The Orbital Debris Quarterly News

Volume 9, Issue 3

July 2005

A publication of

The NASA Orbital Debris Program Office

at

Johnson Space Center
Houston, TX, USA

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Space Debris Mitigation Guidelines at the UN

During the recent annual meeting of the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS) in Vienna, Austria, the Space Debris Working Group of the Scientific and Technical Subcommittee (STSC) assembled to begin drafting a set of space debris mitigation guidelines. Proposed outlines and text by the United States, Japan, India, and western European countries were used as a foundation for developing a consensus set of guidelines, based upon the space debris mitigation guidelines of the Inter-Agency Space Debris Coordination Committee (*Orbital Debris Quarterly News*, 9-2, p. 2).

Representatives from over a dozen member States and the European Space Agency, which holds an official Observer status, participated in the session. The U.S. drafting team included personnel from the NASA Orbital Debris Program Office, the Department of State, and the Department of Defense.

By the end of the four-day effort (13-16 June), a consolidated set of draft space debris mitigation guidelines was produced. All member States of COPUOS and especially those of the STSC are encouraged to review the draft guidelines before the next meeting of the working group in February 2006. The STSC space debris work plan envisions the adoption of finalized space debris mitigation guidelines by 2007. ◆

Recent Satellite Breakups

Four satellite fragmentation events were recorded during the second quarter of 2005, including the breakups of two Proton Block DM auxiliary motors, becoming the 32nd and 33rd events for this class overall. The first recent event, on 23 April 2005, involved an ullage motor used by the fourth stage of a Russian Proton launch vehicle for the Cosmos 2224 mission launched in late 1992. The International Designator of the parent object is 1992-88F, with corresponding U.S. Satellite Number 22274. At the time of the event the 55-kg motor was in a highly elliptical orbit of approximately 200 km by 21,140 km, with an inclination of 46.7º. No debris were officially cataloged, although over a dozen fragments were initially detected by the U.S. Space Surveillance Network following the breakup and preliminary tracking data was developed for six.

The second Proton Block DM auxiliary motor fragmentation occurred on 1 June 2005 and was associated with the Cosmos 2392 mission launched in mid-2002. The parent object, also 55 kg, has an International Designator of 2002-37E with a corresponding U.S. Satellite Number of 27474. The object was in an orbit of only 255 km by 835 km, at an inclination of 63.7º at the time of the event. As many as 40 objects were initially seen, 5 surviving long enough to be cataloged (U.S. Satellite Numbers 28689 – 28693). Due to the relatively low perigees, all of the debris were probably very short-lived. Just over four weeks later, on 30 June, Satellite Number 27474 experienced another fragmentation. This time more than 50 debris were cataloged prior to decay. Interestingly, the other auxiliary motor (International Designator 2002-37F, U.S. Satellite Number 27475) for the Cosmos 2392 mission experienced a fragmentation in October 2004 (*Orbital Debris Quarterly News*, 9-1, p. 2). The fragmentations of 2002-37E and 2002-37F are the only known events for Proton Block DM auxiliary motors that were launched after 1996.

A third satellite fragmentation occurred on 21 June 2005. Meteor 2-17 (International Designator 1988-5A, U.S. Satellite Number 18820) generated one small piece of debris in an apparent low-energy incident, normally referred to as an anomalous event. The piece exhibited a very low separation velocity from the Russian spacecraft, which was in an orbit of approximately 930 km by 960 km, with inclination near 82.5º at the time of the event.

The fourth event might have been the result of a collision between a rocket body and a small, uncataloged object. On 22 June 2005, a Cosmos 3M rocket body (International Designator 1990-17B, U.S. Satellite Number 20509) released a single piece of debris (International Designator 1990-017C, U.S. Satellite Number 28706) with a moderate velocity. The rocket body had been in an orbit of 950 km by 1015 km with an inclination of 83º. The energized event placed the fragmentation debris in an orbit more than 40 km lower at perigee and 20 km higher at apogee than the parent object, as well as giving it a slight inclination increase. The event was possibly caused by a collision between the rocket body and a small piece of orbital debris or a meteoroid (see *Orbital Debris Quarterly News*, 7-3, p. 1). ◆

PROJECT REVIEWS

SBRAM Upgrade to Version 2.0

P. KRISKO, M. MATNEY, M. HORSTMAN, D. WHITLOCK, & E. HILLARY

The NASA Satellite Breakup Risk Analysis Model (SBRAM) is an in-house program which provides near-term risk estimates to selected low Earth orbit (LEO) assets in the days-to-weeks following satellite explosive breakup events (*Orbital Debris Quarterly News*, 3-3, p. 7). Its primary use has been in safety assessments for the International Space Station (ISS) and Space Shuttle missions in the period immediately after an accidental satellite explosion, when the breakup fragments still form a cloud of a density distinct from the background debris environment. Upgrades to the model (SBRAM 2.0) are in progress. These include the NASA JSC current standard explosive breakup and propagation models, and an updated GUI and input/output file structure. The impetus of these changes is the slated delivery of the SBRAM 2.0 package to the Mission Operations Directorate of the Flight Design and Dynamics Division at NASA JSC.

Upgrades to the breakup and propagation process result in a state-of-the-art representation of the generation and decay of breakup fragments, and therefore, a more reliable estimate of the near-term collision risk to LEO assets from the debris cloud.

The improved orbital propagator, PROP3D, was developed for the long-term debris environment prediction code LEGEND in 2001. It updates five orbital elements (excluding true anomaly) per time step, given the perturbations of Earth gravity J_2, J_3, and J_4 zonal harmonics, solar and lunar gravity, Jacchia 77 atmosphere, and solar radiation pressure with Earth shadowing. PROP3D replaced the older THALES propagator which included only J_2 perturbations and Jacchia 77 atmosphere. Comparisons of actual evolution of orbits of chosen satellites in LEO, medium Earth orbit (MEO), and geosynchronous transfer orbit (GTO) to those predicted by PROP3D, have shown excellent agreement.

The advent of PROP3D was coupled with an update of the 2000 NASA breakup model. Estimated on-orbit fragment area-to-mass values in the breakup model are necessarily propagator dependent. Modeling the atmospheric decay of an object requires an ‘effective’ area-to-mass of the object, one that is compatible with the perturbation terms of the orbital propagator. The more thorough and accurate the perturbation terms of the propagator, the more closely the effective area-to-mass matches the actual average area-to-mass of the object. For the NASA breakup model update, actual decay profiles of tracked explosion fragments were fit to new effective area-to-mass values by propagating with PROP3D. Given the proven accuracy of PROP3D in previous testing, these area-to-mass values were noted to be close to the fragment true average area-to-mass values. From these data, semi-analytical area-to-mass functions of the NASA breakup model were re-derived.

