National Aeronautics and Space Administration

Orbital Debris Quarterly News

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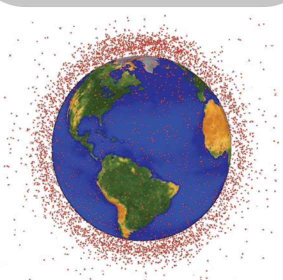
Inside...



A publication of

The NASA Orbital Debris Program Office

Three More Satellites Involved in Fragmentations

During the one-month period from early August to early September, the U.S. Space Surveillance Network (SSN) detected fragmentations of three different resident space objects. Fortunately, all events appear to have released only small amounts of relatively shorted-lived debris. The causes of two of the fragmentations have been assessed, but the circumstances surrounding the third object are less well understood.

On 8 August the H-2A second stage (International Designator 2006-002B, U.S. Satellite Number 28932), which was used to place the Japanese ALOS-1 spacecraft into orbit in January, released four debris with very low relative velocities. At the time the stage was in an orbit of approximately 550 km by 700 km with an inclination of 98.2°. The debris immediately began to fall away from the stage due to their higher area-to-mass ratios. Then, on 27 August the stage released at least 17 more debris, again with low relative velocities. A total of 21 objects were officially cataloged by the SSN in early September. The status of the debris orbits at that time (Figure 1) indicated significant orbital decay had already been experienced by many of the debris. Reentry of the debris into the atmosphere is expected in the near term; hence, no long-term effect on the space environment will result. The cause of these two events is currently under investigation.

Sometime during 1-2 September another small auxiliary motor from a Russian Proton launch vehicle experienced a breakup, producing at least seven new debris. The object (International Designator 2000-036E, U.S. Satellite Number 26398), employed on the Cosmos 2371 mission, was in an orbit of 220 km by 21,320 km with an inclination of 46.9°. This was the 35th breakup event associated with this class of motor since 1984; the cause of the fragmenta-

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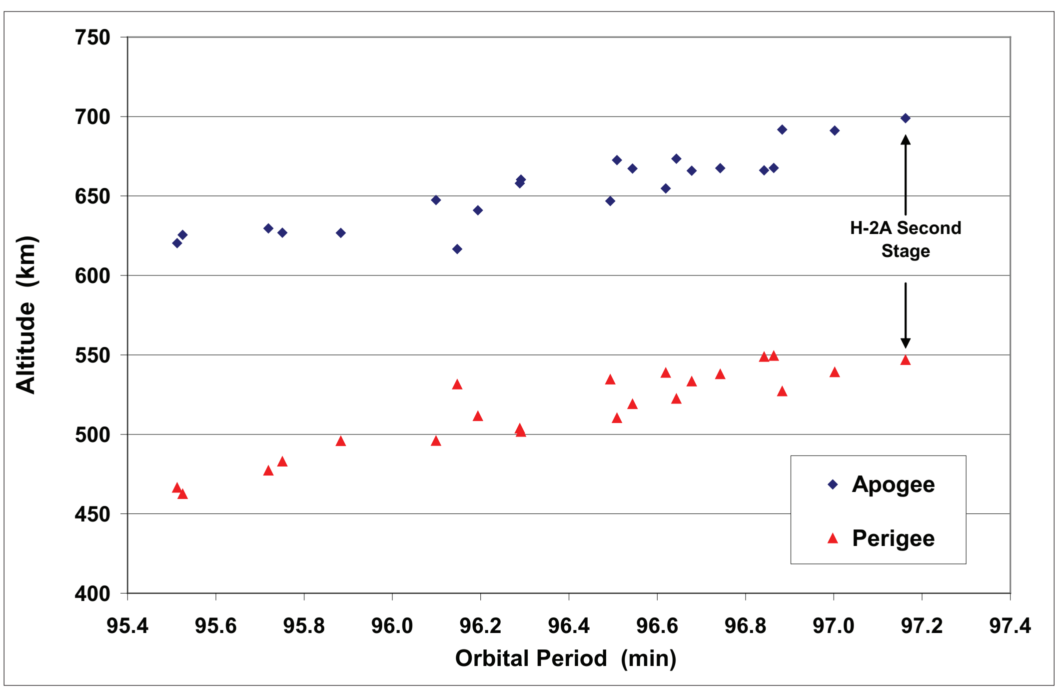

Figure 1. Orbits of the ALOS-1 H-2A second stage and its debris on 9 September 2006.

Fragmentations

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tions is assessed to be related to onboard residual propellant. The previous breakup in this series (International Designator 1989-039G, U.S. Satellite Number 20081) occurred on 10 June 2006 (*Orbital Debris Quarterly News*, 10-3, pp. 1-2) and was responsible for more than 130 new tracked debris, of which about one-third had been cataloged by early September.

The third identified breakup of the quarter appears to have occurred in the second half of August or early September. The parent object was a Russian Molniya upper stage (International Designator 1990-052D, U.S. Satellite Number 20649) in an orbit of about 130 km by 37,710 km with an inclination of 62.4°. Less than 10 new debris were detected by the SSN. The cause of the breakup was likely related to aerodynamic forces encountered during the stage's very low perigee. The stage reentered the atmosphere on 13 September, indicating that any debris generated earlier should also have been very short-lived. ♦

John L. Africano

The orbital debris, space surveillance, and astronomy communities lost a valued and beloved friend when John L. Africano passed away on 27 July. John suffered a major heart attack a week earlier while playing racquetball. He was on Maui collecting data on high area-to-mass orbital debris at the time. John was 55.

John graduated from the University of Missouri at St. Louis and received a Master's degree in Astronomy from Vanderbilt University in 1974. He held operational staff positions at several major observatories including McDonald Observatory in Texas, Kitt Peak National Observatory in Arizona, and Cloudcroft, New Mexico where he developed a wide network of friends and colleagues. One of John's great assets was his ability to build diverse teams from this network to address and solve almost any observing task. He also mentored and encouraged many young astronomers. As a Boeing employee, he worked for many years at the Air Force Maui Optical and Supercomputing Site (AMOS) where he contributed his operational and instrumental expertise to both the astronomy and space surveillance communities. He was also the co-organizer of the AMOS Technical Conference.

John moved to Houston, Texas in 1998 and worked full time on orbital debris projects including the Liquid Mirror Telescope and the CCD Debris Telescope. He later moved to Colorado Springs, Colorado where he could spend more time with his grandchildren. From Colorado Springs, he supported both the NASA Orbital Debris Program Office (ODPO) and AMOS. John was very instrumental in establishing cooperative programs between the ODPO and AMOS which will benefit both organizations for many years to come.

