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INSIDE...

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Recent Satellite Breakups

On 15 April a decommissioned US Defense Meteorological Satellite Program (DMSP) spacecraft suffered a moderate breakup, resulting in the creation of dozens of debris. Known as USA 73 (International Designator 1991-082A, US Satellite Number 21798), the approximately 850 kg spacecraft was in a nearly circular orbit at an altitude of about 840 km and an inclination of 98.7º. By 26 May a total of 56 debris had been officially cataloged by the US Space Surveillance Network (SSN).

Figure 1 illustrates the relatively wide dispersion of the debris, extending 200 km above and below the pre-breakup orbit. The debris cloud was slightly asymmetric with twice as many debris being thrown to higher orbits than ejected into lower orbits. On the other hand, exactly half the debris moved into orbits with greater inclination and half into orbits with less inclination.

The most likely causes of the breakup were a collision with a small man-made or natural object or an explosion involving an on-board energy source. Whereas the former cause cannot be ruled out, the potential sources of an explosion have been evaluated and most have been eliminated. The batteries had been discharged and disconnected from the charging circuit. Virtually no nitrogen remained on board due to a leak detected early in the mission of USA 73. The most likely energy source for an explosion was approximately 6 kg of residual hydrazine, nearly 40% of the nominal hydrazine load for this type spacecraft.

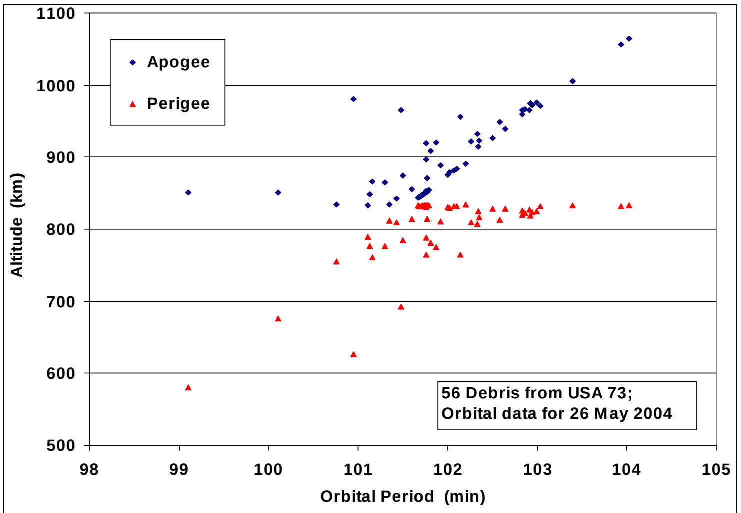

Figure 1. Dispersion of debris from USA 73 breakup.

Yet another Proton Block DM auxiliary motor broke-up on 10 July, creating more than 100 new debris. The source of this event, the 30th for this class of objects, was one of the two auxiliary motors used for the Cosmos 2204-2206 mission in 1992. The International Designator of the object is 1992-47G, and the corresponding US Satellite Number is 22066. The sister motor for this mission broke-up nearly 10 years earlier on 8 November 1994.

Although no debris from this breakup had been officially cataloged as of 30 September, orbits for a total of 30 objects had been defined by the SSN within five days of the event. The orbit of 1992-47G at the time of the event was 415 km by 18,820 km at an inclination of 64.9º. ♦

Burton G. Cour-Palais, 18 April 1925 - 20 July 2004

Burton G. Cour-Palais

D. KESSLER,
E. CHRISTIANSEN,
J. CREWS

The orbital debris community has lost another member whose contributions helped shape current orbital debris research. Burt Cour-Palais passed away on 20 July 2004. Most people will remember Burt for his internationally recognized contributions to hypervelocity research; however, few likely realize that Burt also help set the stage for what eventually grew into the orbital debris program of today.

Burt was born a British citizen in India, where he also attended college. After graduating, he worked for several aircraft companies in England and Canada as a structural engineer before going to NASA Langley in 1960. The next year he transferred to what would eventually be known as the Johnson Space Center (JSC) in Houston, Texas where Burt began his meteoroid and hypervelocity research.

In 1961, the hazards to man in space from meteoroids were unknown; one of the first experiments at JSC to help understand that hazard was to lay

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NEWS

Burton G. Cour-Palais

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a space suit on the ground and shoot it with a shotgun. While this experiment may not have provided any useful results, it is a reflection of the state of the art when Burt began his research. One of the first things Burt did was to provide the design and requirements for the "west wing" of JSC Building 31, which became the original hypervelocity laboratory at JSC. It was here that Burt was able to conduct the many experiments that helped lead to the equations still used today to describe the effects of hypervelocity impacts on aluminum bumper configurations.

During the early 1960s there were two very different models describing the meteoroid environment. One, based on what was known as acoustical sensors, predicted a large hazard for manned missions. The other, based on penetration sensors, predicted only a moderate hazard for the then-planned missions. Perhaps because of Burt's knowledge of hypervelocity penetrations, he was one of those who believed the lower hazard was correct. To test that belief, he organized and participated in the examination of the surfaces of the recovered Mercury spacecraft for hypervelocity impacts, especially the window on the spacecraft. These examinations supported the lower hazard. At the same time, Burt's responsibilities increased: in 1964, Burt was appointed Assistant Chief of the Meteoroid Environment Section; in 1965, Manager of Apollo Subsystem Meteoroid Protection; and in 1967, Chief of the Meteoroid Sciences Branch; members included Herb Zook and Don Kessler, who could both point to Burt as inspiring their interest in the field.

As Manager of Apollo Subsystem Meteoroid Protection, Burt established the basis of the meteoroid/debris risk assessment process. That process formulated the protection requirements for the Apollo vehicles (Command Module-Service Module, Lunar Module) and the astronaut's space suit from the meteoroid and lunar surface secondary environment models and hypervelocity impact models. The process included developing ballistic limit equations and the use of extensive hypervelocity testing to understand the response of spacecraft structures to meteoroid impact, and to identify what needed to change in order to meet requirements. This process is followed to this day by all space-faring nations.

In 1966, NASA Headquarters identified a need for a "monograph" describing the meteoroid environment. The purpose of this monograph was to establish the best interpretation of all meteoroid experiments and a baseline meteoroid environment for all spacecraft operations. Burt was asked to write it, which he did with the help of an ad hoc committee. It was published as NASA SP-8013, *Meteoroid Environment Model – 1969 (Near Earth to Lunar Surface)*. This environment became the recommended meteoroid environment model for all spacecraft for the next 25 years. It was supplanted during the design of the International Space Station, where Burt's environment was replaced with a slightly modified environment model with roots in research conducted by members of Burt's Branch. Burt encouraged Branch members to conduct independent research; he was always more concerned about determining scientific truth than receiving credit.

