Orbital Debris Research at NASA

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Abstract. The United States has one of the most active programs in the world on research of the orbital debris environment. Much of the research is conducted by NASA's Orbital Debris Program Office at the Johnson Space Center. Past work by NASA has led to the development of a national space policy which seeks to limit the growth of the debris population and limit the risk to spacecraft and humans in space and on the Earth from debris. NASA has also been instrumental in developing consistent international policies and standards. Much of NASA's efforts have been to measure and characterize the orbital debris population. The U.S. Department of Defense tracks and catalogs spacecraft and large debris with it's Space Surveillance Network, while NASA concentrates on research on smaller debris. In low Earth orbit, NASA has utilized short wavelength radars such as Haystack, HAX, and Goldstone to statistically characterize the population in number, size, altitude, and inclination. For higher orbits, optical telescopes have been used. Much effort has gone into the understanding and removal of observational biases from both types of measurements. NASA is also striving to understand the material composition and shape characteristics of debris to assess these effects on the risk to operational spacecraft. All of these measurements along with data from ground tests provide the basis for near- and long-term modeling of the environment. NASA also develops tools used by spacecraft builders and operators to evaluate spacecraft and mission designs to assess compliance with debris standards and policies which limit the growth of the debris environment.

1. INTRODUCTION

One of the important uses of space surveillance is understanding and monitoring the orbital debris environment. Earth orbiting spacecraft have become an integral part of our everyday lives. We depend on them for communications, weather information, scientific research, and national security. A real and growing concern for the safety and reliability of these satellites is the threat from collision with other orbiting objects including space debris. Even small particles can damage, degrade, or destroy spacecraft due to the very high velocities involved in a collision, on the average about 11 km/sec. The first accidental collision between two intact satellites in February 2009 illustrates the danger to operational spacecraft from human made and natural space debris.

This paper endeavors to provide a summary of research activities of the NASA Orbital Debris Program Office (ODPO) and to discuss some future plans.

2. ON-GOING ACTIVITIES

2.1 Measurements of the Orbital Debris Environment

The NASA ODPO places great emphasis on obtaining and understanding direct measurements of the orbital debris environment. The ODPO's environmental models are all based on these measurements.

Because orbital debris measurements must cover a very wide range of sizes and altitudes, one technique realistically cannot be used for all measurements. In general, radar measurements have been used for lower altitudes and optical measurements for higher altitude orbits. For very small debris, *in situ* measurements such as returned spacecraft surfaces are utilized.

2.1.1 U.S. Space Surveillance Network

In the U.S., the Department of Defense (DoD) maintains a catalog and ephemeris of orbital objects and debris for sizes as small as 5- to 10-cm diameter in LEO and about 1-m diameter in GEO using its worldwide network of radar and optical sensors that comprise the U.S. Space Surveillance Network (SSN) (see Figure 1).