John left an indelible mark on his programs and all those who knew and loved him. The impact of his untimely departure will reverberate for many years. As John's wife Linda put it, "John is now visiting the stars and galaxies he adored from afar." ♦

PROJECT REVIEWS

Ground Truth Measurements of the FORMOSAT III Spacecraft

K. ABERCROMBY

Determining the material types of objects in space is conducted using laboratory spectral reflectance measurements from common spacecraft materials and comparing the results to remote spectra. The common materials which are used for the comparison are educated guesses of the material on the surface of the spacecraft. This project gathered laboratory spectral measurements prior to flight on the FORMOSAT III so that a true comparison can be made between remote and laboratory spectra. FORMOSAT III launched in April 2006 into a circular orbit of 500 km. There are six identical satellites that will take approximately 13 months to get to their final circular orbit of ~800 km altitude, 72° inclination, and separated by 24° in ascending node.

The satellite measured was enclosed in

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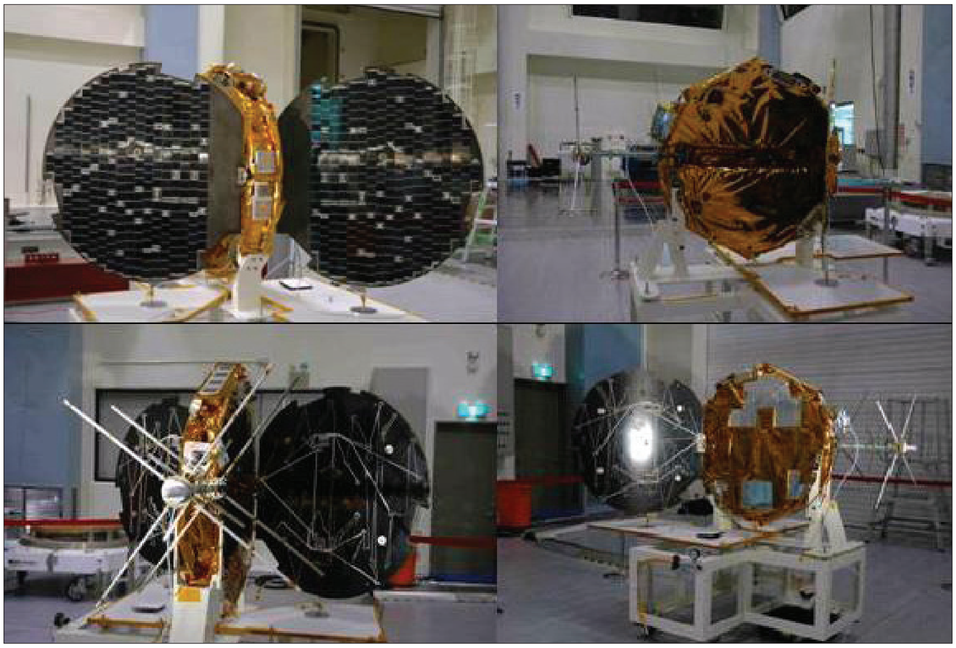

Figure 1. Various views of the FORMOSAT III in the laboratory.

FORMOSAT

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a clean room. All of the individual materials were tested as well as broad views of the entire spacecraft resulting in over 200 spectra. The satellite was oriented such that the normal nadir pointing of the satellite was toward a wall instead of the floor seen in Figure 1. The top left image in Figure 1 is from the top surface and likely a side that ground observers will not see. The solar panels are set off-axis to the body making a larger angle between the panels and the body on one side of the spacecraft than the other. The angles are 59° on one side, and 121° on the other in reference to the body. The solar panels do move around the y-axis (x-axis is defined by the body of the spacecraft) to track the Sun, but keep the same angles to the body of the spacecraft. This is illustrated in Figure 2. The solar panels are nearly 100% populated with a very dark backside. The top right image of Figure 1 shows the acute angle of the solar panels to the body. Multi-layer insulation (MLI) that has an outer layer of Kapton® covers the main body and is seen in the photo with the normal orange/copper color. The bottom left image of Figure 1 shows the side view with the white nadir-pointing boom, a view that the observer would see if the objects were directly overhead. The bottom right photo shows the larger angle of the body to the solar panels. All materials were considered flight ready, which means all the paints and coatings on the spacecraft are the same when we measured it as when it launches.

Figure 2. Side view of FORMOSAT III to illustrate the solar panel orientation to the spacecraft body.

Laboratory spectral measurements were taken using the Analytical Spectral Device (ASD) field spectrometer that has a wavelength range of 0.3 to 2.5 microns (µm) with a resolving power of 10 nanometers and 717 channels. Multi-layer insulation (MLI) covers both sides of the spacecraft body. This material is an orange/copper color and can bend and move like aluminum foil. Because of this aspect, it is difficult to get a spectral measurement of MLI due to light reflections. In the spectrum shown in Figure 3 labeled as "mli small," the MLI appears to be much dimmer than it actually seems in person. There is a strong color band gap near 0.5 microns, which is consistent with the orange/copper color of the material. In addition, one can see the absorption feature near 0.85 µm, which is usually associated with aluminum. The next features that can be used to identify material are those associated with C-H in the material near 1.7 and 2.3 µm. The MLI outer surface is consistent with other measurements of MLI with a Kapton® surface.

Due to specular reflectance it is difficult to obtain a true diffuse spectral measurement of the small MLI sample so the entire MLI side of the spacecraft body was measured. The results show a larger reflectance but with similar absorption features as seen in the Figure 3 curve labeled as "mli entire." Within this spectrum are absorption features due to the color of the MLI (0.5 µm), aluminum (0.8 µm), water (1.4 and 1.9 µm), and C-H (near 1.7 and 2.3 µm) among others. Studies have shown that Kapton® erodes in the low Earth orbit (LEO) environment due to atomic oxygen interactions. If that is the case here, the band gap due to the orange/copper color of Kapton® will be absent and the aluminum feature will be more apparent because the spectrum will be showing the lower layers of the MLI.

While taking the measurements of the broader and larger views of the spacecraft, we tested pseudo-terminator views. The resultant spectrum is shown in Figure 3 as the red or top line labeled as "reflection off the back." An interesting result not seen in prior experiments was the back scattering of the light off the MLI onto the back of the solar panel and then back to the observer. This situation is exaggerated in this orientation because of the orientation of the solar panels to the spacecraft body and is only seen on the smaller-angle side of the spacecraft. The spectrum of the solar panel back is shown with a sample of MLI only and the back of the solar panel with direct light. Notice how dark and flat the back is without the MLI reflection. This situation will be advantageous for ground observers because the back of the solar panels can now contribute to the overall reflectance of the spacecraft.