In late 1969, Apollo 12 returned parts of the Surveyor 3 spacecraft that had been placed on the moon 2-1/2 years earlier. Burt was requested by JSC management to lead a team to examine those Surveyor parts for meteoroid impacts. The results of the examination confirmed Burt's lower meteoroid environment model predictions on the lunar surface. In October 1970, JSC management abolished the Meteoroid Sciences Branch, commenting that its members had done such a good job defining a lower spacecraft hazard that they were no longer needed.

Burt was able to continue limited meteoroid research for a few years before being transferred to the Environmental Effects Project Office, headed by Drew Potter. There, Burt was responsible for defining and documenting the environmental concerns in the Earth's troposphere that the Space Shuttle program would cause. To do this, Burt conducted a large workshop, and published the results of that workshop. Those results became part of the Shuttle Environmental Impact Statement that was required by new federal law. It was in this office that Don Kessler and Burt began work on their own initiative to describe the environmental impact of leaving debris in orbit. This initial debris work was published in the Journal of Geophysical Research in 1978 … just after the Environmental Effects Projects Office, having completed its assigned task, was abolished by JSC management.

Burt was then transferred to the Technical Planning Office, under Joe Loftus. Part of his responsibility there was to prepare a 10-year program plan for orbital debris research in an attempt to get funding from NASA Headquarters. The next year, the program was approved by the JSC Center Director and orbital debris research found its home under Don Kessler within the newly formed Space Sciences Branch, headed by Drew Potter. Later that year, NASA Headquarters approved the first funding for the program. In 1983, Burt transferred to the Space Science Branch, and began working with Jeanne Crews and Eric Christiansen who were rebuilding the hypervelocity gun facilities at JSC, and beginning to test composite materials. Once again, after 13 years, Burt was able to conduct the hypervelocity research that he loved. Burt, Jeanne, and Eric began researching new ways to design spacecraft shielding, and discovered the innovative shield design using several layers of a ceramic fabric as a bumper material in place of aluminum.

Burt retired from NASA in 1989, but he didn't retire from hypervelocity work. For the next five years, he worked for McDonnell Douglas supporting the design of the shields for the Space Station. After that, he continued to consult with NASA on hypervelocity issues through Southwest Research Institute (SwRI). In 1996, Burt received the Distinguished Scientist Award from the Hypervelocity Impact Society. When he died, he was enthusiastically compiling a reference list of important hypervelocity research for SwRI as well as reviewing the ballistic limit equations used in BUMPER code to assess Shuttle meteoroid/orbital debris risks.

Burt will be missed by many. We owe him a debt that can best be repaid by our continuing the quality of work he maintained, the enthusiasm he exhibited, and the giving of our best for the love of the job. ♦

Caricature of Burt by Pat Rawlings, presented to Burt at his retirement party.

PROJECT REVIEWS

Reentry Survivability Analysis of the Hubble Space Telescope (HST)

R. SMITH, K. BLEDSOE, & J. DOBARCO-OTERO

The Hubble Space Telescope (HST) was launched in 1990 on Space Shuttle Discovery during Flight STS-31 to an orbit of 569 km altitude and an inclination of 28.5º. The HST is part of the NASA Origins mission to learn more about the history and origin of the universe. The HST has been serviced four times since launch, the last time in March 2002. Engineers from the NASA Orbital Debris Program Office were tasked to calculate the risk to human population should the HST reenter the Earth's atmosphere in an uncontrolled manner.

The reentry survivability analysis was performed with the NASA Object Reentry Survival Analysis Tool (ORSAT), version 5.8. The analysis broke the satellite into 627 different objects, and was performed to assess compliance with the NASA Safety Standard (NSS) 1740.14 Guideline 7-1.

This analysis assumed an uncontrolled reentry (orbital decay) for the satellite at an altitude of 122 km. The parent body was modeled with an estimated mass of 11,792 kg, a length of 12.9 m, and a diameter of 4.6 m. A standard breakup altitude of 78 km was considered, at which point all the primary spacecraft components were exposed to reentry heating. In many cases, fragmentation of sub-components occurred. Approximately 75% of the total mass was analyzed and another 16% was accounted for but not modeled.

A 1-D heat transfer model was used to model the heat conduction in the fragments. An object was assumed to demise when the absorbed heat (net heat rate flux integrated over time multiplied by its surface area) was greater than or equal to the heat of ablation of the object.

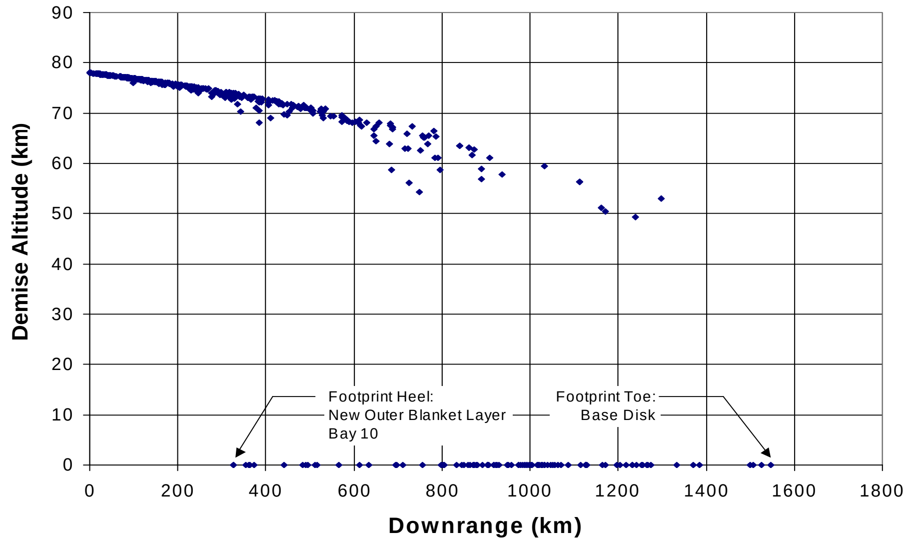


Figure 1. Demise altitude vs. downrange for analyzed HST objects.

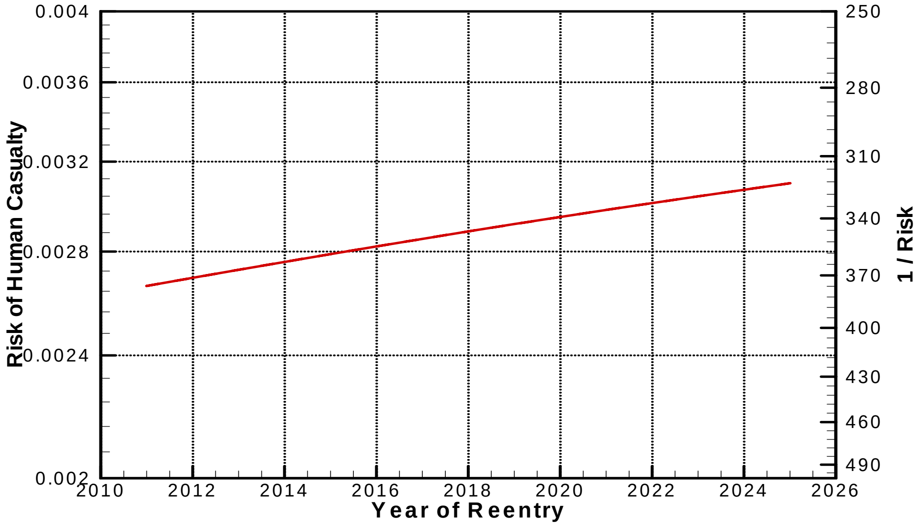


Figure 2. Calculation of the risk to the population as a function of the reentry year.

