Integrating Orbital Debris Measurements and Modeling – How Observations and Laboratory Data are used to Help Make Space Operations Safer

S. M. Lederer[1], A. Vavrin[2], H. M. Cowardin[3], M. Matney[1], P. Anz-Meador[3], P. Hickson[4]

[1]NASA Johnson Space Center, Orbital Debris Program Office
[2]GeoControl Systems, Jacobs JETS
[3]Jacobs JETS
[4]University of British Columbia/Euclid Research

ABSTRACT

The NASA Orbital Debris Program Office has been statistically surveying human-made resident space objects (RSOs) in geocentric orbits for several decades, using optical and infrared telescopes. The prime goal has been to understand the evolving population and characteristics of debris generated by RSOs. Any object generated by a collision, explosion, or fragmentation event may pose a future collisional threat to active satellites. Key questions immediately surface from this knowledge: What can we do to protect our precious functioning satellites from collisions? How do we design our satellites to prevent them from being future sources of debris? And what can we do as a society to protect the environment surrounding Earth to preserve it for future generations?

To begin to address these questions, and to better understand this population as well as break-up events contributing to it, NASA has developed a suite of models and experimental laboratory data to work in tandem with observational and laboratory measurements of RSOs. These models include the Orbital Debris Engineering Model (ORDEM), the Standard Satellite Break-up Model (SSBM), and the LEo to Geo ENvironment Debris model (LEGEND).

Ground-based data have been collected from the 3.8m infrared telescope UKIRT (UK Infrared Telescope) in Hawaii, as well as the 1.3m Eugene Stansbery Meter Class Autonomous Telescope, ES-MCAT, historically called MCAT, on Ascension Island. MCAT will be tasked to collect GEO (Geosynchronous) survey data, scanning orbits to search for uncatalogued objects (e.g. fragmentation/break-up events), and targeted observations of catalogued objects for more intensive studies, e.g. when a break-up or anomalous event occurs. Laboratory experimental data includes DebriSat, a satellite impacted at ~6.8 km/s in an impact laboratory on Earth, and optical photometry from the Optical Measurements Center at NASA JSC.

An integrated view will be discussed of how our telescopic observations and lab measurements interplay with models to understand the current (ORDEM) and future (LEGEND) environment, the evolution of satellite breakups (SSBM), and how this knowledge can help to promote an environment that is safer for operations.

1. INTRODUCTION

The prime goal of NASA's Orbital Debris Program Office (ODPO) has been to understand the evolving population and characteristics of debris generated by Resident Space Objects (RSOs), including functional and non-functional spacecraft, rocket bodies and debris. The debris population itself cannot be maneuvered, but is moving at hypervelocity speeds and as such poses potential great risk to our satellite assets in orbit. Orbital debris includes any non-functioning RSO that no longer serves a useful purpose. Any object that cannot be purposely maneuvered (including non-functioning satellites, rocket bodies, and any object generated by a collision, explosion, or fragmentation event) may pose a future collisional threat to active satellites, whether government or industry, large sats, small sats, cubesats, or microsats. All reside in a congested and risky environment. Anyone who has relied on GPS on their cell phone to guide them is counting on continued operations of both the Global Positioning System (GPS) satellites as well as communications satellites. Anyone who has checked weather imagery of the Earth, or lived through a hurricane whose path was monitored minute by minute with satellite images, counts on another set. Today, so much technology is

Fig. 1. ES-MCAT on Ascension Island. *Left*: The John Africano Observatory comprises the 1.3m ES-MCAT telescope, the 0.4m Officina Stellare telescope (on the platform to the left of MCAT in the newly installed 2.5m Observa-Dome), and is monitored by a suite of weather sensors (mast between telescopes).
Right: The 1.3m f/4 DFM telescope is designed to track directly through the zenith at Ascension Island's low latitude location (7º 58′ S, 14º 24′).

utterly dependent upon satellites that it is a sobering thought knowing there are an estimated half million objects, centimeter sized and larger, orbiting the Earth and moving at speeds that can reach 10x greater than a sniper rifle's bullet. Encountering any object at this speed can, and likely will, destroy a spacecraft.

With this in mind, the NASA ODPO has been obtaining sensor and laboratory measurements for decades, and developing a suite of models with the critical driver that we must understand this dynamic and ever growing population if there is going to be hope of preserving this precious resource for both current and future generations.

2. MEASUREMENTS

2.1 The Eugene Stansbery Meter-Class Autonomous Telescope (ES-MCAT)

ES-MCAT (Fig. 1) was known for nearly a decade and a half as MCAT, prior to naming it in honor of (now retired) Eugene Stansbery of NASA's Orbital Debris Program Office (ODPO) for his contributions to MCAT and the field of orbital debris over his career [1].

