DEBRISAT – A PLANNED LABORATORY-BASED SATELLITE IMPACT EXPERIMENT FOR BREAKUP FRAGMENT CHARACTERIZATION

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ABSTRACT

The goal of the DebriSat project is to characterize fragments generated by a hypervelocity collision involving a modern satellite in low Earth orbit (LEO). The DebriSat project will update and expand upon the information obtained in the 1992 Satellite Orbital Debris Characterization Impact Test (SOCIT), which characterized the breakup of a 1960s U.S. Navy Transit satellite. There are three phases to this project: the design and fabrication of DebriSat – an engineering model representing a modern, 60-cm/50-kg LEO satellite; performance of a laboratory-based hypervelocity impact to catastrophically break up the satellite; and characterization of the properties of breakup fragments down to 2 mm in size. The data obtained, including fragment size, area-to-mass ratio, density, shape, material composition, optical properties, and radar cross-section distributions, will be used to supplement the DoD and NASA satellite breakup models to better describe the breakup outcome of a modern satellite.

1 INTRODUCTION

A key element to providing good short- and long-term orbital debris (OD) environment definition and OD impact risk assessments for critical space assets is the ability to reliably predict the outcome of a satellite breakup. The two major classes of satellite breakups are explosions and collisions. Before the anti-satellite test on the Fengyun 1-C (FY-1C) weather satellite by China in 2007, the fragmentation debris population was almost all generated by explosions. After the FY-1C event and the collision between Cosmos 2251 and the operational Iridium 33 in 2009, the numbers of catalogued explosion fragments and collision fragments were about equal. Based on various modelling projection studies of the debris environment in low Earth orbit (LEO, the region below 2000 km altitude), collision fragments are expected to dominate the environment in the future – a phenomenon known as the "Kessler Syndrome" and predicted by Kessler and Cour-Palais in 1978 [1].

A satellite breakup model consists of three fundamental components – fragment size, area-to-mass ratio (A/M), and relative velocity (ΔV) distributions. The fragment size distribution quantifies the number of fragments generated from the event and the ΔV distribution specifies the initial spread of the fragment cloud. The A/M distribution determines the solar radiation pressure and atmospheric drag perturbations on the fragments. The latter is directly related to the orbital lifetimes of fragments below about 1000 km altitude. These three components provide the key information to model the orbital evolution of fragments and their short- and long-term distributions, including spatial density, velocity distribution, and flux, in the near-Earth environment. For satellite OD impact damage assessments, additional information, such as the shape and material density of the impacting debris, is needed to improve the reliability of the assessments.

The U.S. Space Surveillance Network (SSN) provides tracking data and maintains a catalog of the large objects in near-Earth space. The lower size limits for the cataloged objects are about 10 cm in LEO and about 1 m in the geosynchronous region (36,000 km altitude). The size information of a tracked debris object can be inferred from its radar cross section (RCS). The A/M of a cataloged LEO debris object below 1000 km altitude can also be estimated, based on the atmospheric drag perturbations of its orbital history. For smaller debris, however, no such data exist. Because of the high impact speed in LEO (with an average of 10 km/sec), even sub-millimeter debris could be a safety concern for human space activities and robotic missions. Laboratory-based satellite impact experiments, therefore, are necessary to provide data for the physical properties of fragments smaller than 10 cm.

To characterize the outcome of a satellite collision and the properties of the generated fragments, the

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Department of Defense (DoD) and NASA conducted several series of laboratory impact tests in the 1980s and the early 1990s. One of the test series, the Satellite Orbital Debris Characterization Impact Test (SOCIT), led to a key laboratory-based dataset used in the development of the current NASA and DoD satellite breakup models [2]. These models have been used for various orbital debris applications for more than 10 years. The target used for SOCIT was a flight-ready Navy Transit navigation satellite (46-cm diameter by 30-cm height, 34.5 kg) fabricated in the 1960s. As materials, subsystems, components, and construction techniques for satellite design and fabrication continue to advance, there is a need to conduct new impact experiments on targets more representative of modern satellites. The new data could be used to supplement the existing models to better describe the breakup outcome of a modern satellite.