A total of 2055 kg of mass is predicted by the analysis to survive reentry and produce a debris casualty area of 156 m^2 and a footprint length of 1220 km. A plot of demise altitude versus downrange from breakup for all HST objects can be seen in Figure 1. Most objects are shown to demise above 50 km in altitude. Of those that survive, the objects with the lowest ballistic coefficient will comprise the heel of the footprint and the objects with the highest ballistic coefficient will comprise the toe of the footprint. A number of these objects impact with a kinetic energy below an established casualty threshold limit of 15 J. For the purpose of calculating risk, the casualty area contributed by these objects can be ignored. The resulting total debris casualty area for objects that impact the ground with an impact kinetic energy above the 15-J casualty limit is 146 m^2.

Figure 2 displays the risk of an HST reentry for the years ranging from 2011 to 2025. The risk is shown to increase each year due to a predicted increase in population. This risk ranges from 1:375 in the year 2011 to 1:325 in the year 2025. Based upon the latest configuration and orbit of HST and on solar activity projection, HST is expected to reenter Earth's atmosphere around the year 2020. With the inclination angle of 28.5º and the expected reentry date of 2020, the resulting risk to the population is 1:340. Since only 75% of the mass was analyzed, the remaining 25% poses a possible risk. If the risk from the remaining mass is scaled based on the risk of the analyzed mass, then the resulting weighted risk posed to the human population in the year 2020 is 1:250. This risk exceeds the risk of 1:10,000 cited in NASA Safety Standard 1740.14. ♦

An Assessment of the Role of Solid Rocket Motors in the Generation of Orbital Debris

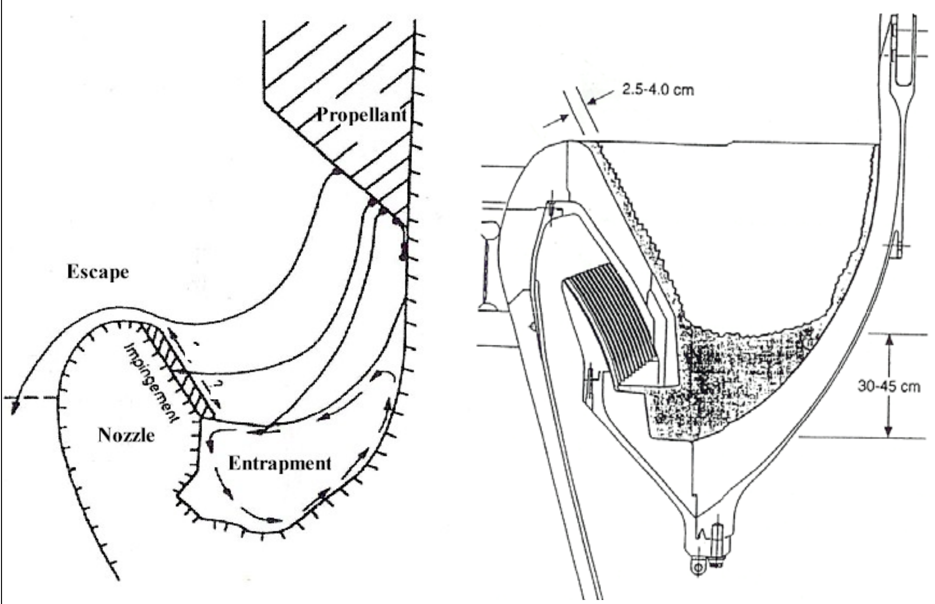
M. MULROONEY

It has been known for some time that solid rocket motor (SRM) effluent contributes to the orbital debris environment. Heretofore, attention has primarily been focused on the very smallest components of the solid emissions – the main burn phase exhaust. It is this phase that drives SRM design and consequently it is the dust-like products (diameter, D < 100 µm) of this phase that are best understood. The emission of larger particles (100 µm < D < 5 cm), which constitute a much more significant orbital debris hazard, is the result of various mechanisms which are only partially understood. The lack of a rigorous analytical model describing the generation of large particle emissions and thereby the absence of quantitative assessments, has led to a conservative approach to the inclusion of large SRM particles in the definition of the orbital debris environment. An investigation performed by the NASA Orbital Debris Program Office during FY2004, via an intensive collection and assimilation of SRM-related data and resources, has led to a partial resolution of the uncertainties surrounding SRM particulate generation - sufficiently so to enable a first-order incorporation of SRMs as a source term in space debris environment definition.

SRM exhaust consists of two phases – gaseous and solid particulate. The quantity, size, and relative proportion of the solid component, expressed as the time-dependent size distribution function, varies as the SRM progresses from ignition, through its main burn, to Tail-off and eventual termination. The solid propellant consists of an oxidizer (typically ammonium perchlorate, AP), powdered aluminum fuel (Al), and a combustible hydrocarbon binder (e.g. Hydroxyl-terminated polybutadiene, HTPB). These ingredients are mixed in a semi-liquid state and then cast into the rocket motor, solidifying into various predetermined configurations chosen to yield various burn rates and profiles. The primary combustion products are gaseous oxides of carbon (CO and CO_2), water vapor, and solid particulates of aluminum oxide (Al_2O_3). Since aluminum constitutes normally between 16 and 18% of SRM propellant, its oxidation product (Al_2O_3) accounts for 30-34% of the combusted and then ejected propellant mass (based upon the molecular weights of Al and O: 27 and 16 amu, respectively). Understanding the size and velocity distributions of what can amount to several tons of solid particulate emissions per SRM firing (e.g. 3200 kg for an Type-1 Inertial Upper Stage, IUS, SRM) is critical to assessing the orbital debris environment.

SRMs are generally designed to yield a smooth thrust profile with maximum integrated impulse within as compact and efficient a package as possible. Although the burn rate may be tailored to provide variable thrust (eg. Space Shuttle SRB thrust is decreased during maximum dynamic pressure), it is imperative that output be well-behaved, i.e., absent any anomalous pressure pulses or deficits. With this unanimity of focus, engineers optimize those performance parameters associated solely with the main phase of the SRM burn. What occurs after this phase has generally been considered ancillary and of marginal interest from a design perspective. Consequently, behaviors can and are introduced which are undesirable from an orbital debris perspective. Specifically, the almost universal use of re-entrant or immersion nozzles, wherein thrust continuity is improved and motor length is reduced by moving the forward end of the motor nozzle well inside the motor chamber, has deleterious consequences.