The primary *observing goal* for MCAT is to statistically characterize under-sampled orbital regimes, with emphasis on monitoring the GEO debris belt to determine the distribution function of debris. The prime *objective* is to monitor and assess the orbital debris environment by surveying, detecting, and tracking orbiting objects at all orbital altitudes: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geo Transfer Orbit (GTO), and Geosynchronous Orbit (GEO). MCAT can also be used to track and characterize an RSO with known orbital elements. As a dedicated NASA asset, MCAT can be tasked for rapid response to break-up events after they have occurred, and is intended to become a contributing sensor for the Space Surveillance Network (SSN) for the purpose of Space Situational Awareness (SSA).

MCAT will largely be tasked for surveying the sky autonomously to statistically characterize the orbital debris environment [1, 2, 3, 4]. Its prime survey strategy is designed to maximize coverage of the GEO belt to produce input data for the ORDEM model (see Sec 3.1, and [5]). Measurement data (including uncertainties) of debris detected by MCAT will include: photometry (brightness, called 'apparent magnitude'); astrometry (positions); field center files (telescope pointing center for the images); SSN (Space Surveillance Network) ID when correlated with an object in the catalogue (CT, or correlated target) or a UCT (uncorrelated target) designation otherwise.

The object's size may subsequently be calculated using an Optical Size Estimation Model (OSEM), which will be developed in concert with the DebriSat program (see Sec. 2.4). The estimate is dependent upon: the observed apparent

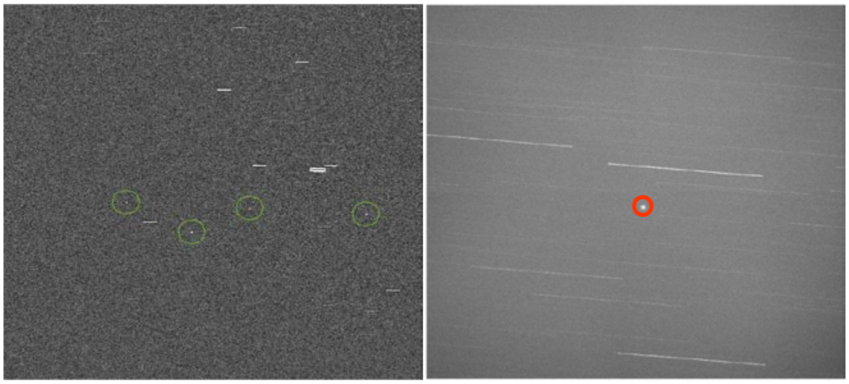

Fig. 2. Images taken by the MCAT telescope of four objects in GEO (left) and one in LEO (right). *North is up, East is left.*

magnitude of the object (measured); the solar phase angle at the time of the observation (known); the range/distance to the object (sometimes known, often assumed); and the bond albedo (ratio of incident to scattered power averaged over all solar phase angles, rarely known and thereby assumed, [6]). For tracked objects, orbital elements (two-line element sets, or TLEs) may also be calculated from the data. Examples of data collected by MCAT at GEO and LEO altitudes are shown in Fig. 2.

2.2 United Kingdom Infrared Telescope (UKIRT)

The 3.8m infrared UKIRT telescope on Mauna Kea, Hawaii has been heavily tasked by the ODPO in recent years to collect data on individual debris objects as well as in survey modes to study both the general GEO population and a break-up event [4, 7]. Data collected include photometry and spectroscopy in the near-infrared (0.85 – 2.5 µm) and the mid-infrared (8-16 µm).

As an example, the spectrum of SSN 3692, a Titan 3C Transtage, was taken with UIST (UKIRT Imager-Spectrometer) in Oct 2015, after the first breakup event was documented (June 4, 2014), but before the second break-up (Feb 28, 2018). The overall shape of rocket body spectra are different for other types of rocket bodies (re: Ariane and Briz-M), but are similar from one Titan rocket body to the next [8]. Future spectral measurements of SSN 3692 could be compared with the spectra taken in 2015 with UIST to investigate whether the slope of the spectrum or spectral features were altered due to the breakup, and results compared with laboratory data (see Sec. 2.4).

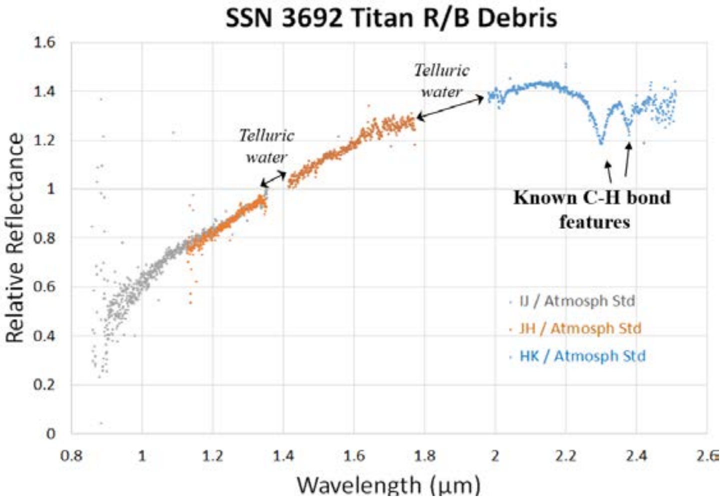

Fig. 3. UIST Spectrum of Titan rocket body debris SSN 3692. A C-H bond feature near 2.3 µm is typical of paint, while the absorption feature ~ 2.37 µm is attributed to organics. [8] The slope of the spectrum could be used to investigate space weathering trends or phase angle effects (see Sec. 4).

