National Aeronautics and Space Administration

Characterization of Orbital Debris via Hyper-velocity Ground-based Tests

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The DebriSat Team

- **NASA Orbital Debris Program Office (ODPO)**
  - Co-sponsor, project and technical oversight, data collection, data analyses, NASA model improvements. *J.-C. Liou, J. Opiela, H. Cowardin, P. Krisko,* et al.
- **AF Space and Missile Systems Center (SMC)**
  - Co-sponsor, technical oversight *T. Huynh, D. Davis,* et al.
- **The Aerospace Corporation**
  - Design of DebriSat, design/fabrication of DebrisLV, data collection, data analyses, DoD model improvements: *M. Sorge, C. Griffice, P. Sheaffer,* et al.
- **University of Florida (UF)**
  - Design/fabrication of DebriSat, data collection, fragment processing and characterization: *N. Fitz-Coy and the student team*
- **AF Arnold Engineering Development Complex (AEDC)**
  - Hypervelocity impact tests: *R. Rushing, B. Hoff, M. Nolen, B. Roebuck, D. Woods, M. Polk,* et al.

Background

To replicate a hyper-velocity fragmentation event using modern-day spacecraft materials and construction techniques to better improve the existing DoD and NASA breakup models

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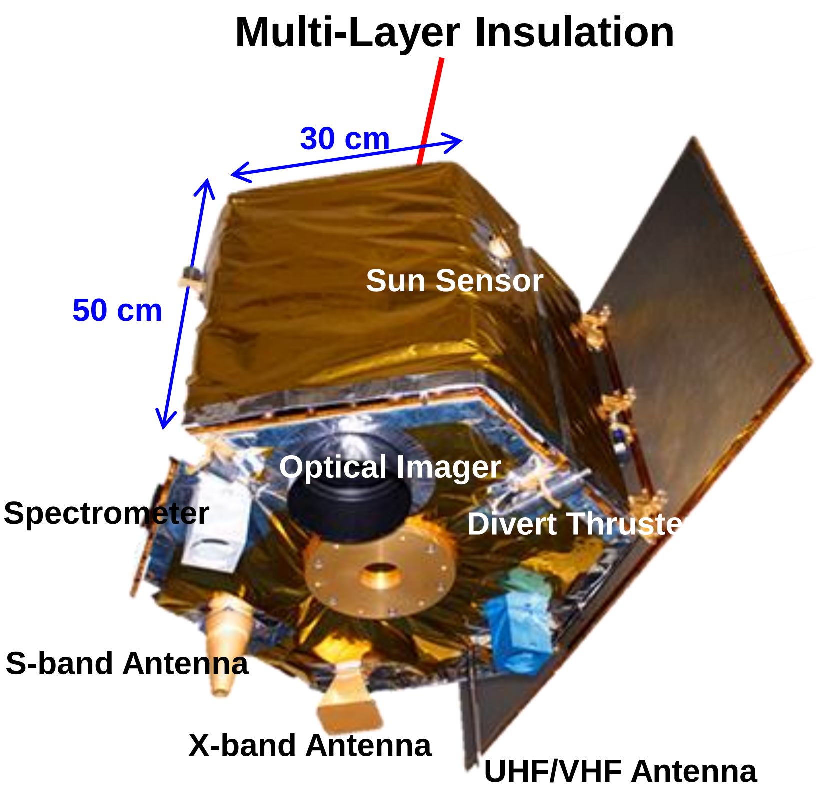
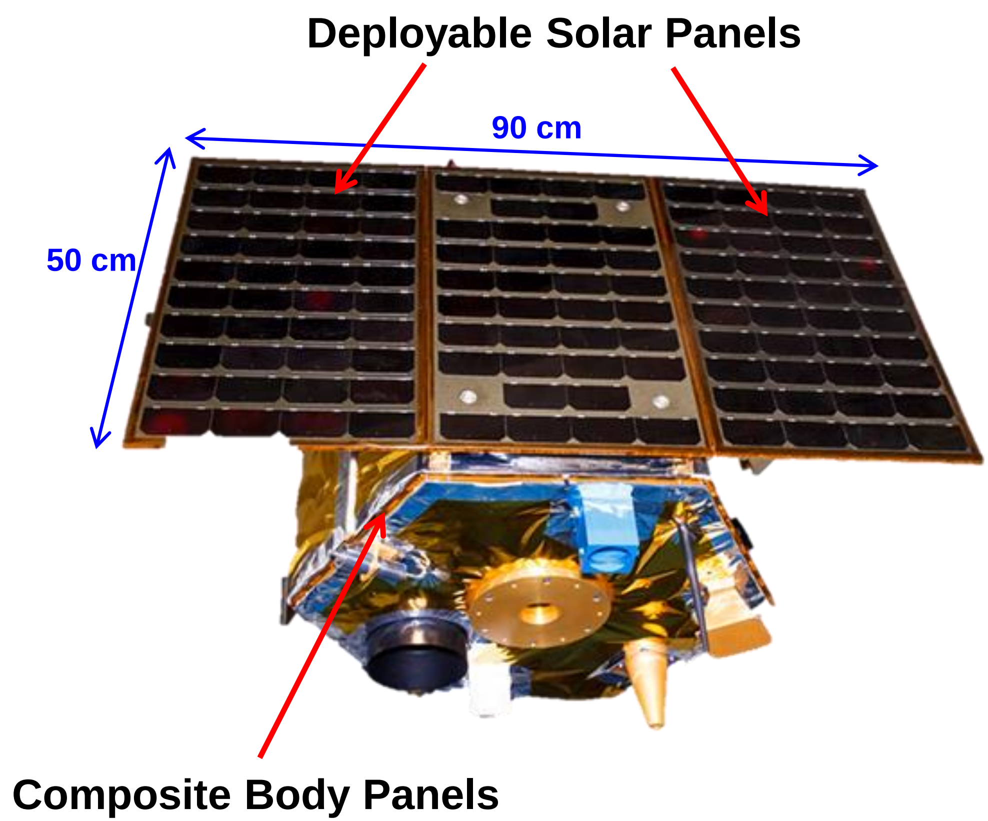
- DebriSat is intended to be representative of modern LEO satellites
    - Major design decisions were reviewed and approved by Aerospace subject matter experts from different disciplines

