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IMPROVING THE NEAR-EARTH METEOROID AND ORBITAL DEBRIS ENVIRONMENT DEFINITION WITH LAD-C

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ABSTRACT

To improve the near-Earth meteoroid and orbital debris environment definition, a large area particle sensor/collector is being developed to be placed on the International Space Station (ISS). This instrument, the Large Area Debris Collector (LAD-C), will attempt to record meteoroid and orbital debris impact flux, and capture the same particles with aerogel. After at least one year of deployment, the whole system will be brought back for additional laboratory analysis of the captured meteoroids and orbital debris. This project is led by the U.S. Naval Research Laboratory (NRL) while the U.S. Department of Defense (DoD) Space Test Program (STP) is responsible for the integration, deployment, and retrieval of the system. Additional contributing team members of the consortium include the NASA Orbital Debris Program Office, JAXA Institute of Space and Astronautical Science (ISAS), Chiba University (Japan), ESA Space Debris Office, University of Kent (UK), and University of California at Berkeley. The deployment of LAD-C on the ISS is planned for 2008, with the system retrieval in late 2009.

INTRODUCTION

Meteoroids and orbital debris exist in the near-Earth environment. In addition to general scientific interests in these two populations, the growing space activities also demand a good characterization of the particle environment for reliable operations risk assessments and cost-effective shielding designs for satellites. The data needed include population breakdown, flux, velocity, size, and material density distributions.

To develop a good environment model with sufficient information for impact risk assessments, one must rely on observational data. Although the meteoroid populations do not vary noticeably on a yearly basis¹, the orbital debris populations have increased dramatically in the last 50 years², and are expected to follow a similar trend in the foreseeable future³. Therefore, there is an additional need to collect data on a regular basis to update the environment definition.

To cover the full size spectrum of the meteoroid and orbital debris populations that is important to the safety community, ground-based radars and optical telescopes and space-based *in situ* sensors must be utilized. In general, telescopes and radars are used to sample objects a few millimeters and larger in the low Earth orbit (LEO, 200 to 2000 km altitude) region while *in situ* sensors are used to probe smaller particles, as illustrated by Figure 1⁴. Although ground-based observations have been conducted on a regular basis, there has been a lack of large area *in situ* sensors to characterize and update the small particle environment since the retrieval of the Long Duration Exposure Facility (LDEF) in 1990. Recent dedicated sensors, such as the DEbris In orbit Evaluator (DEBIE⁵) and the Micro-PARTicle Captured (MPAC⁶) system, only detected particles about 20 μm and smaller, due to their limited sensing areas. Such small particles are not a safety concern for operational satellites. Large surfaces returned from space, such as Shuttle window panels and radiators⁷ and the Hubble Space Telescope Solar Arrays⁸, have been examined to estimate the larger meteoroid and orbital debris populations. The results, however, are not as useful as those from surfaces designed specifically to be used as impact sensors. Additional factors, such as the lack of impact timing information and the difficulty to distinguish meteoroids from orbital debris, also add deficiency to the returned-surface data. From the safety and satellite operations perspective, there is an immediate need for a large and dedicated meteoroid and orbital debris sensor to monitor and update the populations.

The Large Area Debris Collector (LAD-C) project is being developed by a consortium of members from international space agencies and universities. Their roles and responsibilities are: NRL (lead, management, acoustics, electronics, engineering), NASA Orbital Debris Program Office (project development support, science planning and operations), JAXA/ISAS and Chiba University (aerogel manufacture,

calibration), ESA Space Debris Office (system software, hardware manufacture, thermal analysis, calibration), University of Kent (calibration), and UC Berkeley (calibration). The U.S. Department of Defense (DoD) Space Test Program (STP) Office is in charge of the system launch manifesting, deployment, and retrieval. LAD-C post-flight analysis will be a major task. It may include acoustic signal processing, analysis, and correlation; aerogel inspection; impact feature classification and measurement; orbit determination; residual extraction; composition analysis; and population modeling. The responsibility of post-flight analysis will be shared by all team members. The LAD-C Preliminary Design Review was held in May 2006. The Critical Design Review is scheduled for early 2007. The deployment of LAD-C on the International Space Station (ISS) is planned for a Shuttle flight in mid-2008, with the system retrieval scheduled for 2009.