Models are being developed to predict how orientation and orbit will affect the spectrum. In addition, space weathering effects will be included in the model. In the future, it would be preferable to predict a space weathered spectrum as well as the pristine sample to show the level of degradation with time. Remote observations of the FORMOSAT III spacecraft are planned for this year. The true comparison of the laboratory and remote spectral reflectance will commence at that time. ♦

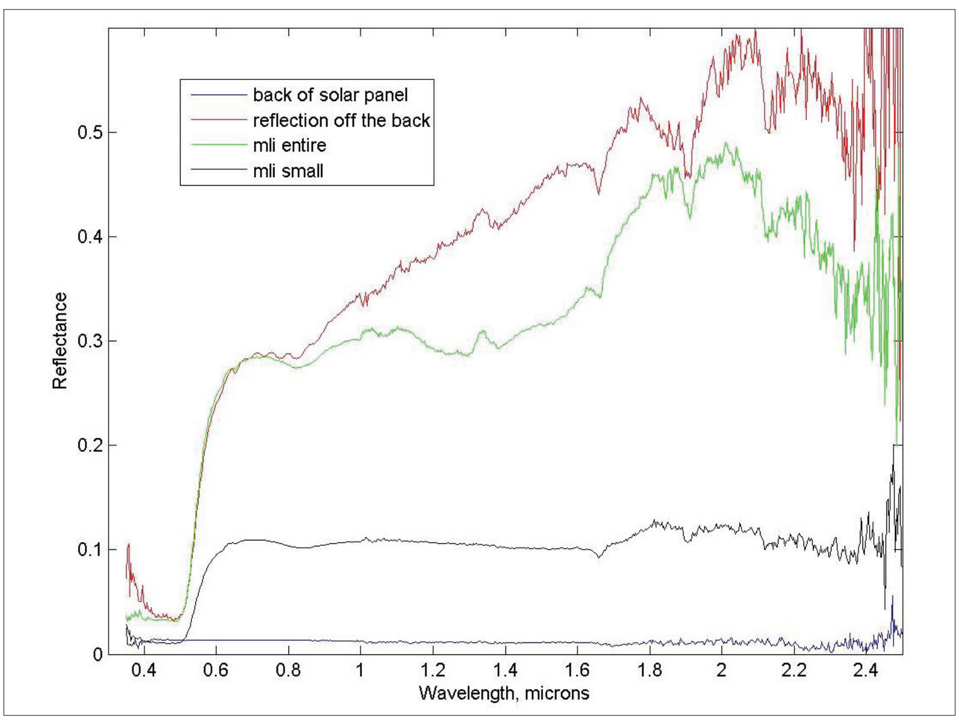

Figure 3. Reflectance spectra of the side of the spacecraft due to terminator lighting. The blue line is the back of the solar panels with direct lighting, the black line is the spectrum of a small piece of MLI, the green line is a larger section of MLI, and the red line is the reflection off the back of the solar panel with side lighting.

Debris Flux Comparisons from the Haystack Radar Prior, During, and After the Last Solar Maximum

C. STOKELY & E. STANSBERY

Increased solar activity is thought to play an important role in depleting the orbital debris population in low Earth orbits (LEO) through reentry by increased atmospheric drag. Simulation models of the effects of various levels of solar activity on the orbital debris environment indicate that high solar flux activity can dramatically affect orbits below about 600 km. However, radar observation data of small debris (<10 cm diameter) before, during, and after a solar cycle peak have not been available until now. The MIT Lincoln Laboratory (MIT/LL) Haystack radar started small debris observations in 1990. The last two peaks in solar activity occurred in 1990 and 2001.

The atmospheric drag experienced by an orbiting object is a function of atmospheric density. Variations in atmospheric density are primarily driven by solar activity fluctuations. To give an indication of solar activity levels during the periods of interest, solar flux during the last two solar activity peaks is shown in Figure 1[1]. The ordinate is expressed in solar flux units (sfu, one solar flux unit = 10^{-22} $W/m^2/Hz$). The observation periods are expressed in fiscal years. A fiscal year (FY) is defined as starting in October and ending in the following September; for example, fiscal year 2003 starts in October 2002 and ends in September 2003. Fiscal years 1998, 2001, and 2003 are investigated here.

The Haystack radar is a highly sensitive radar capable of detecting debris with sizes as small as 5 mm. It is located in Massachusetts at latitude 42.62° N. The Haystack data discussed here are for 75° elevation with east pointing of the radar. With this radar pointing condition and the latitude of the radar, the Haystack radar observes orbits with inclinations between 43° to 137°. Haystack utilizes a monopulse system that allows the position of a debris piece within the beam to be determined. The radar cross section (RCS) can be augmented by the relative antenna gain determined by the antenna beam-pattern calibration. Thus, the RCS can be estimated as if the object were at the center of the radar beam. The RCS is converted to size with an extension of the NASA Size Estimation Model (SEM) referred to as Statistical Size Estimation Model (SSEM)[3]. Haystack measures principal polarization and the orthogonal polarization radar returns. Both polarizations are required in order to use the SSEM, which provides statistical uncertainties in the observed populations. The error bars for the Haystack fluxes are statistical and assume Poisson sampling.

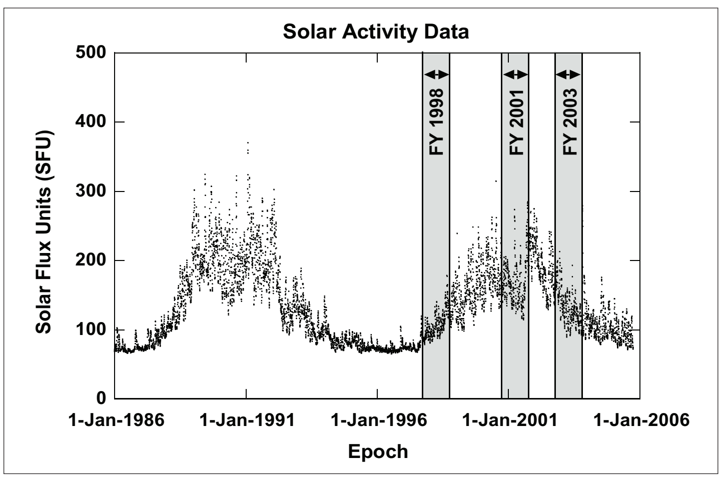

Figure 1. The solar flux activity versus year over the last two solar activity peaks. The highlighted zones on the figure indicate the time regions discussed here.

An analysis of the Haystack data from year to year indicate some changes in the average flux for the lower altitude bins among subsets of the debris population. Many of these changes typically vary from 10% to 30%, consistent with some debris model estimates[1]. Even 10% to 30% variations in flux due to solar activity are considered significant, but these changes cannot be distinguished from 1-sigma statistical variations, typically ranging from 30% to 45% of the mean flux[2,3].

The 400 km to 600 km altitude region illustrates a statistically significant decrease in the debris population below 1 cm before, during, and after the solar cycle maximum, as shown in Figure 2. For the smallest debris, the decline of the mean flux is more than 50%. The 600 km to 800 km region shown in Figure 3 indicates a statistically significant increase in the debris population above 3 cm over this same time period. For the largest debris, the mean flux increases by a factor of approximately 2. In both altitude regions, the changes in flux occur from 1998 to 2001, with almost no change from 2001 to 2003. The 800 km to 1000 km region shows no statistically significant variation in debris flux versus epoch. The 1000 km to 1200 km region indicate some variations for larger sizes versus epoch but poor statistics at large sizes prohibit firm conclusions.