- DebriSat includes 7 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
    - To reduce cost, most components are emulated based on existing design of flight hardware and fabricated with the same materials

- A key laboratory-based test, Satellite Orbital debris Characterization Impact Test (SOCIT), supporting the development of the DoD and NASA satellite breakup models was conducted at AEDC in 1992
    - Breakup models based on SOCIT have supported many applications and matched on-orbit events reasonably well over the years

Design


Multi-Layer Insulation
30 cm
50 cm
Sun Sensor
Optical Imager
Spectrometer
Divert Thruste
S-band Antenna
X-band Antenna
UHF/VHF Antenna


Deployable Solar Panels
90 cm
50 cm
Composite Body Panels

DebriSat versus SOCIT/Transit

- **DebriSat has a modern design and is 63% more massive than Transit**
- **DebriSat is covered with MLI and equipped with solar panels**

	SOCIT/Transit	**DebriSat**
Target body dimensions	46 cm (dia) $\times$ 30 cm (ht)	60 cm (dia) $\times$ 50 cm (ht)
Target mass	34.5 kg	56 kg
MLI and solar panel	No	Yes
Projectile material	Al sphere	Hollow Al cylinder
Projectile dimension/mass	4.7 cm diameter, 150 g	8.6 cm $\times$ 9 cm, 570 g
Impact speed	6.1 km/sec	6.8 km/sec
Impact Energy to Target Mass ratio (EMR)	78 J/g (2.7 MJ total)	235 J/g (13.2 MJ total)

