MODELING THE METEOROID ENVIRONMENT WITH EXISTING *IN SITU* MEASUREMENTS AND WITH POTENTIAL FUTURE SPACE EXPERIMENTS

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ABSTRACT

To have reliable impact risk assessments for space instruments, vehicles, and extravehicular activities, one needs a good environment definition for meteoroids and orbital debris. Of particular significance are particles about 50 μm and larger in size. Smaller particles are not a safety concern. In general, data for particles between 50 μm and 1 mm must rely on space-based *in situ* measurements. Such measurements have been carried out since the beginning of the space age. Our current understanding of the meteoroid environment came from data collected in low Earth orbit as well as data collected in interplanetary space. However, despite all the data collected in more than 40 years, the meteoroid environment definition is far from complete. In this paper, we present three proposed *in situ* measurements to address several deficiencies in the current meteoroid environment database and knowledgebase. It is our opinion that future *in situ* measurements must focus on the following: large sensor areas and long mission duration to improve detection statistics between 50 μm and 1 mm, capability to measure impact velocity distribution, and identification of flight opportunities to cover regions important to future space exploration missions.

1. INTRODUCTION

Meteoroids are known to exist throughout the Solar System. The main sources of micrometer-to-centimeter sized meteoroids in the inner Solar System are asteroids and comets (both long-period and short-period). The Earth's accretion rate of meteoroids is estimated to be about 15,000 to 40,000 tons per year (Grün et al., 1985; Love and Brownlee, 1993). It has been known since the beginning of the space age that meteoroid impacts represent a threat to space instruments, vehicles, and extravehicular activities. Of particular significance are particles about 50 μm and larger. Meteoroids smaller than 50 μm are generally too small to be of concern to satellite operations.

To characterize the near-Earth meteoroid environment, one can utilize ground-based optical and radar observations, space-based *in situ* measurements, and the lunar crater records. There are advantages and limitations associated with each approach. Spacecraft measurements of the near Earth meteoroid environment began very early. Both acoustic and penetration sensors were used in the 1960's and 1970's while more sophisticated impact ionization detectors were designed for recent Ulysses, Galileo, and Cassini missions (*e.g.*, McDonnell, 1978; Zook, 2001; Grün et al., 2001).

The Long Duration Exposure Facility (LDEF) was deployed in 1984 and retrieved in 1990. Due to the large surface area, fixed orientation of the vehicle, and the unexpectedly long mission duration, it provided the cosmic dust and orbital debris communities a great collection of data (LDEF - 69 Months in Space, NASA CP-3134, 1991; NASA CP-3194, 1992; NASA CP-3275, 1993). Impacts on different surfaces were used to derive meteoroid and orbital debris fluxes and their velocity distributions statistically (*e.g.*, Love and Brownlee, 1993; Zook, 1991).

Although LDEF was a successful milestone mission, there were several shortcomings with the impact data. For example, the lack of impact timing (for most data) and impact velocity information led to ambiguity in the velocity and orbit determination of the impactors. The lack of impact velocity is especially critical since the velocity distribution is very important for spacecraft shielding design and for the calculation of the gravitational focusing effects. In addition, about 50% of LDEF craters left no residuals for chemical composition analysis to distinguish meteoroid impacts from orbital debris impacts.

The impact detectors onboard Ulysses, Galileo, and Cassini have collected valuable meteoroid data in interplanetary space over the last decade (*e.g.*, Grün et al., 2001). A good understanding of the meteoroid environment in interplanetary space certainly can lead to a good meteoroid environment definition near Earth. However, due to the small sizes of the detectors (0.1 m^2), the collected data are limited to meteoroids about 100 μm and smaller. In addition, the orbit of the impactor is difficult to determine due to the fact that the impact direction is not well measured.

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Any near Earth in situ measurements will also include impacts from orbital debris. Unlike meteoroids, the orbital debris populations in the 50 µm to 1 mm size regime are highly dynamic both in time and in altitude. However, there is a lack of well-designed, large surface area *in situ* measurements since LDEF in the low Earth orbit to better characterize the meteoroid environment and to monitor the fast-changing small orbital debris populations.