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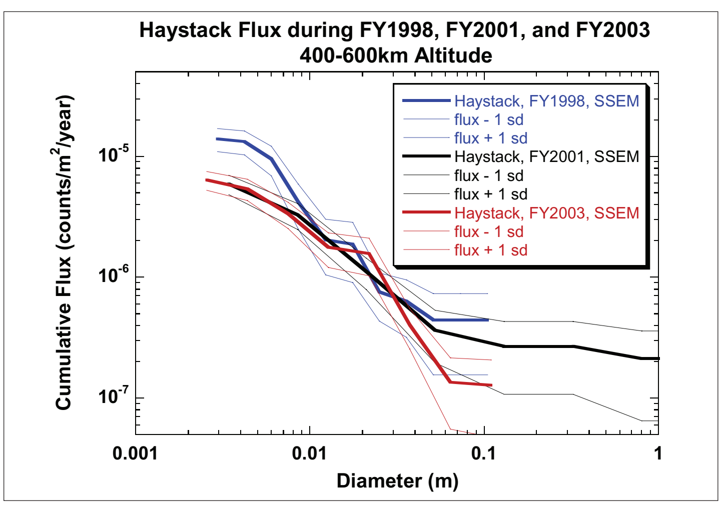

Figure 2. The debris flux versus diameter at 400 km to 600 km for Haystack 75° elevation, east pointing measurements during FY1998, 2001, and 2003.

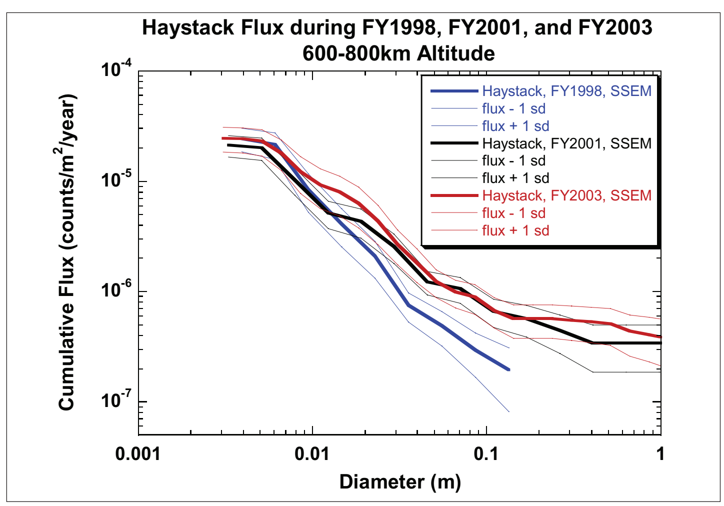

Figure 3. The debris flux versus diameter at 600 km to 800 km for Haystack 75° elevation, east pointing measurements during FY1998, 2001, and 2003.

Haystack

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Isolating the effects of solar activity from unknown debris sources is not completely possible. There are, however, some plausible simple scenarios that may explain the trends in the debris populations for each of the altitude windows. Consider that smaller debris have on average a larger area-to-mass ratio than larger debris, assuming similar shapes. For example, a sphere of radius *r* and uniform density ρ has an area-to-mass=3/4(ρ· *r*). Hence smaller debris should descend faster than larger debris due to the effects of atmospheric drag. This may explain the resultant decrease of the smallest debris for 400 km to 600 km. The increase in the population of larger debris between 600 km to 800 km may simply be a result of new debris being generated in this region. If this is the case, the population of small debris should also increase. The lack of increase of small debris may simply be the result of a reduction of the small debris population from increased atmospheric drag via an increased solar flux mixed with an overall increase in the debris population from debris sources. Between 800 km to 1200 km, the atmospheric drag is expected to be much smaller than at lower altitudes, so changes are most likely the result of new debris sources, or statistical errors from inadequate observation periods.

In summary, statistical uncertainties prohibit firm conclusions of the effects of increased solar activity on the debris populations, except for debris smaller than 1 cm diameter in the vicinity of 500 km altitude and debris larger than 3 cm near 700 km altitude. Providing more accurate error estimates of debris flux may require substantially more radar observation hours and could help isolate year to year changes in the debris populations.

1. Whitlock, D., *Modeling the Effect of High Solar Activity on the Orbital Debris Environment*. Orbital Debris Quarterly News, 10-2, pp. 4-5, 2006.

2. Stokely, C.L., et al. *Haystack and HAX Radar Measurements of the Orbital Debris Environment; 2003*, NASA JSC Publication JSC-62815, Houston, TX, to be published.

3. Xu, Y.-l and C.L. Stokely. *A Statistical Size Estimation Model for Haystack and HAX Radar Detections*, 56th International Astronautical Congress, Fukuoka, Japan, 2005. ♦

ABSTRACTS FROM THE NASA ORBITAL DEBRIS PROGRAM OFFICE

2006 Advanced Maui Optical and Space (AMOS) Surveillance Technologies Conference
10-14 September 2006, Wailea, Maui, Hawaii, USA

Comparisons of Ground Truth and Remote Spectral Measurements of the FORMOSAT and ANDE Spacecraft

K. ABERCROMBY, J. OKADA, M. GUYOTE, K. HAMADA, & E. BARKER

Determining the material type of objects in space is conducted using laboratory spectral reflectance measurements from common spacecraft materials and comparing the results to remote spectra. This past year, two different ground-truth studies commenced. The first, FORMOSAT III, is a Taiwanese set of six satellites to be launched in March 2006. The second is ANDE (Atmospheric Neutral Density Experiment), a Naval Research Laboratory set of two satellites set to launch from the Space Shuttle in November 2006. Laboratory spectra were obtained of the spacecraft and a model of the anticipated spectra response was created for each set of satellites. The model takes into account phase angle and orientation of the spacecraft relative to the observer. Once launched, the spacecraft are observed once a month to determine the space aging effects of materials as deduced from the remote spectra. Preliminary results will be shown of the FORMOSAT III and ANDE laboratory data. ♦

Comparison of Orbital Parameters for GEO Debris Predicted by LEGEND and Observed by MODEST: Can Sources of Orbital Debris be Identified?