In the immersion nozzle design, the point where the nozzle nosetip penetrates the combustion chamber is surrounded by a toroidal shaped volume which acts as a catchment basin that entraps burning propellant particles in the aft end of the SRM. The resultant flow of dual-phase exhaust gas and particulates into and out of this reservoir has been extensively modeled in the viscous and inviscid regimes and is well documented[1]. While the re-entrant nozzle does inhibit the ability of large condensates to exit the nozzle intact (and thereby reduces pressure pulsing), the resultant circulation zone enables the accumulation of molten aluminum oxide and unburned aluminum in the form of slag around the nozzle (Figure 1a). Based on empirical measurements acquired via dozens of static ground tests[1], the resultant slag pool can collect between 0.12 and 1.9% of the Al_2O_3 emissions - corresponding to between 0.04 and 0.65% of the initial propellant mass. For the Type-1 IUS this can amount to a mass of as much as 60 kg and a volume of roughly 38 liters (assigning 1.6 g/cc as the nominal slag density). The slag pool is readily and consistently measured in static-ground tests (after quenching) for all re-entrant style SRMs as a solid annular slug of material (Figure 1b.). It is important to emphasize that although the degree of accumulation varies wildly (even for SRMs of the same type) for reasons which are still not fully understood, the accumulation of slag is assured - regardless of SRM design or orien-



Figures 1a and 1b. (1a) Streamlines illustrating the trajectory of combustion gas and burning aluminum agglomerates. Most particles escape the chamber unhindered, while others impinge on the walls, interior portion of the nozzle, or enter the circulation zone in the immersion reservoir. (1b) The net result is the formation of a slag pool which accumulates from the start of the main burn phase[1].

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Solid Rocket Motors

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tation relative to the gravity vector – indicating recirculation zone fluid-dynamic processes dominate.

SRM design is a delicate compromise between slag accumulation and thrust continuity. Immersing the nozzle reduces pressure oscillations, but as a corollary, the accumulated slag reduces SRM specific impulse by representing an excess load and lost propellant conversion efficiency. In fact, for some flight tests it is via telemetry that slag accumulation has been assessed by comparing the deviation between the actual track and that predicted in the absence of slag formation. The sloshing slag pool has also been identified as the likely cause of large coning errors in some spin-stabilized SRMs[2]. Overall, the trade-off in terms of performance favors the immersion design, however from an orbital debris perspective the residual slag represents the primary source term for the generation of objects of sufficient size and quantity to qualify as an orbital debris hazard. Although the detailed mechanism of ejection is still being investigated, the preponderance of available evidence indicates that in space firings the accumulated slag is ultimately liberated from SRMs in the form of numerous 100 μm to 5 cm diameter debris objects.

From a space environment standpoint there are two identifiable processes by which slag is transformed into orbital debris. The first involves the loss of slag during the SRM main burn phase due to the onset of instabilities in the slag pool. The second occurs during the Tail-off phase and is due to boil-over of the slag pool in the ambient low pressure Tail-off environment. In fact, a general consensus that slag was ejected at Tail-off by boiling-related processes was reached as early as 1994[3]. The support for these particulate generation mechanisms and their regimes of operation come from a variety of sources including theoretical modeling, static ground-test imagery (vacuum and non-vacuum, covering all spectral regions from X-Ray through Infrared), static ground-test particle collection, ground-based imagery of sub-orbital SRM firings, and in-situ imagery of sub-orbital and orbital insertion SRMs.

Figure 2. Space Shuttle SRB slag emission at SRB separation +30.5 sec. Chamber pressure < 6.9 kPa. Numerous Tail-off ejecta are clearly resolved as the plume brightness fades. Ejecta continue to stream from the SRBs, although at a reduced rate, for several minutes.

A wealth of empirical evidence indicates that by the time the chamber pressure has declined to below 6.9 kPa (1 psia), the slag pool has completely boiled, its contents have spread throughout the chamber, and they have already begun to diffuse out the nozzle. Because in the low pressure Tail-off environment these particles are not subject to shearing forces[4] (and may already have cooled below the melting point), they leave the SRM undisrupted and can be of very large (cm) size. Unlike dust creation via normal propellant burning, this mode of SRM particle generation is capable of producing very large quantities (> 10^5 per event) of orbital debris in a size range (500 μm < D < 5 cm) which poses a significant debris hazard. Figures 2 and 3, representing two examples of both ground and in-situ imagery, show the qualitative nature of large particulate Tail-off emissions.

The ultimate objective of this research endeavor into the analysis of SRMs as a source of orbital debris has been to provide NASA with information sufficient to enable an incorporation of SRM emissions as a source term in environment definition models. Although the details are beyond the scope of this article, the key conclusions are as follows:

1) Large particle emissions (100 μm < D < ~5 cm) from SRMs occur during Tail-off. Furthermore, large particulate emissions do not occur in significant quantity during the main burn phase of SRM activity, including losses via nozzle streaming and bulk slag ejections.

2) The available mass for the generation of large SRM particulates is related to the volume of slag that accumulates in the immersion nozzle reservoir. Static-ground tests and telemetry of flight motors indicates that between 0.04 and 0.65% of the initial propellant mass is accumulated as slag. This mass is available for conversion to large Tail-off ejecta.

3) The emission of most large SRM particulates occurs during Tail-off at chamber pressures below 34.5 kPa. Empirical measurements, conducted by analysis of time sequences of individual slag particle motions, indicate a representative velocity envelope for these particles of approximately 0-100 m/s. The distribution is weighted toward the lower end of the range possibly because the bulk of observed emissions occur at almost negligible chamber pressures of less than 6.9 kPa.

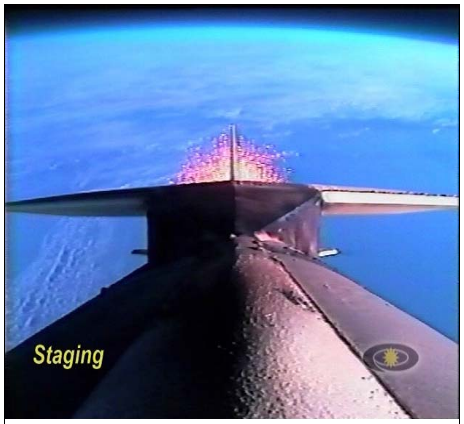

Figure 3. Pegasus Launch Vehicle (First Stage). Bulk large particle emission at Tail-off +15.5 sec.