The justification for a new laboratory-based impact experiment on a modern satellite is also supported by the FY-1C destruction and the collision between Cosmos 2251 and Iridium 33. Cosmos 2251 was an older satellite while Iridium 33 and the target for the ASAT test, the FY-1C weather satellite, were relatively modern. The U.S. SSN data have indicated that Cosmos 2251 fragments are well-described by the NASA standard satellite breakup model, as indicated by the comparison in Fig. 1 [3].

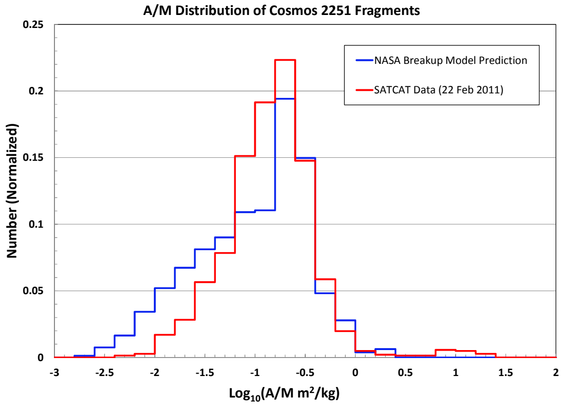


Figure 1. A/M comparison of the Cosmos 2251 fragments. NASA breakup model prediction (blue) matches reasonably well with the observation data (red).

For the Iridium 33 and FY-1C fragments, noticeable discrepancies exist between the model predictions and the observation data, as shown in Figs. 2 and 3, respectively. By design, lightweight composite materials were extensively used in the construction of the Iridium vehicles and each vehicle was equipped with two solar panels (3.9 m^2 each) [4]. This could contribute to the discrepancy between the model prediction and the data. For FY-1C, it is reasonable to assume the vehicle included some lightweight materials as well. In addition, FY-1C was covered with approximately 13 m^2 of multi-layer insulation (MLI) and equipped with two large solar panels (6 m^2 each). It is very likely that the excess of fragments with A/M values above ~0.3 m^2/kg consists of composite material, solar panel, and MLI pieces [5].

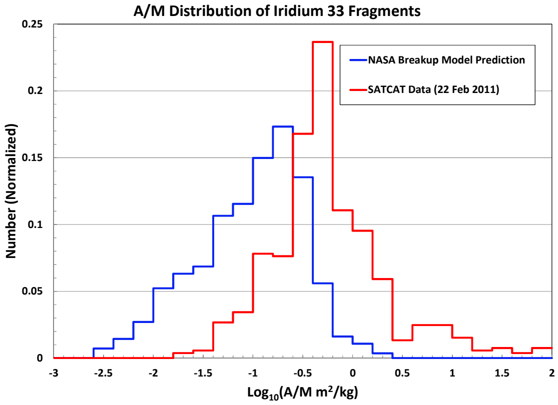


Figure 2. A/M comparison of the Iridium 33 fragments. NASA breakup model prediction (blue) and the observation data (red) are off by approximately a factor of 3.

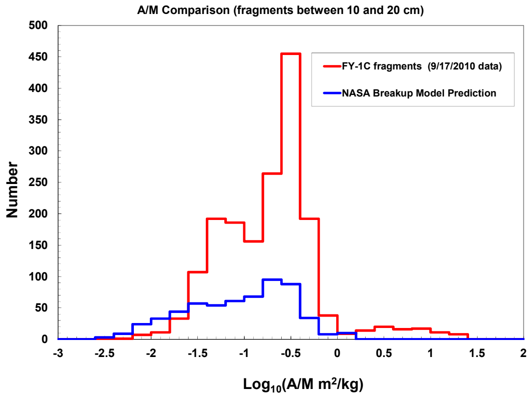


Figure 3. A/M comparison of the FY-1C fragments. NASA breakup model (blue) under-predicts the amount of fragments. There is also a significant excess of high A/M fragments.