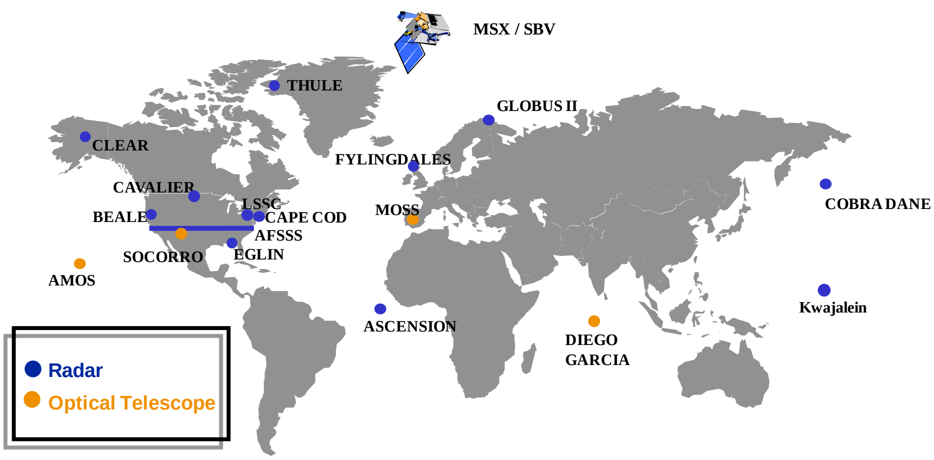

Figure 1. U.S. Space Surveillance Network

The number of objects in the catalog has grown over the years (see Figure 2). The number has grown significantly in recent years due to the Fengyun 1C event in 2006 and the Iridium/Cosmos collision in 2009. In addition to cataloged objects, the SSN is also routinely tracking a significant number of objects which have not yet been entered into the catalog. At the time of this writing, the SSN is tracking an additional ~5000 objects for a total on-orbit population of ~19,000 tracked objects. Trajectories of these objects can be predicted and used to calculate potential conjunctions with operational satellites, including crewed spacecraft such as the International Space Station, the Space Shuttle, Soyuz, and the Shenzhou spacecraft.

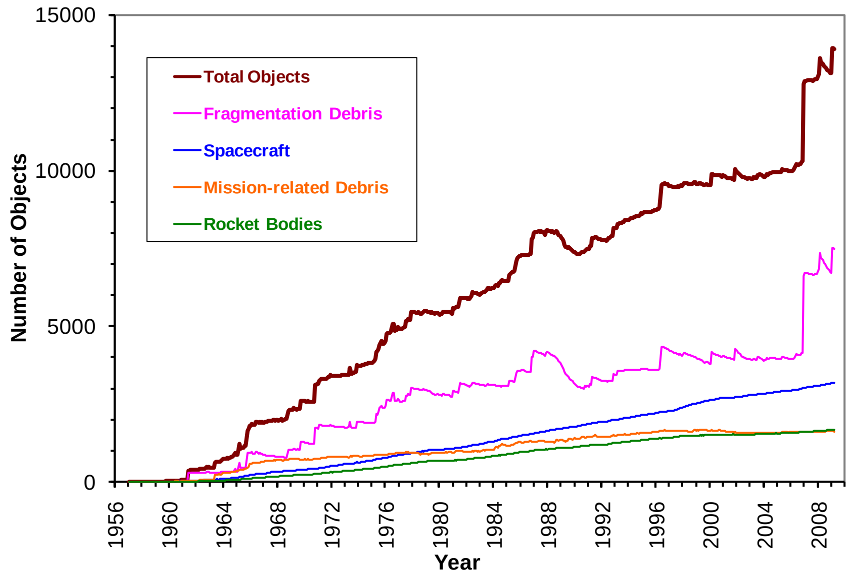

Figure 2. – Growth of the SSN catalog[1].

NASA performs measurements of the environment for debris sizes that are too small to be included in the SSN catalog. The measurements are intended to statistically characterize the orbital debris environment, rather than to create and maintain a catalog of these small objects.

2.1.2 Radar Measurements

To obtain debris data down to 2 mm in diameter, NASA has been utilizing radar observations of the LEO debris environment from the NASA Jet Propulsion Laboratory (JPL) Goldstone Deep Space Network radars, the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL) Haystack LRIR, and the MIT/LL Haystack Auxiliary, or HAX radar. The Goldstone radar is located in southern California's Mojave Desert at a latitude of 35.2° and the Haystack and HAX radars are co-located in Massachusetts near Boston at a latitude of 42.6°. Unlike Goldstone, whose primary mission is to monitor deep space probes, Haystack and HAX are both extensively utilized for debris observations, typically collecting several hundred hours each year.

Both Haystack and HAX are monostatic radars that measure the range, the radial velocity, the principal polarization RCS, the orthogonal polarization RCS, and the position within the radar beam using a monopulse system. For debris observations, the radars statistically sample the debris populations by operating in a staring, or "beam park," mode. In this mode, the antenna is pointed at a specified elevation and azimuth and remains there while debris objects randomly pass through the field of view (FOV) of the radar beam. This operational mode provides a fixed detection area important to the measurement of the debris flux, or number of objects detected per unit area per unit time, which is the defining quantity for debris risk analysis.

