National Aeronautics and Space Administration

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

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In support of the NASA Orbital Debris Program Office

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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, M.E. Vojtek, 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

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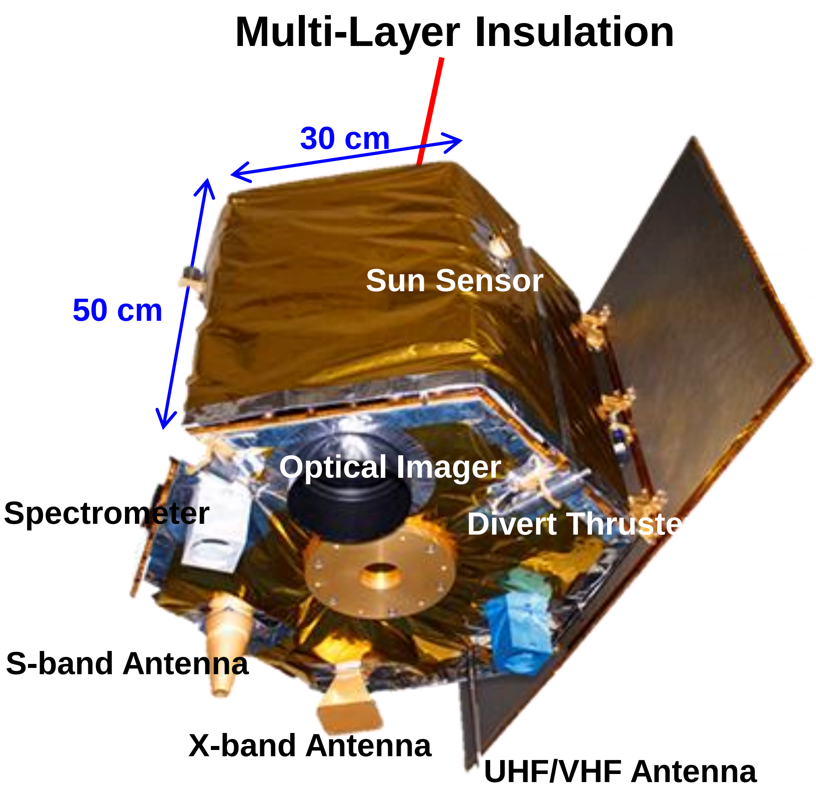
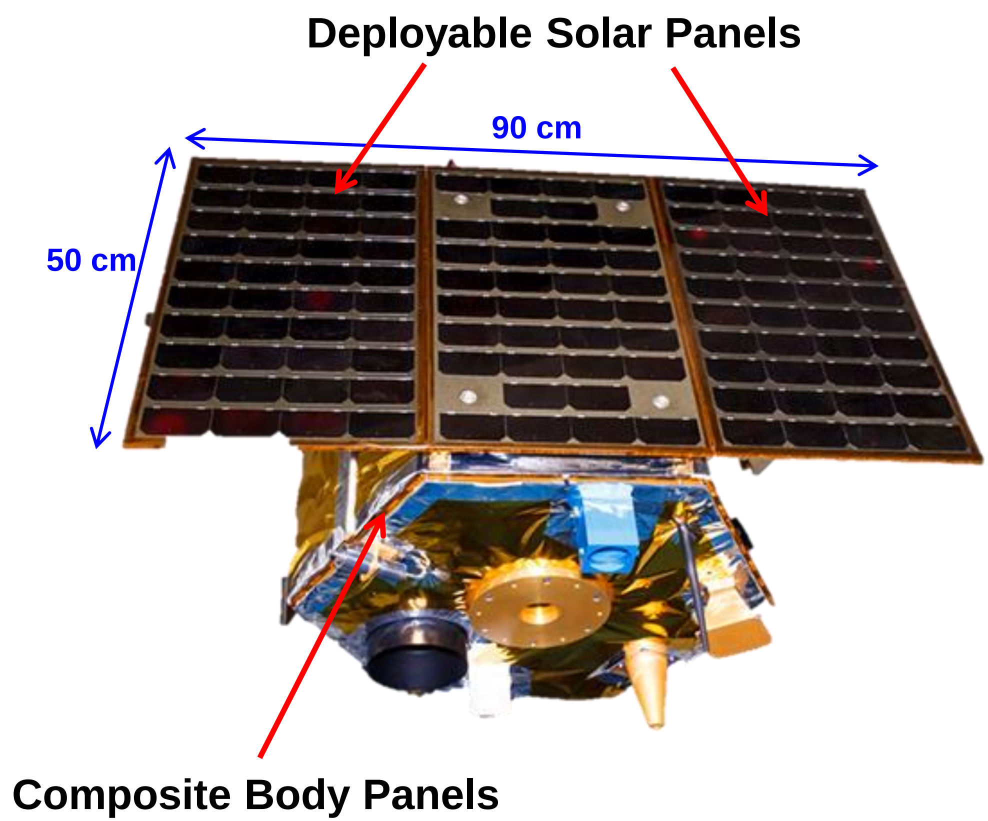
- DebriSat is intended to be representative of modern LEO satellites
  - Major design decisions were reviewed and approved by Aerospace subject matter experts from different disciplines