2.3 Laboratory Impact Experiment: SOCIT/Transit

The Satellite Orbital debris Characterization Impact Test (SOCIT)/Transit test provided ground-truth measurements of how a 1960's era satellite fragments due to a hypervelocity impact [9]. The target satellite, under a rough vacuum of 2.4 Torr in a laboratory test chamber, was impacted at 6.0 – 6.1 km/s by a 150g, 4.7 cm solid aluminum sphere, imparting 78 – 81 J/g impact energy to target mass ratio (2.8 MJ total) into the 34.5kg test satellite (46cm diameter x 30m). Impacts imparting > 40 J/g of impact energy to target mass ratio result in catastrophic destruction, as was evidenced by the SOCIT and later the DebriSat (Sec 2.4) experiments.

Conducted in 1992, the test satellite was built with more 'traditional' spacecraft materials including aluminum, metal, batteries, circuit boards, an on-board computer, an antenna, carbon fiber reinforced plastic (CFRP) outer walls, and glass fiber reinforced plastic (GFRP) boards. Solar panels were removed for the experiment. Measurement data of the material type, shape, size (x, y, z dimensions) and mass were collected for each of the cataloged fragments.

Data from this experiment have aided NASA in predicting break-up events reasonably well throughout the years, until recent advancements in spacecraft building, not surprisingly, led to discrepancies between our Standard Satellite Breakup Model (SSBM; See Sec. 3.3 and [10]) predictions (based on older spacecraft materials) and data observed from break-ups of satellites made of newer materials.

2.4 Laboratory Impact Experiment: DebriSat

With the evolution of spacecraft materials and construction techniques came the need for a new laboratory impact test to improve the existing DOD and NASA breakup models. DebriSat was a flight-like satellite designed to represent typical modern LEO satellites (Fig. 4) [11, 12]. Conducted in 2014, it was 63% more massive than the SOCIT/Transit spacecraft [13]. Materials included multi-layer insulation (MLI), solar cells, and all components shown in Fig. 4. Similar to SOCIT, it was performed under rough vacuum at 1.8 Torr in a laboratory test chamber. The 56 kg satellite (60 cm dia x 50 cm high) was impacted at 6.8 km/s by a 570g, 8.6 x 9 cm hollow aluminum cylinder, imparting 235 J/g impact energy to target mass ratio (13.2 MJ total), nearly 5 times greater total energy than SOCIT/Transit and catastrophic destruction (as intended) of the spacecraft.

Collection of fragments began immediately after the test was completed and is ongoing at the time of this publication. To date, estimates indicate that the impact generated over 250,000 fragments 2mm and larger, ~3x more than predicted by the SSBM break-up model (Sec. 3.3; 85,000 predicted), a model that does not (at the time of this publication) incorporate modern spacecraft materials as input. Measurements collected include:

Quantitative measurements: size and mass
Qualitative data: material type, color, shape
Derived quantities: Volume, cross sectional area, area-to-mass ratio (A/M ratio or AMR), and bulk density

Depending upon the fragment's size, 2D or 3D images are collected; the 2D imager utilizes a mirror to image the third dimension. In addition, both laboratory optical and radar measurements of a subset of fragments will also be collected.

Optical *photometric* measurements will be taken with the Optical Measurements Center (OMC) at NASA JSC and used to estimate the Bidirectional Reflectance Distribution Function (BRDF). This describes how light is reflected off an opaque surface and allows us to quantify the scattering characteristics of the surface material. Optical to near-infrared *spectral* measurements of DebriSat fragments were collected prior to impact, and will be compared with both post-impact spectra, and with a subset of fragments irradiated in a laboratory setting to investigate the effects of space weathering and variations in albedo pre- and post-test to further investigate size calculations based on assumed albedo (see Sec. 4 for further discussion). Laboratory *radar* measurements will provide the radar cross section, a quantity regularly measured for debris in space by ground-based radars. This will be measured using a wide-range of frequencies and aspect angles to help improve the current NASA radar Size Estimation Model (SEM).

