlikely for MSFC or Eglin; however, both sites are mobile and can move to clear seeing), this dispersal gives very good coverage of the 2001 Leonids, some 22 hours total (see figure 3). No matter which prediction is right (if any), the observations made during this campaign will allow for forecast discrimination and improvement. If there is a peak over Hawaii, then the Asher/McNaught predictions of an even greater Leonid storm in 2002 can be discounted, but if the general trend follows their prediction then the possibility of yet another Leonid storm next year remains. If no prediction is close, then the physics and propagators of the dynamical stream models must be modified to get a match to recent years, i.e., it's "back to the drawing board." Certainly, the 2001 observations, along with those of previous years, will be incorporated into the new stream model under development at MSFC.

Note: A more detailed description of the 2001 Leonid forecasts can be found at http://see.msfc.nasa.gov/see/Leonid_Forecast_2001.html.

Acknowledgement

I would like to thank the following for funding Leonid observational efforts and analyses over the past two years: Tony LaVoie of the Chandra X-Ray telescope project, Nicholas Johnson of Johnson Space Center, Bob Sodano at Goddard Space Flight Center, Brigadier General Simon "Pete" Worden of U.S. Space Command, Billy Kauffman of the Space Environments and Effects Program, and the management of the Marshall Space Flight Center Engineering Directorate.

References

1. The Asher/McNaught and Lyytinen/Van Flandern ZHR profiles (and the resulting fluences) have been constructed from an expression given by Brown in his 1999 paper on historical Leonid observations. It should be emphasized that Asher/McNaught predict only the maximum ZHRs of the trails (no durations are given), and that Lyytinen has his own ZHR profiles, located at http://www.sci.fi/~fmbb/astro/meteorit.htm
2. Fluences are given for meteoroid masses down to 10 mg. ❖

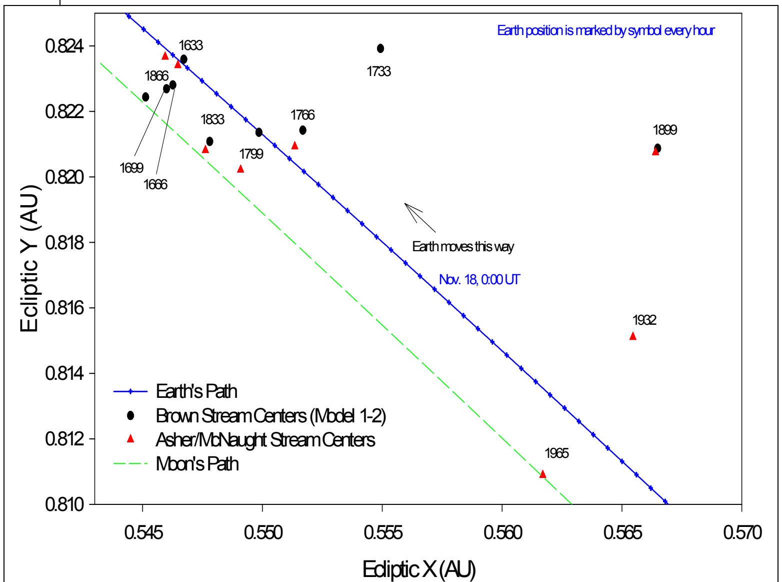

Figure 2. Locations of Leonid trail centers in 2001.

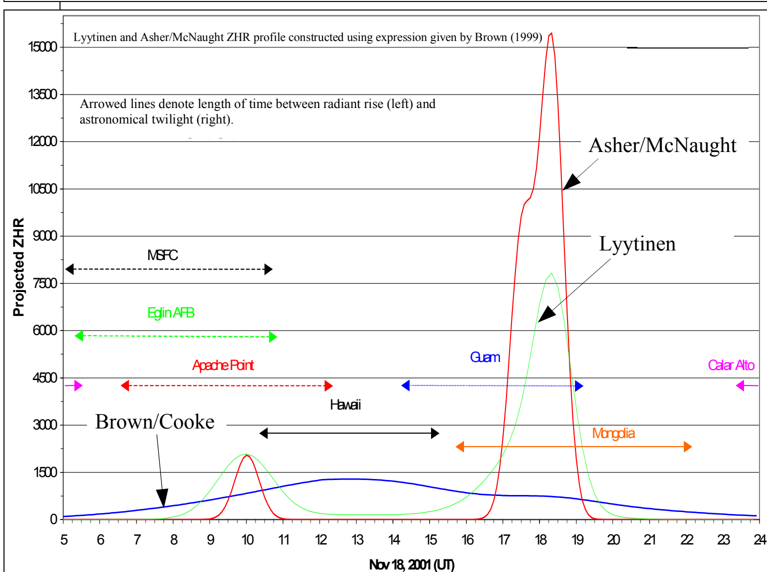

Figure 3. 2001 Leonid coverage by site.

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New Collision Probability Algorithms for Orbital Debris Models

D. Hall, M. Matney

In 1981 Don Kessler [1] came up with an elegant method for computing average collision rates between satellites. Since then, his formulation has been the workhorse for collision risk calculations in NASA's orbital debris models. A fundamental assumption in Kessler's spatial density approach is that the argument of perigee and longitude of ascending node for each satellite orbit have random distributions with respect to one another. This assumption is often justified because secular perturbations can induce orbital precession in the form of progressive changes in the argument of perigee and longitude of ascending node. For instance, when applied to two specific satellites, the spatial density approach accurately indicates the probability of collision averaged over time scales that are much longer than the maximum period of orbital precession for either of the two satellite orbits. However, Kessler's method is known to suffer certain problems—e.g., in cases where the orbiting objects have similar inclinations.

Some new ideas about computing collision probabilities might be worth implementing in the next generation of computer models that simulate Earth's evolving orbital debris population. The objective of these new algorithms would be to calculate the likelihood of collisions between orbiting objects, but using an efficient method that accounts for the short-term variations in collision probabilities rather than simply using the long-term average given by Kessler's spatial density approach. These algorithms would have the advantage of indicating the exact locations where collisions are likely to occur as well as the specific identities and relative velocities of the colliding objects.