- 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

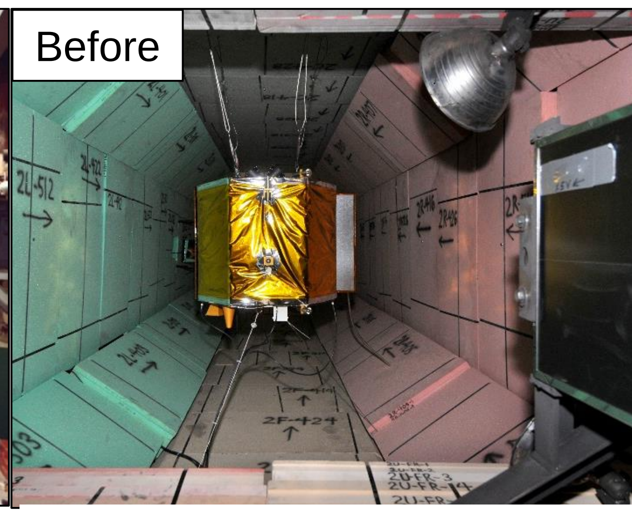
DebriSat versus SOCIT/Transit

- 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)

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**



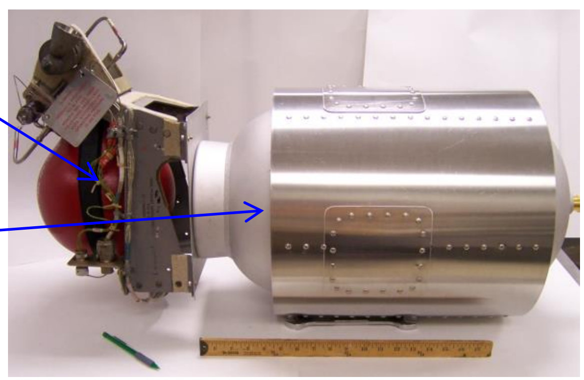
Target chamber before and after impact (10' × 20').

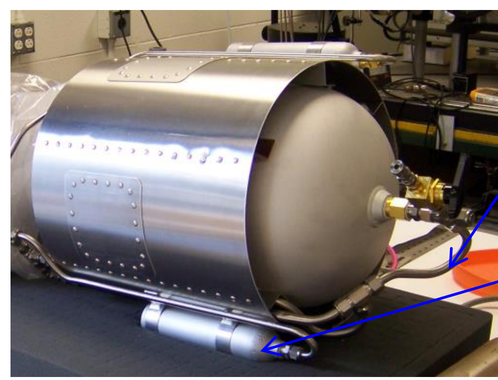
Pre-test Shot

- **To further increase the benefits of the project, Aerospace built a target resembling a launch vehicle upper stage ("DebrisLV") for the pre-test check 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