E. BARKER, M. MATNEY, J.-C. LIOU, K. ABERCROMBY, H. RODRIGUEZ, & P. SEITZER

Since 2002, the National Aeronautics and Space Administration (NASA) has carried out an optical survey of the debris environment in the geosynchronous Earth-orbit (GEO) region with the Michigan Orbital DEbris Survey Telescope (MODEST) in Chile. Under gravitational perturbations the distributions of uncontrolled objects, both Correlated (CTs) and Uncorrelated (UCTs) targets, in GEO orbits will evolve in predictable patterns, particularly evident in their inclination and right ascension of the ascending node (RAAN) distributions. There are several clusters (others have used a "cloud" nomenclature) in observed distributions that show evolution from year to year in their inclination and ascending node elements. Identification of the source(s) for these "clusters of UCTs" would be advantageous to the overall definition of the GEO orbital debris environment. This paper will present arguments for the identity of the source of the "clustering of UCTs" roughly centered on an inclination of 12° and a RAAN of 345°. The breakup of the Titan 3C-4 transtage on 21 February 1992 has been modeled using NASA's LEGEND (LEO-to-GEO Environment Debris) code to generate a GEO debris cloud. Breakup fragments are created based on the NASA Standard Breakup Model (including fragment size, area-to-mass (A/M), and delta-V distributions). Once fragments are created, they are propagated forward in time with a subroutine GEOPROP (GEO Propagator). Perturbations included in GEOPROP are those due to solar/lunar gravity, radiation pressure, and major geopotential terms.

The question to be addressed: are the UCTs detected by MODEST in this inclination/RAAN region related to the Titan 3C-4 breakup? Discussion will include the observational biases in attempting to detect a specific, uncontrolled target during given observing session. These restrictions include: (1) the length of the observing session, which is 8 hours or less at any given date or declination; (2) the assumption of ACO elements for detected object when the breakup model predicts debris with non-zero eccentricities; (3) the size and illumination or brightness of the debris predicted by the model and the telescope/sky limiting magnitude. Possibly, one of the major restrictions is the primary focus of the MODEST program, which is to uniformly survey the GEO belt region and then move to declinations above and below the belt region as observing time permits. ♦

Using Light Curves to Characterize Size and Shape of Pseudo-Debris

H RODRIGUEZ, K. ABERCROMBY, K. JARVIS, & E. BARKER

Photometric measurements were collected for a new study aimed at estimating orbital debris sizes based on object brightness. To obtain a size from optical measurements the current practice is to assume an albedo and use a normalized magnitude to calculate optical size. However, assuming a single albedo value may not be valid for all objects or orbit types and material type, and orientation can mask an object's true optical cross section. This experiment used a CCD camera to record data, a 300 W Xenon Ozone Free collimated light source to simulate solar illumination, and a robotic arm with five degrees of freedom to move the piece of simulated debris through various orientations. The pseudo-debris pieces used in this experiment originate from the European Space Operations Centre's ESOC2 ground test explosion of a mock satellite. A uniformly illuminated white ping-pong ball was used as a zero-magnitude reference. Each debris piece was then moved through specific orientations and rotations to generate a light curve. This paper discusses the results of five different object-based light curves as measured through an x-rotation. Intensity measurements, from which each light curve was generated, were recorded in five degree increments from zero to 360 degrees. Comparing light curves of different shaped and sized pieces against their characteristic length establishes the start of a database from which an optical size estimation model will be derived in the future. ♦

57th International Astronautical Congress
2-6 October 2006, Valencia, Spain

Improving the Near-Earth Micrometeoroid and Orbital Debris Environment Definition with LAD-C

J.-C. LIOU, F. GIOVANE, R. CORSARO, & E. STANSBERY

The Large Area Debris Collector (LAD-C) is a 10 m^2 aerogel and acoustic sensor system designed to characterize and collect sub-millimeter micrometeoroids and orbital debris on the International Space Station (ISS). The project is led by the U.S. Naval Research Laboratory (NRL) with major collaboration by the NASA Orbital Debris Program Office at Johnson Space Center. The U.S. Department of Defense Space Test Program (STP) is responsible for the integration, deployment, and retrieval of the system. The deployment is scheduled for August 2008 with an orbital collection period of one to two years.

The combined area-time product of LAD-C will provide a much needed orbital debris population update in the size regime that is important to the safety community – 100 μm and larger. Another key element for LAD-C is the source identification of the collected samples. Impact features such as track length and track volume can be used to estimate the impact speed and direction of any selected residual embedded in aerogel. Acoustic sensors can provide impact timing and impact location information. The combined dynamical signatures make it possible to reconstruct the orbits of some of the collected samples and lead to their source identification. Compositional analysis on the residuals can also separate debris from meteoroids and provide additional population breakdown for orbital debris (*e.g.*, Al, paint, steel, Al_2O_3).

To maximize the science return and minimize potential contamination from other ISS modules, a careful selection of the location and orientation of LAD-C on the ISS is needed. Key issues and engineering constraints encountered during mission preparation, and the expected science return based on the mission configuration, are summarized in this paper. ♦

Current Characteristics and Trends of the Tracked Satellite Population in the Human Space Flight Regime

N. JOHNSON

Since the end of the Apollo program in 1972, human space flight has been restricted to altitudes below 620 km above the Earth's surface with most missions restricted to a ceiling below 400 km. An investigation of the tracked satellite population transiting and influencing the human space flight regime during the past 11 years (equivalent to a full solar cycle) has recently been completed. The overall effects of satellite breakups and solar activity are typically less pronounced in the human space flight regime than other regions of low Earth orbit. As of January 2006 nearly 1500 tracked objects resided in or traversed the human space flight regime, although two-thirds of these objects were in orbits of moderate to high eccentricity. Since the beginning of the International Space Station era, the spatial density of tracked objects in the 350-400 km altitude regime has demonstrated a general decline, decreasing by 40% by the beginning of 2006. On the other hand, the region immediately above 600 km experienced a significant increase in its population density. This regime is important for future risk assessments, since this region represents the reservoir of debris which will influence human space flight safety in the future. The paper seeks to put into sharper perspective the risks posed to human space flight by the tracked satellite population, as well as the influences of solar activity and the effects of compliance with orbital debris mitigation guidelines on human space flight missions. Finally, the methods and successes of characterizing the population of smaller debris at human space flight regimes are addressed. ♦

Historical Collisions in Low Earth Orbit

P. KRISKO

Collisions between objects in orbit have been known to occur for many years. The available evidence includes returned surfaces which have recorded impacts by sub-millimeter sized objects (*i.e.*, orbital debris and meteoroids), and more recent unexplained debris generating events that hint at possible impacts of resident space objects (RSOs) with objects on the order of one centimeter in size. The NASA Orbital Debris Program Office is engaged in a study to formulate the low-Earth-orbit (LEO) environment in terms of past and current-day collisional activity between objects larger than one centimeter in size. One prong in the study is a modeling effort involving the debris environment evolution models LEGEND and EVOLVE. These models were developed at NASA JSC for the purpose of providing insight into the long-term effects (over 100 years) of controlled/uncontrolled fragmentation in Earth orbit. They find additional application in the current study. Preliminary results suggest a small but nontrivial collision rate, on the order of tens of events, over the last 35 years in LEO. This rate is dominated by events involving breakup fragments and large RSOs, though a sizeable minority of the events (*i.e.*, around 30%) involve RORSAT sodium-potassium droplets and RSOs. The sodium-potassium droplets/RSO rate appears to decrease over time as atmospheric decay takes those droplets out of the LEO high-traffic regions. The modeled increasing rate of breakup fragment/RSO events is expected given the continuing addition of small fragment sources to the environment.