Two new collision algorithms are currently being considered. The first algorithm, the "pair-wise interaction" method, takes a somewhat deterministic approach. It calculates collision rates for two spherical satellites averaged over their mean-anomaly angles for a given fixed configuration between the two orbit planes. The resulting collision probability can be considered an "intermediate" time-scale average as opposed to the long time-scale average generated by Kessler's spatial density method. Extension of the method to longer time periods is accomplished by propagating the two satellite orbits forward in time.

The second method, the "bubble" algorithm, evaluates collision probabilities by calculating the magnitude of overlap between two probability "bubbles" centered on the positions of two orbiting satellites. These bubbles can be thought to represent the volume of space where the satellites may actually be located at some future time. This method employs a Monte-Carlo technique to evaluate the likelihood of collisions. Normally, Monte Carlo calculations require the numerical integration of the collision rate over an appropriate time period and then the use of a random number to determine if a collision actually occurs during that period. The bubble method can be used to bypass the majority of this computation. Instead, the bubble Monte Carlo procedure itself accomplishes the numerical integration, potentially speeding the overall calculation significantly. This algorithm may be particularly applicable to modeling the GEO environment, where the overall collision risk to satellites would be evaluated by performing many Monte-Carlo projections of the orbiting population.

References

1. Kessler, D. J., Derivation of the Collision Probability between Orbiting Objects: The Lifetimes of Jupiter's Outer Moons, *ICARUS* **48** 39-48 1981. ❖

In-Situ GEO Debris Measurements Utilizing a Near Earth Dust Detector

J.-C. Liou, J. Opiela

A Galactic DUNE (DUst measurements Near Earth) mission has been recently proposed by an international team of scientists, led by Eberhard Grün, to measure interstellar dust near 1 AU [2]. The mission payload is a dust "telescope" consisting of several instruments to measure the impact parameters as well as chemical composition of the impactors. At least two orbit options are being considered for the mission: a heliocentric orbit at the Sun-Earth Lagrange equilibrium point of L1 (or L2) and a geocentric High Earth Orbit (HEO) at 38,000 km altitude. However, with a slight modification of the latter orbit, the DUNE mission may provide the orbital debris community with much needed in-situ debris measurements in the Geosynchronous Earth Orbit (GEO) at 36,000 km altitude while still accomplishing its primary objective of measuring interstellar dust.

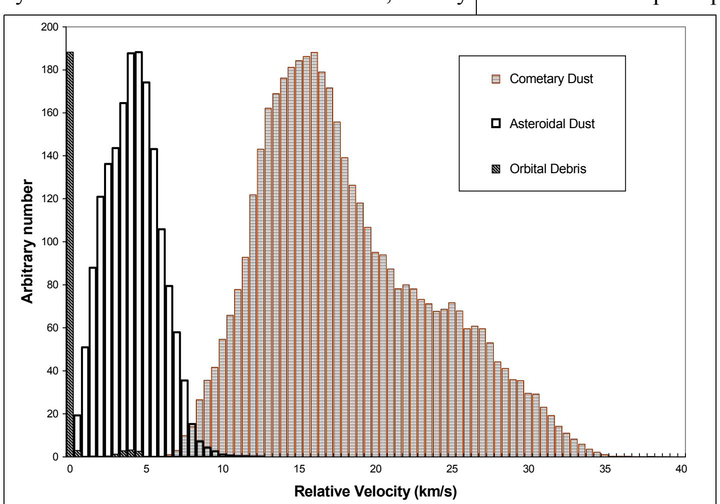

Figure 1. Velocity distributions of orbital debris, asteroidal, and cometary dust particles with respect to a GEO detector.

Unlike the Low Earth Orbit (LEO) region, the GEO debris environment is not well characterized. Ground-based GEO optical measurements in general have been limited to objects greater than about 60 cm. A recent Inter-Agency Space Debris Coordination Committee (IADC) GEO debris campaign has identified substantial numbers of unknown objects, indicating the possibility of unknown historical breakups or non-fragmentation sources in the GEO region [4]. Since there is no natural mechanism to remove debris in GEO, where atmosphere drag is negligible, the GEO debris population will continue to grow. As satellites continue to be launched into the GEO region, it is very important to characterize the GEO debris environment (flux, size distribution, orbit distribution, sources) before any effective mitigation measures can be developed. A good environment definition is also needed for GEO satellite designers and operators to have reliable debris impact risk assessments and

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In-Situ GEO Debris Measurements Utilizing a Near Earth Dust Detector, Cont'd

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protection for their satellites.

One of the instruments being proposed for DUNE is a Dust Detector System (D2S). It has a detection area of about 1 m^2 and is capable of measuring impacts with accuracy of ~1% in impact speed, ~1% in impact angle, ~10% in charge, and a factor of 2 in projectile mass [2]. The four major dust populations in GEO are orbital debris, asteroidal, cometary, and interstellar dust. Each of these populations has its own unique dynamical signature and should be recognized by D2S. According to recent Ulysses measurements, interstellar dust penetrates the Solar System from a direction of 253° ecliptic longitude and 5° ecliptic latitude with a speed of 26 km/s [2]. Most interstellar dust particles are smaller than 1 μm. Their heliocentric velocities exceed the Solar System escape velocity at 1 AU (42 km/s). In addition, as the Earth moves around the Sun, a strong seasonal variation is expected due to the interstellar dust's mono-directional motion through the Solar System. Orbital debris and interplanetary dust particles (asteroidal and cometary) are typically larger than 1 μm. Asteroidal dust approaches the Earth with low eccentricity (~0.1) and low inclination (< 20°) heliocentric orbits while cometary dust approaches the Earth with high eccentricity (~0.5) and high inclination (> 30°) heliocentric orbits [3]. Their relative velocities with respect to a circular GEO-orbit detector with 0° inclination are quite different, as shown in Figure 1. The distributions are derived from the asteroidal and cometary populations based on the zodiacal cloud observations at 1 AU [5]. Finally, the relative velocity between orbital debris and a circular GEO-orbit detector is in general less than 1 km/s. To better demonstrate the differences in relative velocity, the three populations in Figure 1 are scaled to about the same arbitrarily peak value. The expected number of detections and other impact characteristics from the four populations are summarized in Table 1. All numbers are based on a randomly oriented detector in a circular GEO-orbit with 0° inclination. Although most of the impacts on a GEO-orbit DUNE detector come from orbital debris, D2S should be able to distinguish impacts from the other three sources. It is possible to further optimize the detection of a specific population by arranging the orientation of the detector during certain parts of the orbit.