Delta-II Ti roll control thruster assembly

Al alloy tank (xenon 15 psia) and Al alloy skin



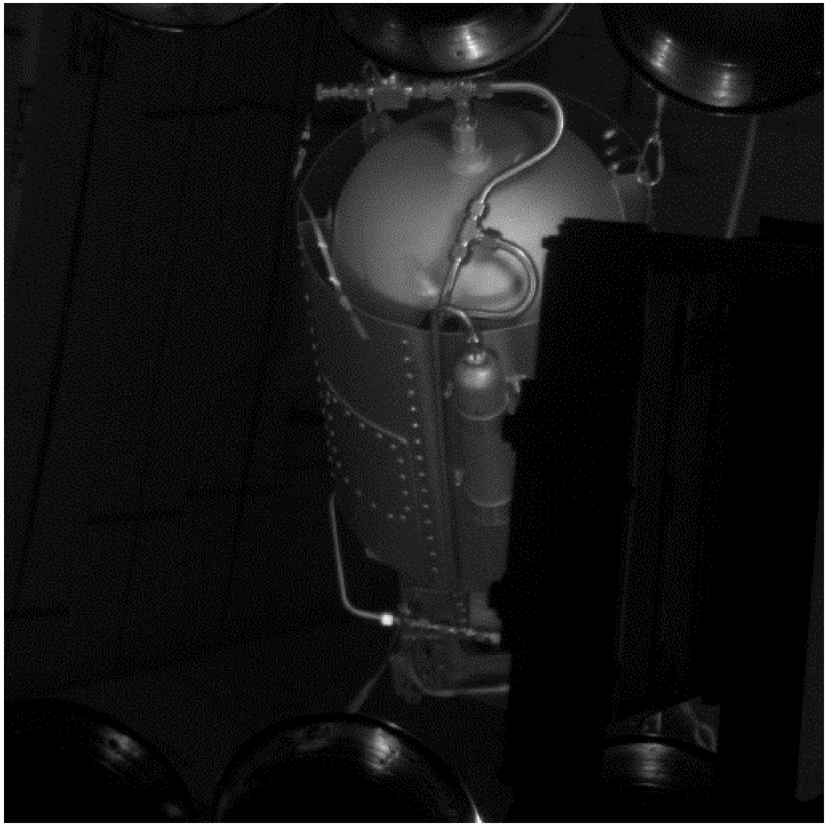


Stainless steel fuel lines

Al alloy strap-on tanks (one on each side)