Verification of this historical collision activity is difficult in radar tracking data since the small impactors generally result only in cratering of the large RSOs (*i.e.*, non-catastrophic collisions). Still the activity may be notable in small unexplained changes in RSO ephemeris. ♦

Benefits and Risks of Using Electrodynamic Tethers to De-Orbit Spacecraft

C. PARDINI, T. HANADA, & P. KRISKO

Space tethers represent an exciting and innovative technique offering immense technological and scientific opportunities. Propellantless propulsion and momentum-exchange transportation have been considered among the most promising applications of tethers in space since early studies in the field over 35 years ago. Despite a small number of full-scale experiments made so far using space tethers, the possibility of de-orbiting spacecraft by means of electrodynamic tethers has been on the drawing board of theorists for almost a decade. By using electrodynamic drag to greatly increase the orbital decay rate, an electrodynamic space tether can remove spent or dysfunctional spacecraft from low Earth orbit rapidly and safely. Moreover, the low mass requirements of such tether devices make them highly advantageous compared to conventional rocket-based de-orbit systems. However, tethers are usually very long and thin, providing increased opportunities for something to go wrong. In particular, a tether system is much more vulnerable to space debris impacts than a typical spacecraft and its design must prove to be safe to a certain confidence level before being adopted for potential applications.

To assess the space debris related concerns, a new task (Action Item 19.1) on the "Benefits and Risks of using Electrodynamic Tethers to De-Orbit Spacecraft" was defined by the Inter-Agency Space Debris Coordination Committee (IADC) in March 2001. The task was assigned to the IADC Working Group 2, on "Environment and Data Base," and a study plan was successively formulated with the main objective of investigating the potential risk to the tether system integrity due to impacts with space debris. Two tests were proposed to compute the fatal impact rate of meteoroids and orbital debris on space tethers in circular orbit, at different altitudes and inclinations, as a function of the tether diameter, and to assess the survival probability of an electrodynamic tether system during typical de-orbiting missions. IADC members of three agencies (ASI, JAXA and NASA) volunteered to participate in the study and different computational approaches were specifically developed in the framework of this IADC task.

This paper summarizes the content of the IADC AI 19.1 final report. In particular, it introduces the potential benefits and risks of using tethers in space, it describes the assumptions made in the study plan, and it compares and discusses the results obtained by ASI, JAXA and NASA for the two tests proposed. Some general conclusions and recommendations are eventually highlighted as a result of a massive and intensive study. ♦

Survey and Chase: A New Method of Observations for the Michigan Orbital DEbris Survey Telescope (MODEST)

K. ABERCROMBY, P. SEITZER, H. RODRIGUEZ , & E. BARKER

When in normal-operation mode the Michigan Orbital DEbris Survey Telescope (MODEST) is used to survey the geosynchronous orbit (GEO) environment to obtain a statistical assessment of the debris population. Due to the short time that the object is in the field-of-view (usually five minutes), it is common practice to assume a circular orbit when calculating the orbit from this limited observational arc. Some objects in the GEO regime are geo-transfer orbit (GTO) objects which are observed at their apogee or objects with varying eccentricities such as those with high area-to-mass ratios. For these objects, an assumed circular orbit (ACO) prediction would not be accurate. The new method of observing entails using normal-operation survey mode detections and propagating the orbits to obtain specific right ascensions and declinations to look for follow-up observations. During the follow-up observations, longer arcs are obtained and thus more accurate orbits are calculated. Beginning in July 2005, the MODEST team successfully completed real-time survey and follow-up observations in an effort to establish better orbit predictions for GEO debris.

During the July 2005 run, survey mode (normal-operations) was conducted for the first few hours of the night. Using ACO predictions, successful follow-up observations were conducted on those previously detected objects on the same night. With only a circular orbit propagator available, two targets were recovered both with circular orbits. During the October 2005 run, the first night was completed in survey mode. Using an ACO prediction, MODEST was used in follow-up mode on the second and third night specifically targeting the fields where the projected orbits placed the objects. On night one, nine objects were detected, of which five were reacquired on the later nights. Two of the objects were circular UCTs and the other three were circular CTs. The January 2006 survey and chase run was conducted similarly to the October 2005 run where the survey was completed on night one and the follow-up observations were conducted on the subsequent nights. By acquiring a 24-hour arc of data, it was possible to use the eccentric orbit propagator to calculate the orbit. Unfortunately, none of the objects recovered were UCTs. These processes prove that real-time detection is possible with this telescope and also demonstrated that fast reacquisition of an object is feasible. ♦

Calculating Statistical Orbit Distributions Using GEO Optical Observations with the Michigan Orbital DEbris Survey Telescope (MODEST)

M. MATNEY, E. BARKER, P. SEITZER, K. ABERCROMBY, & H. RODRIGUEZ

NASA's Orbital Debris measurements program has a goal to characterize the small debris environment in the geosynchronous orbit (GEO) region using optical telescopes ("small" refers to objects too small to catalog and track with current operational systems). Traditionally, observations of GEO and near-GEO objects involve following the object with the telescope long enough to obtain an orbit suitable for tracking purposes. Telescopes operating in survey mode, however, randomly observe objects that pass through their field-of-view. Typically, these short-arc observations are inadequate to obtain detailed orbits, but can be used to estimate approximate circular orbit elements (semi-major axis, inclination, and ascending node). From this information, it should be possible to make statistical inferences about the orbital distributions of the GEO population bright enough to be observed by the system.

The Michigan Orbital DEbris Survey Telescope (MODEST) has been making such statistical surveys of the GEO region for four years. During that time, the telescope has made sufficient observations in enough areas of the GEO belt to have achieved nearly complete coverage. That means that almost all objects in all possible orbits in the GEO and near-GEO region had a non-zero chance of being observed. Some regions (such as those near zero inclination) have had good coverage, while others are poorly covered. Nevertheless, it is possible to remove these statistical biases and reconstruct the orbit populations within the limits of sampling error.

In this paper, these statistical techniques and assumptions are described, and the techniques are applied to the current MODEST data set to arrive at our best estimate of the GEO orbit population distribution. ♦

Statistical Inference in Modeling the Orbital Debris Environment

Y.-L. XU

Reliable information on orbital debris (OD) populations, such as the spatial density, flux, size, and shape distributions, is important for satellite impact risk assessments. Research concerning the characterization of the OD environment often deals with problems of a statistical nature. For example, the NASA Orbital Debris Engineering Model, ORDEM2000, is based on OD populations derived statistically from ground-based and in situ measurements through a maximum likelihood estimator. Also, the size distribution of the OD objects detected by Haystack radar is estimated by a statistical size estimation model from the measured radar cross section (RCS) distributions. This paper reviews three statistical approaches that have been used for the statistical inference of the Haystack radar OD data, and discusses their respective pros and cons. These include: (1) the Generalized Linear Model, (2) the Expectation Maximization algorithm for solving linear inverse problems with positive constraints, which was used in the development of ORDEM2000, and (3) a Bayesian approach that is a simple application of the multiplicative rule of probability and Bayes' theorem.