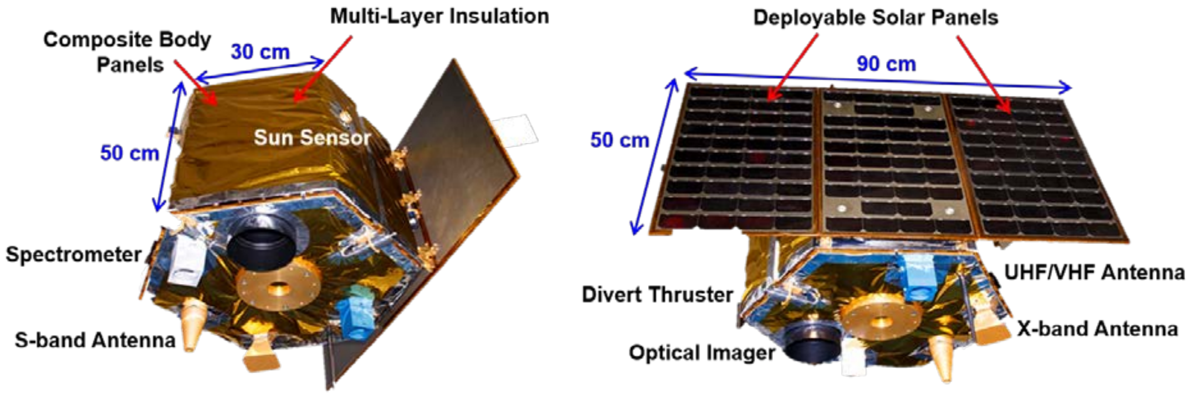

Fig. 4. DebriSat was composed of modern spacecraft materials, representative of LEO satellites. It was impacted at 6.8 km/s in a laboratory test chamber under vacuum.

Ultimately, DebriSat laboratory measurements will apply to both updating SSBM models (see Sec. 3.3 and 4) as well as improving our understanding of sensor measurements made with telescopes and radars. Near-infrared spectra collected with UKIRT and photometric observations collected by MCAT will ultimately benefit from DebriSat measurements. Optical photometry (brightness) collected by telescopes must assume a range (distance), albedo (relative reflectivity) and phase function (intensity/brightness change with respect to the Sun-object-Earth phase angle) to estimate sizes of objects. Ground-truth data (e.g. BRDF) from DebriSat will improve our mathematical input values used for Optical Size Estimation Models (OSEM – under development). Likewise, radar laboratory data of fragments will improve our radar SEM by providing a database of measured physical sizes of modern materials correlated directly to measured radar cross sections [12]

3. MODELING

3.1 ORbital Debris Engineering Model (ORDEM 3.0 to 4.0)

The ORbital Debris Engineering Model (ORDEM) is a mathematical tool that is designed to describe the population of debris in Earth-orbits, ranging from LEO to GEO. Specifically, ORDEM is used to estimate debris spatial density and population fluxes. The primary purpose of ORDEM is for satellite owner/operators and engineers to have a tool designed specifically to understand the long-term on-orbit collision risks for their mission and how those risks might be mitigated (e.g. for developing shielding requirements from impacts due to debris) [14]. The current ORDEM version 3 (3.0 and beyond) also has a "telescope/radar mode" that can be used to predict the flux a ground-based sensor should be capable of detecting to aid in designing a sensor [15].

With time, ORDEM itself has evolved from a simple flux-curve basis, to incorporating populations derived from data. ORDEM 3 includes data collected by sensors inlcuding optical telescopes (0.6 m Michigan Orbital Debris Survey Telescope, MODEST telescope in Chile), radars (HAX, Haystack Ultrawideband Satellite Imaging Radar (HUSIR), Goldstone), and returned surfaces from space (space shuttle windows and radiators).

ORDEM 3 employs better computing techniques than its predecessors to model the dynamic environment. It models a greater range in altitude (100 km LEO through 40,000 km, beyond GEO) and updated time ranges (2010 to 2035). Major break-up and anomalous events expected to significantly alter the environment are incorporated, such as the Chinese ASAT (2007) breakup, Iridium 33/Cosmos 2251 (2009) collision, and sodium-potassium (NaK) droplets from broken coolant lines. Modeled debris populations (e.g., historical and future environment data from LEGEND simulations) are used as "reference populations". The predicted fluxes from the reference populations are compared to the data, and reweighted using maximum likelihood estimation and Bayesian statistical techniques to match the observed data in different size and orbital regimes. This rescaling of the reference populations allows us to estimate the debris populations in regions where little or no data are available (e.g., sub-millimeter sizes at altitudes above the International Space Station [ISS], and all sizes below ISS) [15].