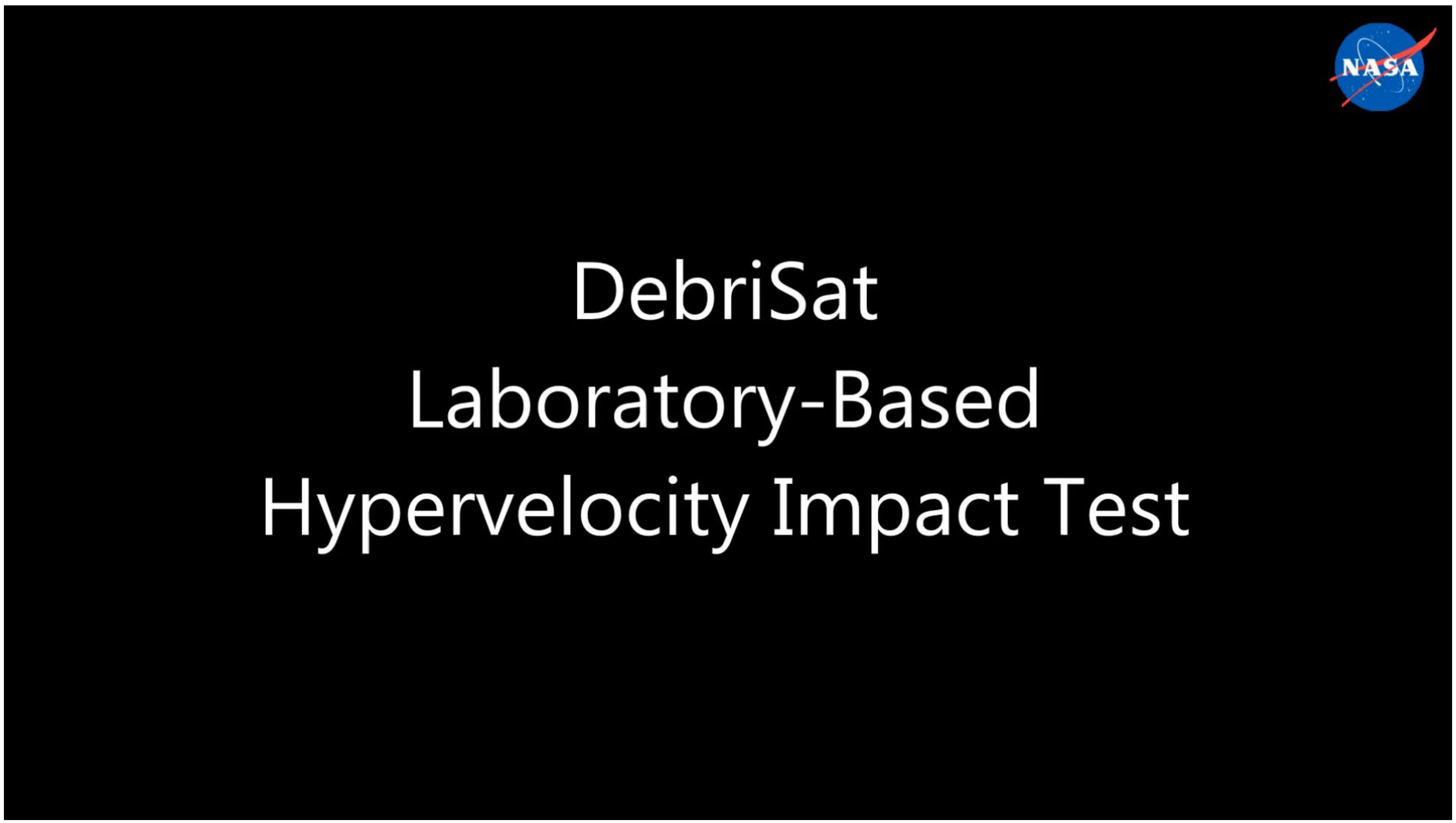
DebrisLV Impact Sequences

- **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 (~2 × 2 × 2 m) of boxes were packed between the two tests

DebriSat Stages

Planning & Fabrication
2009-2014

Impact Test
April 2014

Fragment Collection
April 2014

Fragment Extraction & Measurement Planning
2014-now

Fragment Characterization & Defining Requirements for Characterization Data for Models
Early 2016-now

Radar & Optical Measurements for Data Analyses and Models
Mid-late 2016

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
- Assign each individual fragment unique identification number
- Recover at least 90% of the total DebriSat mass from the fragments
- Current estimate for the >2mm DebriSat fragments to be collected is more than 200,000

Sifting thru dust for 2mm fragments

Panel-processing status

Panels prepped for X-ray:	337/564
Panels completed X-ray:	256
Debris collected:	~112K
Original Estimate:	85K
Debris recorded:	>107K

X-ray image projected on panel to identify debris

Fragment Characterization

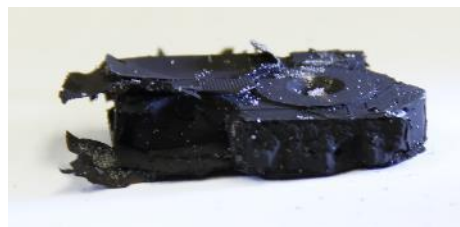
- **Implementing new ways to acquire measurements without using "human-in-the-loop" methodologies**

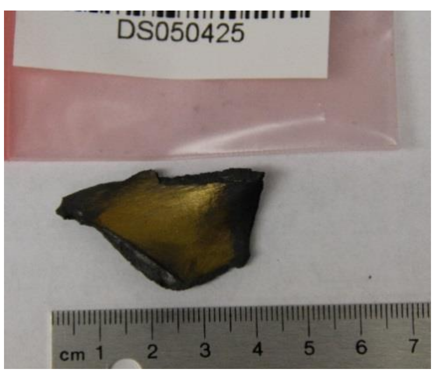
- **Acquire individual mass measurements, data sent directly to database via usb/serial cable**

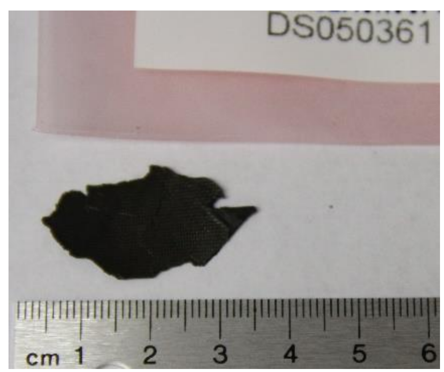
- **Define fragment's physical parameters from specific drop-down data fields, limited text input to restrain "unknowns"**
  - **Shape**
    - **Defined by NASA/Aerospace collaboration**
  - **Material**
    - **Material density automatically input once material is chosen**
  - **Color**