	Impact Speed	Size Range	Seasonal Variation	Estimated Detections
Orbital Debris	< 1 km/s	1 μm – 1 mm	No	~20 /m^2/day
Asteroidal	1 – 10 km/s	1 μm – 1 mm	Yes	1~2 /m^2/day
Cometary	10 – 30 km/s	1 μm – 1 mm	No	1~2 /m^2/day
Interstellar	1 – 80 km/s	≤ 1 μm	Yes	1 /m^2/day

Table 1. Impact characteristics of the four populations. Debris impact rate is based on GORID measurements [1].

A GEO-orbit DUNE mission will broaden the scientific scope of the mission. Debris impacts are very different from interstellar dust impacts. The primary objective of the DUNE mission will not be affected by placing the detector in GEO. Debris detection will not require any new instrument or modification of the instruments being proposed. A GEO-orbit DUNE mission will benefit interstellar dust, interplanetary dust, and orbital debris communities. It is the best cost-efficient option for maximizing science return.

References

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EVOLVE 4.1 Provides Information Regarding the Types of Debris in Orbit

J. Opiela

Recent upgrades to NASA's long-term orbital debris environment simulation model, EVOLVE, include the separation of object types. Output spatial densities were previously reported by altitude, object size, and time. The output spatial densities of EVOLVE 4.1 are now additionally separated into three object types: launched ("intact") objects, explosion fragments, and collision fragments. Reporting of collision events also includes the types of the colliding objects. This allows an important characterization of the types of collisions (*e.g.* debris colliding with an intact object, or debris colliding with

TEST	Number of Objects with Size ≥ 10cm			Cumulative Number of Collision Events*		
	Intact	Collision	Explosion	I-I	I-C	I-E
Baseline	6310	42374	5499	17.3	43.5	8.1
Safing	6309	41250	3199	16.9	41.6	5.2
Decay 50	4958	11917	3201	10.5	10.4	4.1
Decay 25	4279	8965	3201	7.3	6.9	3.9
Collec. 2000 + Decay 25	4487	8424	3201	7.2	6.4	3.2
Collec. 2500 + Decay 25	4304	9861	3201	8.2	6.9	3.8

* I-I (intact-on-intact), I-C (intact-on-collision fragment), I-E (intact-on-explosion fragment)

Table 1. EVOLVE 4.1 results for 100-year projection periods. Values are the average of 30 Monte Carlo runs. Collision events are categorized by parents.

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EVOLVE 4.1 Provides Information Regarding the Types of Debris in Orbit, Cont'd

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other debris).

The present study repeats some previous work in order to gain additional insights offered by the new EVOLVE 4.1 code. We chose to perform tests on the long-term effects of explosion suppression, specified decay lifetimes, collection orbits, and constellation satellite disposal. Table 1 summarizes the results of the first three tests.

The baseline test simply retains the characteristics of the objects launched during the historical period. As with previous versions of EVOLVE, the future launch traffic is modelled as a cycle through the last eight years of the historical period. Figure 1 shows how a continuation of past practices leads to an exponential increase in the number of objects in orbit over the next hundred years as collision debris grows and exceeds explosion debris and intacts in population after approximately 30 years. Collisional activity by object type is displayed in Figure 2. Here, collisions between intact objects and collision debris (I-C) exceed those between intacts and explosion debris (I-E) after about 30 years, and exceed those between intacts and other intacts (I-I) after about 60 years. For the time period studied, 100 years, collisions between collision fragments (C-C) appear to play a very minor role.

As noted in previous EVOLVE 4.0 studies, explosion suppression alone does not significantly alter the future LEO debris environment. But when coupled with an active deorbit rule (*i. e.*, payloads and rocket bodies at end-of-mission being forced into orbits which result in orbital decay within a specified period of time) a significant reduction in the debris environment after 100 years is achieved.

A decay lifetime of 25 years, supported by the NASA Safety Standard NSS 1740.14[1], results in a 73% decrease in the number of collision events, most of which are intact-on-collision debris events. Intacts are reduced by 32% and collision fragments by 78%. A 50-year decay lifetime decreases collisions by 62%. Intacts are reduced by 21% and collision fragments by 71%.

The current standard also allows for the use of a collection or storage orbit for spent intacts. For LEO intacts this collection orbit is recommended to have a perigee altitude above 2500 km. Any realistic use of such a collection orbit must consider the cost (*i.e.*, total DV) of such a maneuver compared to that of a perigee-lowering disposal maneuver. If the collection orbit scenario is chosen the EVOLVE mitigation software internally calculates and applies the cheapest of three options:

1. perigee lowering to decay within N years,
2. perigee raising to the collection orbit altitude (if apogee is already above collection altitude),
3. perigee and apogee raising to a circular orbit at or above the collection altitude.

The cost in DV of applying either mitigation option is of course lowest for the case of a 2000 km collection orbit. The total required DV for all affected spacecraft is about 6% lower than that for a 2500 km altitude collection orbit standard. This is due to both the lower DV required to reach the lower collection orbit and to the fact that some spacecraft (those above the collection altitude) would not require re-orbiting.

The collision rate within the collection orbit is calculated to be statistically insignificant in both cases. A previous study does indicate a much less benign environment within the collection band.[2] Clearly, further study is required concerning this mitigation option. In any case, a wider collection orbit altitude band will reduce the probability of a collision between objects within or traversing the collection orbits. This is provided that the orbit altitude is chosen *a priori* so as to avoid operational altitudes. If collection orbits are chosen as a viable mitigation option, then satellite operators must weigh their pros and cons accordingly.

Satellite constellations represent a special case of increased launch rate within a small altitude range. Placing many objects into a single orbital configuration requires special attention to debris mitigation. The constellation disposal study includes nine different cases, listed in Table 2. Each case includes only one constellation, which varies in its altitude, number of members, and disposal option. The two disposal options are immediate deorbit or abandonment.