LAD-C consists of two major components: acoustic sensors and aerogel tiles. The combined area-time product of the system, about $10 \text{ m}^2\text{-year}$, will provide a much needed orbital debris and meteoroid flux characterization in the size regime that is important to the satellite operations safety community – $100 \mu\text{m}$ and larger. A second key mission objective is the source identification of the collected samples. The combination of acoustic sensors and aerogel tiles will make it possible to estimate the impact locations and velocities of some of the collected samples. The data can be used to reconstruct their orbits, and lead to the possible identification of their sources (asteroidal, cometary, orbital debris). Compositional analysis of the collected samples can also separate debris from meteoroids, and provide additional breakdown of the orbital debris populations (*e.g.*, Al, paint, steel, Al_2O_3). The combined science return of LAD-C will greatly advance our knowledge of the near-Earth meteoroid and orbital debris environment.

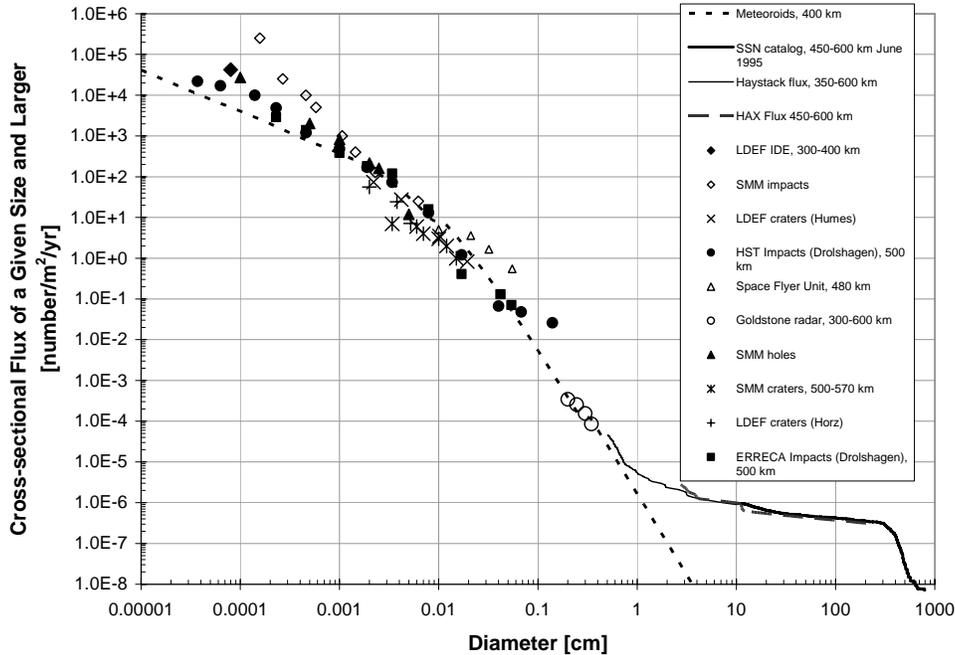


Fig. 1: Approximate measured debris flux in low Earth orbit, by object size (adopted from the United Nations Technical Report on Space Debris, Anon 1999). Particles 1 mm and smaller are detected by space-based *in situ* sensors or surfaces returned from space, including LDEF, Solar Maximum Mission (SMM), Space Flyer Unit, European Retrieval Carrier (EURECA), and Hubble Space Telescope (HST) solar panel post flight analyses (PFA) 1 and 2.