The HAX radar has less sensitivity than Haystack, but has a larger beamwidth. Both radars are capable of full-sky pointing. The Goldstone radar operates in a bi-static mode in conjunction with a second, smaller antenna a few hundred meters from the main antenna. It can measure the range, radial velocity, and principal polarization RCS of debris. Until recently, the Goldstone radar could only point near the zenith for debris observations. Haystack's availability, along with its very high sensitivity, makes it the primary source of data for characterizing the small debris environment.

The Goldstone radar generally observes objects at altitudes from 300 km to 3200 km with near-zenith pointing. Commonly, both Haystack and HAX collect data by pointing the radars east at 75° elevation.

Sometimes, Haystack points south at 10° elevation or at 20° elevation in order to sample debris from lower inclination orbits. With 75° east-pointing, both radars observe debris from 350 km to 1800 km. The overlapping size regions among the radars allow a continuous measurement of debris with diameters from less than 1 cm to several meters. Moreover, the overlapping size regions allow comparisons in order to understand systematic and statistical variations in the data. Figure 3 shows cumulative debris flux versus diameter from altitude 1000 km to 1200 km for all three radars.

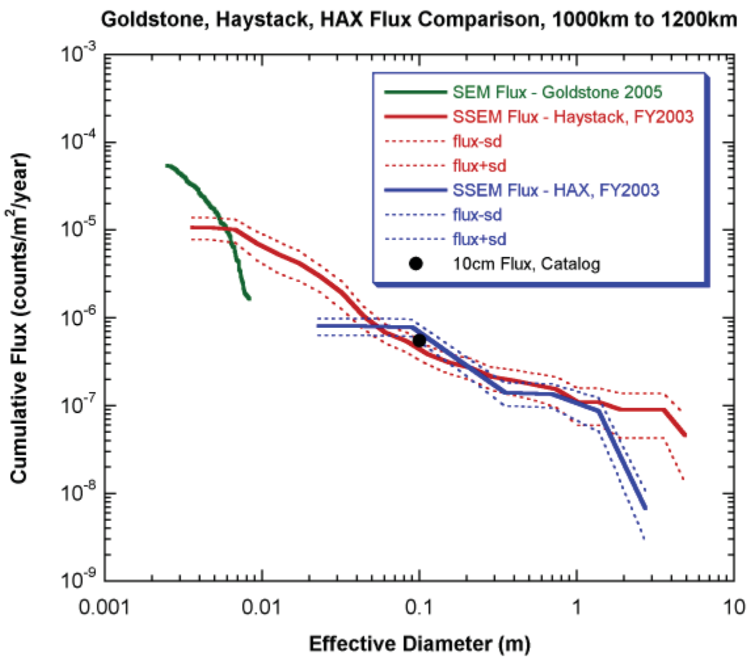

Figure 3. - Comparison of orbital debris flux from three radars.

Note: The SEM and SSEM are the Size Estimation Model[2] and the Statistical Size Estimation Model[3]. Both models relate radar cross section (RCS) to physical size.

2.1.3 Optical Measurements

In 2002, NASA began observations using the MODEST telescope, a 0.6/0.9 m Curtis Schmidt telescope operated by the University of Michigan located at Cerro Tololo Inter-American Observatory (CTIO) in Chile. It has a 1.3° x 1.3° FOV, uses a 2048 x 2048 pixel thinned SITe CCD (Peak QE 90%). Each pixel covering 2.3 arc seconds and the system is capable of detecting 19th magnitude objects in a 5-s integration that corresponds to an ~12-cm diameter, 0.175 albedo object at 36,000 km, assuming a diffuse Lambertian phase function.