The constellation member satellites are each given a lifetime of eight years before

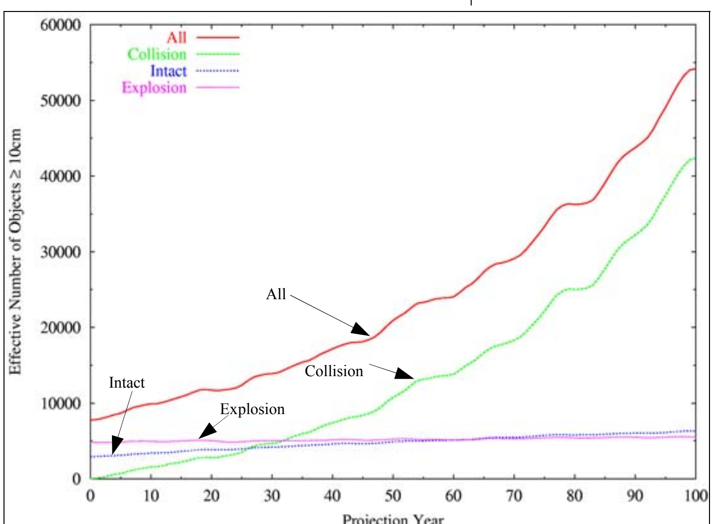

Figure 1. Growth of EVOLVE 4.1 LEO baseline populations.

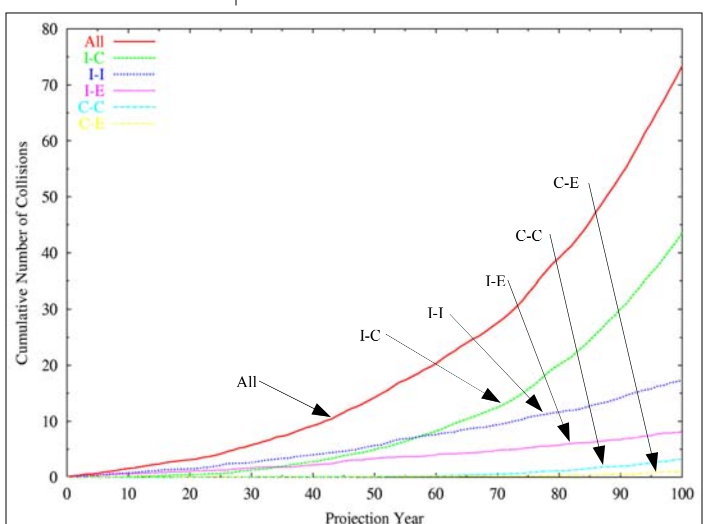

Figure 2. EVOLVE 4.1 baseline cumulative numbers of collisions in LEO.

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EVOLVE 4.1 Provides Information Regarding the Types of Debris in Orbit, Cont'd

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entering the mitigation phase. The operational satellites in each case are immediately replaced after eight and sixteen years. The 50-member constellations are populated in one year, but the 300-member constellation is launched in sets of 100 over three years. Results of the eight cases show that abandoning the large (300-member) constellation has the most significant affect on the debris environment. Table 2 shows the roughly 75% increase in intact-on-intact collisions when comparing cases 6 and 8 with all the other cases. Intact-on-collision fragment collisions increase 65% in case 8 and 90% in case 6. In all cases the intact-on-collision fragment events dominate the collision rate after 100 years.

Over the years, EVOLVE has proved to be a useful and versatile tool in the study of the generation and growth of orbital debris. The most recent upgrades, termed EVOLVE 4.1, have led to a more detailed understanding of future growth in the debris environment under specified conditions. Specific systems, such as large satellite constellations in LEO, are treated with EVOLVE 4.1 and shown to require special care in mitigation planning. Super-LEO collection orbits provide a ΔV savings when compared with the strict deorbit option, and yield only a small increase in collision rate within the collection altitude range.

It is an accepted fact within the orbital debris community that both explosion suppression and some form of active mitigation are needed to significantly prevent the exponential growth of orbital debris. But EVOLVE 4.1 also indicates that the 10-cm and larger collision fragment population will overtake that of intacts within this century. It also predicts the dominance of intact-on-collision fragment collisions if no mitigation is performed. This has not been previously noted. The simulations also suggest that collisions between collision fragments will not be contribute significantly to the LEO debris population this century.

Constellation Parameters				Cumulative Number of Collision Events		
Case	Alt (km)	# Sats.	Disposal	I-I	I-C	I-E
1	800	50	deorbit	16.1	40.7	5.5
2	800	50	abandon	17.4	41.1	5.4
3	1400	50	deorbit	16.2	42.5	5.6
4	1400	50	abandon	16.8	39.6	6.4
5	800	300	deorbit	17.2	39.4	5.0
6	800	300	abandon	30.2	78.6	6.3
7	1400	300	deorbit	18.8	42.5	5.5
8	1400	300	abandon	29.0	67.0	7.3

Table 2. Constellation disposal cases and EVOLVE 4.1 100-yr projection results (calculated values are the average of 30 Monte Carlo runs).

References

1. *NSS 1740.14, NASA Safety Standard, Guidelines and Assessment Procedures for Limiting Orbital Debris*, Office of Safety and Mission Assurance, Washington, D.C., August 1995.
2. Rossi, A., "Energetic cost and viability of the proposed space debris mitigation measures, AAS 01-118," AAS/AIAA Space Flight Mechanics Meeting, Santa Barbara, CA., 11-14 February 2001. ❖

The Critical Density Theory as Analyzed by EVOLVE

P. Krisko

The critical density theory refers to a condition in low Earth orbit (LEO) in which, given a constant intact population, the rate of increase of objects due to random collisions just balances the rate of decrease due to atmospheric decay. If the population is below critical density it will tend to a lower equilibrium since the decay will be dominant over the generation process. If above, it will tend to a higher equilibrium as the fragments grind to smaller pieces, which will remain in the environment but will not be effective colliders. The condition for higher equilibrium is further categorized as unstable or runaway, depending on whether that new equilibrium is finite or infinite, respectively.[1] This theory has been studied previously with particle-in-box type models, which are well suited for the extremely long-term projections required (+1000 years). Recent upgrades to the long-term debris simulation model EVOLVE make it feasible to pursue the study of critical density phenomenon now (see 'EVOLVE 4.1 Provides Information Regarding the Types of Debris in Orbit' this edition). The EVOLVE results show general agreement with these past analyses. The advantage of using EVOLVE here is two-fold. First, the model implements the latest data-derived breakup model thus eliminating the simplifying assumptions used in the earlier models. Second, it explicitly applies mitigation procedures directly to the EVOLVE projected