4) Empirical observations and physical arguments indicate that the majority of Tail-off emissions occur during the 30 second period that begins as the chamber pressure declines below approximately 34.5 kPa and on to ambient (vacuum) conditions. Although emissions persist for several minutes, the flux peaks broadly at thousands of particles per second at or below 6.9 kPa and then declines rapidly to dozens per second.

5) A luminosity-time blackbody analysis of Space Shuttle SRB ejecta indicates these particulates have diameters of order 2-5 cm. Measurements of Tail-off particulates recovered after a static vacuum chamber ground test of a Star-37 SRM indicated particle diameters from 1 mm to 1.5 cm. Physical arguments place a lower range near 100 μm. Therefore, essentially all Tail-off ejecta reside between approximately 100 μm and 5 cm diameter and thus can be of a size sufficiently large to pose an orbital debris threat.

It remains to obtain an empirical size distribution function via measurements of static ground test SRM firings in high-altitude test cells (e.g., those at Arnold Engineering and Development Center)[5]. In the interim a trial power law distribution (i.e. 1/mass) is suggested for preliminary incorporation into the predictive environment models.

1. Salita, M., *Deficiencies and Requirements in Modeling of Slag Generation in Solid*

See SRM on page 10

Searching for Faint Debris in the GEO Ring

P. SEITZER

Since February 2001, the **M**ichigan **O**rbital **DE**bris **S**urvey **T**elescope (**MODEST)** has been dedicated to an optical survey of debris in the geosynchronous (GEO) regime. A description of the project can be found in the ODQN Vol. 8, Iss. 1, page 8. Briefly, the facility is the University of Michigan's 0.6/0.9-m classical Curtis Schmidt telescope located at Cerro Tololo Inter-American Observatory in Chile. Normally the telescope takes 5 second long exposures every 37.9 seconds with a scanning CCD through a broad R filter, leading to a limiting magnitude for signal to noise ratio = 10 of R = 18th magnitude on clear nights.

One night of every observing run is dedicated to a 1.3º high scan along the region of the GEO station-keeping ring visible from Chile. The purpose is to search for all objects close to the ring, with special interest in faint debris. We are looking for objects such as panels, insulation blankets, covers, etc., which might have separated at low velocity from an active spacecraft.

The previous article discussed the data taken on four nights between November 2002 and March 2003. No objects were found fainter than R = 13th magnitude in this sample.

Beginning in September 2003, the scan procedure was changed by increasing the exposure time to 20 seconds from 5 seconds, in order to detect fainter objects. The signal to noise ratio = 10 resulted in a limiting magnitude of 18.8. The sensitivity of the system was consequently increased by a factor of 2. Unfortunately, the tradeoffs were less sensitivity to fast moving objects due to the detected streaks being longer, more confusion with stellar streaks, and fewer detections in the same 5.2 minute observing window.

The top panel of Figure 1 shows the histogram of all detected objects with total motion less than +/- 2.0 arc-seconds/second in hour angle, and +/- 5.0 arc-seconds/second in declination. This rate box covers comfortably all expected motions for GEO objects moving on circular orbits and inclinations up to 17º. Detector saturation occurs at R = 10, so there are many active spacecraft not counted here because they saturate the system. No effort has been made to remove duplicate observations of the same station-keeping spacecraft.

Only two objects were detected fainter than R = 13.5 along the GEO ring, and the bottom panel shows what happens when a total motion cutoff of 0.1 arc-seconds/second is imposed on the sample. This cutoff is appropriate for an object which only recently ceased station-keeping. All objects with motion less than this value are bright, intact spacecraft. There does not appear to be a substantial population of faint objects at GEO which recently (a few weeks or months) ceased station-keeping. We conclude that in the time span reported here (September 2003 through April 2004), and in the previous ODQN article (November 2002 through March 2003) there was no significant source of slowly moving faint debris in the GEO ring.

This survey will continue when the next series of MODEST observations begins in September 2004. ♦

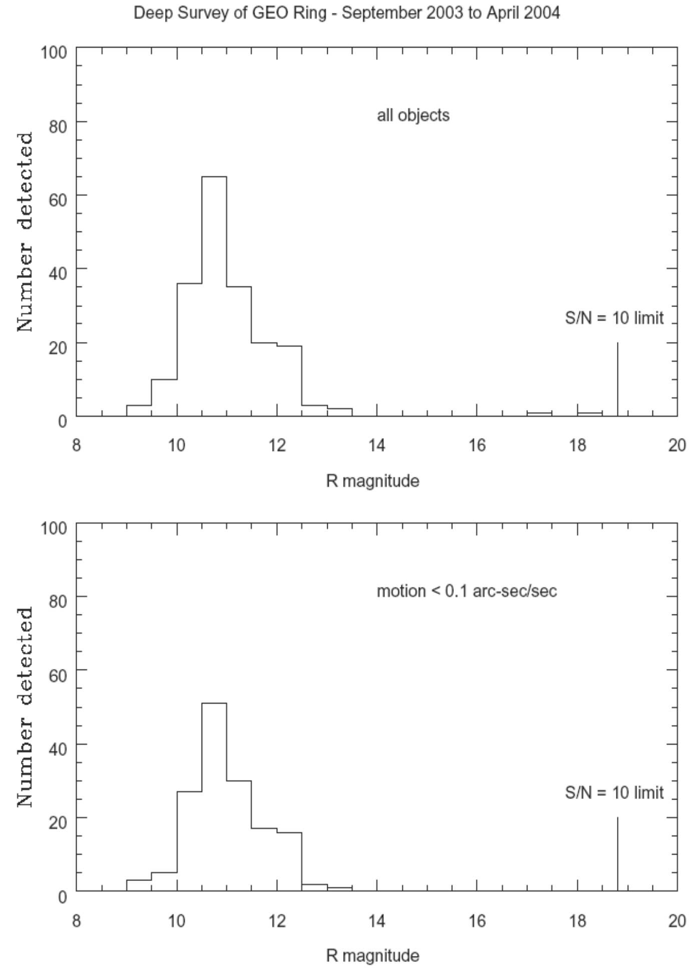

Figure 1. The top histogram shows all detections in the GEO ring during 4 scans in the period September 2003 through April 2004. The bottom histogram shows only objects with total motion less than 0.1 arc-seconds/second. No slowly moving faint objects have been detected in the arc of the GEO ring visible from Chile.

Historical Small Debris Collision Activities

P. H. KRISKO

Small particle collisions with resident space objects are a well-documented phenomenon through the analysis of returned surfaces. It was recognized by the early 1970s that not only meteoroids but debris from spacecraft also contributed to the activity. These debris sources include fragments of payloads and rocket bodies that have experienced explosion or collision, solid rocket motor slag and discharge, paint flakes, and sodium potassium coolant spheres from ejected nuclear cores. They were identified as impactors in some well established cases by analysis of constituents of the remains within craters of the returned surfaces. Databases of the impacts are kept at NASA JSC and used in risk analysis models such as the engineering model ORDEM2000. This model tabulates the low Earth orbit (LEO) environment for the years 1990 through 2030, for the purpose of predicting the expected orbital debris flux on spacecraft. The risk assessment model BUMPER makes use of ORDEM2000 fluxes along with meteoroid fluxes to analyze, with high fidelity, the specific shielding requirements of the Space Shuttle and the International Space Station (ISS).