LAD-C COMPONENTS

LAD-C consists of two major components: aerogel tiles and acoustic sensors. The former is intended for intact capture of hypervelocity impact particles while the latter is designed to record the impact characteristics (timing, location, energy, *etc.*) of the captured particles. Several small area (~10 cm × 10 cm) adjunct passive sensors are also being considered to be integrated into the system for additional calibration purposes. The basic structure of LAD-C is an upside down T-shaped system with a total of twelve 1 m × 1 m aluminum panels mounted on a central hub. Each panel is further divided into 36 units filled with aerogel tiles (2.1 cm thickness). A total of 12 acoustic sensors will be attached to each panel. The system will be mounted on a starboard side truss of the ISS with the aerogel collection surface facing the starboard direction. The selection of the mounting location and orientation is based on the balance between minimizing possible particle contamination (*e.g.*, ISS water/waste dumps and thruster plume particles coming from

Shuttle) and maximizing particle collection with aerogel.

Aerogel

Aerogel has been used previously to capture meteoroids and orbital debris in the near-Earth environment. For example, the Orbital Debris Collector (ODC) was deployed on the *Mir* Station between 1996 and 1997⁹, and MPAC was placed on the ISS in 2001¹⁰. Two key differences make LAD-C stand out from previous aerogel experiments. First, the collection area of the LAD-C aerogel is 10 m². It is more than one order of magnitude larger than all previous aerogel experiments combined. With a mission duration of at least one year, the LAD-C aerogel will be able to capture a significant number of large (≥100 μm) meteoroids and orbital debris. In addition to addressing safety concerns caused by these large particles, LAD-C will return a collection of meteoroids in this size range, something not previously attempted. Analyzing the physical properties and chemical compositions of these

large meteoroids will extend our knowledge from small cosmic dust captured by high altitude aircraft to a size regime that is one or two orders of magnitude larger. The second unique feature of LAD-C is the ability to record impact timing data of the particles captured by aerogel with the acoustic sensors (see the Acoustic Sensors Section). The information can be used to analyze any seasonal variation in the environment, and to identify significant temporal events. In addition, impact features embedded in aerogel will be further analyzed to estimate the impact characteristics for the possible source identification of the captured particles.

Many hypervelocity impact tests on aerogel have been performed previously to correlate impact speed, impact angle, projectile properties, and aerogel density with impact features embedded in aerogel¹¹⁻¹⁵. The impact direction can be reconstructed, from a good track, to within 2°. Below the range of 7 km/s impact speed, there are clear trends that relate impact speed to track length, track volume, and other features. For impacts above 7 km/s, the correlation is less certain due to a lack of laboratory data. However, the ODC collection on *Mir* and the subsequent analysis show a clear transition in impact feature morphology that is most likely a result of impacts from different velocity regimes⁹. Many additional calibration

tests will be performed to aid the LAD-C post-flight aerogel data interpretation.

The LAD-C aerogel is a special water-resistant silica aerogel originally developed for Cherenkov counters at Japan's national KEK high energy laboratory and Chiba University^{16, 17}. Similar KEK-produced aerogel was flown on the ISS as part of the MPAC package¹⁰. The selection of LAD-C aerogel density was based on careful consideration of two competing factors. Lower density aerogel produces better impact features (*e.g.*, longer tracks), but leads to weaker impact acoustic signals. In order to find the right balance, a series of hypervelocity impact experiments were conducted at the Centre for Astrophysics and Planetary Sciences (CAPS), School of Physical Sciences, University of Kent in August 2006. Glass microspheres (103 ± 3 μm diameter) were used as projectiles for the CAPS two-stage light gas gun¹⁸. A test unit consisted of one aerogel tile (~14.5 cm × 14.5 cm × 2.2 cm) inserted into an aluminum frame, with two cross bars (4 mm wide) on the front and rear surfaces. Three acoustic sensors were attached to each test unit. Aerogel tiles with densities ranging from 0.0368 to 0.0600 g/cm³ were used during the tests. Each test unit was placed in the target chamber with the aerogel surface perpendicular to the flight path of the projectiles. Table 1 summarizes the main results from the 11 calibration tests.