Sample comparisons of SBRAM and SBRAM 2.0 collision event results show a similar activity between the models. Figures 1 and 2 display the total daily fluence values (collision probability per m^2 of ISS surface) for the first ten days after satellite explosion. The fragments in the case of Figure 1 resulted from the propulsion explosion of a 1000 kg rocket body in a 28^o inclined circular orbit at 360 km altitude (ISS altitude). The first day after the explosion

See SBRAM on page 9

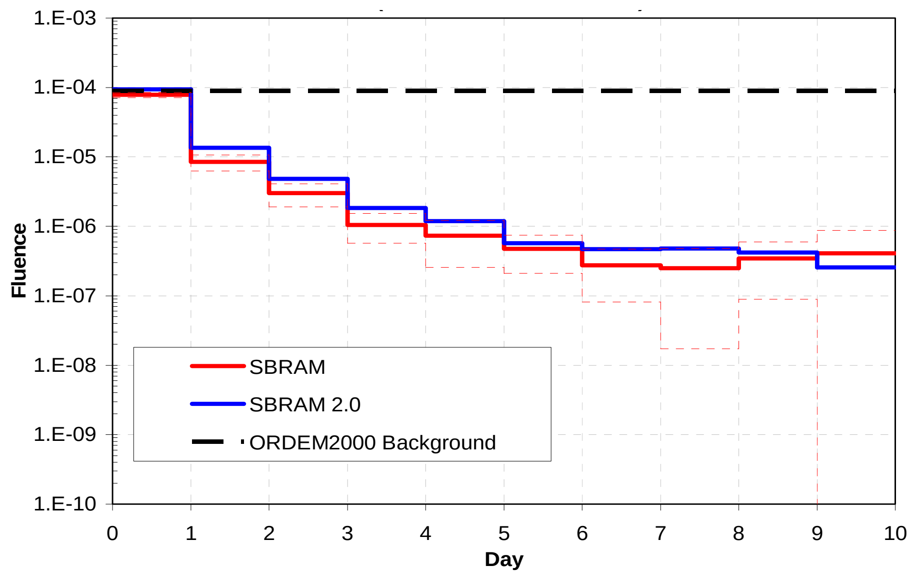

Figure 1. Total Daily Fluence on ISS from breakup at 360 km (10 Monte Carlo iterations).

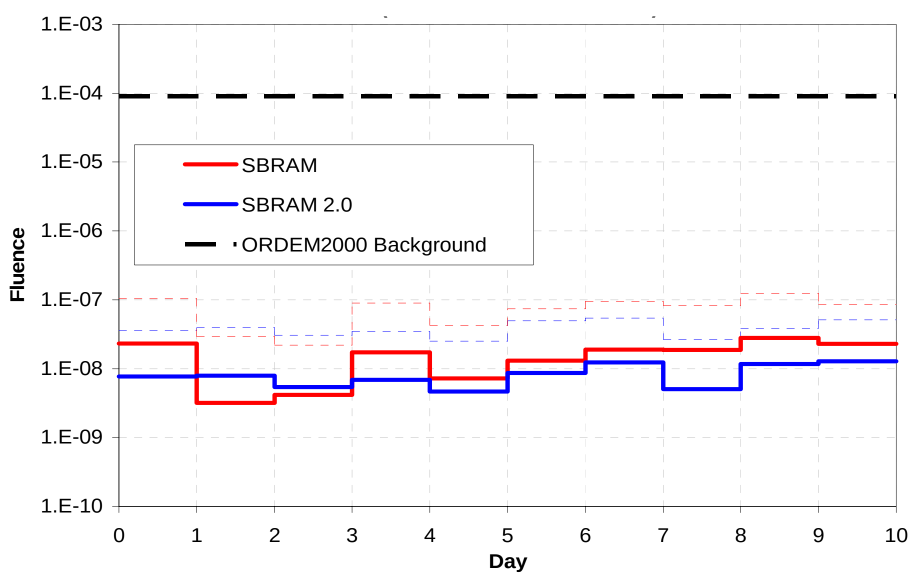

Figure 2. Total Daily Fluence on ISS from breakup at 900 km (200 Monte Carlo iterations).

The GEO Environment as Determined by the CDT: Inclination Distributions

E. BARKER, K. JARVIS, J. AFRICANO, K. ABERCROMBY, T. PARR-THUMM, M. MATNEY, & E. STANSBERY

Understanding the evolving debris environment is essential if the human race continues to venture into space. Of particular interest is the geosynchronous environment where satellites have been placed since the 1960s. This interest stems from the fact that debris in geosynchronous orbits (GEO) has the potential for collision with operational satellites due to the extremely long orbital lifetimes of both the debris and the satellites. The NASA CCD Debris Telescope (CDT), which was located at Cloudcroft, New Mexico, conducted systematic searches of the GEO environment to help characterize and determine the extent of the debris found in this volume of near-Earth space. The observations, carried out between January 1998 and December 2001 provided distributions in brightness, mean motion, inclination, range, and Right Ascension of Ascending Node (RAAN) of detected debris. Data reduction has been completed on the four years of survey data.[1] This article presents one aspect of the analysis of this sample of GEO environment. Many aspects of the CDT operation and orbital dynamics have counterparts in the Michigan Orbital DEbris Survey Telescope (MODEST) operations which are described in the article *Michigan Orbital Debris Survey Telescope (MODEST) Results* appearing in this issue.

The CDT system, designed specifically to search for orbital debris, used a wide field-of-view, utilizing a 32-cm Schmidt telescope equipped with a SITe 512 x 512 CCD camera. The large pixels (24 microns square or 12.5 arcseconds) provided a significant 1.7° x 1.7° field-of-view. The CDT was operated in a GEO stare mode reaching a limiting V magnitude of 17 which corresponds to a ~60 cm sphere (assuming a specular reflection and a 0.2 albedo).

The automated observing sequence consisted of a series of four exposures taken of approximately the same field. Each exposure was 20 seconds in duration with a 15 second "dead time" between exposures used to read out the CCD and to reposition the telescope. On average, 250 fields were collected per night, or 1000 individual images. The CDT used a search strategy optimized to collect data at low solar phase angle where objects should be brightest. By observing near the GEO belt, most uncontrolled objects will sooner or later pass through the field-of-view.

The CDT observed a strip of GEO space 8° tall, centered at –5° declination (the GEO belt as viewed from Cloudcroft). This observational strip either led or followed the Earth's shadow by about 10°. The actual length of the strip depended upon the length of the night and the elevation of the Earth's shadow. The search pattern started in the east and gradually moved to the west, tracking the Earth's shadow.