As yet, the space debris environmental modeling programs at NASA JSC (e.g., EVOLVE, LEGEND) have focused on the long-term future period and on collisions between objects larger than 10 cm. The distant future is of concern with regards to for-

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Historical Small Debris Collision Activities

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mulation of government policy on the generation of orbital debris. The point of limiting analyses to larger than 10-cm sized objects is not only practical (constraints on computing time and computer memory), but also reasonable: the larger object collisions are much more likely to result in complete fragmentation of both projectile and target, and, therefore, to effect the future environment.

This report shows preliminary results of an adaptation of the environmental model EVOLVE to the study of the collisional activity between LEO objects 1 cm and larger in the historical period (1957-2002). These objects are larger, by two to three orders of magnitude, than the impactors believed to have left craters on returned surfaces. Still, the study of the 1 cm and larger population does give insight into what would be an even greater activity of the smaller impactors. Also, it would possibly reveal one mechanism by which the smaller impactors are formed in orbit.

The EVOLVE code was manipulated to apply its one-dimensional, spherical-shell, spatial density grids and Poisson collision probability model to the historical period. The colliding object size threshold was lowered to 1 cm. The only standard EVOLVE particle population that extends to the 1-cm (and lower) size regime is that generated by the historical breakups. For this study, the breakup fragment population was augmented by the sodium potassium (NaK) reactor coolant population. The NaK droplets were added and propagated by the NASA JSC NaK droplet model, which was developed last year. The NaK droplet spatial densities were calculated in the course of the computation and kept separate for the purpose of identification of collision pairs.

A 30 Monte Carlo iteration computation results in an average of 33 collisions during the 45-year period concentrated within two altitude bands, the highly populated LEO regions of 700 km through 1000 km and 1300 km through 1500 km, as shown in Figure 1. In the low altitude band the NaK droplet population boosts the collision probability sharply and rivals that of the breakup fragments.

The collision activity appears to be increasing over time (Figure 2) which would be reasonable since the population of breakup fragments is increasing over time.

The dominant collision size pairings are objects smaller than 5 cm and very large objects (> 1 m). These account for 90% of the activity. This huge size/mass difference results in dominantly non-catastrophic collisions. That is not to say that collisions involving 10 cm projectiles are not seen in this study. But over the 30 Monte Carlo iteration tests, they account for an average of only one collision during the historical period.

The characteristics of this historical collisional activity are consistent with observation, or lack thereof; 1) the collisions are dominated by those between the small fragments or droplets currently untracked by the US Space Surveillance Network and large fragments or intacts, 2) the most active collisional regime is between 700 km and 1000 km in altitude, the most populous region in LEO for objects of all sizes, and 3) due to the size differences between the impactor pairs, the collisions are generally non-catastrophic (i.e., small projectiles are destroyed, but large targets remain intact). All these characteristics point to the fact that it is likely that such events might remain undetected by current measurement techniques. On the other hand, recent unexplained debris events could be evidence of such activity (ODQN Vol. 7, Iss. 3) ♦

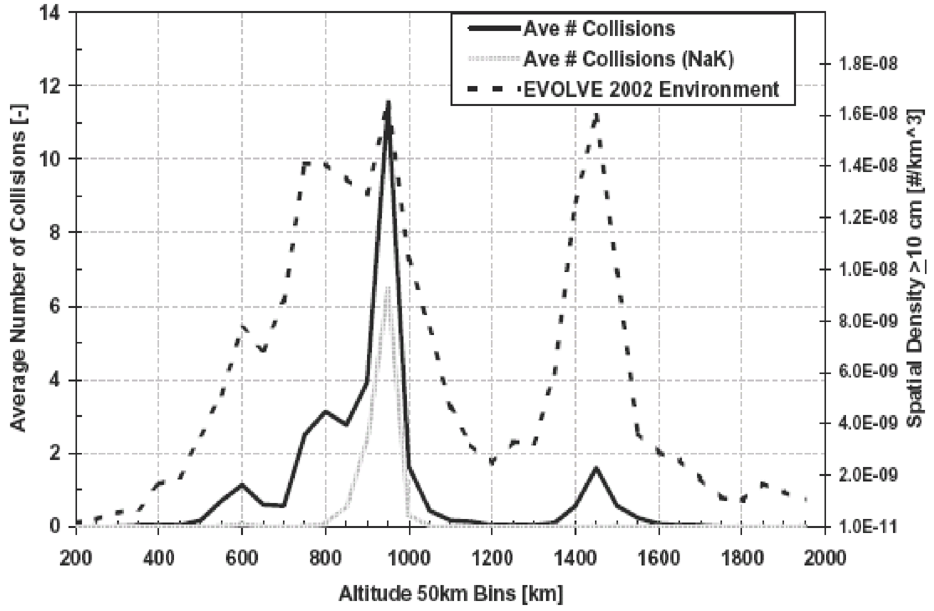

Figure 1. Calculated collision activity through the historical period (1957-2002) in LEO.

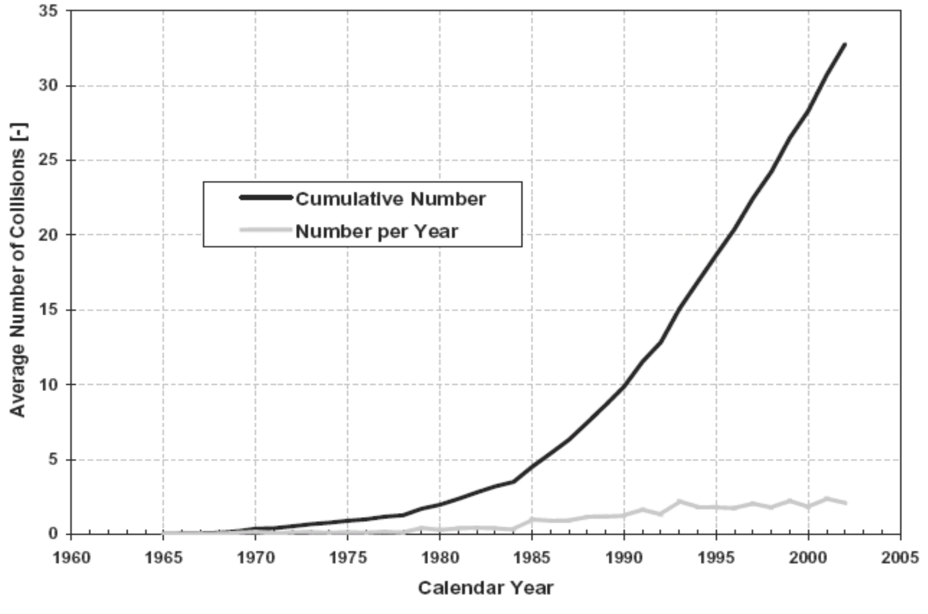

Figure 2. Average number of collisions generated over the test period (1957-2002).