The effort to conduct a laboratory-based impact experiment on a new target satellite, known as DebriSat, was initiated by the NASA Orbital Debris Program Office (ODPO) in 2011. The responsibilities of the ODPO are to provide project and technical oversight and lead the efforts for data collection, analyses, and NASA model improvements. The DebriSat project is co-sponsored by the Air Force's Space and Missile Systems Center (SMC). The SMC team provides technical oversight, supports data analyses, and leads the effort for DoD model improvements. The design and fabrication of DebriSat are led by the University of Florida (UF) with subject matter experts' support provided by The Aerospace Corporation. The UF team also leads the post-impact fragment collection and measurements. The hypervelocity impact destruction of DebriSat will be conducted at the Air Force's Arnold Engineering Development Complex (AEDC).

2 DESIGN OF DEBRISAT

DebriSat is intended to be representative of modern LEO satellites. To achieve additional improvements over the SOCIT test series, DebriSat is 45% more massive than the Transit satellite. It is also covered with MLI and equipped with deployable solar panels. Tab. 1 provides a comparison between DebriSat and Transit and the hypervelocity impact conditions.

Table 1. DebriSat versus Transit (SOCIT). EMR is the impact energy to target mass ratio. The parameters for DebriSat impact are planned numbers.

	Transit (SOCIT)	DebriSat
Target body dimensions (cm)	Diameter: 46 Height: 30	Diameter: 60 Height: 68
Target mass (kg)	34.5	50
MLI, solar panel	No	Yes
Projectile	Al sphere	Al sphere
Projectile diameter, mass	4.7 cm, 150 g	5 cm, 176 g
Impact speed	6.1 km/sec	7 km/sec
EMR (J/g)	78	86

The design of DebriSat started with a survey of LEO satellites launched between 1997 and 2011. Based on the availability of the public domain data, 50 representative satellites were selected for analysis [6-10]. Additional information on subsystems was derived from an analysis of nearly 150 LEO satellites with masses ranging from less than 50 kg to greater than 1000 kg. Common subsystems, materials, mass fractions, structure, and construction methods of the sample satellites were identified [8-10]. DebriSat includes seven major subsystems: attitude determination and control system (ADCS); command and data handling (C&DH); electrical power system (EPS); payload; propulsion; telemetry tracking and command (TT&C); and thermal management [8, 10].

The ADCS subsystem includes two star trackers, four sun sensors, one inertial measurement unit, one magnetometer, three magnetorquers, four reaction wheels, and one avionics module. The C&DH subsystem includes a flight computer and data recorder, inside separate shielded boxes, and cables. The EPS includes lithium-ion battery analogues, one power management and distribution module, and three deployable solar panels (30 cm × 50 cm each). DebriSat payloads consist of two spectrometers and one optical imager. The propulsion subsystem includes one composite overwrapped pressure vessel (COPV), three thruster pairs, and one plumbing system. Based on the assumption that future satellites will be in compliance with the post-mission passivation guideline adopted by the international community, the tank will not contain any propellant. The TT&C includes one S-band antenna, one X-band antenna, two UHF/VHF omni-directional antennas, and several shielded avionics boxes. Based on capillary pump loop designs, the thermal management subsystem includes one thermal reservoir, heat pipes, and Kapton heaters. MLI will also be used to wrap some components and cover most of the exterior of DebriSat.

To reduce the cost of the project, a decision was made to emulate the majority of the components. The emulated components were based on existing designs of flight hardware, including structure, dimensions, materials, and connection mechanisms. To ensure the quality of the products, emulated component designs were reviewed by subject matter experts. For example, the DebriSat design includes four reaction wheels in the ADCS subsystem. A Sinclair Interplanetary unit was used to emulate the four reaction wheels (see Fig. 4). In addition to the components, some flight-qualified cables, harnesses, and connectors for the fabrication of DebriSat were obtained from a cancelled DoD satellite project.

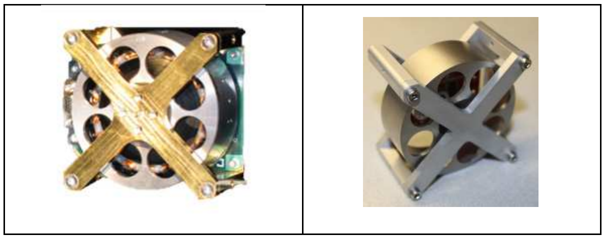


Figure 4. A reaction wheel from Sinclair Interplanetary (left) and one of the four emulated reaction wheels (right).