Calendar Year (CY)	# of Nights	On-sky hours	# of Detections (UPN)	# of CTs (UPN)	# of UCTs (UPN)
1998	58	~255	5765	4606	1159
1999	81	~530	5746	4829	917
2000	48	~255	3416	2983	433
2001	53	~380	3894	3307	587

Table 1. Observational Summary

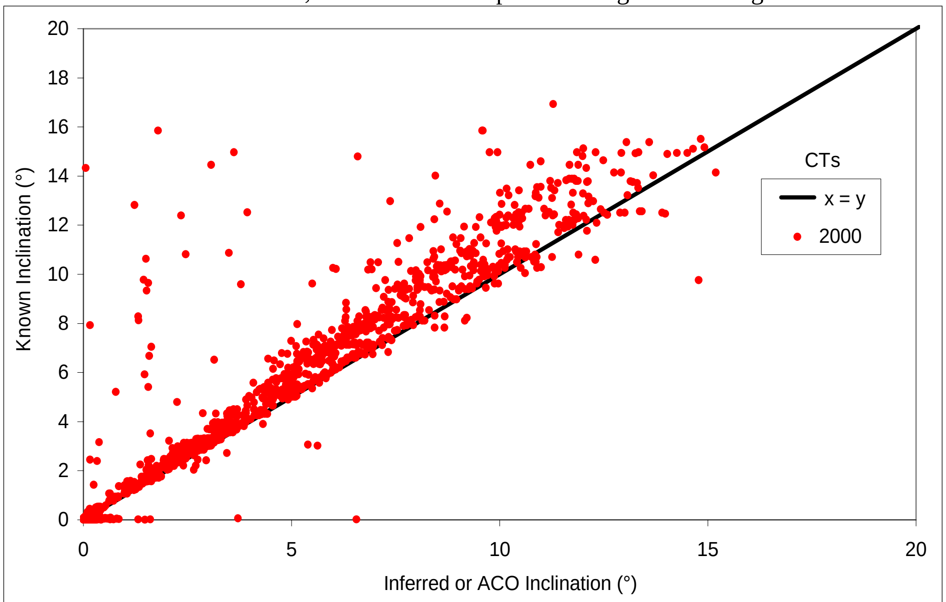

Figure 1. Known vs. ACO Inclinations for CTs observed in 2000.

The final data reduction software packages produced astrometric positions for each detection which were subsequently fitted under the assumption of a circular orbit (eccentricity = 0°) to produce inferred values for the inclination, range, mean motion, and RAAN. Using these assumed circular orbit (ACO) elements for both correlated targets (CTs) and uncorrelated targets (UCTs), we will define the dimensions of the near-GEO environment to be between 34,000 km and 40,000 km and 0° and 17° inclination. Approximately 50% of the detections during the four years of CDT observations were of targets having non-GEO orbital parameters. The non-GEO objects were primarily those with high inclinations (Molniya) and objects with large eccentricities that are in transition from low Earth orbits to GEO and above (supersynchronous and GEO transfer orbits (GTOs)). The scope of this article is limited to the subset of near-GEO observations and their inclination distributions.

Studies have shown that the orbits of uncontrolled GEO objects oscillate around the stable Laplacian plane, which has an inclination of 7.5° with respect to the equatorial plane. Numerous studies provide compelling arguments that most uncontrolled debris objects in GEO should be at inclinations less than or equal to 15°. The ~50 year period of this oscillation is dominated by the combined gravitational effects of the Earth's oblateness (J_2 term) and solar and lunar perturbations.

The four calendar years (CY) are summarized in Table 1 where the objects with U.S. Space Surveillance Network (SSN) numbers are denoted as CTs. Those objects without assigned SSN numbers are designated as UCTs. The detections are reported as unique per night (UPN) as all

Continued on page 4

Inclination Distributions

Continued from page 3

detections of the same object within one night were used in calculating the assumed circular orbit elements. UPN indicates that regardless of how many frames within a night an object appeared, it was counted only once. No attempts were made to link detections between nights.

Orbital elements determined under the assumption of a circular orbit can be compared with those elements determined by the SSN observations (TLEs). Since the UCTs have only ACO determined elements, there is a need to test the validity of the use of these inferred elements to define the distributions of UCTs.

Figure 1 demonstrates the lack of a perfect correlation between the inferred ACO and known inclinations. A similar bias is noted for all four years in that the ACO inclination is systematically smaller than the true inclination. Preliminary investigations into the cause of this bias and scatter above the x = y line show the magnitude of the inclination error is inversely related to the length of the orbital arc that was used to determine the circular orbital elements.

When we limited the yearly datasets to those detections with near-GEO orbital elements, we were able to calculate differences or errors introduced by assuming circular orbits. We can use these differences between the values of the known and ACO orbital parameters to assess the accuracy of the circular orbit assumption for the UCTs for which we have only ACO derived orbital parameters. The average error or inclination bias was about -0.3±1.1° which suggests utilizing the ACO values to interpret the inclination distribution of UCTs will not introduce large errors, but possibly systematic errors as shown in Figure 1.

Objects that were seen by the CDT on more than one night in an observing year are termed "repeaters." By understanding the causes behind repeaters we can better judge our percent chance of seeing objects based upon whatever biases may apply (*i.e.*, magnitude, orbital elements, etc.), thus enhancing our population modeling. Because no attempt was made to correlate UCTs between nights in the CDT program; we need to understand statistically how many of the UCTs are potentially repeat detections.

Since the orbital behavior of non-functioning spacecraft should have the same form as debris (within limits of the effects as related to area-to-mass ratios), we divided the CT population into two subsets: functioning (under active control) and non-functioning (no longer being station-kept) targets. CTs that were non-functional at the end of a calendar year were listed as non-functional for the entire year. It is a reasonable assumption that it will take a few months for a CT to become completely free from the station-keeping momentum changes and begin drifting only under the gravitational forces; however, a later study may consider these "transitional objects" in greater detail.