ABSTRACTS FROM THE NASA ORBITAL DEBRIS PROGRAM OFFICE

35th COSPAR Scientific Assembly
18-25 July 2004, Paris, France

Collision Activities in the Future Orbital Debris Environment

J.-C. LIOU

We have analyzed potential collision activities among orbiting objects for the next 100 years from the low Earth orbit (LEO), medium Earth orbit (MEO), to geosynchronous orbit (GEO) regions. The analysis was based on results from the NASA orbital debris evolutionary model, LEGEND. A total of 30 Monte Carlo simulations were performed. The 1996-to-2003 launch cycle was repeated in the future projection. No post-mission disposal options were applied to satellites and rocket bodies. All collisions among objects 10 cm and larger were identified for the analysis.

One of the new features of LEGEND is its ability to identify objects involved in collisions individually. This allows the user to better quantify the characteristics of future collision events, for example, by orbit type (e.g., LEO/GTO/GEO, inclination, right ascension of the ascending node), by object type (satellite, rocket body, breakup fragment), by breakup time, location, and by mass. Our analysis shows that almost all future collisions occur in LEO. Intact-intact and intact-fragment collisions contribute almost equally to the generation of future debris populations. The majority of intacts involved in collisions come from future launches. This underlines the importance of postmission disposal of satellites and rocket bodies to reduce future collision activities. More than half of the “projectile fragments” involved in intact-fragment collisions originated from future collisions, indicating the nature of the feedback process in future collisions.

Most LEO collisions occur in regions of high spatial density, around 800 km and 1000 km altitudes. Although there is a wide spread in impact speed, about half of the collisions occur with impact speeds greater than 14 km/s.

Since collisions are likely to produce more fragments than explosions in the future, it is critical to have a high fidelity model to analyze future collision activities to ensure reliable environment predictions. With the new capabilities of LEGEND we are able to examine the process in great detail and have a better understanding of the nature of collisions. ♦

Detection of Small Radar Cross Section Orbital Debris with the Haystack Radar

J. L. FOSTER, J. R. BENBROOK, & E. G. STANSBERY

NASA has been making statistical measurements of the orbital debris environment for more than a decade using the MIT Lincoln Laboratory Haystack Radar. The goal has been to characterize the environment for debris sizes as small as possible. Like all sensors which operate in the presence of noise, the Haystack radar has limited sensitivity. As the returned energy from small targets begins to approach the sensitivity limit, the probability-of-detection decreases, eventually approaching zero. The slope of the cumulative size distribution of debris begins to flatten out. This paper explores the possibility of extending the cumulative size distribution to smaller sizes by adjusting the distribution for probability-of-detection. ♦

Space Debris Mitigation Strategies and Practices in Geosynchronous Transfer Orbits

N. JOHNSON

Missions to geosynchronous orbits remain one of the most important elements of space launch traffic, accounting for 40% of all missions to Earth orbit and beyond during the four-year period 2000-2003. The vast majority of these missions leave one or more objects in geosynchronous transfer orbits (GTOs), contributing on a short-term or long-term basis to the space debris population. National and international space debris mitigation guidelines seek to curtail the accumulation of debris in orbits which penetrate the regions of low Earth orbit and of geosynchronous orbit. The orbital lifetime of objects in GTO can be greatly influenced by the initial values of perigee, inclination, and right ascension of the orbital plane, leading to orbital lifetimes of from less than one month to more than 100 years. An examination of the characteristic GTOs employed by launch vehicles from around the world has been conducted. The consequences of using perigees above 300 km and super-synchronous apogees, typically above 40,000 km, have been identified. In addition, the differences in orbital behavior of launch vehicle stages and mission-related debris in GTOs have been investigated. Greater coordination and cooperation between space launch service providers and spacecraft designers and owners could significantly improve overall compliance with guidelines to mitigate the accumulation of debris in Earth orbit. ♦

Air Force Maui Optical and Supercomputing (AMOS) Technical Conference
13-17 September 2004, Wailea, Maui, Hawaii, USA

A Size-Based Albedo Model (SiBAM): The First Step Toward an Albedo Distribution Model

K. S. JARVIS, T. L. PARR-THUMM, E. G. STANSBERY, & E. S. BARKER

Ground-based measurements of the orbital debris environment are made using both radar and optical observations in order to gain a more complete understanding of the environment. Comparing the results of the two methods is problematic, however, since neither method directly measures the physical size of the object. National Aeronautics and Space Administration (NASA) measured the radar cross section (RCS) of a number of fragments from a ground hypervelocity collision test and developed the Size Estimation Model (SEM) to be used in conjunction with RCS. Researchers have had to rely on indirect measurements by comparing optical brightness of cataloged objects with characteristic length size estimates generated by the SEM from non-simultaneous radar measurements. As a first step toward an albedo distribution model, a size-based albedo model (SiBAM) has been developed using a subset of the Correlated Targets (CTs) from the 1998-2000 Liquid Mirror Telescope (LMT) data sets. The subset consists of debris from rocket body explosions and Cosmos 1275, a satellite that is also believed to have exploded. It is hoped that the explosion debris may mimic the basic character of which smaller debris are thought to consist. SiBAM studies indicate that the assumed al-

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A Size-Based Albedo Model (SiBAM): The First Step Toward an Albedo Distribution Model

Continued from page 8

bedo of 0.1 (a commonly assumed albedo for low Earth orbit objects) is too low and that different albedos need to be considered for intact objects versus debris objects. This model is a work in progress and is still "young" with many expected modifications as more data is processed and integrated into the model. As SiBAM matures, better values are anticipated and ultimately SiBAM will provide a metric for the Albedo Distribution Model. ♦

Analysis of Working Assumptions in the Determination of Populations and Size Distributions of Orbital Debris from Optical Measurements

E. S. BARKER, J. L. AFRICANO, D. T. HALL, K. S. JARVIS, K. JORGENSEN, T. L. PARR-THUMM, P. SEITZER, M. J. MATNEY, & E. G. STANSBERY

The Orbital Debris Program at NASA Johnson Space Center has undertaken a review of the optical techniques and working assumptions inherent in the conversion from observed optical brightness to physical sizes and populations of orbital debris. The detailed analysis will be limited to the observations of orbital debris in the low Earth orbit (LEO) and geosynchronous orbit (GEO) environments made by NASA-related optical telescopes including the 0.32-m CCD Debris Telescope, 3.0-m Liquid Mirror Telescope, Michigan 0.6/0.9-m Schmidt, and other Air Force-related facilities. The conclusions may apply to other international programs carrying out optical orbital debris observations. Assumptions regarding search methodology and completeness, detection algorithms, debris type, debris shape, albedo, phase functions, and mapping to radar cross sections will be discussed in the framework of the resulting uncertainties in the debris size and flux densities. ♦