Shot ID	Aerogel Density (g/cm ³) & Tile Thickness (cm)	Impact Speed (km/sec)	No. of Projectile Tracks	Perforation of the Tile	Degree of Penetration
1	0.0420, 2.34	5.05	1	yes	100%
2	0.0509, 2.15	5.14	2	no	~95%
3	0.0368, 2.24	5.11	4	yes	100%
4	0.0368, 2.24	5.29	0 ^(a)	–	–
5	0.0509, 2.15	5.17	2	no	~95%
6	0.0509, 2.15	5.21	0 ^(b)	–	–
7	0.0509, 2.15	5.14	1	no	~90%
8	0.0441, 2.32	5.18	1	yes	100%
9	0.0596, 2.24	5.02	2	no	~50% ^(c) ; ~70%
10	0.0600, 2.24	4.92	0 ^(d)	–	–
11	0.0596, 2.24	4.84	4	no	~50% ^(c) ; ~50% ^(c) ; ~70%, ~80%

Table 1: A summary of the 11 impact tests.

^(a)Several large metal pieces (possibly from sabot) impacted the aerogel tile and created large (~7 mm diameter) craters.

^(b)No projectile impact observed. The aerogel surface was rather clean.

^(c)The shorter track split into 2 narrower tracks near the end.

^(d)One piece of metal (possibly from sabot) impacted the aerogel tile and created a large (~3 mm diameter) crater.

After each shot, the aerogel tile was inspected visually, as well as with a microscope (up to 56× magnification), for impact features and damages. A digital camera was used to record images of the impact features. Surface entry and exit holes were measured with scales. However, track lengths and degrees of penetration were just estimated visually, due to the lack of equipment to cut the large aerogel tile into smaller pieces. Figure 2 shows the entry hole of the only track from the first shot. The diameter of the hole was about 1.114 mm. The projectile actually perforated the aerogel tile (0.0420 g/cm³) and left a classic carrot-shaped track behind. The exit hole on the rear surface had a diameter of 218 μm. As expected, when higher density aerogel targets were used, the projectiles did not perforate the tiles. For example, the two projectiles from Shot 2 stopped just short of reaching the rear surface of the tile. Both projectiles were clearly visible from the rear surface, and appeared to be well-preserved. One of them is shown in Figure 3. The degrees of penetration of the aerogel tracks were consistent with previous experiments. Burchell¹⁴ provided empirical expressions relating impact speed to track length for aerogel of three different densities, 0.06, 0.096, and 0.18 g/cm³. Their equation for 0.06 g/cm³ aerogel, with split tracks excluded, is

$$L = 4174 + 4331 V - 356 V^2, \quad (1)$$

where L is the track length in μm and V is the impact speed in km/s. The regression coefficient for Eq. (1) is 0.99. Applying the above equation to Shots 9 and 11, the degrees of penetration for non-split tracks are 76% and 75%, respectively. The visual inspection estimates of the two shots are consistent with these predictions.

Based on the track characteristics of all 11 shots, *i.e.*, total perforation for density 0.441 g/cm³ or lower aerogel, 90% to 95% penetration for density 0.0509 g/cm³ aerogel, and 50% to 80% penetration for density 0.0596 g/cm³ aerogel, the aerogel density selected for LAD-C was 0.06 g/cm³.

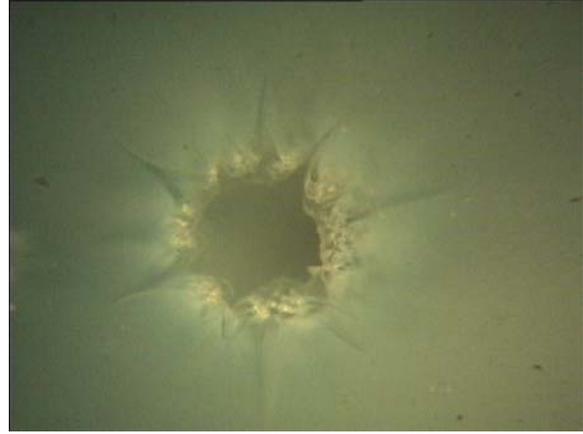


Fig. 2: The entry hole of the track from Shot 1 (magnification: 32×).