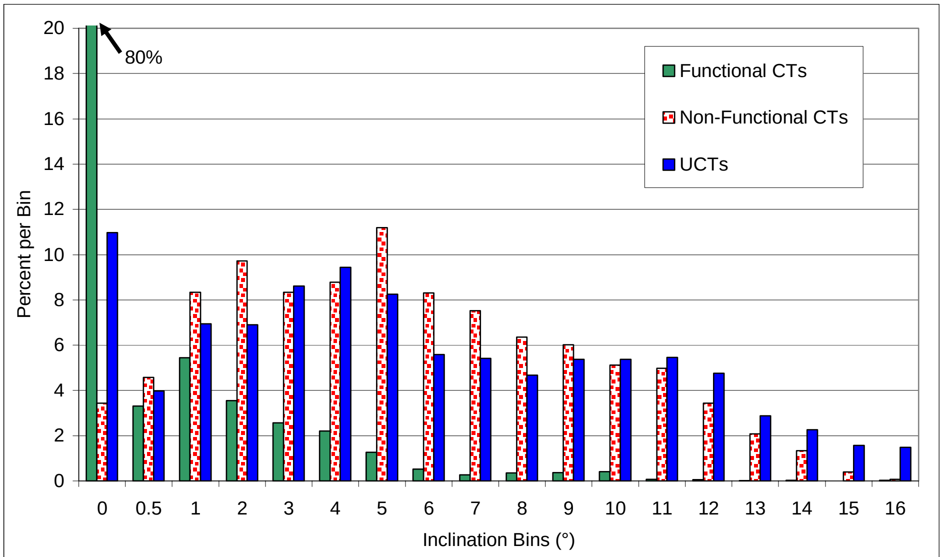

Figure 2. Inclination distributions for 2288 UCTs, 7747 functional and 2974 non-functional CTs observed within the GEO environment during 1998-2001. Each bar represents the percentage of each category in each inclination bin.

As noted previously, uncontrolled or non-functional CTs should drift to higher inclinations as they are perturbed by gravitational forces. They should reach a maximum of 15° before decreasing as part of their 50 year inclination oscillation. The non-functional and functional distributions of CTs are shown in Figure 2 for the four-year dataset.

Approximately 83% of the functional CTs had inclinations less than 1° and less than 1% of the functional CTs had inclinations above 5°, whereas the non-functional CTs had a broad distribution peaking between inclination of 2° and 10°.

The main CDT goal to determine the number (Unique per Year (UPY)) and distribution of UCTs in the GEO environment can be realized by noting that the UCTs in Figure 2 have a very similar inclination distribution to the non-functional CTs. The average number of repeats for a non-functional CT over the four year period is 5.5. If we apply this repeatability factor to the number of UCTs seen each year we find an average of 96 UPY UCTs. The average number of 96 UPY UCTs (within the limits of the CDT's sensitivity, *i.e.*, brighter than 17th magnitude) over the four year period is in excellent agreement with the statistically estimated number of 100 UPY UCTs in the 1999 data set[2].

All four years of CDT UCT data show similar distributions in inclination, eccentricity, RAAN, mean motion and magnitude, thereby indicating a general stability in the UCT environment between 1998 and 2002. The inclination distribution of non-functional CTs is similar to those seen for UCTs. The ratio of UPY UCTs to UPY non-functional CTs should be similar over the four year period. When presented in an angular momentum plot (see *MODEST* article), the UCTs and non-functional CTs showed the same amount of drift between calendar years which confirms they are both reacting to the same gravitational perturbations of their orbital planes.

1. Barker, E. et al., *The GEO Environment as Determined by the CDT between 1998 and 2002*, Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 2005 (ESA SP- in press).

2. Matney M. et al., *Extracting GEO Orbit Populations from Optical Surveys*, Proceedings of the 2002 AMOS Technical Conference, Maui, HI, 2002, p. 107-116. ◆

Michigan Orbital DEbris Survey Telescope (MODEST) Results

K. ABERCROMBY, P. SEITZER, T. PARR-THUMM, M. MATNEY, E. BARKER, & K. JARVIS

An optical survey for orbital debris at geosynchronous orbit (GEO) has been conducted with the University of Michigan's 0.6/0.9-m Schmidt telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile. The dark skies in Chile and the excellent seeing conditions at CTIO make it an ideal location for GEO debris survey work. The project, termed MODEST (Michigan Orbital DEbris Survey Telescope), has been collecting data since 2002. Using MODEST, one can observe orbital longitudes ranging from 25° west to 135° west covering most of the orbital slots assigned to the continental United States. A 2048 x 2048 SITe thinned, backside illuminated CCD is mounted on the telescope at the Newtonian focus. The CCD field-of-view is 1.3° x 1.3°, with 2.318 arc-second pixels.

This article covers 66 nights of observations from calendar years 2002 through 2005 that yielded 100 different field locations. The data stems mostly from 2002 where 30 nights of data were collected, while in 2003 15 nights, 2004 18 nights, and 2005 6 nights of data contribute to the total nights of observation. All of the data were collected and then reduced in the same fashion.

For each observational night, the system takes a 5-second exposure every 37.9 seconds at a constant right ascension and declination. A strip of sky 1.3° high by over 100° long is covered. The next night, the telescope is offset in location and the next strip of sky is scanned. Typically, over 700 images are obtained each night. An image shows space objects as dots while stars appear as streaks.

A typical GEO object will be seen in eight images and thus gives about five minutes of data. Objects have been detected with as little as 4 detections and as many as 12 detections using the automatic detection process. From these detections various observational parameters can be obtained. Using a circular orbit assumption, inclination, right ascension of ascending node (RAAN), and mean motion can be calculated. Visual and absolute magnitude are also calculated, using the surrounding catalog stars with known magnitudes. Using the catalog, one can compare the prediction position of an object with the calculated position and divide objects into categories of correlated targets (CTs) and uncorrelated targets (UCTs).

If one combines all four years of data, MODEST observed 1014 CTs (unique per night) and 401 UCTs (unique per night). All of these objects were manually verified by inspection to guard against false positives in the automatic detection and correlation software. No attempt has been made to remove duplicates from night to night, thus the statement of unique per night.

Differences or errors between orbital parameters determined from the assumption of circular orbits compared to catalog values for CTs are as follows. The standard deviation in inclination for all CTs is 0.78°. The standard deviation for RAAN is 2.4°. In addition to the orbital parameters, calculations of visual and absolute magnitude have been made. The CTs absolute magnitude peak is near 11 and the UCTs absolute magnitude peak is near 16-17. The falloff in sensitivity of the telescope keeps the absolute magnitude peak of the UCTs from being identified accurately. If one assumes an albedo of 0.20, an object with an absolute magnitude of 17 correlates to a size of ~ 60 cm.

Depending on the pointing of the telescope, the possible orbital planes in which an object (assuming e = 0) resides is shown in Figure 1 and are depicted by the gray colors. Detected objects are shown in either black for CTs or red for UCTs. The coverage is nearing completion but is still missing one segment from 5° inclination through 30° within the RAAN ranges of 250–300°. These observations have achieved complete coverage of the GEO ring.