DebriSat Stages

Planning & Fabrication
2009-2014

Impact Test
April 2014

Fragment Collection
April 2014

Fragment Extraction & Measurement Planning
2014-now

Fragment Measurements
TBD 2015/early 2016

Radar & Optical Measurements
Data Analyses for models
2016

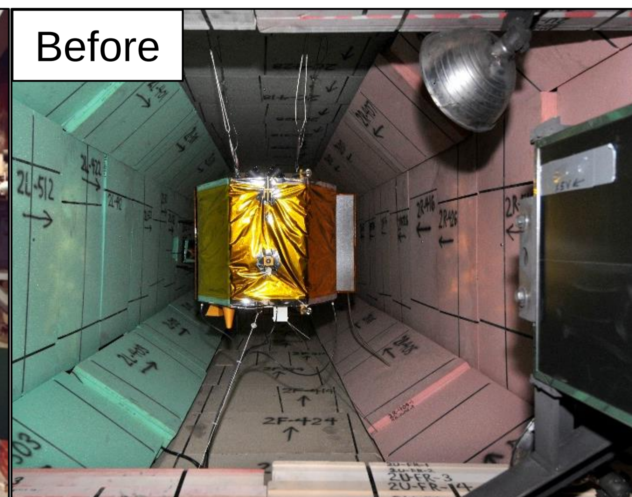
- **X-ray foam panels to determine location of debris**
- **Extract fragments**
- **Sift dust for small fragments**
- **Assign each fragment an identification number**
- **Evaluate best methodology for individual fragment measurements**

Panel-processing status

Panels prepped for X-ray:	267/564
Panels completed X-ray:	130
Debris collected:	~77K
Debris recorded:	>53,000

Impact Test

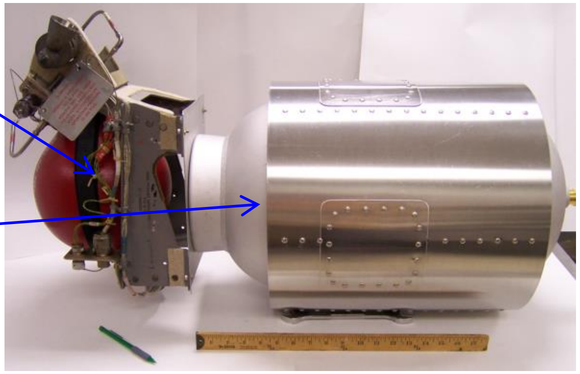
- **AEDC's Range-G operates the largest two-stage light gas gun in the U.S.**
- **Standard diagnostic instruments include X-rays, high-speed Phantom cameras, and lasers**
  - With additional IR cameras, piezoelectric sensors, and witness plates
- **Low-density polyurethane foam panels are installed inside target chamber to "soft catch" fragments**

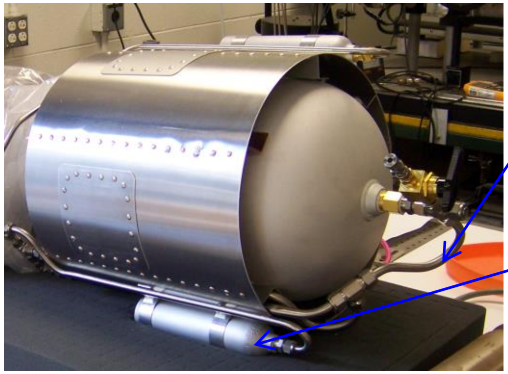


Target chamber before and after impact (10' × 20').