- **Calculate/derive following parameters using 2D and 3D imaging systems:**
  - **Principle dimensions (x,y,z)**
  - **Characteristic length**
  - **Average cross-sectional area**
  - **Area-to-mass ratio**
  - **Volume**
  - **Bulk density**

Examples of DebriSat Fragments

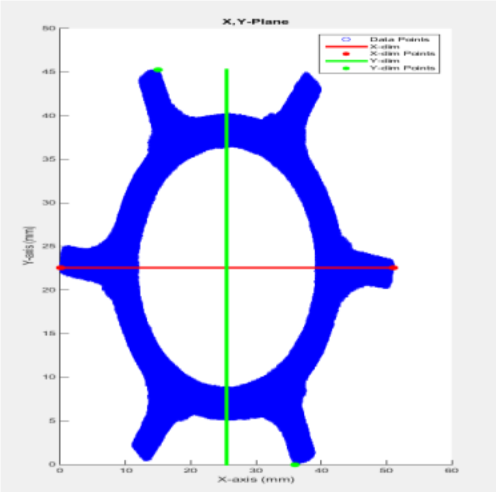


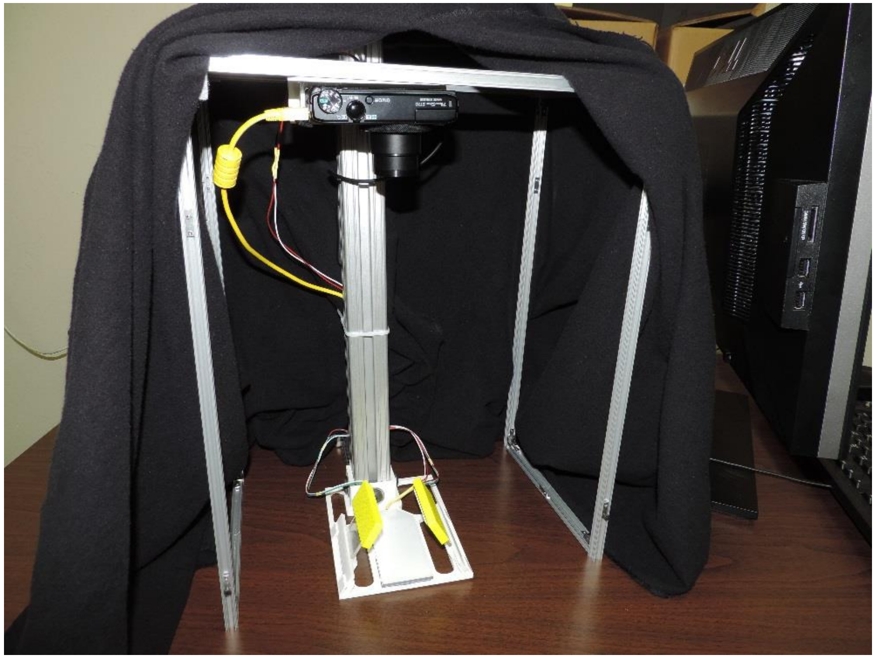




Imaging Systems

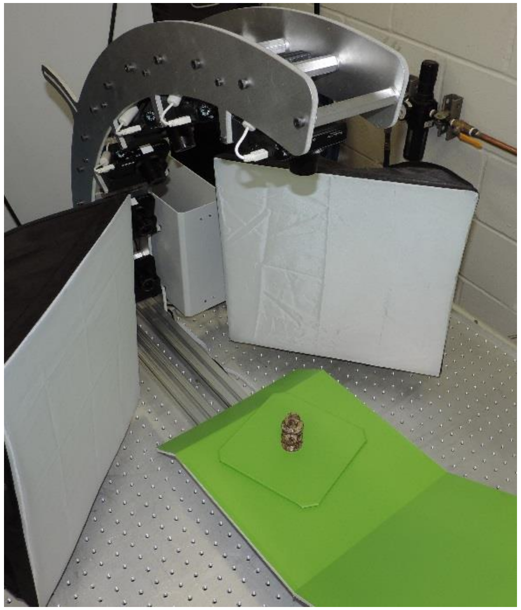
- **2D Imaging System**
  - X and Y dimensions
  - Z dimension is derived from material density (volume) of known materials
  - Characteristic Length
  - Average Cross-Sectional Area