The next observing run at MODEST is scheduled for July 2005 and will focus on obtaining the remaining areas in this figure. Figure 2 shows the same data but in polar form which is analogous to the orbit momentum axis. Again in this figure, the gray are the orbits one could have possibly seen, the black dots are CT detections, and the red circles are the UCT detections. The GEO ring is seen clearly in this figure starting at (0,0) and forming the outer ring. This figure also shows more objects in an inner ring and an investigation is under way to determine what is causing those objects to be in that orbit. Note that the UCT population is more randomly placed on this plot than the CT population.

See MODEST Results on page 9

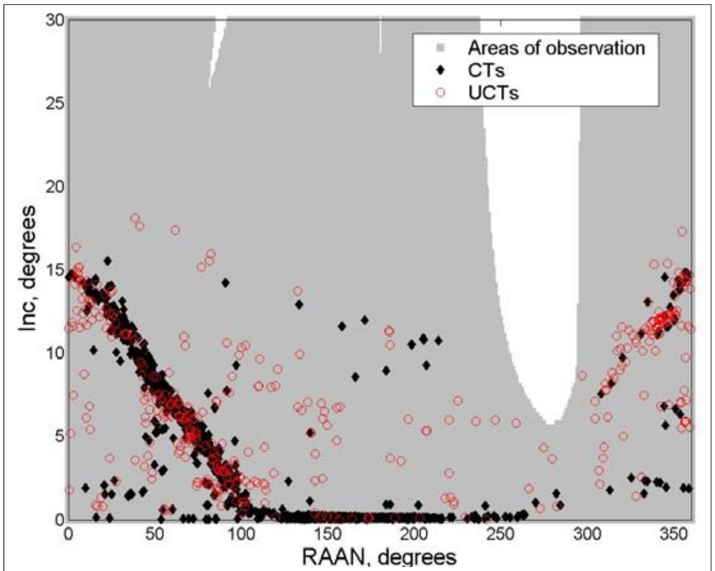

Figure 1. The Prediction Map for the four years of data using the telescope position data

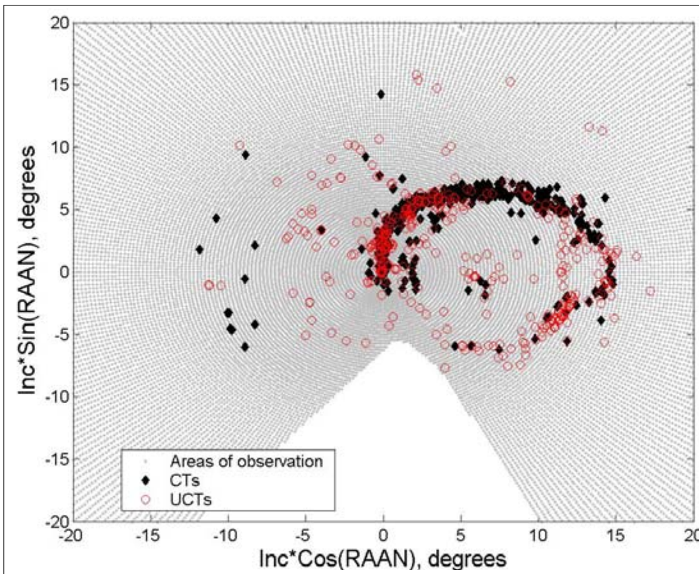

Figure 2. Polar Plot for the same data as seen in Figure 1.

A New Low-Velocity Satellite Impact Experiment

T. HANADA

Harada[1] and Goto[2] investigated low-velocity impact phenomena, applicable for geosynchronous orbit (GEO) collisions, through laboratory impact tests. They developed a low-velocity collision model in a similar manner to what had been done in the area of hypervelocity impacts. For hypervelocity impacts in low Earth orbit (LEO), a commonly referenced model is the NASA Standard Breakup Model[3]. It was based on several ground tests as well as one on-orbit collision.

Hanada[4] reanalyzed the low-velocity impact data obtained by Harada and Goto based on the method used in the NASA breakup model, and then compared the results with the NASA model. It was concluded that the NASA breakup model could be applied to low-velocity collisions with some simple modifications. Since the low-velocity impact tests conducted by Harada and Goto were considered non-catastrophic collisions, characterized primarily by fragmentation of the projectile and by crater or hole on the target, additional tests are needed to model low-velocity catastrophic collisions. The difference between a catastrophic and a non-catastrophic collision may be determined by the kinetic energy at impact to target mass ratio. According to the NASA breakup model, any impact with a ratio of 40 J/g or higher can be considered catastrophic.

To investigate the outcome of a low-velocity catastrophic collision, a new test was conducted recently at the Kyushu Institute of Technology. The target was a cylindrical-shaped micro satellite with a diameter of 14 cm and a height of 16 cm (see Figure 1). This micro satellite had four layers and one ceiling made of Carbon Fiber-Reinforced Plastics (CFRP) plates but no side panel. This micro satellite was fully functional with a Global Positioning System (GPS) device, a magnetic sensor, two Sun sensors, a thermal sensor, two gyro sensors, a memory card unit, two lithium-ion batteries, four micro computers, two DC-DC converters and communications devices. The total mass of the satellite was approximately 680 grams. The target satellite was hung from the vacuum chamber ceiling with wires. The inner walls of the vacuum chamber were covered with polystyrene foams to collect fragments scattered after impact without any further damages.

The projectile was a solid sphere made of aluminum alloy, A2017, with a diameter of 3 cm and a mass of 40 grams. The projectile was launched from a two-stage light gas gun. The impact speed measured before the projectile hit the target satellite was 1.35 km/s. As a result, the estimated kinetic energy at impact to the target mass ratio was 48 J/g. The target micro satellite was totally fragmented after the impact, consistent with the NASA model criterion for a catastrophic collision. Figure 2 shows the reconstructed main structure of the satellite after the impact. The projectile remained intact after the impact. Its mass after impact was 35.7 grams.

A total of 1568 fragments were collected from the vacuum chamber and analyzed individually. They accounted for about 79% of the target mass. Investigation on the fragment size distribution, area-to-mass ratio distribution, and size-to-area conversion equation are underway at the Kyushu University with collaboration of NASA JSC. Detailed results will be presented at the 56th International Astronautical Congress to be held in Fukuoka, Japan in October 2005.

1. Harada, S. *Experiments of Simulating Space Debris Impacts at Geostationary Orbit*, Kyushu University, B. Eng. Dissertation, Fukuoka, Japan, 1996.

2. Goto, K. *Dispersion Velocity Distribution Analysis of Fragments from Low-Velocity Impact*, Kyushu University, M. Eng. Dissertation, Fukuoka, Japan, 1997.