Reflectance Spectra of Human-Made Space Objects

K. JORGENSEN, J. OKADA, M. GUYOTE, D. T. HALL, K. HAMADA, J. L. AFRICANO, E. G. STANSBERY, E. S. BARKER, & P. KERVIN

A study termed NASS (NASA AMOS Spectral Study) commenced in May 2001 using spectra to distinguish materials using reflectance spectra. NASS observed large orbiting objects spectrally and compared the overall shape of the reflectance spectra as well as the location of spectral absorption features in an effort to distinguish material types. The Spica spectrometer, a sensor based on the commercial Acton Sp-500 spectrograph, which is mounted on the rear-blanchard of the AMOS 1.6-m telescope, was the main instrument used in the study. To date, more than 120 space objects have been observed with either the blue (3500-6500 angstroms) or red (5500–9000 angstroms) filters. When comparing the remote measurements to the database of laboratory samples, the samples are showing darkening and reddening. Reddening is a term used to describe an increase in reflectance as the wavelength increases and is seen in some types of asteroids as well. The cause for this reddening in human-made materials will be discussed. In addition to the reddening, material types of rocket bodies, satellites, and human-made debris will be shown. Also, the results of using principle component analysis (PCA) as a means to determining the material type will be discussed. ♦

MEETING REPORTS

35th COSPAR Scientific Assembly
18-25 July 2004, Paris, France

The 35th COSPAR Scientific Assembly was held in Paris, 18-25 July 2004. The Space Debris Programme was organized by W. Flury and N. Johnson. A total of 45 papers, including 35 oral presentations and 10 posters, were presented during the 3-day Space Debris Sessions. Highlights of the presentations included ESA and NASA's recent efforts to monitor and survey debris from low Earth orbit to geosynchronous orbit using ground-based optical and radar instruments, preliminary results from analyzing the returned Hubble Space Telescope solar arrays, recent advance in space-based in situ measurement techniques, mitigation strategies and practices in geosynchronous transfer orbits, and new debris modeling results. It is expected that most papers will be submitted to *Advances in Space Research* and, after peer-review, be published in a future issue. ♦

Air Force Maui Optical and Supercomputing (AMOS) Technical Conference
13-17 September 2004, Wailea, Maui, Hawaii, USA

The 2004 Air Force Maui Optical and Supercomputing Site (AMOS) Technical Conference occurred 13-17 September 2004 in Maui, Hawaii. The general topics discussed at the conference were open sessions on: non-resolved object characterization, metric, imaging, lasers, orbital debris, space, atmospherics, telescopes, adaptive optics, astronomy, high performance computing, and a poster session with various topics. Below is a discussion of the orbital debris session.

Thomas Schildknect discussed a new population of objects found by the ESA telescope at Tenerife; these objects are faint (18th magnitude), high altitude, and have a high eccentricity. Patrick Seitzer presented findings on the University of Michigan/NASA JSC MODEST project which is an optical survey of GEO space. Doyle Hall talked of a study of RORSATs and the determination of diffuse and specular albedo components with an albedo somewhere between 0.8 and 0.9. Ed Barker presented the error analysis conclusions for the JSC optical observation programs of LMT, CDT, and MODEST. Kandy Jarvis presented a Size-based albedo model (SiBAM) which is applicable to LEO debris smaller than 1 m in characteristic length. Michael Oswald informed the attendees of the new upgrades and improvements to the ESA programs of MASTER and PROOF. PROOF 2005 will be ready for distribution in 2006. Heiner Klinkrad discussed the ESA programs of SCARAB and DRAMA which are tools for debris reentry, risk assessment, and mitigation.

Because of the tremendous growth of this conference, the hotel is no longer able to accommodate the conference in September; next year's conference has been moved up to 15-19 August 2005. ♦

INTERNATIONAL SPACE MISSIONS

July—September 2004

International Designator	Payloads	Country/ Organization	Perigee (KM)	Apogee (KM)	Inclination (DEG)	Earth Orbital Rocket Bodies	Other Cataloged Debris
2004-026A	AURA	USA	702	703	98.2	1	0
2004-027A	ANIK F2	CANADA	35785	35786	0.0	1	0
2004-028A	COSMOS 2407	RUSSIA	949	1009	83.0	1	0
2004-029A	DOUBLESTAR (TC-2)	CHINA	599	38630	89.9	1	0
2004-030A	MESSENGER	USA	HELIOCENTRIC			1	0
2004-031A	AMAZONAS	SPAIN	35770	35806	0.1	1	1
2004-032A	PROGRESS-M 50	RUSSIA	356	369	51.6	1	0
2004-033A	FSW-3 2	CHINA	166	520	63.0	1	3
2004-034A	USA 179	USA	NO ELEM. AVAILABLE			1	0
2004-035A	SJ-6A	CHINA	593	603	97.7	1	0
2004-035B	SJ-6B	CHINA	594	602	97.7		
2004-036A	GSAT 3	INDIA	EN ROUTE TO GEO			1	0
2004-037A	COSMOS 2408	RUSSIA	1470	1496	82.5	1	0
2004-037B	COSMOS 2409	RUSSIA	1473	1496	82.5		
2004-038A	COSMOS 2410	RUSSIA	212	327	67.2	1	0
2004-039A	FSW-3 3	CHINA	205	320	63.0	1	1

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4. Reed, R.A., *Possible Effects of Solid Rocket Motor Slag Ejection Upon the Space Station Environment*, NASA Private Communication, 1991.

5. Brandon, M., Davis, C., Fette, M., Reed, R., Wilcher, G., Winkleman, B., *Star-37 Plume Radiative Heat Transfer Test*, AEDC Internal Document, 2004. ♦

ORBITAL BOX SCORE

(as of 29 SEP 2004, as catalogued by US SPACE SURVEILLANCE NETWORK)

Country/ Organization	Payloads	Rocket Bodies & Debris	Total
CHINA	45	294	339
CIS	1352	2634	3986
ESA	33	29	62
FRANCE	36	284	320
INDIA	28	109	137
JAPAN	83	50	133
US	996	2884	3880
OTHER	336	23	359
TOTAL	2909	6307	9216

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UPCOMING MEETING

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

The conference will be held at the European Space Operations Centre (ESOC). Six sessions have been planned to include measurements and modeling of debris and meteoroids, hypervelocity impacts, risk assessments and debris mitigation, and standards and regulations. For further information contact Walter.Flury@esa.int or go to http://www.esa.int/spacedebris2005.

Visit the NASA Orbital Debris Program Office Website

www.orbitaldebris.jsc.nasa.gov