Pre-test Shot

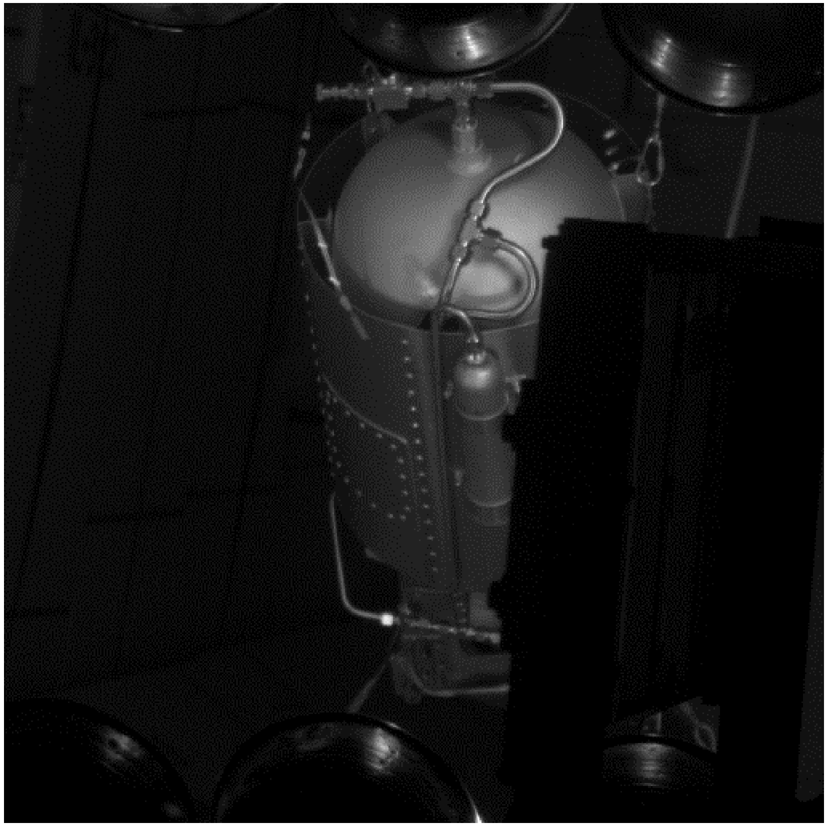
- **To further increase the benefits of the project, Aerospace built a target resembling a launch vehicle upper stage ("DebrisLV") for the pre-test shot**
  - DebrisLV: 17.6 kg, body dimensions ~ 88 cm (length) × 35 cm (diameter)
  - Test conditions were identical to the impact on DebriSat (facility setup, projectile, impact speed, *etc.*)
- **Pre-test shot was successfully conducted on April 1st**
  - Projectile impacted DebrisLV at 6.9 km/sec resulting in a catastrophic fragmentation of the target
  - Fragments and soft catch foam panels/pieces were collected in boxes on 19 pallets for shipment





