IN SITU MEASUREMENT ACTIVITIES AT THE NASA ORBITAL DEBRIS PROGRAM OFFICE

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ABSTRACT

The NASA Orbital Debris Program Office has been involved in the development of several particle impact instruments since 2002. The main objective of this development is to eventually conduct in situ measurements to better characterize the small (millimeter or smaller) micrometeoroid and orbital debris (MMOD) populations in the near-Earth environment. In addition, the Program Office also supports similar instrument development to define the micrometeoroid and lunar secondary ejecta (MMSE) environment for future lunar exploration activities.

The instruments include impact acoustic sensors, resistive grid sensors, fiber optic displacement sensors, impact ionization sensors, and laser curtain sensors. They rely on different mechanisms and detection principles to identify particle impacts. A system consisting of these different sensors will provide data that are complimentary to each other, and will provide a better description of the physical and dynamical properties (*e.g.*, size, mass, and impact speed) of the particles in the environment. Testing of various prototype units at both low velocity and hypervelocity regimes is underway. Details of the test results and several systems being considered by the Program Office and their intended mission objectives will be summarized in this paper.

1. INTRODUCTION

The particle environment in space is important in several areas – satellite shielding design, impact risk assessment, mission operations, and science. In the near Earth environment there are micrometeoroids and orbital debris (MMOD). Around and on the surface of the Moon, micrometeoroids and lunar secondary ejecta (MMSE) are of particular concern. These populations follow different yet continuous size distributions, from sub-micrometers to meters or larger in size. In order to fully characterize these populations, different observation techniques must be employed for particles in different size regimes. In situ measurements are specifically designed for particles about one millimeter or smaller.

The NASA Orbital Debris Program Office at the NASA Johnson Space Center initiated an effort to support the development of in situ instruments for the detection of the near Earth MMOD particles in 2002. To support NASA's Vision for Space Exploration, the effort was recently extended to include the detection of MMSE particles near the Moon. The two long-term objectives of the effort are to:

- Conduct in situ measurements to better characterize the small (millimeter or smaller) MMOD populations in the near-Earth environment. The measurements include data from dedicated sensors as well as data from the inspection of available, returned space-exposed surfaces.
- Conduct in situ measurements to define the small (millimeter or smaller) MMSE environment for future lunar exploration activities.

This paper provides a summary of various past, present, and future projects the Office supports.

2. PAST PROJECTS

2.1 Particle Impact Noise Detection and Ranging on Autonomous Platform (PINDROP)

The goal of PINDROP was to develop a modern acoustic sensor for MMOD impact detections. It was a 3-year project funded by the NASA Planetary Instrument Definition and Development Program between 2003 and 2005. After a series of hypervelocity impact testing and analyses, polyvinylidene fluoride

(PVDF) was selected to be the best sensor material for the intended applications. The reasons for selecting PVDFs were its highly sensitive, low mass/power requirement, and high flexibility [1, 2]. Additional low velocity and hypervelocity impact tests on target articles made of aluminum, aerogel, mylar, circuit board, Kevlar, spectra shield, and multi-layer insulation, with PVDF attached to the test articles, have been conducted. Analyses of the impact acoustic signals show that PVDF is indeed an excellent material for MMOD impact detections.

2.2 Large Area Debris Collector (LAD-C) on the International Space Station (ISS)

After the successful conclusion of PINDROP, the Orbital Debris Program Office joined the Naval Research Lab (NRL) to take on an ambitious project – LAD-C. The goal was to deploy 10 m^2 of aerogel, with PVDF acoustic sensors attached to the aerogel collection trays, on the ISS to collect 100 μm to 1 mm MMOD particles for at least one year, and then retrieve the aerogel trays for lab analysis. A combination of impact characteristics (timing, location, speed, *etc.*) from the acoustic sensors and impact direction and material composition information from the aerogel would make it possible to identify the orbits and origins of some of the MMOD particles captured by the aerogel [3].