Observations are made at a single right ascension and declination over an observing period. Observations are targeted near to the Earth shadow at GEO, so that the target objects will have minimum solar phase angle, but still are clear of the shadow. This is done to (hopefully) maximize the brightness of the objects. In addition, the observations are usually chosen to avoid the plane of the Milky Way as much as possible, for the multitude of stars in that region of the sky can easily mask the dim GEO objects, or overwhelm the automated object detection algorithm.

Once the field centers are determined, the data are run through a code that determines the probability of detecting an object in a specific orbit while in that FOV and at that specific time[4]. Such a probability chart is shown in Figure 4. The different colors represent the probability of detection. The redder the color, or the closer the probability is to 1, the greater the likelihood an object in that orbit was detected. Overlaid on the probability chart are the actual detections for the 3 years of data, where the CTs are solid diamonds and the UCTs are open circles. Using this analysis, a total population can be derived from the measurements.

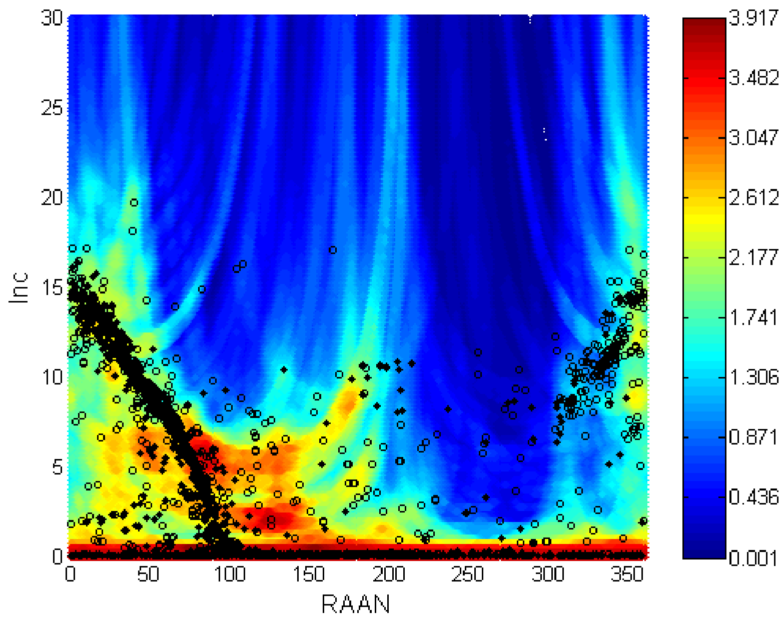

Figure 4. - Probability of finding specific orbits from fields observed by the telescope.

2.1.3 In Situ *Measurements*

Debris smaller than about 2-3 mm cannot be detected easily by ground-based radars or optical telescopes. Space-based in-situ measurements, the study of surfaces that have been exposed to space in Earth orbit, have been the only means to describe sub-millimeter debris populations. All spacecraft collide with very small orbital debris particles and meteoroids; consequently, spacecraft surfaces returned to Earth are found to have many small craters resulting from hypervelocity impacts.

One of the primary sources of data in this size regime is the Space Shuttle. After each flight, the Shuttle windows are examined for small impacts. Hypervelocity testing of

Shuttle window material has been done in order to relate impact crater size to the size of the impacting debris. Also, for each Shuttle mission, the time history of the orientation of the Shuttle while it is on orbit is known. From these data, the population of small debris particles can be estimated using certain assumptions about the orbit distribution of the debris.

Figure 5 shows one of the largest impacts seen on the Shuttle. This feature was found on the Shuttle radiator located inside the payload bay doors on STS-115.