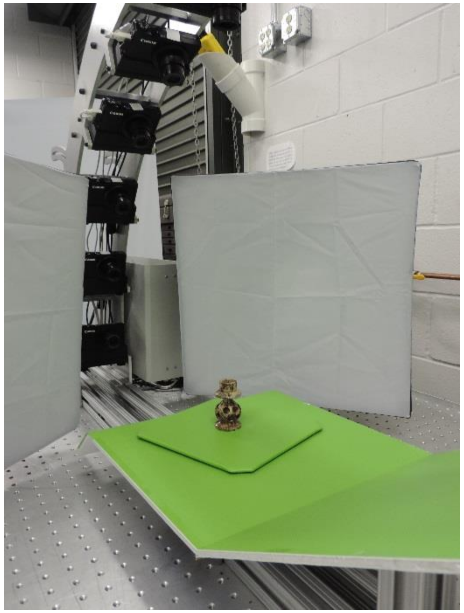


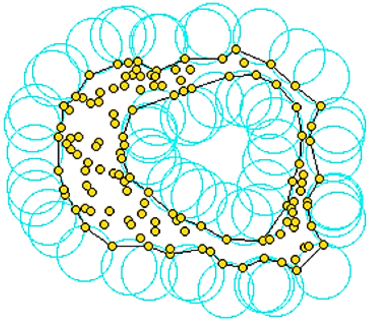


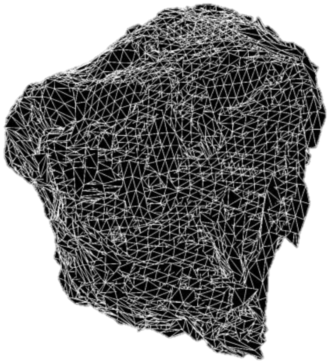
Imaging Systems

- **3D Imaging system**
  - X,Y, and Z dimensions
  - Characteristic Length
  - Volume-->Bulk density
  - Average Cross-Sectional Area using point cloud
- ***Space Carving,*** automated imaging system developed for the size characterization of debris fragments
- ***Alpha Shapes*****,** new program written by NASA interns that employs alpha shape theory to create a closed volume from 3D scanner generated point clouds and then calculates the volume using Gauss' divergence theorem









Laboratory
Radar & Optical 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. The data will also provide valuable information regarding variability on the same object as a function of material, shape, and aspect angles.**

- **Radar will provide a radar cross section at a set of frequencies, while optical will provide a newly defined term, optical cross section**