LAD-C was originally led by NRL, then by the U.S. Naval Academy (USNA). It had key international support and contributions from the European Space Agency (hardware and signal processing software), the Japan Aerospace Exploration Agency (aerogel and curation), and the University of Kent (hypervelocity impact calibration and analysis). Unfortunately, the project was terminated by the Department of Defense (DoD) Space Test Program (STP), due to its budget constraints, in early 2007.

2.3 Debris In-orbit Evaluator (DEBIE)

The DEBIE proposal was developed in response to the Announcement of Opportunity for the Lunar Atmosphere and Dust Environment Explorer (LADEE) released in late 2008. The highly-demanding mission requirements include quick turnaround time for a 2011 launch, high Technical Readiness Level (TRL) for the instruments, demonstrated capability to detect sub-micrometer lunar dust particles at impact speeds below 2 km/s, and a total budget of 5 million dollars. After a review of existing technologies, a consortium of scientists and engineers from NASA, ESA, Carlo Gavazzi Space, the Max Planck Institute, NRL, Patria, the University of Maryland, USNA, and Virginia Tech was formed to propose deploying DEBIE to the moon. DEBIE consists of impact ionization sensors and impact acoustic momentum sensors [4, 5]. It has been flown twice in the low Earth orbit region for MMOD detection, and is a good candidate for LADEE. Nevertheless, when the selection announcement was made in early 2009, DEBIE was not selected.

3. CURRENT PROJECTS

3.1 Debris Resistive/Acoustic Grid Orbital Navy Sensor (DRAGONS)

The two components of DRAGONS are a PVDF acoustic sensor and a Resistive Grid Sensor (RGS). The RGS is designed as a very robust detector with low resource requirements. It relies on a simple principle for MMOD detection [6]. Thin resistive lines, lying in parallel, are produced by a lithographic process on a substrate. In the current configuration of a basic unit, 1000 resistive lines 75 μm in width and 15 cm long, separated by a 75 μm gap, are produced on a circuit board having a resistive coating. Each of these 1000 resistive lines is connected at each end to a bus, as seen in Fig. 1, to create a single resistor composed of the individual resistive line. The lines are connected in parallel and have a total sensitive area measuring 15 cm × 15 cm. Several prototype boards have been fabricated by the Applied Physics Laboratory at the Johns Hopkins University using standard microelectronics technology.

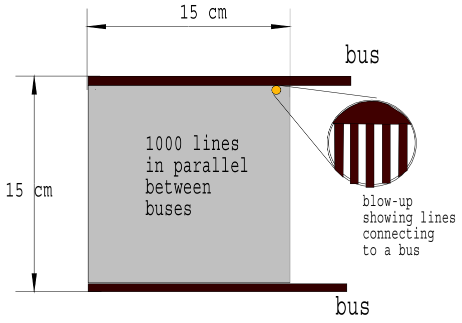

Figure 1. An illustration of the RGS system design.

In the size regime (≥50 μm) for which the RGS sensor is designed, there are two possible outcomes after a particle impact. Either the particle will penetrate the substrate or it will create a crater on the surface, thereby destroying an area of approximately 3 to 10 times its diameter. One or more of the resistive lines will be destroyed as a result of the impact. By measuring the resistance increase of the sensor (*i.e.*, between the bus lines) the number of resistive lines destroyed can be determined, leading to an estimation of the size of the impacting particle.

The PVDF acoustic sensors are attached to the backside of the RGS board. In addition to measuring impact acoustic signals, they provide triggers for RGS data acquisition. Resistance measurements can be made at regular intervals or when PVDF sensors indicate an impact. The resistance is then compared with previous measurements (corrected for temperature) to determine the number of lines destroyed by the impact.

Because each RGS unit is only 15 cm × 15 cm, several RGSs are tiled (typically on the same backing substrate) to form a larger sensor area. As with other sensors, the sensor's area requirement depends on the mission duration and the targeted particle-size regime. The electronics to measure resistance of an RGS consist of a voltage reference and a 12-bit A/D. A microprocessor is used to control the measurement and record the data for download. Only one voltage reference and A/D for the entire RGS array is needed since the measurements can be multiplexed.

