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 1960's US 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 class LEO satellite; conduction 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's and NASA's satellite breakup models to better describe the breakup outcome of a modern satellite.

1 INTRODUCTION

A key element to provide 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 Iridium 33 and Cosmos 2251 in 2009, the numbers of the catalogued explosion fragments and collision fragments were about equal. Based on various modelling projection studies of the debris environments in low Earth orbit (LEO, the region below 2000 km altitude), collision fragments are expected to dominated 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 amount 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 spacecraft (S/C) 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 for the large objects in the near-Earth space. The size limits for the catalogued objects are about 10 cm in LEO and about 1 m in the geosynchronous region. The size information of a tracked debris can be inferred from its radar cross section (RCS). The A/M of a LEO debris below 1000 km altitude can also be estimated based on the atmospheric drag perturbations on 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 a 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 Department of Defense (DoD) and NASA conducted several series of laboratory impact tests in the 1980's and the early 1990's. 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 1960's. As materials, 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 the modern satellites. The data can be used to supplement the existing models to better describe the breakup outcome of a modern satellite.

The justification for a new impact experiment 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, Fengyun-1C weather satellite, were relative 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].

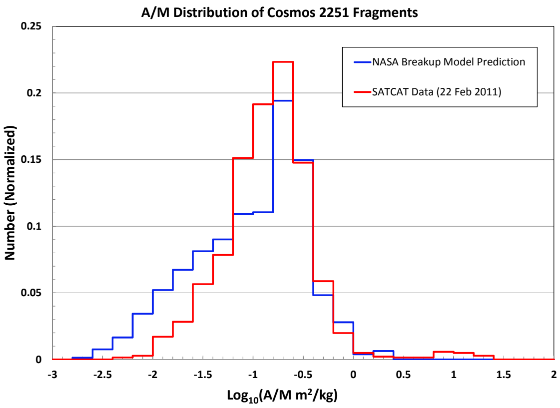


Figure 1. A/M comparison of the Cosmos 2251 fragments. NASA breakup model prediction (blue) matches well with the observation data (red).

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 vechicle was equipped with two solar panels (3.9 m^2 each) [4]. This could be a reason behind the discrepancy between the model prediction and the data. For FY-1C, it is reasonable to assume the vehicle included some lightweight material materials as well. In addition, FY-1C was covered with approximately 13 m^2 of Multi-Layer Insulation (MLI) and equipped with two larger 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 consist of composite material, solar panel, and MLI pieces [5].

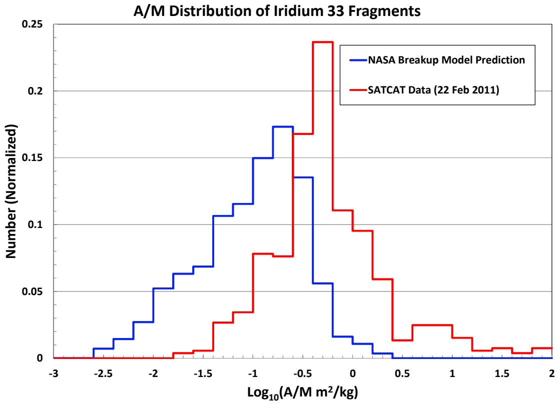


Figure 2. A/M comparison of the Iridium 33 fragments. NASA breakup model prediction (blue) and the observation data (red) are off by approximately a factor of 3.

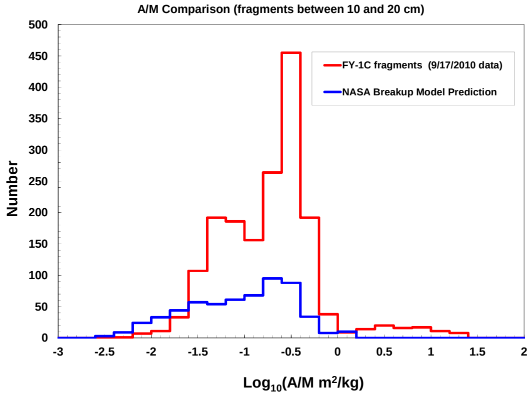


Figure 3. A/M comparison of the FY-1C fragments. NASA breakup model (blue) under-predicts the amount of fragments. There is also a significant excess of high A/M fragments.

The effort to conduct an impact experiment on a new target satellite, the "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 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 Transit. It is also covered with MLI and equipped with deployable solar panels. Tab. 1 provides a comparison between DebriSat and Transit.

Table 1. DebriSat versus Transit (SOCIT). EMR is the impact energy to target mass ratio.

	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 data, 50 representative satellites were selected for analysis [6-8]. Common subsystems, materials, mass fractions, structure, and construction methods of the sample satellites were identified [9-10]. 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, one data recorder, and cables inside shielded boxes. The EPS subsystem includes mock-up batteries, one power management and distribution module, and three deployable solar panels (30 cm × 50 cm each). The 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. The tank will not contain any propellant. This is based on the assumption that future payloads will be in compliance with the post-mission passivation guideline adopted by the international community. The TT&C includes one S-band antenna, one X-band antenna, two UHF/VHF omni-directional antennas, and avionics boxes. The thermal management subsystem is based on the capillary pump loop design. It includes one thermal reservoir, heat pipes, Kapton heaters. Multi-layer insulation (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 dimensions, materials, and connection mechanisms. The designs of the emulated components were reviewed by subject matter experts to ensure the quality of the products. For example, the DebriSat design includes four reaction wheels in the ADCS subsystem. One of them was acquired from Sinclair Interplanetary while the other three were emulated based on the design of the first one (see Fig. 4). In addition to the subsystems, flight-quality cables, harnesses, and connectors were obtained from a cancelled DoD satellite project for the fabrication of DebriSat.