To address the critical size regime between 50 µm and 1 mm, much larger detection area with long mission duration will be needed for the next generation *in situ* measurements. In addition, impact characteristics, including impact time, location, and velocity must be measured. Several such experiments have been proposed for ISS and for other missions. Innovative designs have been developed to increase the detection areas to several m^2 and larger while keeping the mass, power, and cost requirements low. A brief review of several commonly referenced meteoroid models is presented in Section 2. Our proposed experiments are presented in Section 3.

2. THE METEOROID ENVIRONMENT

The early NASA meteoroid model was based on ground-based radar meteor data and *in situ* penetration measurements (Meteoroid Environment Model - 1969, NASA SP-8013, 1969). The velocity distribution was derived from the radar meteor data. The cumulative flux as a function of meteoroid mass at 400 km altitude is shown in Fig. 1. The conversion from mass to diameter depends on the material density and shape of the meteoroid. The minimum mass for a given diameter shown is based on a 0.5 g/cm^3 spherical particle assumption.

The analysis by Grün et al. (1985) included lunar crater record, zodiacal light observations, and additional *in situ* measurement data. Instead of using a velocity distribution, the model assumed a single average atmospheric entry velocity for meteoroids (20 km/s). The derived meteoroid flux was similar to the NASA 1969 model (Fig. 1). This flux has been considered the standard by the community. It was also the model adopted by the International Space Station (ISS) Program for meteoroid impact risk assessments (Space Station Program Natural Environment Definition for Design, SSP 30425 Revision B, 1994).

Divine (1993) took a different approach to develop a meteoroid flux model. Five distinct meteoroid populations were created to fit radar meteor data, zodiacal light observations, and *in situ* data. Since the data sources were similar to those used by Grün et al., the resultant flux was within 30% of the Grün flux. The idea of using multiple physical populations to fit the data was certainly an improvement over previous models. However, the orbit distributions of the five populations created did not match the physical sources (asteroids, comets) well. The model was later revised to include data from Ulysses and Galileo (Grün et al., 1997), but the differences were limited to meteoroids with masses smaller than 10^{-9} g.

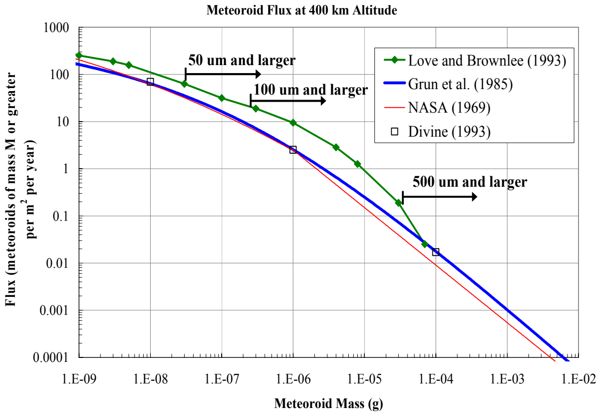

Figure 1. Meteoroid fluxes from four commonly quoted models. There is about a factor of two to three difference in the 50 to 500 µm size regime.

Love and Brownlee (1993) analyzed the impact craters on the space-facing side of LDEF and derived a meteoroid flux, assuming an average meteoroid speed of 16.9 km/s, between 10^{-9} and 10^{-4} g. It was about a factor of two to three higher than the other three models in the 50 to 500 µm size regime (Fig. 1). The improvements of this flux over the other models included better detection statistics and the damage equations they used to convert crater sizes to projectile sizes were more reliable (Zook, 2001). The shortcoming of the model is still the lack of timing, velocity, and orbit distributions.

3. PROPOSED *IN SITU* MEASUREMENTS

In light of the above-mentioned issues for meteoroid and orbital debris populations in the 50 µm to 1 mm size regime, future *in situ* measurements should focus on the capabilities to (1) measure flux for particles 50 µm and larger with good sampling statistics, (2) cover a wide range in altitude, (3) measure impact parameters, including impact time, location, and velocity, (4) separate meteoroids from orbital debris, (5) determine the chemical composition of particles, and (6) provide some source identification. To achieve these objectives, innovative design of large area, low mass, low power consumption, and low cost sensors is needed. In reality, limited resources and flight opportunities will certainly place heavy constraints on what can be done. In this section, we summarize several of our proposed *in situ* experiments to characterize the meteoroid environment near Earth as well as near the moon.