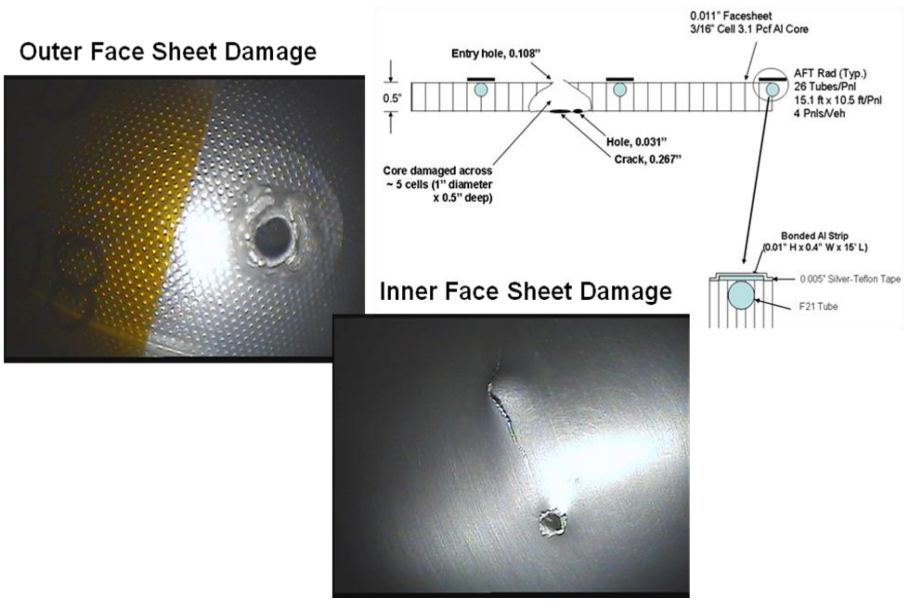

Figure 5. – Impact feature seen on STS-115 radiator. The entry hole is 2.7 mm diameter which created a 2.5 cm void in the radiator's honeycomb structure.

2.2 Modeling the Orbital Debris Environment

Models are used to take the information obtained by measurements and turn them into useful estimates of the population of debris and how they are divided into different orbits and debris types. The idea is to put together as accurate a picture of the past, present, and future environments as possible.

2.2.1 NASA Orbital Debris Engineering Model: ORDEM2010

Engineering models are applicable to questions regarding what debris environment a particular spacecraft/sensor might encounter/measure.

NASA is in the process of developing the next generation of ORDEM models. There are several reasons for this. The most important is that the future predictions of the changing orbital debris environment are always uncertain, so engineering models need to be updated at regular intervals to conform to new measurements. In addition, new types of measurements become available over time, adding new insight into the environment. Also, new analysis techniques become available to better analyze new and existing data.

For ORDEM2010, there is an interest in quantifying some factors that are known to be important for risk analyses, but have been difficult to obtain so far. One of the primary features of the new model is its use of Bayesian algorithms which provide an estimate of the uncertainty in the hazard calculations. This requires an estimate of the uncertainty in the modeled populations and the accompanying measurements, and estimates of the uncertainties in the calculations themselves.

Another desired feature is information on the makeup of debris – their shape and material composition. At this stage, the plan is to include uncertainty estimates in the flux results, and to include a simple model of debris material types. Research is ongoing to determine if it is feasible to include debris shapes in future models.

As with previous engineering models, ORDEM2010 will be able to compute fluxes on spacecraft. However, previous models were limited to calculations in the LEO environment, where the debris fluxes were mostly confined to the local horizontal plane. ORDEM2010 will not have this restriction. At the time of this writing, the model is undergoing beta testing.

2.2.2 NASA Long-Term Model: LEGEND

NASA's long term environment model, LEGEND, or LEO-to-GEO Environment Debris model, was completed in 2003. It is capable of simulating the historical and future debris populations in the near-Earth environment[5]. The historical simulation in LEGEND covers the period from 1957 to the present epoch. The model adopts a deterministic approach to mimic the known historical populations. Launched rocket bodies, spacecraft, and mission-related debris (rings, bolts, etc.) are added to the simulated environment based on a comprehensive, NASA Orbital Debris Program Office internal database. Known historical breakup events are reproduced[6], and fragments down to 1 mm in size are created with the NASA Standard Breakup Model (SBM), which describes the size, A/M, and velocity distributions of the breakup fragments[7]. All objects are propagated forward in time, while decayed objects are removed from the environment immediately. The simulation program outputs the orbital elements and other physical properties of the objects at the end of each year for post-processing analysis. The future projection component of LEGEND covers 200 years from the end of the historical simulation. Orbit propagation is handled in a way identical to the historical simulation.