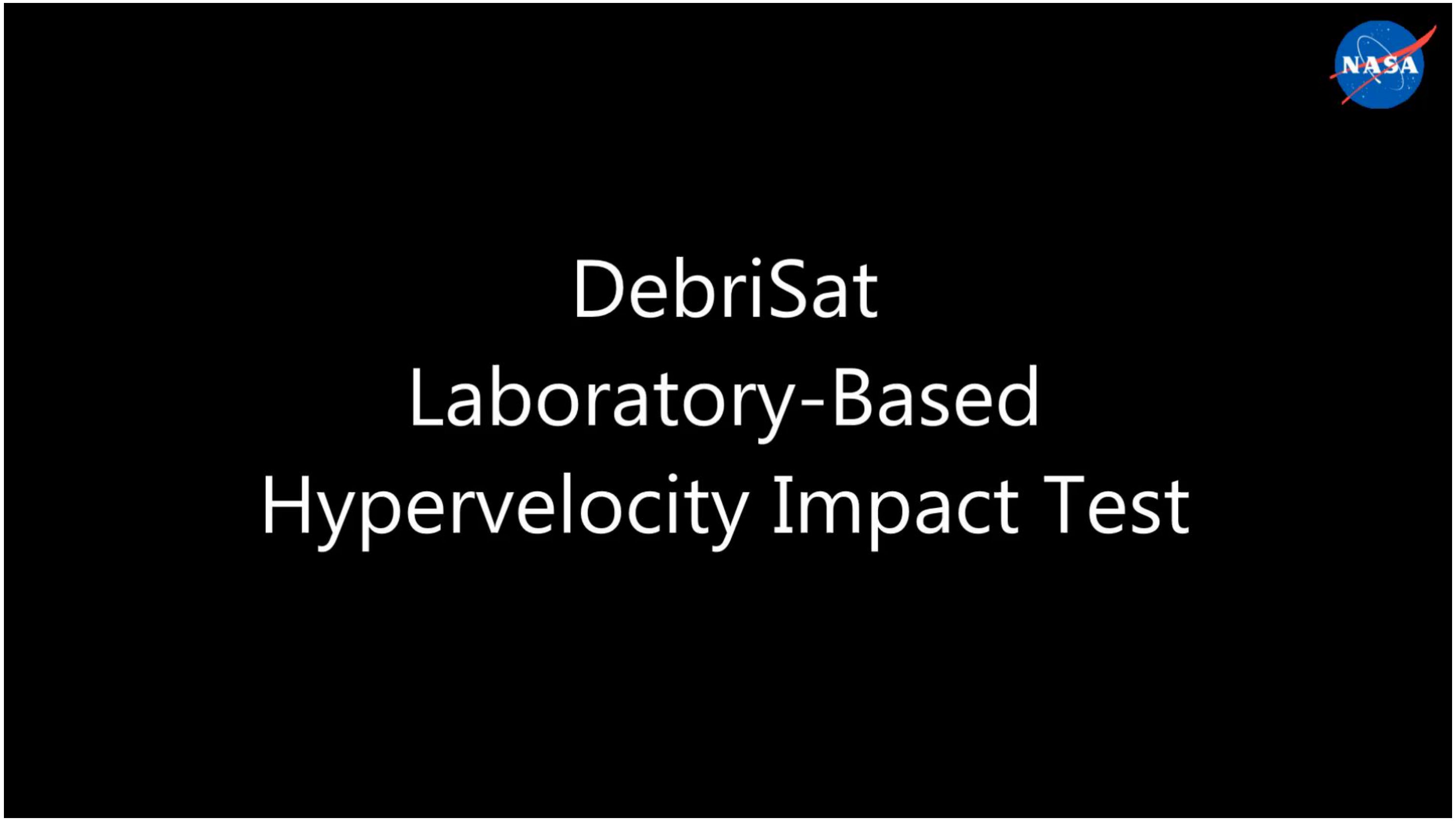
DebrisLV Impact Sequences

- **DebrisLV shot was successfully conducted on April 1st**
  - DebrisLV was impacted by 598 g projectile at 6.9 km/sec resulting in a catastrophic fragmentation of the target



DebriSat Impact Sequences

- **DebriSat shot was successfully conducted on April 15th**
  - DebriSat impacted by 570 g projectile at 6.8 km/sec resulting in a catastrophic fragmentation of the target



Post-Impact Fragment Collection

- **After impact, all intact foam panels, broken foam pieces, loose fragments, and dust were carefully collected, documented, and stored**
  - 41 pallets of ~2 m × 2 m × 2 m boxes were packed between the two tests
  - Estimated ≥2 mm DebriSat fragments are on the order of 85,000
  - Estimated > 40,000 pieces have been collected so far






Fragment Extraction & Measurement Planning

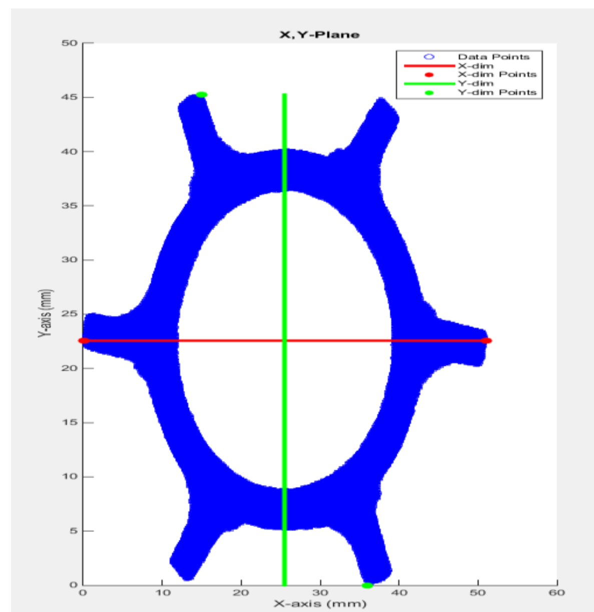
- Conduct X-ray scanning of foam panels/pieces to identify locations of ≥2 mm fragments
- Extract ≥ 2 mm fragments from foam panels/loose pieces/dust
- Recover at least 90% of the total DebriSat mass from the fragments