3.1 Lunar Orbiter Meteoroid Impact Sensor (LOMIS)

Meteoroid impact risks near and on the moon were recognized before the Apollo missions. It was of modest concern to the Apollo engineers due to the relatively small surface area of all Apollo hardware and the short periods they were resident on the moon. For example, the total EVA time for all 6 Apollo missions combined was only 80 hours 32 minutes. Obviously, this perspective must be changed with the relatively large structures and long stay times that will be needed to support a future, more substantial, and possibly permanent human presence on the moon. Previous meteoroid measurements included pressurized-cell detectors aboard Lunar Orbiters 1 through 5, which had a combined area-time exposure of 139 m^2day. Only 22 penetrations were recorded and most of them were caused by very small meteoroids (< 50 μm). The data were insufficient to come up with a reliable meteoroid environment definition near the moon.

The Lunar Orbiter Meteoroid Impact Sensor (LOMIS) is a system designed to characterize a key environment parameter for future robotic and human lunar exploration. It is intended to measure the flux and size distribution of meteoroids 50 μm and larger. An accurate description of the meteoroid environment in this size regime is needed for reliable meteoroid impact risk assessments to ensure the safety for lunar vehicles, critical hardware/structures, and extravehicular activity (EVA). It is cost-effective to define the lunar meteoroid environment early, prior to the detailed design stages to meet the safety and reliability requirements of future lunar operations.

The LOMIS system consists of three components: TRACE, PING, and FLUX. TRACE is a resistive network where each resistor is made up of parallel traces 75 μm wide. In all 256 resistors are mounted on a 1 m by 1 m board. A hypervelocity meteoroid impact of sufficient size on TRACE destroys one or more trace lines, increasing the resistance of one of the resistors. From the change in resistance, the number of traces being cut can be determined, and therefore the size of the impacting meteoroid can be estimated. We augment the TRACE measurement capability by attaching four PING acoustic sensors to each TRACE board. In this way PING provides an immediate indication that an impact has occurred, and a direct measure of the impacting energy of the meteoroid. In addition, since the boards are good transmitters of the acoustic waves generated by the impact, it may be possible to extract additional information (such as velocity and particle density) from the waveforms generated by the impact and sensed by PING.

The nominal configuration of the TRACE/PING system has a total detection area of 1 m^2. Depending on the structure and resources of the vehicle, several 1 m^2 TRACE boards can be mounted with different orientations. An additional upgrade option is to place resistors on both sides of the TRACE board. A large meteoroid can potentially penetrate the board and damage the conducting traces on the other side of the board. From the impact time and impact location of the traces being damaged on both sides, information related to density, speed, and direction of the large meteoroid may be obtained.

The FLUX component of the LOMIS system is based on a new concept intended to utilize other parts of a vehicle as a large area impact detector. The idea is to attach PING-type acoustic sensors to the thermal blankets, or Multi-Layer Insulation (MLI), that cover instruments aboard a satellite. MLI often consists of layers of thin aluminized Mylar®, Kapton®, or Nomex®. The outermost layer can be used as a simple strike detector. The advantages of utilizing MLIs include large surface area and different orientations, not to mention very small mass required to implement this system. FLUX can be attached to different thermal blankets (MLI) at different locations and will not affect the performance of the blankets. Multiple acoustic sensors can be distributed around the satellite. Most of them will be attached to MLIs with the remaining sensors attached to the frame of the satellite, acting as "reference" acoustic sensors and used to identify acoustic signals generated by the spacecraft (vs. meteoroid impacts). Depending on how many thermal blankets are equipped with FLUX, the total area for meteoroid impact detection can reach more than 10 m^2. The designs of TRACE/PING and FLUX complement each other. While TRACE and PING provide a comprehensive description of meteoroid impact characteristics, FLUX will improve the overall statistical sampling of the meteoroid environment

The acoustic sensors we propose to use for PING and FLUX have been developed under the NASA Planetary Instrument Definition and Development (PIDD) program. The system is called Particle Impact Noise - Detection and Ranging on Autonomous Platforms, PIN-DROP, (Corsaro et al., 2004). A highly sensitive and low mass material, polyvinylidene fluoride (PVDF) has been selected and tested. Each acoustic sensor is thin (100-200 μm), low mass (1.5 g), with low power requirement (15 mW), and highly flexible.