Explosion probabilities of future rocket bodies and spacecraft are based on an analysis of launch history and recent explosions. The explosion probability of each vehicle is reduced to zero after 10 years of on-orbit lifetime. Vehicles with a history of explosion, but which have had the breakup causes fixed, are not included in future explosion consideration. Collision probabilities among objects are estimated with a fast, pair-wise comparison algorithm in the projection component[8]. Only objects 10 cm and larger are considered for potential collisions. This size threshold is historically the detection limit of the SSN sensors, and more than 95% of the debris population mass is in objects of 10 cm and larger. Fragments down to 1 mm in size are generated based on the NASA SBM, and are added to the simulated environment afterward. Each breakup fragment is assigned a unique identification character to track its origin: explosion, intact-intact collision, intact-fragment collision, or fragment-fragment collision.

The LEGEND future projection adopts a Monte Carlo (MC) approach to simulate potential future on-orbit explosions and collisions. The procedure of this MC approach is simple and straightforward. Within a given projection time step, typically set to 5 days, once the explosion probability is estimated for an intact object, a random number is drawn and compared with the probability to determine if an explosion would occur. A similar procedure is applied to collisions for each pair of target and projectile involved within the same time step. Parent objects are removed from the environment once fragments are generated. Due to the nature of the MC processes, multiple projection runs must be performed and analyzed before reliable and meaningful conclusions can be drawn from the outcome. A statistical study of LEGEND, based on the standard bootstrap method, indicates that the mean from 100 MC runs leads to a standard error of the mean, at the end of a 100-year projection, on the order of 1% or less. Therefore, averages from 100 MC runs in general should be statistically sound and reliable.

Figure 6 shows the result of a study published in 2006[9]. This study examined the "best case" (for orbital debris) scenario of no new launches. It examined the population of 10 cm and larger objects under the condition that no new objects were placed into the environment. The results showed that the number of objects created by accidental collisions would be balanced with the number of objects reentering the atmosphere for about 50 years. After that time, collisions of existing objects would increase the number of >10 cm objects. The actual situation will likely be worse because of the collision events of 2007 and 2009 and the fact that additional mass continues to be launched into space.