The mass of an RGS system for DRAGONS with a 1 m^2 total area would be about 1.1 kg. Electronics, housing, and wire would add another 0.7 kg. Power requirements during measurements would be 32 mW for about one second. If measurements were made once an hour, the total electrical energy requirement (without heaters) essentially would be just the quiescent consumption of the microprocessor. Down-link data requirements can also be very low, as only changes in the resistance of the individual resistive grids need be reported.

A series of hypervelocity impact tests have been conducted at the two-stage light gas gun facility of the University of Kent [7]. Fig. 2 shows the effect of a 100 µm glass particle impacting at 5 km/s on an RGS unit mounted on a fiber-epoxy substrate. The on-going effort aims to characterize how the resistive grids and the board respond to impacts by projectiles made of different materials and with different sizes, impact speeds, and impact angles.

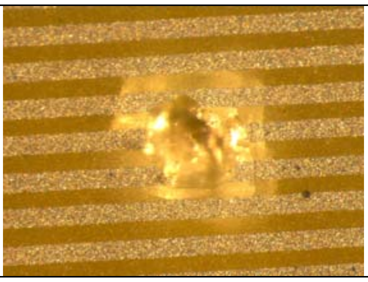

Figure2. Damage caused by a 100 µm glass particle at 5 km/s normal impact on a test RGS unit.

The DRAGONS project is led by the USNA. The plan is to deploy a 1 m^2 unit around 800 to 1000 km altitude to measure the 100 µm to 1 mm orbital debris population in that region. The project has been proposed to the DoD Space Test Program and is currently under review for a potential flight opportunity in the future.

3.2 Fiber Optic Micrometeoroid Impact Sensor (FOMIS)

The objective of FOMIS is to design and build prototype units that can be used as the building block of a large-area (tens of square meters or more), low-cost, low-mass, and low-power-consumption MMSE impact sensor on the surface of the Moon. The basic components of FOMIS are a thin film, under tension, and multiple fiber optic displacement (FOD) sensors mounted below the surface. The FOD sensor was originally developed at NRL [8, 9, 10]. It consists of seven optical fibers with the central fiber serving as a light-emitting-diode (LED) transmitter and the other six functioning as receivers. When a particle impacts or penetrates the thin film, it causes the film to vibrate like a drum. The vibration is a function of particle size and impact speed. It is measured via the variation in intensity of the reflected light (Fig. 3). Due to the high sensitivity of the optical fibers, the measurable vibration amplitude is up to 1 cm with a better than 1 angstrom resolution.

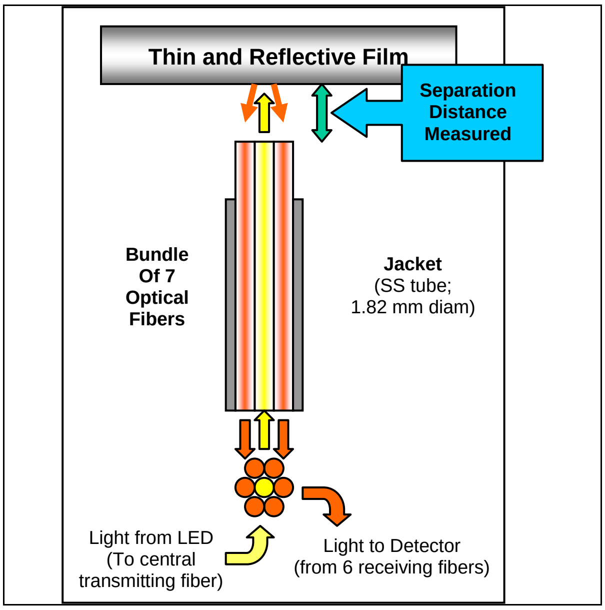

Figure 3. An illustration of the detection principle of the fiber optic displacement sensor.