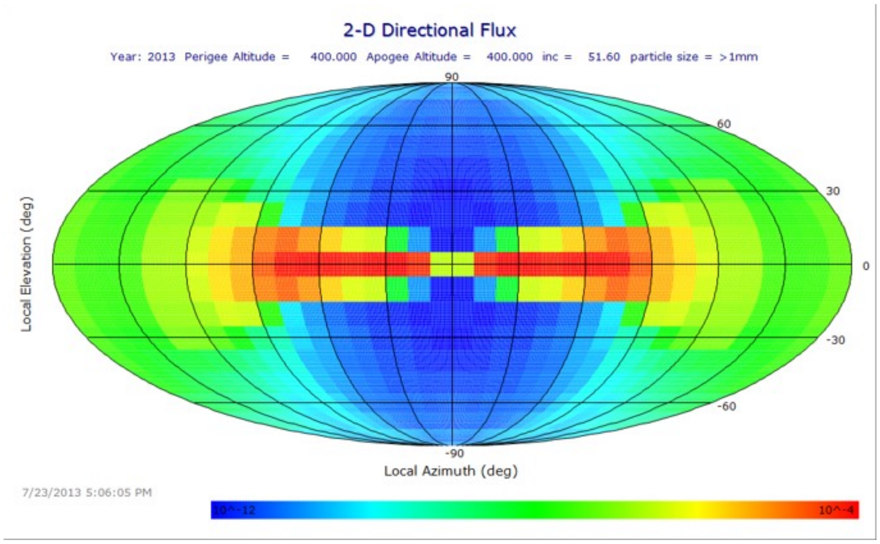

Fig. 5. Spacecraft Assessment 2-D Directional Flux projection. Direction relative to the spacecraft is noted in coordinates (local azimuth and local elevation) where azimuth runs along the horizontal from left to right and ranges from -180º to 180º, and elevation runs vertically from bottom to top and ranges from -90º to 90º. [15].

ORDEM calculates the flux for each particle size (10 µm to 1 m) for 5 material density classes (e.g. intact objects, NaK droplets, high-, medium-, and low-density debris materials). It also estimates the uncertainties in the flux estimates. The program has been released for users outside ODPO who obtain a software usage agreement, and can be requested through NASA's ODPO website.

With MCAT's prime objective defined as providing a continued and improved data source for generating population models, MCAT data is planned for use with the ORDEM 4.0 release, anticipated in 2022. Just as future MCAT data will be used to validate future versions of ORDEM, the current version of ORDEM 3 can be used to predict what MCAT should be capable of detecting now.

3.2 3-D Orbital Debris Evolutionary Model (LEGEND)

The LEO to GEO ENvironment Debris Model (LEGEND) is a high fidelity, three-dimensional numerical simulation model designed to predict the future debris environment, based on scenarios defined by the user (e.g. launch traffic, post-mission disposal, and active debris removal options) [16]. Observational data catalogued in the Space Surveillance Network are downloaded on a regular basis, and allow ODPO to record the historical growth of intact objects (spacecraft and rocket bodies), mission related debris (covers, rings, etc.), and fragments generated by historical explosions or collisions.

The historical component of LEGEND applies a deterministic approach based on recorded launches and break-ups to mimic the historical debris environment. The future projection component of LEGEND uses a stochastic Monte Carlo approach with a pair-wise collisional probability evaluation algorithm to simulate future collision activities. The code itself is an internal tool developed and used solely by NASA's ODPO, and requires days to weeks of run-time depending on user inputs.

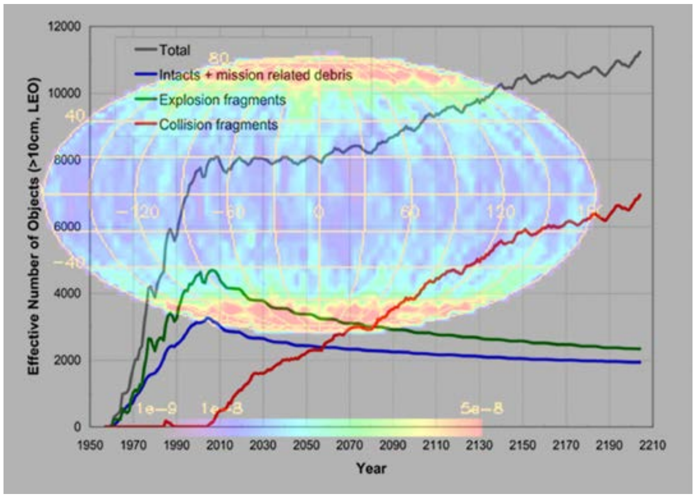

Fig. 6. LEGEND Three-dimensional Evolutionary Model [17]

The model focuses on objects larger than 10 cm (similar to the size limit detected and reported within by the Space Surveillance Network catalogue), but is capable of simulating objects as small as 1 mm in size. By assuming the nature of future launch traffic, LEGEND can project the environment several hundred years into the future, including estimating future on-orbit collisions at all altitude ranges (LEO to GEO). A typical projection period is 100 years in the future, with uncertainties from one model run to the next derived from variations in estimated future collisions/explosions, as well as launches expected, and how solar activity affects the debris environment and atmospheric drag (e.g. expansion/contraction of the Earth's atmosphere due to solar activity will affect how long it takes for LEO objects to decay from orbit, etc.).

As significant changes in launch traffic occur due to previously unforeseen advances in technology (e.g. a proliferation of CubeSat launches, launching constellations of dozens, hundreds or thousands of satellites or CubeSats by individual commercial companies), LEGEND itself must also evolve.