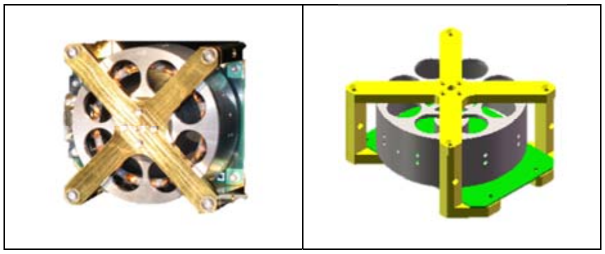


Figure 4. A reaction wheel from Sinclair Interplanetary (left) and the CAD drawing of the other three emulated reaction wheels (right).

The shape of the DebriSat main body is a hexagonal prism, as shown in Fig. 5. The structure includes two aluminium top and bottom hexagonal panels, six composite side panels and six ribs made of 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. Detailed layout and the locations of the major components are shown in Fig. 6.

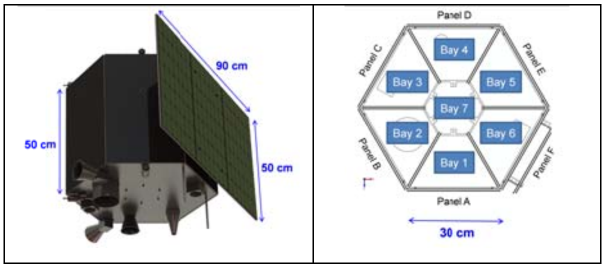
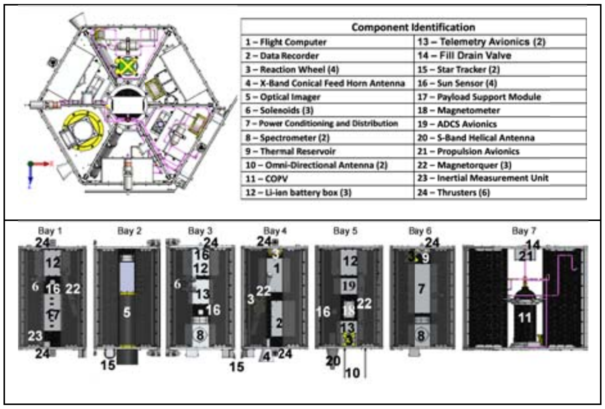


Figure 5. The CAD drawing of the exterior of DebriSat (left) and the top-view layout of the structure (right).



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).

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.

3 HYPERVELOCIYY IMPACT FACILITY AT AEDC

Previous laboratory-based hypervelocity impact tests have indicated that when the impact kinetic energy to the target mass ratio (EMR) is 40 J/g or higher, the outcome of the impact is catastrophic – meaning the target is completely fragmented into tens of thousands of pieces. Similar to the SOCIT tests, to exceed this EMR threshold for DebriSat, the hypervelocity impact has to be carried out at the AEDC facility. The AEDC Range G Complex maintains and operates the largest two stage light gas gun in the United States [11]. The range has several launchers capable of accelerating 500 g projectiles up to 7 km/sec or 15 kg projectiles up to 3 km/sec. The target is placed inside the 3-m diameter cylinder range tank (see Fig. 7). The projectile selected for DebriSat impact is an aluminium sphere with a minimum diameter of 5 cm (176 g mass). The impact speed is planned for 7 km/sec. The expected EMR is 86 J/g.

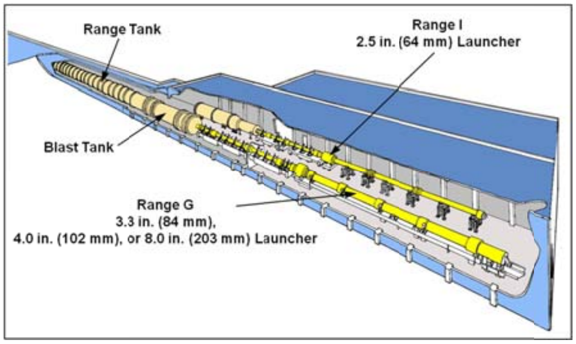


Figure 7. An illustration of the AEDC Range G two-stage light gas gun facility.

The range tank is equipped with several diagnostic instruments. They include x-ray systems with 2 microsecond intervals between frames, high speed CCD cameras, and options for additional systems, such as laser, to record the impact process and to potentially collect data for ΔV measurements for some of the fragments immediately after the impact. 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 of 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 tests series. For DebriSat, new foam materials and configuration will be adopted to capture fragments, reduce damage to the fragments, and to allow for easy extraction of fragments from the panels for post-test measurements.

Figure 8. Inside view of the Range G target chamber. The interior of the range tank is populated with low density foam panels.

4 FRAGMANTS 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 model. 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 per 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 include the selection of sample representative fragments. Those fragments will be subjected to additional three-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 size estimation model and potential improvements to the existing NASA radar size estimation model.

5 CONCLUSIONS

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

Table 2. Major milestones of the DebriSat project.

Date	Milestone
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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