Successful hypervelocity impact tests on a prototype FOMIS unit were also carried out at Kent in early 2008 to demonstrate the capability of the system. Fig. 4 shows the front and back sides of the 17-cm diameter prototype unit, and the setup inside the test chamber. The thin surface is a 25-µm thick, aluminized Mylar film under tension and three FOD sensors are mounted on the backside of the unit. Additional large prototype units, up to 78 cm across with different shapes, are being constructed and will be subjected to both low velocity and hypervelocity impact tests in 2009. A large target chamber is being prepared to house the new prototype units for the next series of tests at Kent.

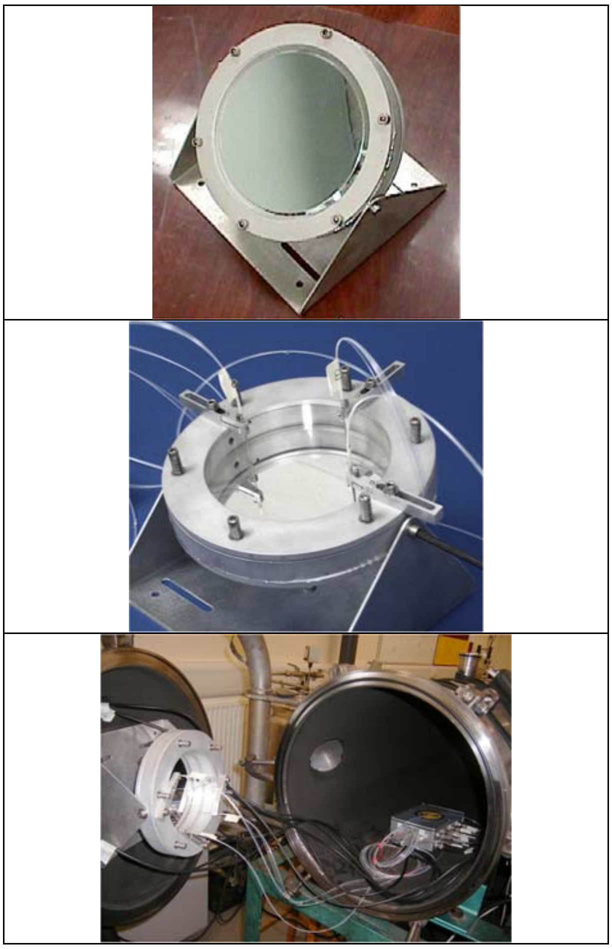

Figure 4. The front (top) and back (middle) views of a prototype FOMIS unit. The bottom image shows the unit and the electronics inside the two-stage light gas gun test chamber at Kent. Right before the closing of the chamber, the unit was turned 180 ° to allow the front side to face the incoming projectile.

The FOMIS project is funded by the Focused Investment Group (FIG) of the JSC Mission Enabling Science Program and the NASA Orbital Debris Program Office. Additional collaborators for the project include members from the NRL, Virginia Tech, and the University of Kent. The near-term goal of the project is to advance the maturity of the system to a Technical Readiness Level of 6 by 2012 and identify any possible lunar deployment opportunities in the future.

3.3 Impact Sensor for Micrometeoroid and Lunar Secondary Ejecta (IMMUSE)

The IMMUSE project aims to apply and integrate previously demonstrated impact sensing subsystems to meet the requirements of characterizing the MMSE environment on the surface of the Moon. Once deployed, data returned from such a sensor system will benefit:

- Fundamental Lunar Science: Providing key data to improve the understanding of lunar cratering processes and the growth, mixing, and transport of the lunar regolith.
- Lunar Exploration Applied Science: Providing an accurate MMSE environment definition for (a) reliable impact risk assessments for human lunar exploration activities, (b) designing cost-effective shielding for habitats, and (c) developing mitigation measures to address dust contamination issues for critical instruments and robotic components.
- Planetary Science: Providing accurate flux and size distribution of micrometeoroids to place constraints on theories of collisions among asteroids and the evolution of comets in the inner Solar System. A well-established link between micrometeoroid impacts and lunar regolith is also key to understanding other regolith-covered Solar System bodies from remote-sensing data.