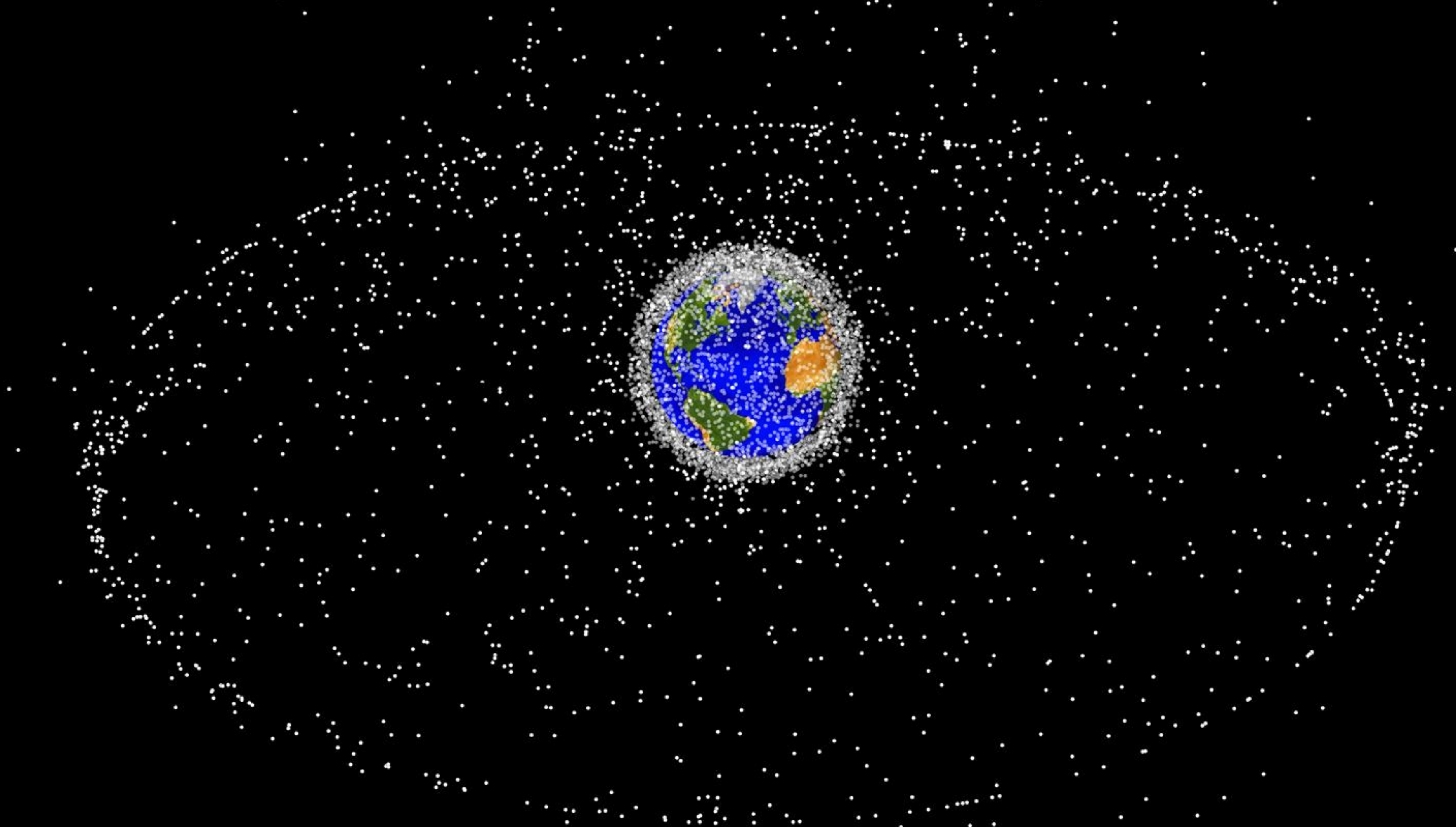
- **Current optical measurements assume a range, albedo, and phase function (how the intensity changes as a function of phase angle) to define a size**
  - Laboratory optical photometric measurements (ie, BRDF) will help refine these assumptions to better provide a size estimate comparable to radar
  - 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 effects chambers to study to how the optical properties of materials change due to space weathering

Data Analyses for Models

- **The current NASA (Radar) Size Estimation Model is purely based on radar measurements from a hypervelocity impact of dated simulated spacecraft. The data from DebriSat will be used to update the NASA Radar Size Estimation Model and to develop a NASA Optical Size Estimation Model**

- **The resulting data will be used to better assess penetration effects and introduce a shape factor into ballistic limit, damage, and penetration equations used by the hypervelocity impact testing and technology group at NASA\JSC**

Thank You



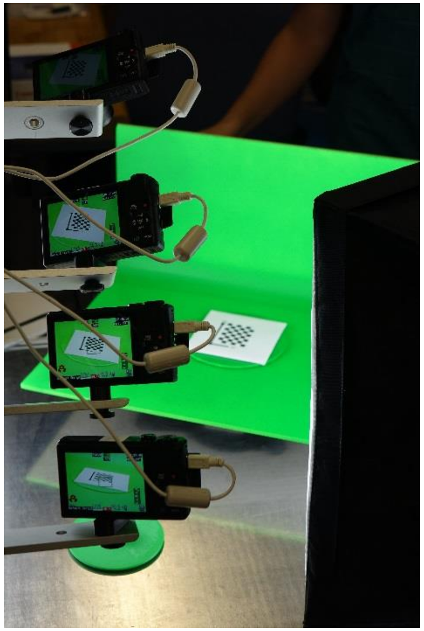
Any Questions?