Sifting thru dust for 2mm fragments

X-ray image projected on panel to identify debris

Fragment Extraction & Measurement Planning

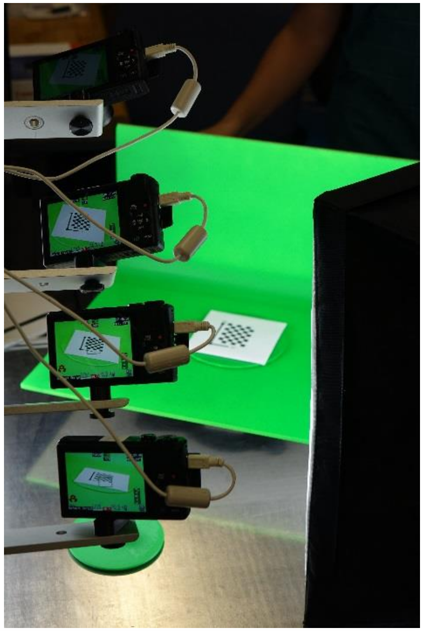
- **Measure individual fragments**
  - Primary: dimensions with associated 3D plots, mass, shape, material estimate, and digital pictures all stored in a accessible database.
  - Secondary: volume and bulk density
  - Investigating new ways to measure the size of an object without using “human-in-the-loop” methodologies: *Space Carving, alpha shapes*
- **Obtain 3D scanning data for selected fragments**
  - Cross-sectional area, Area-to-Mass ratio, volume and bulk density



Space Carving

Space Carving is a technique used to characterize a 3D scene, in the absence of *a priori* geometric information, based on *N* arbitrarily positioned cameras and known viewpoints

- **Set-up:**
  - Turntable mounted on a stepper motor
  - Optically and physically continuous background within camera's field of view (FOV)
  - Multiple cameras and various altitudes to image different aspect angles of object
- **Procedure:**
  - Acquire calibration image data for each camera from known object/calibration panel
  - At each rotation a set of images are collected from each camera
  - Images are stitched together to recreate 3D image
- **Analysis**
  - Initial test measurements prove successful in comparison to caliper measurements and 3D point cloud size measurements with < 1% error
  - Time to complete analysis from imaging to data product is within minutes versus hours



International Journal of Computer Vision 38(3), 199–218, 2000
2000 Kluwer Academic Publishers. Manufactured in The Netherlands.

Alpha Shapes

Alpha Shapes is a technique used to generate a surface from a point cloud. The surface of an alpha shape is defined by facets that can be further restrained by compressing the number of points to produce the accuracy desired for complex shapes.

- Assumptions: (1) the point cloud must include uniformly distributed vertices and (2) there must be an appropriate sample size of vertices to describe the shape.
- Steps: (1) Create a convex hull of a point cloud and (2) Subtract sections of radius alpha(α) or larger from the convex hull that have no points, then repair holes left behind by subtraction

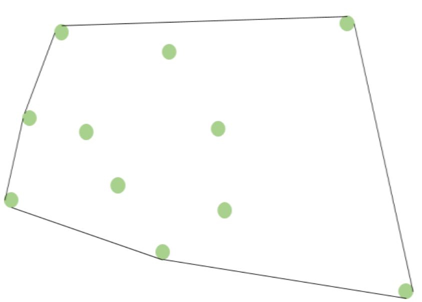
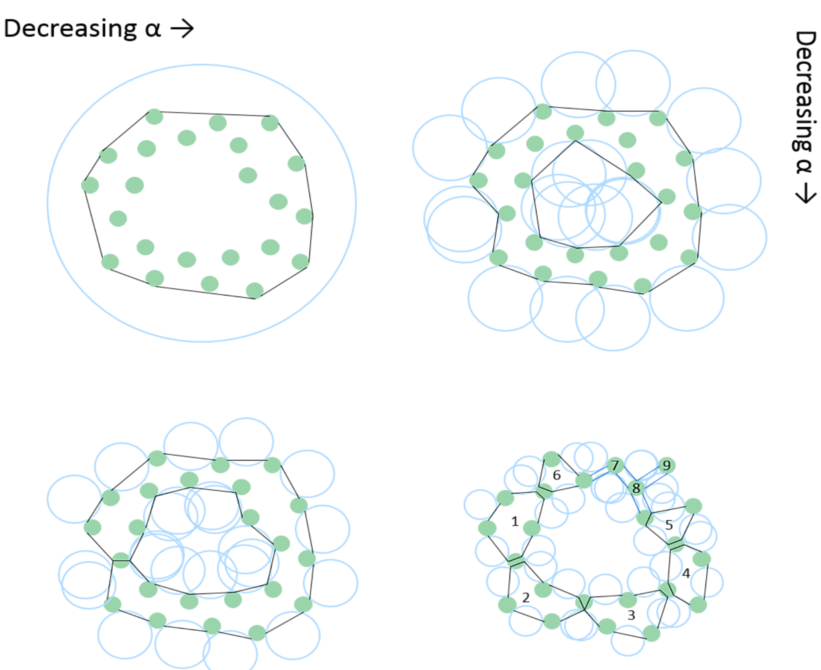