Common to all three statistical inference processes mentioned above, the key quantity required is the probability density function (PDF) specifying the contribution of a given model parameter to a given observed quantity, which can be either empirical or theoretically calculated. The estimation of the Haystack debris populations requires the probability of an object in an orbit of given orbital elements to be detected in a given bin of radar measured range and range-rate values. The inference of a size distribution from an observed RCS distribution requires a similar but different type of distribution density function. In addition to the discussion on statistical algorithms, this paper also discusses the procedure for the construction of the conditional PDF, using the RCS density function as an example. Practical examples on the RCS analysis are included in the paper. ♦

Comparison Between New Satellite Impact Test Results and the NASA Standard Breakup Model

Y. TSURUDA , T. HANADA , Y. AKAHOSHI, & J.-C. LIOU

This paper summarizes two new satellite impact tests. The objective of the tests was to investigate the outcome of low- and hyper- velocity impacts on two identical target satellites and to compare the analyzed results of fragments from those two impact tests with the NASA Standard Breakup Model. The targets were cubed micro satellites (150×150×150 mm, 740-gram in mass) developed in Kyushu University. The low-velocity impact experiment was performed at an impact velocity of 1.45 km/s using the projectile made of aluminum alloy (solid sphere, 30 mm in diameter, 39.2-gram in mass). The hyper-velocity impact experiment was performed at an impact velocity of 4.44 km/s using the projectile made of aluminum alloy (solid sphere, 14 mm in diameter, 4.0-gram in mass). Those two impact experiments were performed by the two-stage light gas gun in Kyushu Institute of Technology. The ratios of impact energy to target mass for those two impacts were approximately the same, and both target satellites were completely fragmented. Approximately 3000 fragments from each impact experiment were collected. The largest 1500 fragments from each experiment were weighed, and measured in size based on the analytic method used in the NASA Standard Breakup Model. The analysis results and comparisons with the NASA Standard Breakup Model are included in the paper. The differences in target property between low- and hyper-velocity impacts are also summarized. ♦

MEETING REPORTS

10th International Symposium on Materials in a Space Environment (ISMSE)
19-23 June 2006, Collioure, France

This meeting was in conjunction with the 8th International Conference on Protection of Materials and Structures in a Space Environment. The one-week conference had a variety of topics including new materials, charging, synergetic effects, contamination, radiation, atomic oxygen, ground testing, flight experiments, and micrometeoroids and debris. Three talks and four posters were dedicated to space debris research, mostly hypervelocity impact effects. Y. Michel, of CNES, discussed the effects of hypervelocity impacts on brittle materials. R. Verker, from the Space Environment Group in Israel, talked about the synergistic effects of hypervelocity impacts and atomic oxygen on the durability of nanocomposites. The final debris talk given by S. Katz was on the effects of hypervelocity impacts on fiber/epoxy composite materials. ♦

2006 National Space & Missile Materials Symposium (NSMMS)
26-30 June 2006, Orlando, Florida, USA

The National Space and Missile Materials Symposium was in conjunction with the overview of the MISSE (Materials on International Space Station Experiment) flight reviews. This conference dealt strictly with the United States' efforts in the area of material interaction with the space environment. Although there were no debris-specific talks, many of the talks were of interest to the debris community. S. Evans delivered a talk regarding the Impact Testing Facility at NASA Marshall, where they house four guns (microlight gas gun, light gas gun, large ballistic gun, and small ballistic gun). In addition, G. Pippin gave an overview talk on the MISSE flights already flown. The MISSE flights are using the International Space Station as a platform for on-orbit materials experiments. Mr. Pippin mentioned seeing one debris hit from the early missions and will examine the newest flight hardware for more hits. ♦

36th COSPAR Scientific Assembly
16-23 July 2006, Beijing, China

The 36th COSPAR Scientific Assembly was held in Beijing, China on 16-23 July 2006. The Space Debris Program was organized by H. Klinkrad and N. Johnson. A total of 43 papers, including 28 oral presentations and 15 posters, were presented during the one and a half day space debris sessions. Presented material included reports on optical and radar surveillance programs, long-term debris environment modeling, impact tests, *in situ* measurements, and resident space object material studies. It is expected that most of the papers will be submitted to a Space Debris edition of *Advances in Space Research* for peer review and publication. ♦

INTERNATIONAL SPACE MISSIONS
July - 24 September 2006

International Designator	Payloads	Country/ Organization	Perigee (KM)	Apogee (KM)	Inclination (DEG)	Earth Orbital Rocket Bodies	Other Cataloged Debris
2006-028A	STS 121	USA	332	351	51.6	0	0
2006-029A	GENESIS I	USA	556	561	64.5	1	1
2006-030A	COSMOS 2422	RUSSIA	568	39770	62.9	2	4
2006-031A	KOMPSAT2	S. KOREA	675	702	98.1	1	0
2006-032A	HOT BIRD 8	EUTELSAT	35776	35797	0.0	1	1
2006-033A	JCSAT 10	JAPAN	35785	35788	0.0	1	1
2006-033B	SYRACUSE 3B	FRANCE	35777	35796	0.0		
2006-034A	KOREASAT 5	S. KOREA	35746	35807	0.0	1	0
2006-035A	SJ-8	CHINA	178	441	63.0	1	5
2006-036A	STS 115	USA	334	350	51.6	0	0
2006-037A	IGS 3A	JAPAN	NO ELEMS. AVAILABLE			1	2
2006-038A	ZHONGXING 22A	CHINA	35744	35810	0.4	1	0
2006-039A	COSMOS 2423	RUSSIA	210	327	64.9	1	1
2006-040A	SOYUZ-TMA 9	RUSSIA	334	350	51.6	1	0
2006-041A	SOLAR-B (HINODE)	JAPAN	319	686	98.3	1	0
2006-041C	SS SAT	JAPAN	319	686	98.3		
2006-041D	HITSAT	JAPAN	319	686	98.3		

2006 Advanced Maui Optical and Space (AMOS) Surveillance Technologies Conference
10-14 September 2006, Wailea, Maui, Hawaii, USA