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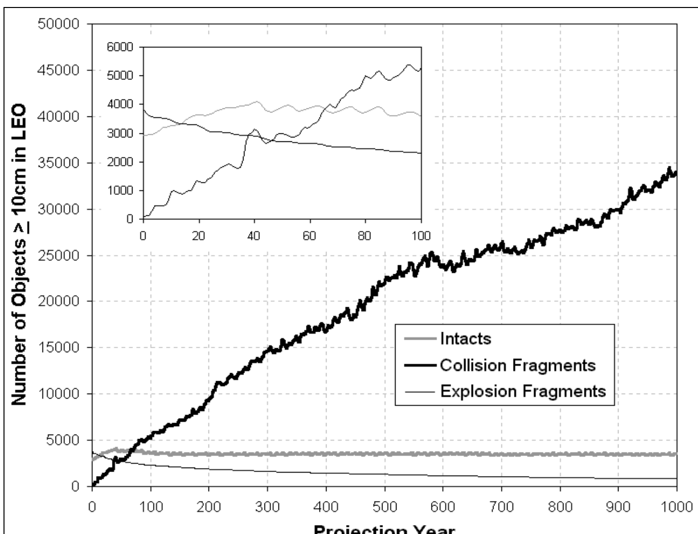

Figure 1. EVOLVE 1000-yr projected environment with 100% explosion suppression and a 25-yr deorbit rule applied.

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The Critical Density Theory as Analyzed by EVOLVE

(Continued from page 7)

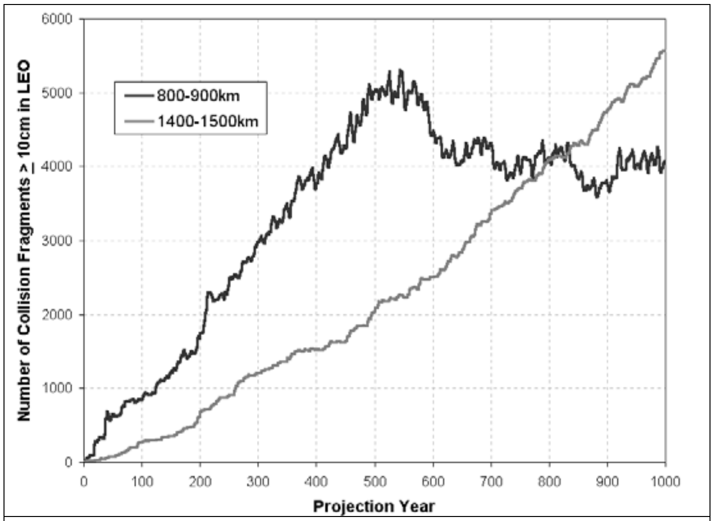

Figure 2. Major LEO altitude regions of growth of collision debris.

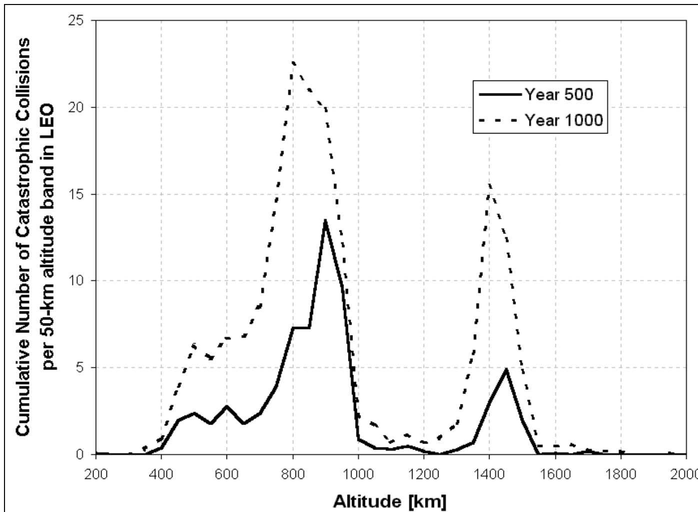

Figure 3. Catastrophic collision activity as a function of altitude and time.

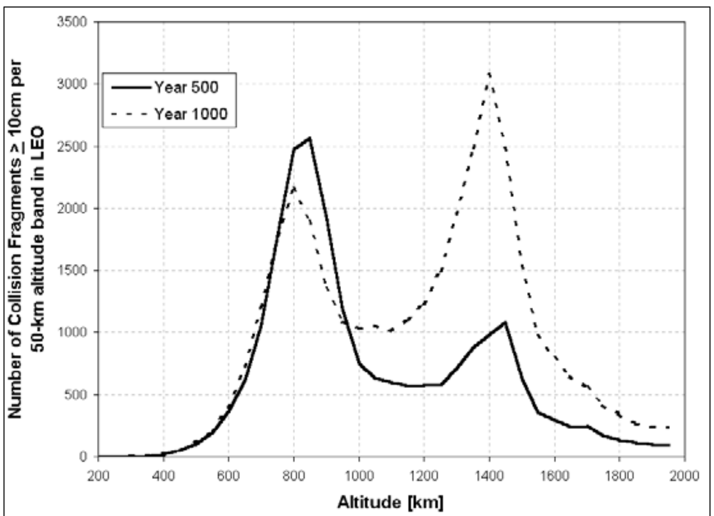

Figure 4. Collision debris as a function of altitude and time.

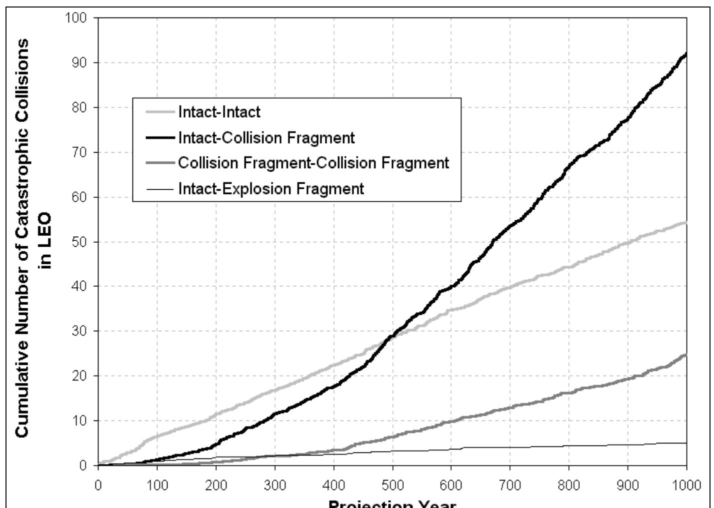

Figure 5. Cumulative number of catastrophic collisions categorized by the four major collider combinations.

environment allowing the analyst to easily test future scenarios.