Fig. 3: An image taken from the rear surface of the aerogel tile from Shot 2 (magnification: 56×). The well-preserved spherical glass projectile was about 1 mm below the surface.

Acoustic Sensors

The acoustic sensor system developed for LAD-C is called PINDROP (Particle Impact Noise Detection and Ranging On autonomous Platforms). The basic idea is to use piezoelectric strain sensors to detect the time and location of individual particle impacts. The design is optimized by fabricating and testing sensors of various configurations and materials. The sensor material selected is a PVDF (poly-vinylidene fluoride) copolymer, which has high sensitivity, low mass, and good transient response. To demonstrate the feasibility of using PINDROP acoustic sensors to detect and characterize hypervelocity impacts on aerogel, two series of tests were conducted at NASA Ames (February

2005) and at CAPS/University of Kent (July 2005). Figure 4 shows the target used at CAPS. It included an aluminum frame with 3 aerogel filled cells and 6 PINDROP sensors. Projectiles ranging from 50 to 100 μm in size, with impact speeds of 2 to 5 km/s, were fired from the two-stage light gas gun at CAPS. Acoustic data collection was performed simultaneously on 7 channels with 16 bit resolution and a sampling rate of 1.25 MS/s.

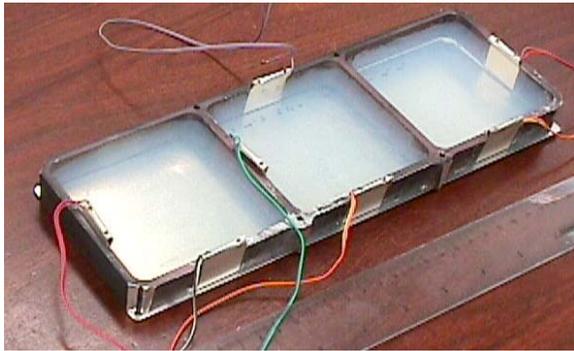


Fig. 4: The test article designed for the preliminary hypervelocity impact calibration at CAPS. Each aerogel tile had a dimension of 10 cm \times 10 cm \times 2 cm. Six acoustic sensors were attached to the sidewall of the aluminum frame to record the impact signals.

Analysis on the acoustic signals confirmed that the occurrence of each impact and the impact timing were well recorded. In addition, the signal arrival time as a function of distance for individual sensor showed a good linear correlation. The data can be used to develop a signal triangulation model to identify the location of an impact. Acoustic signals were also recorded during the calibration tests at CAPS/University of Kent in August 2006 (see the Aerogel Section). Additional calibrations still need to be carried out in the future. They will include the testing of a full scale LAD-C panel (1 m \times 1 m) with all acoustic sensors attached, and the testing of sub-panels to examine the possibility of relating impact speed to signal rise time and amplitude. The objective of the latter is to aid data from aerogel impact features to further improve the estimate of the impact speed.

SUMMARY

LAD-C consists of a large area aerogel collector and acoustic impact sensors. The innovative and low cost design has the unique capability to capture large (100 μm to 1 mm) meteoroids and orbital debris along the orbit of ISS, and record their acoustic impact characteristics. In addition to providing a much needed meteoroid and orbital debris flux data in this size regime, the impact timing and velocity data can be used to reconstruct the orbits of some of the collected particles, leading potentially to their source identification. This dynamical link, combined with the subsequent compositional analysis of the particles extracted from aerogel, will improve our understanding of meteoroids (asteroids, comets) and orbital debris (breakup fragments, paint flakes, solid rocket motor slag, etc.) in the near Earth environment.

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