3. Johnson, N. L., P.H. Krisko, J.-C. Liou, and P.D. Anz-Meador. *NASA's New Breakup Model of EVOLVE 4.0*, Advances in Space Research, Vol. 28, No. 9, 2001, p.1377-1384.

4. Hanada, T. *Developing A Low-Velocity Collision Model Based on the NASA Standard Breakup Model 1998 Revision*, International Journal of Space Debris, Vol. 2, No. 4, 2000, p.1-15. ◆

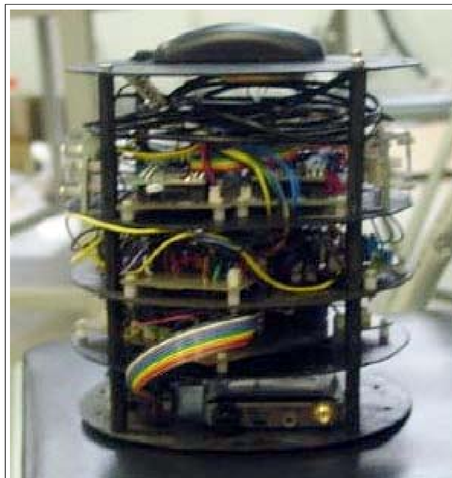

Figure 1. The micro satellite before the low-velocity impact.

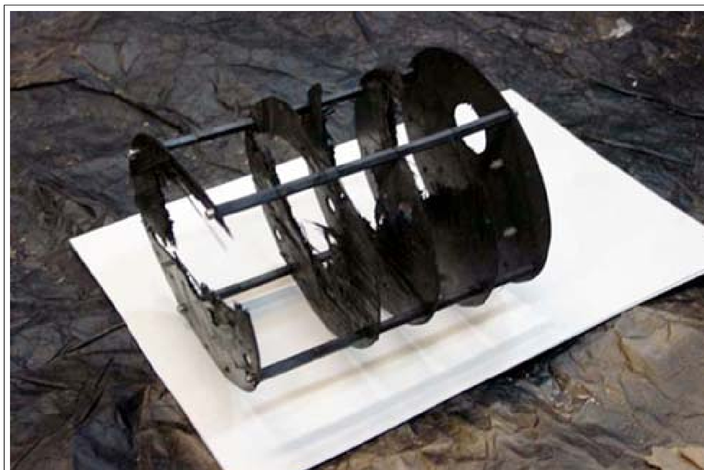

Figure 2. Reassembled micro satellite structure after the experiment. The impact direction was from right to left.

ABSTRACTS FROM THE NASA ORBITAL DEBRIS PROGRAM OFFICE

Fourth European Conference on Space Debris, 18-20 April 2005, Darmstadt, Germany

Additional Abstracts from the Orbital Debris Program Office for this Conference appeared in the April 2005 Issue of the Orbital Debris Quarterly News

Orbital Debris Research in the U.S.

N. JOHNSON

Considerations in the U.S. of the hazards of orbital debris date back to the 1960s, and formal research into the origins and character of the orbital debris population, as well as the means to mitigate its growth, has now been underway for more than 25 years. From a fledgling endeavor at the NASA Johnson Space Center, orbital debris research in the U.S. now encompasses activities by multiple U.S. Government agencies and academia, utilizing a wide variety of terrestrial- and space-based sensors and taking advantage of the examinations of satellite surfaces, to measure, to model, and to mitigate the current and potential future orbital debris population. These labors have led to the development of national orbital debris mitigation policies and guidelines and the promotion by the U.S. of orbital debris mitigation within the international aerospace community.

This paper summarizes (1) the current state of orbital debris measurements in the U.S. and plans for their improvement both in low Earth orbit (LEO) and at higher altitudes; (2) the latest modeling efforts to define the existing and projected orbital debris environment in engineering terms; (3) design and operational techniques for coping with the orbital debris environment; and (4) the hazards posed by reentering debris. All of these elements are vital to the establishment of practical and effective orbital debris mitigation measures. Although NASA remains the center of excellence for orbital debris research in the U.S., interest by and cooperation with other governmental and commercial organizations continues to expand. ◆

Uncertainty in Orbital Debris Measurements and Models

M. MATNEY

Orbital debris science is a relatively new field of research, one that draws on the expertise of many other fields of learning. Ultimately, orbital debris research has two chief goals. First, to give users of the space environment an accurate assessment of the risks to their assets (both manned and unmanned) or how much risk their missions pose to other space assets or to people on the ground, and how to plan their missions so as to reduce that risk. Second, to help nations and other launching entities know what kinds of actions they can take today to mitigate future growth of orbital debris hazards.

These goals are achieved by creating mathematical models. However, all models are ultimately dependent on data. Data is, of course, dependent on measurements, and measurements are subject to uncertainty. Measuring instruments never really measure exactly what it is we want to know – they always measure some auxiliary quantity (*e.g.*, we measure an object's brightness or radar cross section, not the size or penetrating capability we really want to know). Knowledge of the limitations of the instruments (measurement uncertainty) is only half the problem. The actual transformation of the data into models adds more uncertainty to the final model result.

In this paper, I provide examples of the basic types of uncertainties that we encounter in making orbital debris measurements. I also discuss how construction of models adds uncertainty to the final results. I outline the distinctions between Bayesian and frequentist interpretations of statistics and how this influences the types of conclusions one should or should not draw from uncertainty assessments. I also outline how uncertainties tie into such calculations as probabilistic risk assessments (PRAs), and the benefits and pitfalls of such analyses.

We in the orbital debris science community should make it a priority to better understand and report the uncertainties in our products. The road is long and difficult, but the accurate presentation of our models so that users can make meaningful decisions is worth the effort. ◆

Orbital Dynamics of High Area-to-Mass Ratio Debris and Their Distribution in the Geosynchronous Region

J.-C. LIOU & J. WEAVER

A recent optical debris survey near the geosynchronous (GEO) region by ESA has identified a new debris population. These faint, uncataloged objects have orbital periods very close to 24 hours but eccentricities as high as 0.55. A recent NASA GEO survey using a telescope in Chile also reveals many faint objects with high hour angle drift rates that are consistent with highly eccentric orbits. The combination of the 24-hour orbital period and high eccentricity is certainly a surprise to the orbital debris community. However, a simple explanation may solve this puzzle. These may be debris with very high area-to-mass (A/M) ratios.