3.3 Standard Satellite Break-up Model (SSBM)

The NASA Standard Satellite Breakup Model (SSBM) describes satellite break-ups due to either collisions or explosions. SSBM was formulated using laboratory tests and ground based remote measurements of on-orbit fragmentation events to provide an average breakup ensemble for spacecraft and upper stage collisions and explosions. The motivation for developing the SSBM was two-fold: the availability of new radar, optical, and in situ environmental measurements in the late 1980s and early to mid-1990s; and a thorough review of the performance of the then-current breakup model, as used in EVOLVE 3.0, NASA's long-term Monte Carlo environment simulation computer program and precursor to LEGEND.

SSBM output is key input for the LEGEND model, and critical for understanding impact risk assessments for functional spacecraft. This breakup model generates fragment size, A/M ratio, and delta velocity, Δv, distributions. The SSBM uses characteristic length, L_c, as the fundamental independent variable in lieu of the preceding model's use of mass. Distributions in cumulative number, area, and A/M ratio for collision and explosion fragments are provided by the SSBM; the cumulative number distribution for collisions additionally incorporates mass characteristics of the event to model catastrophic and non-catastrophic collisions. The separation velocity (Δv) distribution uses A/M ratio as its independent variable, and the mass of a given object is calculated as the quotient of area and A/M ratio. [18]

As with the other models, this is based on data. The current SSBM includes data from 7 on-orbit rocket body explosions that were well observed and catalogued, laboratory impact experiments (the SOCIT experiment, Sec. 2.3, a set of micro satellite impact tests), and an on-orbit collision [19].

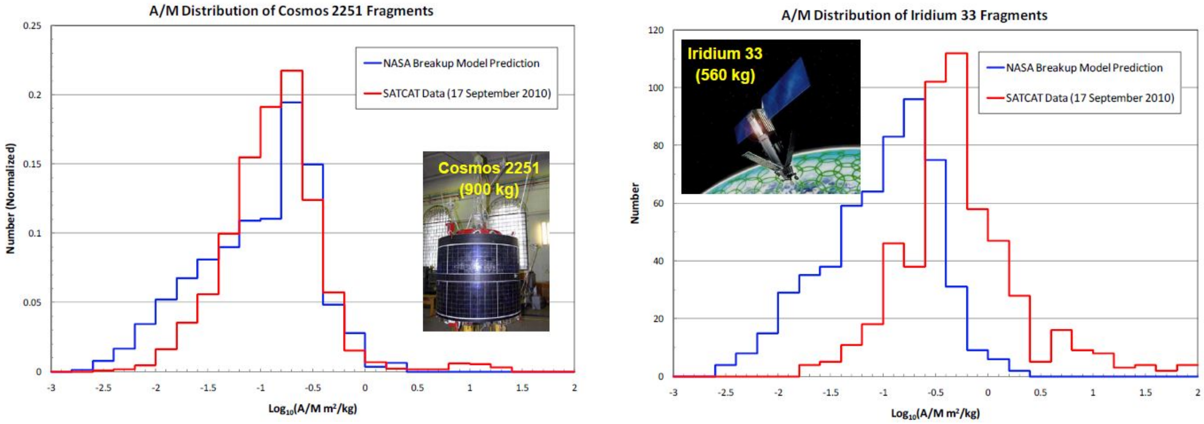

Fig. 7. Area to Mass (A/M) distribution of the fragments from the Cosmos 2251 and Iridium 33 satellites that collided with one another on-orbit in 2009. The SSBM predicts the A/M distribution of the Cosmos spacecraft, composed of older-style materials, well. However, it under predicts the number of fragments generated by the Iridium spacecraft by a factor of 3, indicating that composite, lighter weight spacecraft materials fragment into far more pieces during impact. [20]

The A/M distribution of spacecraft made up of traditional materials (e.g. solar array panels, aluminum, titanium, stainless steel) are modeled well by the current version of SSBM. For example, the predictions for the A/M distribution of the Cosmos 2251 fragments fit the observed A/M well (Fig. 7). In contrast, the breakup model prediction does not fit the distribution of the Iridium 33 fragments, a much newer spacecraft built with lighter weight new materials, and the spacecraft that COSMOS 2251 collided with in 2009. With the technological advancements in spacecraft now including new materials and designs, their break-up and predicted demise behavior has changed, as noted in Sec 2.3 [20]. Carbon fiber composites (e.g. graphite/epoxy) increase their strength while decreasing their launch weight and improving their durability and resistance to damage by heat. However, how these materials fragment is clearly different from how aluminum, titanium, stainless steel, and other more traditional spacecraft materials demise. The measurement from DebriSat will provide the needed data us to update our SSBM models and improve our predictions of breakup events for more modern spacecraft.

4. DISCUSSION

NASA ODPO's prime tasks include monitoring debris that is orbiting Earth's environment, provide engineering models for spacecraft designers and impact simulations tools, and providing impact risk analyses and assessments. A combination of measurements and modeling make this possible.