The case presented here is that of a strict application of NASA's currently accepted mitigation standards (i.e., a 25-year deorbit rule with a 100% explosion suppression for all intacts). The resulting EVOLVE-generated LEO environmental growth for 1000 years is shown in Figure 1. Even with mitigation the collision fragments overtake intacts and explosion fragments within 100 years. The collision fragments appear to be in an unstable state moving to a higher, but finite, equilibrium until about 600 years into the projection period when they begin to exhibit the exponential growth of a runaway state. This behavior, noted in the previous studies is further analyzed with EVOLVE in Figures 2 through 5.

Figure 2 displays the collision debris growth in two important altitude bands, 800km –900km and 1400km – 1500km. Here it is shown that these low-altitude and high-altitude regions are uncoupled, with low altitudes being unstable and high altitudes being in a runaway state. Interestingly, it is the low-altitudes that dominate the collisional activity over the projection period (Figure 3). The explanation for this apparent contradiction in activity is in the behavior of the collision fragments found within the two regions. Figure 4, a plot of collision fragments vs. altitude for two projection times, shows that the growth of fragments in the high altitudes overtakes that of low altitudes over the projection period.

The high-altitude regions dominate the runaway, even though fewer collisions actually occur there because collision fragments generated within higher altitudes of LEO stay within the region for a very long time, on the order of thousands of years. This condition, which is due to the near absence of atmospheric decay, re-

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Project Reviews

The Critical Density Theory as Analyzed by EVOLVE, Cont'd

(Continued from page 8)
sults in a runaway state (exponential growth of the fragment population) as long as the intact population feeds the growth by remaining steady. Within the lower altitudes the high collision rate is mitigated by atmospheric decay, which depletes the region of fragments on a time scale of hundreds of years.

The dominant collision parents play to definitive role in the runaway and are also a function of time. As displayed in Figure 5, intact-on-intact collisions give way to intact-on-collision fragment collisions about half way into the projection period. This coincides with the emerging dominance of the high-altitude runaway region. Long-term dominance of intact-on-fragment events is also noted in previous particle-in-box model studies, where the explosive growth of debris is attributed to these intact-fragment collisions. In addition, EVOLVE demonstrates a non-trivial role for the collision fragment-on-collision fragment events in Figure 5. Fragments resulting from this type of interaction represent another exponentially increasing population as long as the intact population is forced to remain constant.

This study is, of course, academic. It is not anticipated that an intact population will purposefully be kept steady for 1000 years. But it's purpose here is to illustrate the utility of EVOLVE, an orbital debris simulation model, in the analysis of the critical density phenomenon.

References

1. Kessler D., "Critical Density of Spacecraft in Low Earth Orbit: Using Fragmentation Data to Evaluate the Stability of the Orbital Debris Environment", JSC-28949, LMSMSS-33303, February 2000. ❖

Abstracts

Determining the Material Type of Man-Made Orbiting Objects Using Low Resolution Reflectance Spectroscopy
46th Meeting of The International Society for Optical Engineering (SPIE)
San Diego, California 29 July—3 August 2001

K. Jorgensen, J. Africano, E. Stansbery, P. Kervin, K. Hamada

The purpose of this research is to improve the knowledge of the physical properties of orbital debris, specifically the material type. The physical characteristics of debris are taken into consideration in the environment models, the building of shields, and provide base work for future studies. One of the physical characteristics that is not measured currently is the material type but is assumed when used in modeling. Combining the use of the fast-tracking United States Air Force Research Laboratory (AFRL) telescopes with a common astronomical technique, spectroscopy, and NASA resources was a natural step toward determining the material type of orbiting objects remotely.

Each material type has a specific reflectance spectrum due to its composition. An extensive laboratory study has already been conducted on the reflectance spectra of common spacecraft materials. The material type of orbital debris in space would be identified by comparing absorption features of its spectra to that of laboratory spectra. This study will begin with measurements of catalogued objects with known compositions in order to examine the validity of the process.

Currently operating at the AFRL Maui Optical Site (AMOS) is a 1.6-meter telescope designed to track fast moving objects like those found in lower Earth orbit (LEO). Using the spectral range of 6500 – 8000 angstroms, researchers can separate materials into classification ranges. Within the above range, aluminum shows a strong absorption feature that would be apparent in the slopes of the reflectances. Most plastics and metals are consistently increasing in reflectances throughout this region. The spectrograph used on this telescope yields a three-angstrom resolution, large enough to see the features mentioned and thereby determining the material type of the object.

Approximately, 100 LEO objects were observed for the first stage of this project. Each object was observed a minimum of three times depending on the orbit and inclination of the object in question. NASA researchers supplied a list of possible targets to observe. The list consisted of catalogued objects both satellites and debris, concentrating on objects with homogenous materials, in both LEO and GEO. The results of the study are presented herein. ❖

The Optical Space Debris Measurement Program at NASA
The 2001 AMOS Technical Conference
Maui, Hawaii 10-14 September 2001

E. Stansbery, J. Africano, K. Jarvis, K. Jorgensen, T. Hebert, M. Mulrooney, T. Thumm, P. Kervin

NASA/Johnson Space Center has been studying the orbital debris environment for more than 20 years. In 1988, NASA undertook a comprehensive radar measurement program with the goal of characterizing the low earth orbit environment to 1 cm debris diameter. Key to the success of this program was the development of the Size Estimation Model (SEM). The SEM is an empirically derived model which converts radar cross section to physical debris size based on controlled radar measurements of debris from ground hypervelocity impact tests. In the early 1990's the U.S. Air Force conducted tests that provided anecdotal evidence that some optically bright debris pieces were not being detected by UHF (ultra high frequency) radars in the Space Surveillance Network. NASA has begun a measurement campaign to determine how large the class of optically bright and radar dim objects is. Not only is NASA routinely collecting data from its Liquid Mirror Telescope (LMT), it has begun a program to infer size from optical brightness using the radiometer installed on the 3.67 m Advanced Electro-Optical System (AEOS) telescope. NASA has also undertaken spectrographic studies of debris pieces in an effort to infer material properties. ❖