To test this high A/M hypothesis, we performed a series of numerical simulations on objects with A/Ms ranging from 0.1 m^2/kg to 20 m^2/kg using a high fidelity orbit integrator. The results indicated that with such a high A/M distribution, the solar radiation pressure perturbation could easily force the objects' eccentricities to go through yearly variations with amplitudes as high as 0.55. This population could produce observable characteristics similar to those in the ESA and NASA surveys. We also analyzed the spatial density distribution of the same objects and estimated their collision risks to operational satellites in GEO.

Is it possible to have a population of debris with A/M as high as 20 m^2/kg that would match the maximum eccentricity of 0.55? The surfaces of satellites are covered with thermal blankets, or Multi-Layer Insulation (MLI). MLI often consists of layers of thin aluminized Mylar®, Kapton®, or Nomex®. Typical areal density will give the corresponding A/Ms of the layers, varying from below 10 m^2/kg to more than 20 m^2/kg. Therefore, it is conceivable that surface degradation, impacts by small meteoroids, or explosions of GEO satellites have led to a population of MLI pieces in GEO. If this hypothesis is confirmed, MLI design changes will be needed to mitigate the problem and limit the future generation of high A/M debris in GEO. ◆

Simulation of Past Breakup Events and the Correlation with Actual Radar Detections

M. HORSTMAN, J. FOSTER, & E. STANSBERY

Fortunately, large breakups in low Earth orbit (LEO) are relatively rare. Only three have occurred in the last ten years which have deposited more than 100 cataloged objects. The chance to study these breakups is equally rare. Statistical radar observations have provided useful data, but scores of unidentified debris remain in historic radar data. The potential for greater understanding of past breakups exists if only these unknown pieces can be linked to these events. Through the simulation of known breakups, a range of possible radar range and range rates can be used to fence in possible detections. Correlation of historic radar data which falls within these limits makes the likelihood high that detected pieces that fit these parameters originate from the simulated parent body.

The Haystack radar, using a staring campaign with long periods of observation, has the potential to view a large range of orbits encompassing many potential past breakups. Several known satellite breakups were simulated, producing a broad group of debris objects. The orbits of this debris were examined for Haystack radar interception, and equivalent Haystack radar range and range rates were determined. From these simulated debris detections, a range of possible parameters was established. Simulation of the debris cloud as it passed through the Haystack radar beam provided a sample space from which to draw possible evidence of breakup fragments. Detection candidates which were previously unidentified were marked and the probability of these detections originating from the known parent body was computed with the intention of gathering a more complete record of detected breakup debris to improve the understanding of the event. ◆

Modeling and Monitoring the Decay of NASA Satellites

D. WHITLOCK & N. JOHNSON

In January 2002, NASA Headquarters directed that greater attention be paid to the reentry of old NASA space hardware. NASA Policy Directive 8710.3B charges the Orbital Debris Program Office, in support of the Director of the NASA Johnson Space Center, to maintain a list of predicted reentry dates for all NASA spacecraft and their associated orbital stages and to advise appropriate NASA personnel during the final stages of orbital decay. A process, which begins before launch and which includes cooperation with the U.S. Space Surveillance Network (SSN), has been developed to model and to monitor the orbital decay of NASA space objects. NASA's PROP3D orbit propagator is the principal tool used to predict orbital lifetimes in the period prior to 60 days before reentry. PROP3D accounts for complex factors such as the Sun and Moon's gravitational effects, solar activity, J_2/J_4 effects, and solar radiation pressure. One of the most difficult and often most important parameters to estimate accurately is an object's ballistic coefficient. In the final two months before reentry, emphasis is placed on the more accurate numerical tools of the SSN. During a satellite's final four days in space, specific reentry time and location predictions are made by the SSN and distributed by the NASA Orbital Debris Program Office to relevant NASA offices. This paper will explore the detailed procedure in predicting reentry dates, as well as address inherent difficulties in reentry predictions, and suggest areas for improvement for future predictions. ◆

MEETING REPORT

Fourth European Conference on Space Debris
18-20 April 2005, Darmstadt, Germany

The Fourth European Conference on Space Debris was held at the European Space Operations Centre (ESOC) in Darmstadt, Germany on 18-20 April 2005. It included nine technical sessions: Ground-based Measurements (Radar and Optical), Space-based and *In-situ* Measurements, Debris and Meteoroid Environment Modeling, Determination and Prediction of Debris Orbits, Space Debris Mitigation, Accelerators, HVI and Shielding, Risk Analysis, and Standards, Regulations and Legal Issues. A total of 117 papers and 42 posters were presented over the three day conference. All papers and posters will appear in the *Proceedings of the Fourth European Conference on Space Debris.* ◆

UPCOMING MEETINGS

5-9 September 2005: Air Force Maui Optical and Supercomputing (AMOS) Technical Conference, Wailea, Maui, Hawaii, USA.

This meeting is recognized internationally as a major annual meeting for the optical, computing, and space surveillance communities. It is intended for scientists, engineers, and technical managers from academia, industry, government, and military programs. Topics include: Adaptive Optics, Astronomy, Computational Object Identification, High Performance Computing Applications in Astronomy, Imaging Theory, Algorithms, and Performance Prediction, Laser Propagation and Laser Radar, Non-Resolved Object Characterization, Orbital Debris, Satellite Modeling, Small or Autonomous Telescope Systems, Space Situational Awareness, and Space Weather. For more information, visit http://www.maui.afmc.af.mil/conferences.html.

17-21 October 2005: The 56th International Astronautical Congress, Fukuoka, Japan.

The Congress will include four sessions on space debris: Measurements and Space Surveillance, Risk Analysis and Modeling, Hypervelocity Impacts and Protection, and Mitigation and Standards. Additional information on the Congress is available at http://www.iac2005.org.

INTERNATIONAL SPACE MISSIONS

April—June 2005

International Designator	Payloads	Country/ Organization	Perigee (KM)	Apogee (KM)	Inclination (DEG)	Earth Orbital Rocket Bodies	Other Cataloged Debris
2005-011A	XSS-11 (USA 165)	USA	845	863	98.8	1	0
2005-012A	APSTAR 6	CHINA	35780	35794	0.0	1	0
2005-013A	SOYUZ-TMA 6	RUSSIA	351	353	51.6	1	0
2005-014A	DART	USA	397	742	96.6	1	0
2005-015A	SPACEWAY 1	USA	EN ROUTE TO GEO			1	0
2005-016A	USA 182	USA	NO ELEMS AVAILABLE			1	0
2005-017A	CARTOSAT-1	INDIA	619	623	97.9	1	2
2005-017B	HAMSAT	INDIA	607	647	97.9		
2005-018A	NOAA 18	USA	845	867	98.7	1	0
2005-019A	DIRECTV 8	USA	35776	35797	0.1	1	1
2005-020A	FOTON M-2	RUSSIA	255	284	63.0	1	7
2005-021A	PROGRESS-M 53	RUSSIA	351	353	51.6	1	0
2005-022A	INTELSAT AMERICAS 8	USA	EN ROUTE TO GEO			1	0
2005-023A	EXPRESS AM-3	RUSSIA	EN ROUTE TO GEO			2	6

SBRAM

Continued from page 2

marks the most dangerous time for the ISS, due to the high density of the breakup cloud and the common breakup and ISS altitudes. Still the fluence does not significantly exceed that of the background value as derived from ORDEM2000.