The proposed tasks focus on Pre-Phase A development of two integrated MMSE impact sensor systems. The first one, Micrometeoroid Impact Detection System (MIDS), is a combination of FOMIS and PINDROP (Fig. 5). The top portion of the system is FOMIS while the substrate with PVDF sensors is PINDROP. FOMIS provides the first detection of a micrometeoroid as it impacts and penetrates the film. The thin film also filters out and prevents the much smaller secondary ejecta particles from reaching the base plate. As the micrometeoroid hits the aluminum plate, PINDROP provides the second measurement of the impact.

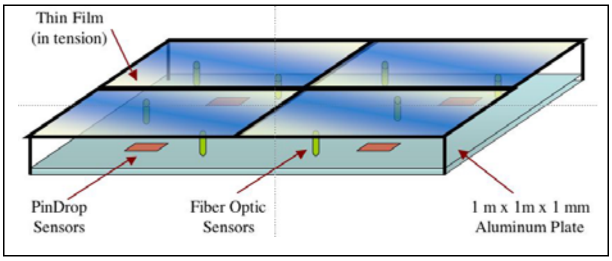

Figure 5. An illustration of the basic configuration of the first IMMUSE component, MIDS.

The second component of IMMUSE, Secondary Ejecta Detection System (SEDS), is a combination of a dual-layer laser curtain sensor and PINDROP (Fig. 6). As a particle goes through the first and the second laser curtains, accurate impact speed and direction measurements can be made. An estimation of the size of the particle is also possible based on the light scattering data. Additional impact acoustic measurements are obtained when the particle finally hits the base plate.

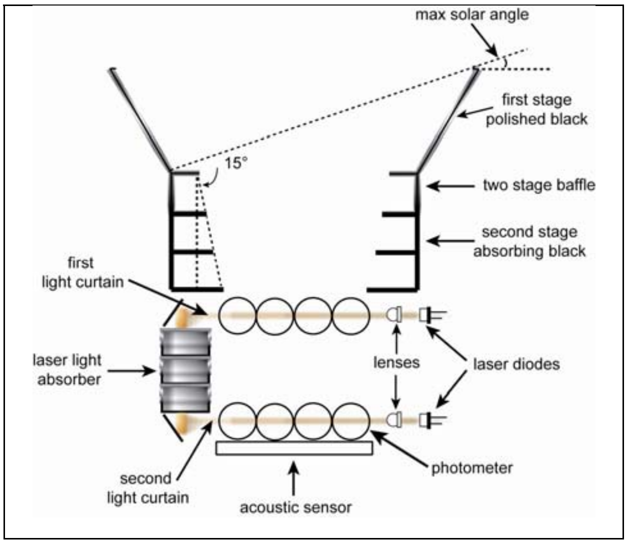

Figure 6. An illustration of the basic configuration of the second IMMUSE component, SEDS.

The two components of IMMUSE are complimentary to each other. A large area micrometeoroid detection system can be made with an assembly of the low-system-requirements units of MIDS. The lunar secondary ejecta flux appears to be several orders of magnitude higher than that of the micrometeoroids [11, 12]. To measure and characterize the lunar secondary ejecta particles, a large detection area is not required. The objective can be achieved by a small area (10 cm × 10 cm) but high-system-requirements unit of SEDS.

The IMMUSE project is funded by the NASA Lunar Advanced Science and Exploration Research (LASER) Program through 2012. The goal of the project is to reach a TRL level of 3 to 4 for both components in four years in preparation for a more advanced development beyond 2012.

4. FUTURE PROJECTS

4.1 Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) Radiator

The WFPC2 was deployed during HST Servicing Mission 1 (SM1) in December 1993. The radiator attaching to WFPC2 is part of the curved cylindrical exterior of HST (Fig. 7). It has been exposed to space since 1993, and will be retrieved when WFPC2 is replaced by WFPC3 during Servicing Mission 4 (SM4) in May 2009. The radiator has a dimension of 2.2 m by 0.8 m. Its outer layer is made of 4-mm thick 6061 aluminum and coated with white zinc orthotitanate (ZOT) paint. Surface inspection of the similar WFPC1 radiator (deployed in 1990, retrieved in 1993) identified at least 53 MMOD impact craters larger than 270 µm [13]. By comparison, the WFPC2 radiator has a longer exposure time and is subjected to a more severe orbital debris environment than the WFPC1 radiator; the expected increase in crater number is about a factor of 8.