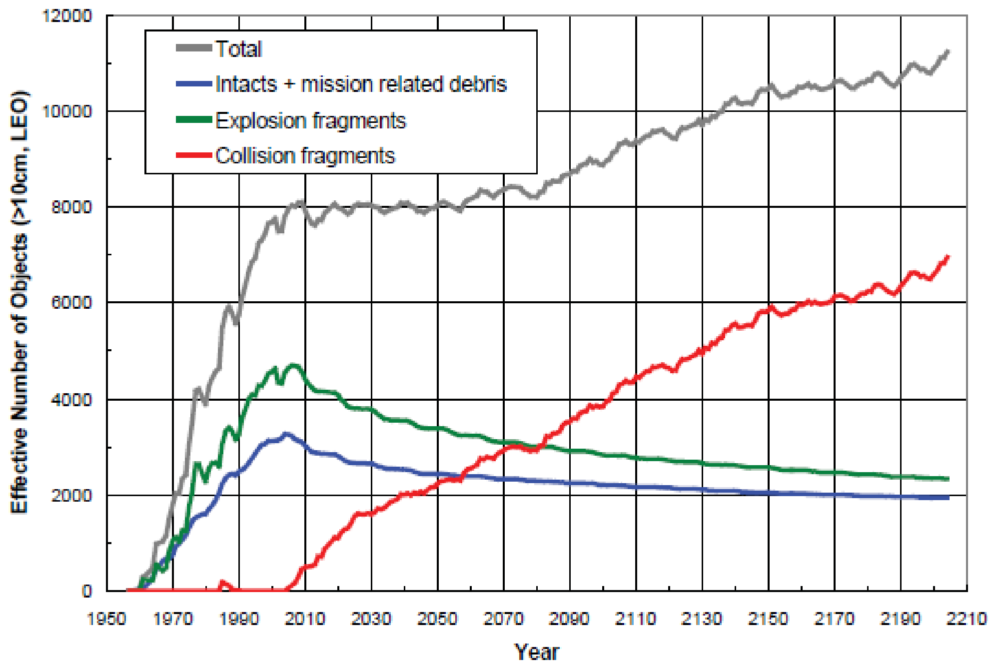

Figure 6. Growth of future debris populations. Effective number of LEO objects, 10 cm and larger, from the LEGEND simulation. The effective number is defined as the fractional time, per orbital period, an object spends between 200- and 2000-km altitudes. Intacts are rocket bodies and spacecraft that have not experienced breakups.

2.2.3 Debris Assessment Software

Requirements for NASA payloads and projects to limit the creation of orbital debris are stated in NASA Standard NASA-STD 8719.14. The Debris Assessment Software (DAS), version 2.0 is a software package that helps projects assess whether or not the project is in compliance with NASA-STD 8719.14. If a project is non-compliant, DAS may also be used to explore debris mitigation options to bring the project within the requirements. DAS can be obtained for free by download from the NASA Orbital Debris Program Office website (www.orbitaldebris.jsc.nasa.gov). Not every requirement from the Standard can be assessed with DAS, some assessments, like the reliability of a subsystem for PMD, or the probability of controlled reentry, must be done separate of the project.

DAS uses the latest NASA models, such as ORDEM, PROP3D, GEOPROP, and others, in order to best evaluate compliance with the Standard. A Graphical User Interface (GUI) allows the user to set up an entire mission, including launch date, orbital parameters, post-mission disposal plans, and so forth. Several “Science and Engineering” tools are included as well, so that the project or user can do simple calculations (such as orbital lifetime or collision risk with small particles) without having to enter each piece of information. DAS includes a simplified tool for evaluating reentry survivability of spacecraft and calculating the risk to people on the ground. If the reentry tool shows that a payload is non-compliant, a more sophisticated analysis can be performed using a separate software program called the Object Reentry Survival Analysis Tool (ORSAT).

3. Future Activities

3.1 Near-Term Future Activities

3.1.1 Hubble Wide Field Planetary Camera 2 (WFPC2) Radiator

The STS-125 astronauts retrieved the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) during a very successful and final servicing mission to the HST in May, 2009. The radiator attached to WFPC2 has dimensions of 2.2 m by 0.8 m. Its outermost layer is a 4-mm-thick aluminum, curved plate coated with white thermal paint. This radiator has been exposed to space since the deployment of WFPC2 in 1993. Due to its large surface area and long exposure time, the radiator serves as a unique witness plate for the micrometeoroid and orbital debris (MMOD) environment between 560 and 620 km altitude.

The NASA Orbital Debris Program Office is leading an effort, with full support from the NASA Hypervelocity Impact Technology Facility, NASA Meteoroid environment Office, and NASA Curation Office, to conduct an MMOD impact survey of the WFPC2 radiator. The goal is to use the data to validate or improve the near-Earth MMOD environment definition. This effort is also very well supported by the HST Program located at the NASA Goddard Space Flight Center. From the on-orbit images taken during the last two servicing missions, 20 large MMOD impacts are clearly visible (Figure 7). The survey team expects to find an additional 600 to 1000 impact craters caused by MMOD particles in the size regime that are important to satellite impact risk assessments[10].