Figure 2 displays the case of the 1000 kg rocket body exploding at 900 km. As would be expected, the risk to ISS is far below the ORDEM2000 background environment due to the disparate altitudes of the breakup and the ISS. Also, there is very little change in the fluence value over this ten day period, attesting to the low atmospheric drag at 900 km. Finally, comparison between Figures 1 and 2 confirms that the required number of simulations (Monte Carlo runs) to achieve a desired accuracy within the runs (*i.e.*, the error as represented by standard deviation) is variable, depending on the collisional activity between fragments and the target (ISS). ◆

MODEST Results

Continued from page 5

In conclusion, 66 nights of data have been collected and reduced for orbit determination and correlation with the catalog. Currently, 1014 CTs and 401 UCTs have been identified. The CTs are unique for each night and it is assumed that the UCTs are unique per night as well. The NASA JSC reduction pipeline is complete and therefore data can now be run as it is received from MODEST. Future work on this project includes reducing the remaining ~70 days already collected by MODEST, collecting and reducing more data as the weather permits, and beginning the correlation of the UCTs from night to night. ◆

ORBITAL BOX SCORE

(as of 29 JUN 2005, as cataloged by US SPACE SURVEILLANCE NETWORK)

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	48	303	351
CIS	1358	2677	4035
ESA	34	32	66
FRANCE	42	294	336
INDIA	30	106	136
JAPAN	86	51	137
US	1010	2925	3935
OTHER	336	20	356
TOTAL	2944	6408	9352

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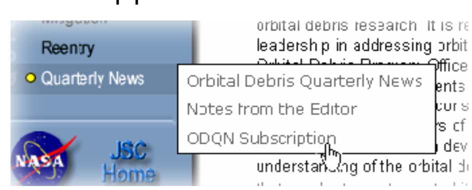
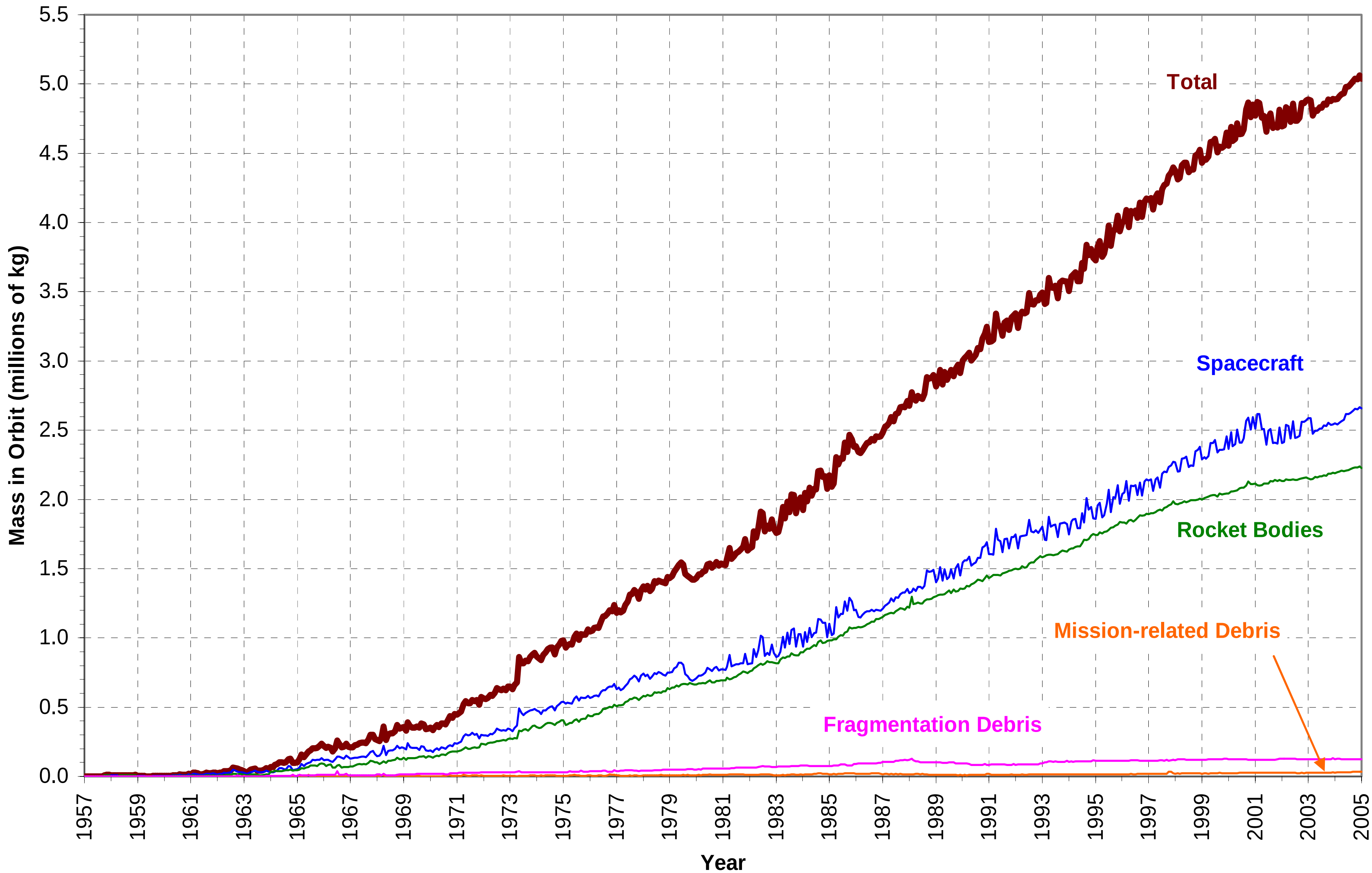


Monthly Mass of Objects in Earth Orbit by Object Type



Monthly Mass of Cataloged Objects in Earth Orbit by Object Type: This chart displays a summary of all objects in Earth orbit officially cataloged by the US Space Surveillance Network. "Fragmentation debris" includes satellite breakup debris and anomalous event debris, while "mission-related debris" includes all objects dispensed, separated, or released as part of the planned mission.