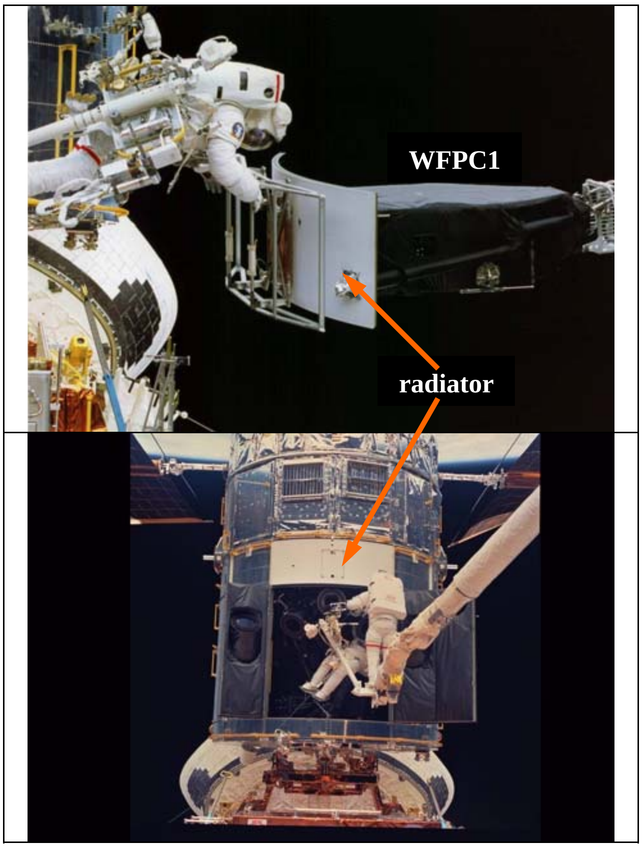

Figure 7. Two images showing the removal of WFPC1 and the installation of WFPC2 during HST SM1 in 1993. Images courtesy of NASA.

Since the return of the Long Duration Exposure Facility in 1990, there has been a lack of in-situ measurements to characterize the near-Earth small (100 µm to 1 mm) MMOD populations. Particles in this size regime can cause non-trivial damage to STS, ISS, CEV, and other critical space assets. On average, one to two Shuttle windows are replaced after each flight due to hypervelocity impacts by small MMOD particles.

The only in-situ data source for the current NASA Orbital Debris Engineering Model, ORDEM [14], comes from post-flight surface inspection of MMOD damage on the Shuttle windows and radiators. This data is limited to the ISS altitude. Therefore, the WFPC2 radiator could be used as a unique MMOD impact witness plate at a different altitude (where the orbital debris environment is expected to be different by approximately an order of magnitude). Although the radiator is not a dedicated MMOD sensor, a careful inspection of the impact features on its surface will still provide a valuable data set to understand the environment for particles between 100 μm and 1 mm. The data can also be used to cross-correlate with data obtained from the inspection of the previous HST Solar Arrays [15, 16] to improve the understanding of how the orbital debris environment at the HST altitude changed with time. The NASA Orbital Debris Program Office is currently working with the HST Program to secure an opportunity to conduct MMOD inspection of the radiator in late 2009.

5. SUMMARY

Data of micrometeoroid and orbital debris in the 100 μm to 1 mm size regime cannot be obtained via ground-based radars or telescopes. Yet, data for particles in this size regime are needed for critical engineering, science, and impact risk assessment applications. The NASA Orbital Debris Program Office will continue to develop in situ experiments to better characterize these small particles in the environment. The Office will also seek opportunities to collaborate with other agencies (U.S. and international) for cost-effective instrument development and flight opportunities to maximize the data return to benefit the community.

6. ACKNOWLEDGEMENT

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