Abstracts

Using AMOS Telescope for Low Resolution Spectroscopy to Determine the Material Type of LEO and GEO Objects
The 2001 AMOS Technical Conference
Maui, Hawaii 10-14 September 2001

K. Jorgensen, J. Africano, K. Hamada, P. Sydney, E. Stansbery, P. Kervin, D. Nishimoto, J. Okaba, T. Thumm, and K. Jarvis

The physical characteristics of debris are taken into consideration in the environment models, the building of shields, and provide base work for future studies. Some of these characteristics are assumed currently, including material type. Using low resolution spectroscopy, researchers have determined the material type of man-made orbiting objects in both lower Earth orbits (LEO) and geosynchronous Earth orbits (GEO).

By comparing absorption features of spectra collected on the 1.6- and 3.67-meter telescopes at AFRL Maui Optical Site (AMOS) with a laboratory database of spacecraft material spectra, the material type of known objects was determined. Using the spectral range of 3500 – 9000 angstroms, researchers can separate materials into classification ranges. Within the above range, aluminum shows a strong absorption feature that would be apparent in the slopes of the reflectances. Most plastics and metals are increasing consistently in reflectances throughout this region. The color of paints and plastics show absorption features in the visible region of the spectrum. The spectrograph used on the telescopes yields a three-angstrom resolution, large enough to see the features mentioned and thereby determining the material type of the object.

NASS (NASA AMOS Spectral Study) began observations in May 2001, with eight nights of data collection. The objects were observed a minimum of three times constrained by the orbit and inclination of the object. NASA researchers supplied a list of possible targets to observe. The list consisted of catalogued objects both satellites and debris (approximately 100 objects), concentrating on objects with homogenous materials such as rocket bodies, in both LEO and GEO. Twenty-two of the objects were observed with both the red and blue filter. AMOS supplied spectral data of the objects corrected for background and the atmosphere. Reduction of the data was completed at NASA JSC using Specpr, an in-house program supplied by the United States Geological Survey (USGS). The results of the study are presented herein. ❖

Evaluation Of Orbital Debris Mitigation Practices Using EVOLVE 4.1
52nd International Astronautical Congress
Toulouse, France 1-5 October 2001

J. Opiela, P. Krisko

Recent upgrades to NASA's long-term orbital debris environment simulation model, EVOLVE, have been implemented this year. These have led to a re-evaluation and extension of studies of debris mitigation measures that are currently endorsed by NASA. This report highlights recent results of these studies. Included here are comparative evaluations of different LEO decay lifetimes, the effect of satellite constellations on the LEO debris environment, and a look at the general utility of collection/disposal orbits in LEO. The studies show how current and proposed launch traffic and mitigation procedures may affect the debris environment. It is made clear that as new issues or possible standards arise, their long-term effects may be tested using the EVOLVE model. ❖

Optical Observations of Geosynchronous Debris
52nd International Astronautical Congress
Toulouse, France 1-5 October 2001

K. Jorgensen, P. Seitzer, R. Smith, J. Africano, D. Monet, E. Stansbery, M. Matney, H. Harris

An optical survey has been started in an effort to characterize the debris population that could endanger operational geostationary satellites. The survey is designed to cover a wide range in orbital longitude, meanwhile encompassing the smallest debris population size as possible. The majority of the observations are being collected using the University of Michigan's 0.6/0.9-m Schmidt telescope at Cerro Tololo, Chile, which is a wide-field ground-based optical telescope equipped with a Charged Coupled Device (CCD) detector. The justification for such a survey, the designs of the survey observing and reduction strategies, and to what types of debris the survey should be sensitive are included herein. Initial results from the first season of observing will be shown. ❖

Observational Results Of NASA's Liquid Mirror Telescope
52nd International Astronautical Congress
Toulouse, France 1-5 October 2001

K. Jarvis, T. Hebert, K. Jorgensen, T. Thumm, M. Matney, J. Africano, M. Mulrooney, and E. Stansbery

NASA has been analyzing data collected by their 3-meter zenith staring liquid mirror telescope (LMT), located in Cloudcroft, New Mexico. Data collection is focused on the LEO debris environment. Collection of data first began in April 1996. Results of new data gathered in 2000 and 2001 will be presented and compared with previous data. Analysis of uncorrelated and catalogued objects include absolute magnitude with inferred size, inclination, altitude, and other derivable information. Using these data it is possible to identify debris families based on inclination and altitude. Improvements are being made in size estimations of debris objects. A clearer understanding exists of observational biases, including meteor contamination in the data. An effort is ongoing to improve the calculated fluxes of LMT observations for comparison with calculated radar fluxes. This will allow for improved modeling of the orbital debris environment and may contribute to improving propagation models of the debris environment. ❖

Abstracts

Latest Revisions to the NASA Debris Assessment Software (DAS)
52nd International Astronautical Congress
Toulouse, France 1-5 October 2001

R. O'Hara, M. Matney, M. Jansen, P. Anz-Meador

The Debris Assessment Software (DAS) was developed as a tool to assist NASA program offices in performing orbital debris assessments, as required by the NASA Safety Standard 1740.14. The software is structured in the same manner as the safety standard, helping to ensure a more complete assessment and compliance with the guidelines. It is organized into nine areas: Assessment of Guidelines, Analysis of Debris Released During Normal Operations, Analysis of Accidental Explosions/ Intentional Breakups, Analysis of Debris Generated by On-Orbit Collisions, Analysis of Postmission Disposal of Space Structures, Analysis of Debris Reentry Risk after Postmission Disposal, Science/Engineering Utilities, Data and Screen Management Utilities, and User Help. DAS was designed to provide a quick, conservative approach to making the necessary calculations for determining compliance to the NASA safety guidelines. In particular, DAS has been widely used to perform first cut reentry analyses for missions that are planning atmospheric reentry as the end of mission disposal option. DAS is a valuable tool that also creates results tables and plots, which can be included in the debris assessment report required for each mission. More recent versions of DAS have also provided several improvements, making the software easier to use and providing more functionality to the user. ❖