The shape of the DebriSat main body is a hexagonal prism, as shown in Fig. 5. The structure includes aluminium top and bottom hexagonal panels, six composite side panels and six composite ribs made with carbon fiber face sheets and aluminium honeycomb cores, and six aluminium longerons. Three deployable solar panels are mounted to one side of the main body. A detailed layout and the major components' locations are shown in Fig. 6.

To ensure the integrity of the structure, the subsystems, and the mounting mechanisms, load analyses were performed. In addition, vibration and thermal vacuum tests are planned for DebriSat after its complete fabrication.

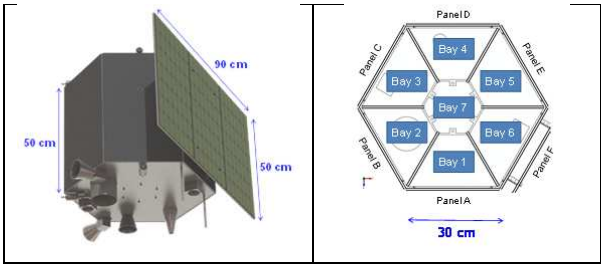
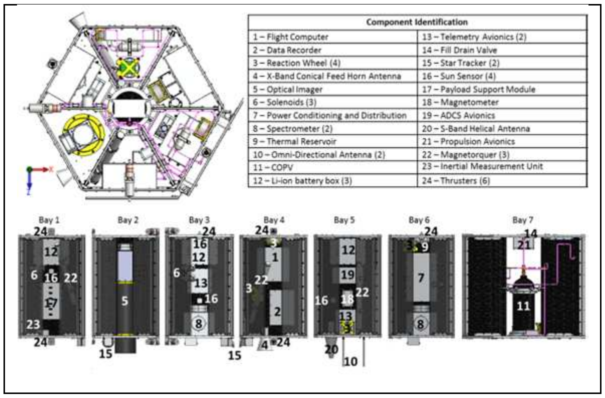


Figure 5. The CAD drawing of the exterior of DebriSat without MLI (left) and the top-view layout of the structure (right).



Component Identification	
1 – Flight Computer	13 – Telemetry Avionics (2)
2 – Data Recorder	14 – Fill Drain Valve
3 – Reaction Wheel (4)	15 – Star Tracker (2)
4 – X-Band Conical Feed Horn Antenna	16 – Sun Sensor (4)
5 – Optical Imager	17 – Payload Support Module
6 – Solenoids (3)	18 – Magnetometer
7 – Power Conditioning and Distribution	19 – ADCS Avionics
8 – Spectrometer (2)	20 – S-Band Helical Antenna
9 – Thermal Reservoir	21 – Propulsion Avionics
10 – Omni-Directional Antenna (2)	22 – Magnetorquer (3)
11 – COPV	23 – Inertial Measurement Unit
12 – Li-ion battery box (3)	24 – Thrusters (6)

Figure 6. Identifications of the major components (top) and the detailed layout of their locations (bottom).

3 HYPERVELOCITY IMPACT FACILITY AT AEDC

Previous laboratory-based hypervelocity impact tests have indicated that when the ratio of impact kinetic energy to target mass (EMR) is 40 J/g or higher, the outcome of the impact to the target is catastrophic – meaning the target is completely fragmented into tens of thousands of pieces. Similar to the SOCIT test series, to exceed this EMR threshold for DebriSat the hypervelocity impact has to be carried out at the AEDC facility. The AEDC Range Complex maintains and operates the largest two-stage light gas gun in the United States [11]. The Range G facility has a demonstrated capability to accelerate 500 g projectiles up to 7 km/sec using an 8.4 cm bore barrel. Up to 15 kg projectiles have been accelerated to 3 km/sec with a 20.3-cm bore barrel configuration. The maximum muzzle energy achieved to date is 96 MJ. The facility can be configured for a variety of test requirements including impact tests, track guided tests (with or without post-test projectile capture via recovery tube), erosive field tests, hypervelocity aerodynamic studies, aerothermal tests, and subscale scramjet testing. The 330-m-long test tank can be evacuated to less than 1 torr pressure levels for high altitude simulation. The tank can be divided into several sections for varying test requirements.