Data from optical telescopes like MCAT are a very important source of information for improving the safety of spacecraft in various ways. Optical telescopes and radars provide constant location/position updates to the Space Surveillance Network database for conjunction analyses by both NASA and the Department of Defense. If a collision with another RSO is possible, spacecraft operators must decide whether to maneuver their spacecraft based on the likelihood of impact. Our MCAT data is planned for distribution to the SSN to aid in this decision process and for Space Situational Awareness. MCAT data is also used as input for ORDEM, a model used by satellite builders to determine how best to shield and design their spacecraft for safety. Next, output from ORDEM (based on measurements from a variety of sources) and SSBM are used by LEGEND to determine long-term environmental changes, which drives policy decisions on how to safely operate in space, and how to safely dispose of spacecraft at end-of-life to safeguard our future environment.

To provide laboratory measurements, key in assessing model accuracy and updating input parameters for the purposes noted above, NASA ODPO recently led the build and subsequent laboratory impact experiment called DebriSat, a flight-like spacecraft composed of newer spacecraft materials (Sec 2.3). It demonstrated that a spacecraft composed of modern materials should not fragment as predicted by SSBM models populated with older-style materials, like the SOCIT impact test. Comparison of these two sets of impact-test laboratory measurements supports ground-based observations of newer spacecraft materials versus old (Fig. 7), and explains why the A/M distribution observed of modern materials from Iridium 33 differs from the old-style COSMOS 2251. Specifically, DebriSat, built with newer materials, generated 3x more fragments than expected based on how the older SOCIT spacecraft fragmented; likewise the A/M distribution of the newer Iridium 33 generated 3x more fragments than expected based on the SSBM populated with classic materials. But SSBM predicts the observations of the older COSMOS 2251 spacecraft well. This exemplifies why having measurements from ground-based sensors (radar and optical) and laboratory “truth” experiments combined with models is of utmost importance. Measurements are critical for confirming how well the model reflects reality, and verifying a model’s validity. Those models can then be used to predict future break-up events, the evolution of the debris environment, and help engineers improve their spacecraft design to protect them from the current environment, and just as their design may help protect the future environment.

In time, radar or telescopic observations could likewise show how the orbits of fragments from spacecraft composed of newer materials evolve with time, especially those that have the potential to generate more fragments with high area-to-mass ratios (HAMR), like the Iridium spacecraft. HAMR objects are known to be affected by atmospheric drag more strongly and thereby their orbits are expected to evolve and deorbit more quickly compared with low area-to-mass fragments, which is good for long-term effects. In contrast, far more fragments are expected to be generated by newer, more modern spacecraft, which is bad for short-term effects. Measurements over time from telescopes like MCAT, and radars can be used to investigate what actually happens on orbit after a breakup event, and how its orbital evolution occurs and affects the short-term versus long-term environment in space.

In addition to orbital evolution, the spectral response of a subset of on-orbit spacecraft surfaces also appears to change and evolve with time, which certainly affects the of the measured data that provides input to the models, and, unknown at this time – whether that weathering also affects spacecraft integrity. A ‘reddening’ effect that increases with time and exposure in space has been indicated in the red to near-infrared (0.8 – 2.5µm). Space weathering (exposure of materials to e.g., solar wind, cosmic rays, and solar radiation) has been hypothesized as one potential cause of this observed effect. Analogies have been drawn to reddening observed in asteroid spectra, and irradiation experiments of silicate rich asteroids have demonstrated the effects of space weathering [21]. A recent laboratory study of spacecraft materials [22] indicates that the specular component of their reflection changes with incidence angle, where the magnitude of these variations depend on surface roughness and material type. Specifically, reddening of spacecraft surfaces is indicated as an unexpected increase in the reflectance long-ward of 600nm [21]. Similar laboratory studies will be conducted with the DebriSat fragments, both for effects due to incident angle and BRDF, as well as due to irradiation. These laboratory data can then be used to interpret telescopic data such as the spectral observations made with UKIRT of a suite of objects (e.g. rocket bodies) to determine how spacecraft evolve with time, and whether these changes compromise the integrity or lifetime of the spacecraft, looping back to allowing industry and the government to design more robust spacecraft that will ultimately protect the very environment in which they live.

5. CONCLUSIONS

The environment surrounding the Earth in which satellites live and must survive is a dynamic one, with the population of resident space objects growing every day. With each launch and each break-up event, satellite operators must remain vigilant in both how they design their spacecraft prior to launch and how to operate safely in space to protect this extremely valuable resource. NASA’s Orbital Debris Program Office is tasked with monitoring and statistically assessing the growing swarm of debris surrounding the Earth. A suite of models, described above, has been developed by NASA’s ODPO with the purpose of providing impact risk assessments to prevent orbital debris impacts to orbiting spacecraft and assets on the ground.

Measurements with optical telescopes and radars are employed to study and characterize the debris environment as input to these models, to improve our capabilities in guiding safety practices, designs, and operations. The current debris environment is estimated by various modeling tools that incorporate a range of measurements from radar, optical telescopes, returned surfaces exposed to the space environment, and laboratory studies. A suite of ground-based telescopes have been tasked by NASA’s ODPO for this purpose, including the Meter Class Autonomous Telescope (MCAT) and the United Kingdom Infrared Telescope (UKIRT). Laboratory impact tests, including SOCIT and DebriSat, provide an additional ‘ground truth’ source of measurements. These data are then ingested into the ORDEM engineering models to estimate the population of RSOs in Earth orbits and help engineers design safer spacecraft, SSBM to characterize breakup events, and these output results propagated into the future using the LEGEND model to follow the evolution of the debris environment with time.