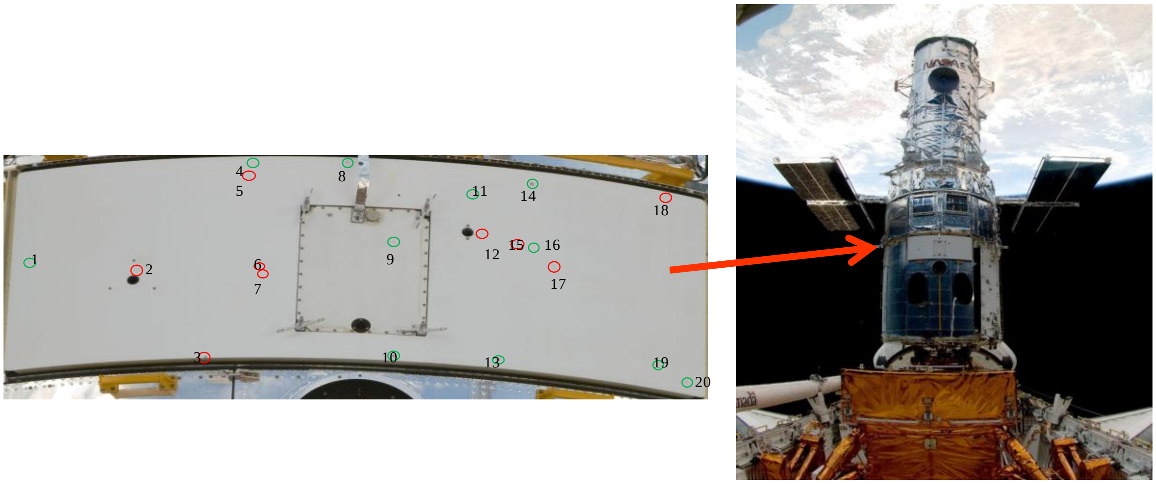

Figure 7. 20 largest impact features seen on the Hubble WFPC2 camera radiator. The read circles are features identified during a 2002 repair mission. Impact features in green circles were created between 2002 and 2009.

3.1.1 Meter Class Autonomous Telescope

NASA and the U.S. Air Force Research Laboratory are cooperating to place a wide field-of-view, 1.3 m aperture telescope on the island of Legan in the Kwajalein Atoll (167.0° E, 9.1° N) for space debris research. The MCAT system will use a Ritchey Chrétien design with a 0.9 deg FOV. The telescope will operate primarily in two different modes. During the twilight hours it will sample low inclination orbits in a “track before detect” mode. In the middle of the night it will perform a more standard GEO survey similar to MODEST. These two modes will address major limitations of the previous LEO and GEO surveys by extending the LEO survey down to 0° inclination and the GEO survey to fainter limits (~20th magnitude). The MCAT is scheduled for deployment in 2011 on Legan.

In the case of MCAT, the telescope will be conducting blind searches. For GEO searches, the search strategy will be similar to that developed for MODEST, which takes into consideration such things as solar phase angle and location of the Earth’s shadow, as well as complete coverage of the inclination versus RAAN parameter space for GEO objects.

Automation is particularly important for the low inclination searches. The track-before-detect mode searches find very limited segments of the RA arcs of an orbit. It is anticipated that most CCD exposures taken during low inclination searches will contain no detections. Having no human involved in either the operation of the telescope or in the data reduction and detection makes this type of search economically feasible.

3.2 Long-Term Future Activities

The NASA ODPO is researching methods for characterizing shape and material composition of orbital debris. This is extremely difficult to accomplish by remote sensing for small, unresolved targets.

NASA is building a database of computer representations of actual debris shapes. This is accomplished by using a computerized 3-dimensional scanner to scan the surfaces of fragments from ground hypervelocity impact tests. Once a digital rendition of the surface is entered, it can be manipulated by the computer to build probability density functions of brightness of the object under different viewing conditions such as observer-object-sun phase angles. It remains to be seen if different shape classes will have identifiable or unique probability density functions.

NASA is also trying to identify the material composition of debris using reflectance spectroscopy in visible and near-infrared wavelengths. Each material has specific absorption features that make it unique. NASA has built a large database of spectra from common spacecraft materials[11]. Using the absorption features, as well as slope of the spectra, NASA creates a model for material composition that best fits the spectrum taken of the object in space.

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