The target is placed inside the 3-m-diameter cylindrical range tank (see Fig. 7) in a specially prepared impact area. Launch packages incorporate sabot petals for non-cylindrical projectile designs. The projectile selected for DebriSat impact is an aluminium sphere with a minimum diameter of 5 cm (176 g mass). The planned impact speed is 7 km/sec. The total impact kinetic energy is approximately 4.3 MJ with an expected EMR of 86 J/g.

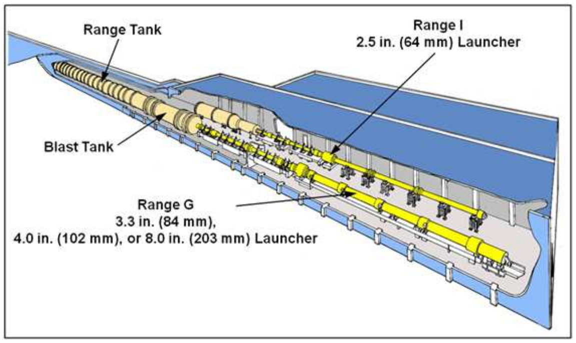


Figure 7. An illustration of the AEDC Range G two-stage light gas gun facility.

The range tank impact area is equipped with several diagnostic instruments suitable for this test program. They include multiple X-ray systems with orthogonal view fields, high speed charge-coupled device (CCD) cameras, and options for additional systems, such as laser photography, make screens, and break screens, to record the impact process and to potentially collect data for ΔV measurements for some of the fragments immediately after the impact. The X-ray systems are equipped with 150 KV or 450 KV pulse heads, as needed, for debris field penetration capability. An option to install lightweight piezoelectric sensors inside DebriSat to measure the propagation of shockwaves during breakup is also being considered.

Low density foam panels will be installed inside the target range tank as illustrated in Fig. 8. The purpose is to "soft catch" fragments after the impact and to protect the chamber. Polyurethane foam stacks, consisting of panels with different densities (0.06, 0.096, and 0.192 g/cm^3) and with a total thickness of up to 25 cm, were used during the SOCIT test series. For DebriSat, new foam materials and a new placement configuration will be adopted to capture fragments, reduce damage to the fragments, and allow for easy extraction of fragments from the foam panels for post-test measurements.

Figure 8. Inside view (down range) of the Range G target chamber. The interior wall of the range tank is covered with low density foam panels.

4 FRAGMENT CHARACTERIZATION PLAN

After the hypervelocity impact on DebriSat, fragments down to ~2 mm in size will be collected and identified individually. The goal is to recover at least 90% of the total DebriSat mass from the fragments. The data measurement task is divided into two parts. The first part is for fundamental data to improve the satellite breakup models. The plan is to measure the three orthogonal dimensions and mass of each individual fragment. Three digital photographs, from three orthogonal directions, will be taken of each fragment. Qualitative classifications of the shape, composition, and density of each fragment will also be documented. Unlike the SOCIT post-test fragment characterization where only 10% of the fragments were measured and many of them were grouped for easy processing, all DebriSat fragments will be individually measured to collect the fundamental data.

The second part of the measurements will start with a selection of sample representative fragments from the collection. These fragments will be subjected to additional 3-dimensional digital scanning for more accurate cross-sectional area and volume data. Additional radar, photometric, and spectral measurements on selected fragments are also planned to provide data for the development of the optical debris size estimation model and potential improvements to the existing NASA radar debris size estimation model.

5 CURRENT AND FUTURE WORK

The DebriSat project was initiated in 2011. Major milestones and planned activities are summarized in Tab. 2. This project is a collaborative effort among academia, DoD, and NASA. Once the data are processed and analysed, the results will be published in literature to help the orbital debris research community better model future satellite breakups and improve the orbital debris environment definition.

Table 2. Major milestones of the DebriSat project.

Date	Milestones
Sep 2011	Project kickoff
Jun 2012	Preliminary DebriSat design
Jan 2013	Final DebriSat design
Sep 2013	Complete fabrication of DebriSat
Oct 2013	Vibration and thermal vacuum tests
Mar 2014	Hypervelocity impact
Dec 2014	Complete fragment measurements
Dec 2015	Process and analyse data for model improvements

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