BACK-UP CHARTS

Size Measurements: 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 at various altitudes to image different aspect angles of object
- **Procedure:**
  - Acquire calibration image data from each camera using known calibration targets
  - At each rotation a set of images is 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 minutes versus hours for laser-scanning techniques

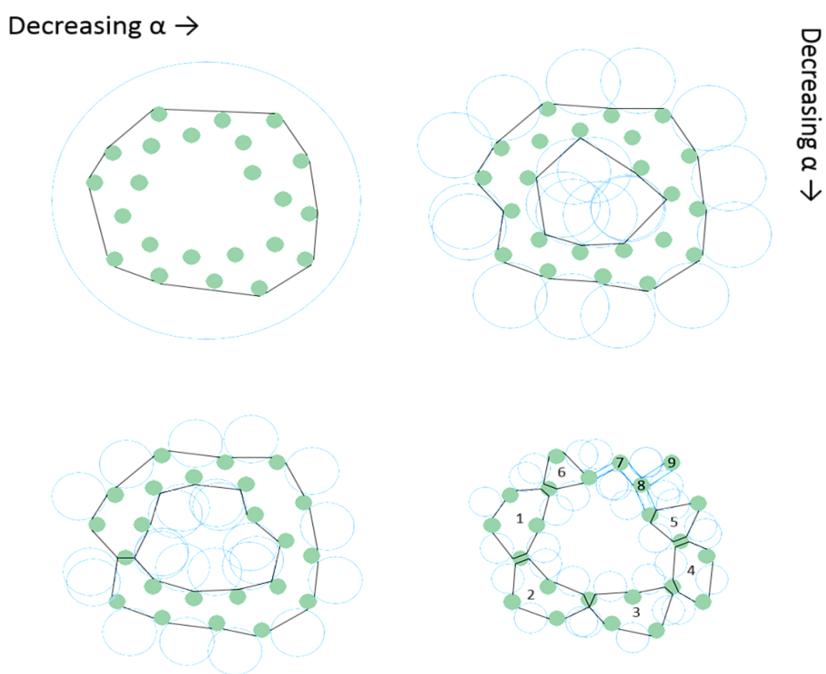


International Journal of Computer Vision 38(3), 199–218, 2000
2000 Kluwer Academic Publishers. Manufactured in The Netherlands.

Volume Measurements: 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 *α* or larger from the convex hull that have no points, then repair holes left behind by subtraction



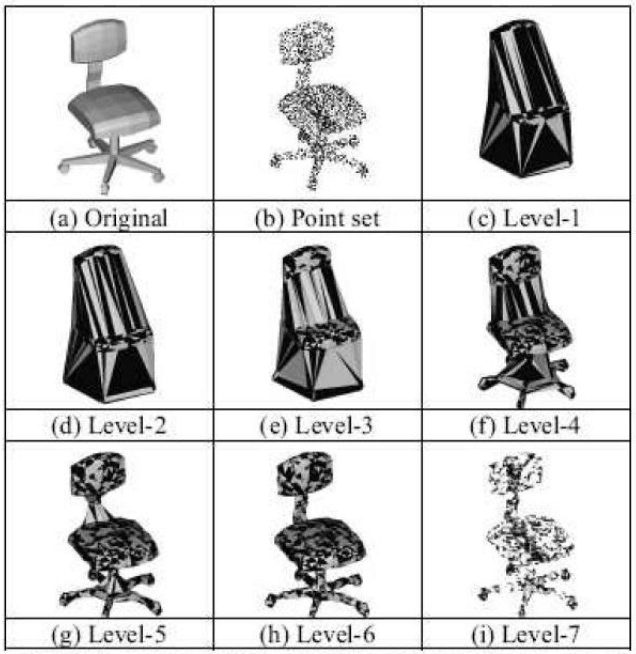


Figure 3. A set of alpha shapes generated from a set of 1024 point generated on the surface of the original model.

http://people.mpi-inf.mpg.de/~jgiesen/tch/sem06/Celikik.pdf
http://research.engineering.wustl.edu/~pless/546/lectures/lecture22.pdf

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

Further analyses underway by Aerospace Corp.

- **Tests**
  - Plasma jetting
  - Plasma vapor deposition (Metal flake creation)
  - Very small particle (mm-nm) sources, characteristics
  - Material properties effects (Material strength – debris size distribution relationships)
  - Time-resolved spectroscopy (Explored plasma temperature, composition variations of characteristics/emission lines with time)

- **Instrumentation used by Aerospace Corp.**
  - Aerospace Hypertemporal Multispectral Imager (AHMI) – High speed infrared (4-5 mm) 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