Through measurements and modeling, techniques and tools have evolved over the past several decades toward gaining a better understanding of the Earth-orbiting environment. They also give humanity insights into how to better protect this environment through impact risk assessments that can and should lead to better spacecraft design and more prudent end-of-life choices. With care and diligence, we, as a space-faring world, can take action to protect current and future spacecraft, and the environment in which they live.

6. REFERENCES

1. Lederer, S.M. et al., NASA's Optical Program on Ascension Island: Bringing MCAT to Life as the Eugene Stansbery-Meter Class Autonomous Telescope (ES-MCAT). AMOS Technical Conference Proceedings, Maui, Hawaii, 2017.
2. Lederer, S.M. et al., NASA's Orbital Debris Optical and IR Ground-based Observing Program: Utilizing the MCAT, UKIRT, and Magellan Telescopes. AMOS Technical Conference Proceedings, Maui, Hawaii 2016.
3. Lederer, S.M. et al., Deploying the NASA Meter Class Autonomous Telescope on Ascension Island. AMOS Technical Conference Proceedings, Maui, Hawaii, 2015.
4. Lederer, S.M. et al., The NASA Meter Class Autonomous Telescope: Ascension Island. AMOS Technical Conference Proceedings, Maui, Hawaii, 2013.
5. Frith, J.M. et al., Characterizing the Strategy and Initial Orbit Determination Abilities of the NASA MCAT Telescope for Geosynchronous Orbital Debris Environmental Studies. AMOS Technical Conference Proceedings, Maui, Hawaii, 2017.
6. Mulrooney, et al., An Investigation of Global Albedo Values, AMOS Technical Conference Proceedings, Maui, Hawaii, 2008.
7. Frith, J.M., et al., Observing Strategies for Focused Orbital Debris Surveys using the Magellan Telescope, 7th European Conference on Space Debris, ESOC, Darmstadt, Germany, 2017.
8. Lederer et al., NASA's Ground-based Observing Campaigns of Rocket Bodies with the UKIRT and NASA ES-MCAT Telescopes. 7th European Conference on Space Debris, ESOC, Darmstadt, Germany 2017.
9. Krisko, et al., SOCIT4 collisional-breakup test data analysis: with shape and material characterization. *Adv. Space Res.* **41 (**7), pp1138-46, 2008.
10. Johnson, N.L., P.H. Krisko, J.-C. Liou, and P.D. Anz-Meador. NASA's New Breakup Model OF Evolve 4.0. *Advanced Space Research*, **28** (9), pp. 1377-1384, 2001.
11. Liou, J.-C., et. al. "Successful Hypervelocity Impacts of DebrisLV and DebriSat," Orbital Debris Quarterly News, **18**, issue 3, pp. 3-6, (2014).
12. Cowardin et al., Characterization of Orbital Debris via Hyper-velocity Laboratory Based Tests, 7th European Conference on Space Debris, ESOC, Darmstadt, Germany, 2017.
13. Ausay, E., et al, "A Comparison of the SOCIT and DebriSat Experiments" 7th European Conference on Space Debris, ESOC, Germany, 2017.
14. Krisko, P.H., The New NASA Orbital Debris Engineering Model ORDEM 3.0, AIAA/AAS Astrodynamics Specialist Conference, 2014.
15. NASA Orbital Debris Engineering Model ORDEM 3.0 - User's Guide, NASA/TP-2014-217370.
16. Liou, J.-C., et al., LEGEND – A three-dimensional LEO-to-GEO debris evolutionary model. *Adv. Space Res*. **34** (5), 981-986, 2004.
17. https://orbitaldebris.jsc.nasa.gov/modeling/evolmodeling.html
18. Krisko, P.H., et al. Material Density Distribution of Small Debris in Earth Orbit, IAC- 08.A6.2.1, 2008.
19. Johnson, N.L., Krisko, P.H., Liou, J.-C., et al. NASA's new breakup model of EVOLVE 4.0. Adv. Space Res. **28** (9), 1377–1384, 2001.
20. Liou, J.-C., Anz-Meador, P.D. An Analysis of Recent Major Breakups in the Low Earth Orbit Region, 61st International Astronautical Congress, 27 Sept – 1, Oct 2010.
21. Marchi, S., et al.,Space weathering of near-Earth and main belt silicate-rich asteroids: observations and ion irradiation experiments. *Astronomy & Astrophysics.* **443** (3), pp. 769-775, 2005
22. Bédard, D., Using a physics-based reflection model to study the reddening effect observed in spectrometric measurements of artificial space objects, AMOS Technical Conference Proceedings, 2011.