Trends And Options In The Disposal Of Launch Vehicle Orbital Stages
52nd International Astronautical Congress
Toulouse, France 1-5 October 2001

N. Johnson

An increasing number of agencies and organizations around the world provide guidelines for the disposal of launch vehicle stages placed in Earth orbit. The limitation of orbital lifetime following the satellite delivery mission, particularly in low Earth orbit, is viewed as one of the most important space debris mitigation measures. For higher altitude missions, orbital stages may be maneuvered into more rapidly decaying orbits or may be left in longer-term disposal orbits. This paper summarizes the recent disposal practices of all launch vehicle types and evaluates their compliance with existing national standards. Although the owners and operators of some satellite systems, e.g., Iridium and Globalstar, have levied orbital stage disposal requirements on launch service providers, in general, insufficient attention and communication is given to this topic. Sun-synchronous and geosynchronous missions may pose some of the most difficult challenges for the responsible disposal of orbital stages. A variety of disposal options are normally available, some of which may even influence the design of the spacecraft to be deployed. Also at issue is whether normal launch vehicle propellant reserves can be relied upon for postmission disposal of orbital stages. ❖

Meeting Report

46th Meeting of The International Society for Optical Engineering (SPIE)
San Diego, California 29 July—3 August 2001

The technical emphasis of the International Symposium on Optical Science and Technology was to create global forums that provide interaction for members of the optics and photonics communities, who gather to discuss the practical science, engineering, materials, and applications of optics, electro-optics, optoelectronics, and photonics technologies. This symposium contained 84 conferences covering the technology areas of Lens and Optical System Design, Photonic Materials, Devices, and Circuits, Image Analysis and Communications, Radiation Technology, and Remote Sensing.

Papers on orbital debris were presented under the Remote Sensing heading and the Dual-Use Technologies for Space Surveillance and Assessments II subheading. Within the subheading, two specific sections dealt with orbital debris: Asteroids and Debris Observations and Multicolor Observations. In the first session, Jennifer Evans spoke regarding the LINEAR system performance analysis, which is taking place at MIT Lincoln Labs. Jennifer Patience from Lawrence Livermore National Lab, presented work on high-resolution imaging with AEOS on Maui. Following that talk, John Africano, from Boeing, gave a presentation on the subject of deep-space satellite observations using the near-Earth asteroid-tracking (NEAT) camera at AMOS (Maui). The multicolor observations session included five talks pertaining to satellite or material type identification. Tamara Payne from the Schafer Corporation discussed the color photometry of geosynchronous satellites using the SILC filters. L.H. Sverdrup of Trex Enterprises conducted a discussion of measurements of geostationary satellite spectral brightness due to solar. Kris Hamada, of Boeing, presented work dealing with spectroscopic observations of space objects and phenomena using Spica and Kala at AMOS. D.J. Sanchez of the Schafer Corporation presented photopolarimetric measurements made at the Starfire optical range for situational awareness applications from the 27 November through 1 December 2000. Kira Jorgensen, NASA JSC, regarding determining the material type of man-made orbiting objects using low-resolution reflectance spectroscopy, gave the final paper of the session. ❖

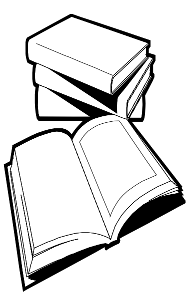
INTERNATIONAL SPACE MISSIONS

July - Sept 2001

International Designator	Payloads	Country/ Organization	Perigee (KM)	Apogee (KM)	Inclination (DEG)	Earth Orbital Rocket Bodies	Other Cataloged Debris
2001-027A	MAP	USA	EN ROUTE TO OP. ORBIT			1	0
2001-028A	STS 104	USA	378	395	51.6	0	0
2001-029A	ARTEMIS	ESA	30899	30955	0.8	1	1
2001-029B	B-SAT 2B	JAPAN	603	17458	3.0		
2001-030A	MOLNIYA 3-51	RUSSIA	500	39858	62.9	2	2
2001-031A	GOES 12	USA	35771	35801	0.3	1	0
2001-032A	CORONAS F	RUSSIA	485	530	82.5	1	4
2001-033A	USA 159	USA	ELEMENTS UNAVAILABLE			3	1
2001-034A	GENESIS	USA	HELIOCENTRIC			2	0
2001-035A	STS 105	USA	373	402	51.6	0	0
2001-035B	SIMPLESAT 01	USA	384	401	51.6		
2001-036A	PROGRESS M-45	RUSSIA	390	400	51.6	1	0
2001-037A	COSMOS 2379	RUSSIA	35730	35891	2.4	2	5
2001-038A	LRE	JAPAN	259	36147	28.5	1	0
2001-039A	INTELSAT 902	ITSO	35644	35929	0.1	1	0
2001-040A	USA 160	USA	ELEMENTS UNAVAILABLE			1	0
2001-041A	PROGRESS DC-1	RUSSIA	329	335	51.6	1	0
2001-042A	ATLANTIC BIRD 2	EUTELSAT	35750	35791	0.1	1	0
2001-043A	STARSHINE 3	USA	468	475	67.1		
2001-043B	PICOSAT 9	USA	789	799	67.0	1	0
2001-043C	PCSAT	USA	791	801	67.1		
2001-043D	SAPPHIRE	USA	793	802	67.1		

The History of On-Orbit Satellite Fragmentations, 12th Edition

Now Available on the NASA Johnson Space Center Orbital Debris Website



http://www.orbitaldebris.jsc.nasa.gov/measure/sat_frag_update.html.

ORBITAL BOX SCORE

(as of 26 September 2001, as catalogued by US SPACE COMMAND)

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	32	325	357
CIS	1331	2540	3871
ESA	30	266	296
INDIA	20	6	26
JAPAN	69	47	116
US	945	2880	3825
OTHER	314	28	342
TOTAL	2741	6092	8833

NASA's Liquid Mirror Telescope (LMT) is located in Cloudcroft, New Mexico. This telescope measures the population of small orbital debris particles.

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