Figure 1: Example of a convex hull for a set of points



Applied Measurements

- **Laboratory radar and optical measurements will be performed on a subset of fragments to provide a better understanding of the data products from orbital debris acquired from ground-based radars and telescopes**

- **Radar will provide a radar cross section at a specified frequency, while optical will provide a newly defined term, optical cross section**

- **The current NASA Size Estimation Model is purely based on radar measurements from a hypervelocity impact of dated simulated spacecraft. The data from DebriSat will be use to update the NASA Radar Size Estimation Model with more modern materials, as well as include optical measurements into the model**

Applied Measurements

- **Current optical measurements assume a range, albedo, and phase function (how the intensity changes as a function of phase angle)**
  - Laboratory optical photometric measurements (ie, BRDF) will help refine these assumptions to better provide a size estimate comparable to radar
  - Laboratory spectral measurements will also be used to analyze albedo changes of the fragments provided the baseline (pre-impact measurements) and post-impact (material darkening, *etc.)*
  - A subset of the fragments will also be sent to space environment effect chambers to study to how the optical properties of materials change due to space weathering

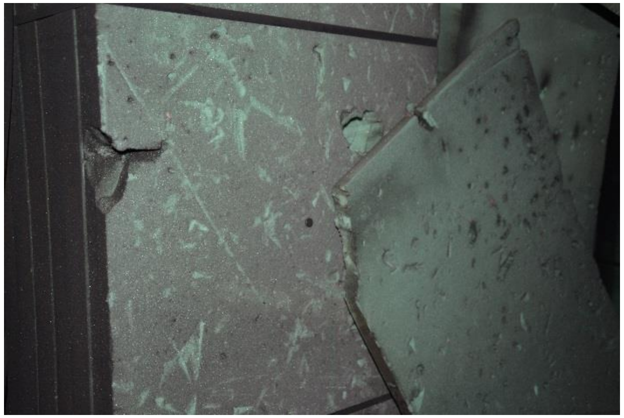
- **Radar/Optical measurements are slated to start 2016, contingent on available resources**

Additional Instrumentation

- Aerospace Hypertemporal Multispectral Imager (AHMI) **–** High speed infrared (4-5 μm) imager (1K-3K frames per second)
- Infrared Hyperspectral Imager (AERHY)
- Borescope and high speed camera – Observe internal propagation of plasma flash within DebrisLV
- Large multi-layer witness plates – Nature and types of deposition
- Small witness plates throughout test chamber – Collected small debris samples
- Intensified gated CCDs using fiber optics for light collection - UV-visible time resolved spectra measured
- Portable FTIR – IR analysis of samples pre and post test

Observations and Research Areas

- **Plasma jetting**
- **Plasma vapor deposition**
  - Metal flake creation
- **Very small particle (μm-nm) sources, characteristics**
  - Very large numbers of this sized debris observed
- **Material properties effects**
  - Material strength – debris size distribution relationships
- **Time-resolved spectroscopy**
  - Explored plasma temperature, composition
  - Variations of characteristics/emission lines with time
- **Expect papers (G. Radhakrishnan, P. Sheaffer, P. Adams)**



BACK-UP CHARTS

AEDC Test Report

- **AEDC Test Report: projectile velocity ~7km/s and "chamber pressure was set to be less than two torr, or 98,000 ft altitude". (1 Torr is ~1 mmHG)**

Table 3 Project Parameters

Parameter	Requirement	DebrisLV	DebriSat
Test Date	-	1 April 2014	15 April 2014
Time of shot	-	1835 CST	1709 CST
Chamber Pressure	< 2.0 Torr	1.3 Torr	1.8 Torr
Velocity	7.0 km/sec	6.9 km/sec	6.8 km/sec
Projectile Weight	550-650 g	598 g	570 g