The 2006 Advanced Maui Optical and Space (AMOS) Surveillance Technologies Conference covered a wide range of topics dealing with Space Situational Awareness (SSA) including SSA systems and programs, telescopes and sensors, astronomy, imaging, lasers, Pan-STARRS, adaptive optics, orbital debris, non-resolved object characterization, and satellite metrics. Within the orbital debris section, there were seven papers and one poster. T. Schildknecht, of the Astronomical Institute (University of Bern), gave a talk on the recent results from the ESA optical space debris survey describing the current work on the high area-to-mass (A/M) objects. This talk was followed by T. Kelecy of Boeing LTS who spoke of orbit predictions and analysis of the A/M objects where the ultimate goal is to provide long-term, accurate orbital histories of the pieces. E. Barker (NASA JSC) detailed a study of finding the uncorrelated targets associated with the Titan break-up. During the 2002 data examined, one object was identified as a likely candidate. K. Poole of Northrup Grumman Corporation spoke of a study where three different types of geosynchronous orbit (GEO) searches (one-dimensional scan centered on the belt, one-dimensional scan offset from the belt, and a square wave scan pattern) were examined to determine the optimum search strategy. It was determined that depending on the type of data for which you are searching, each method has its advantages and disadvantages with no clear strategy being the best overall. A. Nakajima (JAXA) described Japan's newest array of telescopes as well as their new strategies for searching for faint GEO objects. The *in situ* observations of space debris conducted by ESA were discussed by G. Drolshagen. According to their test on GORID in GEO, an average of 2.5 debris hits occur each day. The final talk of the session was given by C. Wiedemann of the Institute of Aerospace Systems (Technical University of Braunschweig) about the reflectivity of NaK droplets, which was found to be 92-98% depending on the alloy present and the temperature of the surface. A poster on light curves of pseudo-space debris was presented by H. Rodriguez of ESCG/Jacobs. These measurements were the first part in a larger study to develop an optical size estimation model without the dependence on the albedo. ♦

ORBITAL BOX SCORE
(as of 20 SEP 2006, as cataloged by US SPACE SURVEILLANCE NETWORK)

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	54	322	376
CIS	1360	2865	4225
ESA	36	36	72
FRANCE	44	309	353
INDIA	31	108	139
JAPAN	96	85	181
US	1028	3038	4066
OTHER	360	28	388
TOTAL	3009	6791	9800

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UPCOMING MEETINGS

14-16 May 2007: The 2nd International Association for the Advancement of Space Safety (IAASS) Conference, Chicago, Illinois, USA.

The conference is an invitation to reflect and exchange information on a number of topics in space safety that are of national and international interest. Among the topics to be discussed are space debris environment and spacecraft reentry. Additional information is available at http://www.congrex.nl/07a02/.

23-27 September 2007: Hypervelocity Impact Symposium (HVIS), Wiliamsburg, Virginia, USA.

This biennial symposium is dedicated to enabling and promoting an understanding of the basic physics of high velocity impact and related technical areas, including spacecraft shielding design and orbital debris environment. More information can be found at http://hvis.org/HVIS_07/index.html.

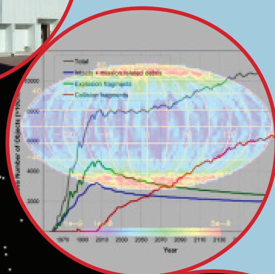
National Aeronautics and Space Administration

orbital debris research

For more than a quarter century NASA has taken the international lead in orbital debris environment characterization and in developing the technical consensus for adopting mitigation measures to protect users of near-Earth space. Since 1994 the growth of the orbital debris population and means to curtail it have been topics of annual discussion at the United Nations. Work at NASA continues with the development of an improved understanding of the risks of orbital debris and the implementation of design and operational countermeasures. The focus of these activities is the Orbital Debris Program Office, located at the NASA Lyndon B. Johnson Space Center in Houston, Texas.

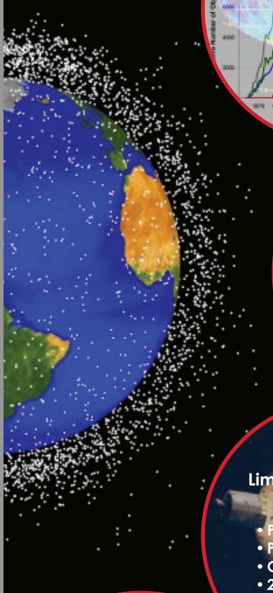
Measurements

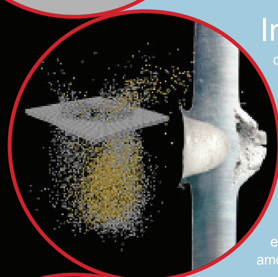
Measurements of the near-Earth orbital debris population are accomplished using ground-based radars and optical telescopes, space-based experiments, and analysis of spacecraft surfaces returned from space. Some important data sources have been the U.S. Space Surveillance Network, the Haystack Radar, Haystack Auxiliary Radar, Goldstone Radar, Michigan Orbital Debris Survey Telescope, and returned surfaces from the Long Duration Exposure Facility (LDEF) and Space Shuttle windows. The data provide the basis for the environment models and identify the presence of new sources. The NASA Orbital Debris Program Office is pioneering remote sensing research that attempts to determine debris shape and material composition.



Modeling

NASA scientists continue to develop and upgrade orbital debris models to describe and characterize the current and future debris environment. Engineering models, such as ORDEM2000, can be used for debris impact risk assessments for critical satellites, including the International Space Station and the Space Shuttle. Evolutionary models, such as LEGEND, are designed to predict the future debris environment. They are reliable tools to study how the future debris environment reacts to various mitigation practices.





Impact Phenomenology

Even small orbital debris can cause serious damage to spacecraft due to high collision velocities, typically 10 km/s or more in low Earth orbit. Such collisions are called hypervelocity impacts and are usually responsible for the creation of even more orbital debris. Using sophisticated light-gas guns and shaped charges, NASA can study the effects of hypervelocity impacts here on Earth. Complex computer simulations called hydrocodes are also helpful in predicting the consequences of debris impacts on spacecraft structures. Equally important, this research can be used to evaluate new materials and shield designs for their effectiveness in protecting critical components with the least amount of mass.

Mitigation

Limiting the growth of the future orbital debris population is a high priority for NASA, the United States, and the major space-faring nations of the world to preserve near-Earth space for future generations. Mitigation measures can take the form of curtailing or preventing the creation of new debris, designing satellites to withstand impacts by small debris, and implementing operational procedures ranging from utilizing orbital regimes with less debris, adopting specific spacecraft attitudes, and even maneuvering to avoid collisions with debris. Limiting the presence of new debris in low Earth orbit to less than 25 years is an important mitigation measure.

Reentry

Because of the increasing number of objects in space, NASA and other international space agencies have adopted guidelines and procedures to reduce the number of non-operational spacecraft and rocket stages orbiting the Earth. Although the majority of most satellites cannot tolerate the extreme conditions of reentry into the Earth's atmosphere, some components, particularly those with high melting temperatures, can survive to impact the surface of the Earth at high velocities. Such components pose a risk of causing damage or injury if they land in populated areas. The NASA Orbital Debris Program Office utilizes a reentry survivability model called ORSAT to determine which components or fragments are likely to strike the ground and the extent of the debris field. This model also supports NASA's "design to demise" engineering philosophy to reduce the risk from future reentries.

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