LOMIS was submitted to NASA for the upcoming Lunar Reconnaissance Orbiter. Unfortunately it was not selected for the mission. We will continue to identify potential flight opportunities for LOMIS to characterize the meteoroid environment near the moon.

3.2 Acoustic Impact Meteoroid Sensor (AIMS)

The recent NASA Research Announcement (NRA) for a planned solar sail mission provides a great opportunity to sample and update the near Earth meteoroid and orbital debris environment. This New Millennium Program (NMP) solicits proposals for its Space Technology-9 (ST9) system flight validation for solar sail technologies. One of the objectives cited in the NRA is to use the sail as a sensing instrument for the detection of dust and micrometeoroid impacts. The minimum requirements for the mission include a 40 m by 40 m sail on a modified geosynchronous transfer orbit (GTO) with perigee altitude above 1500 km and a mission duration of at least four months. The combined area-time product of more than 500 m^2-year makes the sail a unique *in situ* detector to sample small meteoroids and orbital debris from 1500 km altitude to near geosynchronous orbit region.

A major challenge to utilize the sail as a meteoroid and orbital debris detector lies in the development of instruments within the allocated ST9 mass and power budget (≤1 kg and ≤1 W, respectively). The PIN-DROP acoustic sensors are ideal to achieve the measurement objectives and meet the system requirements at the same time. Our proposed system is called Acoustic Impact Meteoroid Sensor (AIMS). It has two components, PIN-DROP acoustic sensors and Fiber Optic displacement Sensors (FOS). FOS is also capable of detecting direct and modal acoustic signals produced by a hypervelocity impact (Corsaro et al., 1995, 1997).

To demonstrate the feasibility of AIMS, several hypervelocity impact tests have been conducted using the NASA Johnson Space Center's 0.17 caliber two-stage light gas gun located at Rice University. The targets were thin films of Mylar® coated with aluminum with a total thickness of 25 μm, similar in nature to the proposed solar sail material. The projectiles were 1 mm diameter aluminum spheres with a typical impact speed around 7.2 km/sec. Fig. 2 shows one of the configurations for the test. The first target panel was a 30 cm x 30 cm film mounted on an aluminum frame. The second target was a round-shaped panel of thin film hanging behind the first target. The entire set was mounted on a rail inside the target chamber during the test. Two PVDF acoustic sensors, also 25 μm thick, were attached to the Mylar® film and a third one was attached to the frame. Each sensor was connected to a high-frequency wideband amplifier. A fiber-optic displacement sensor was mounted near the bottom of the first panel.

Data from all channels were analyzed after each shot. Preliminary results indicate that both the PVDF acoustic sensor and the fiber-optic sensor could detect clear signals generated by the impact of the projectile on the film (Fig. 3). This demonstrates that the sensing capability and the low mass and power requirements of AIMS make it a potentially good sensor to detect meteoroid and orbital debris impacts on the planned ST9 solar sail. Additional tests will be needed to better correlate the detected signals to other impact characteristics (*e.g.*, projectile size and impact speed).

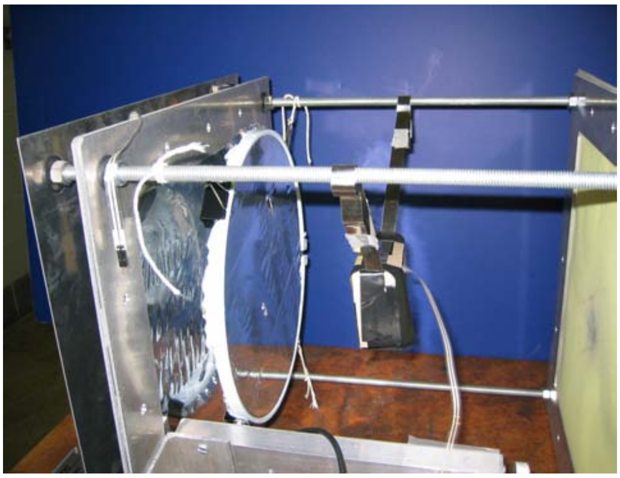

Figure 2. One of the configurations of the test. The square target film (to the left) had an exposure area of 30 cm by 30 cm while the second target hoop had a diameter of 26 cm. Two PVDF sensors were attached to each film while a third one was attached to the frame. A hanging piece of aerogel was also used as the third target.

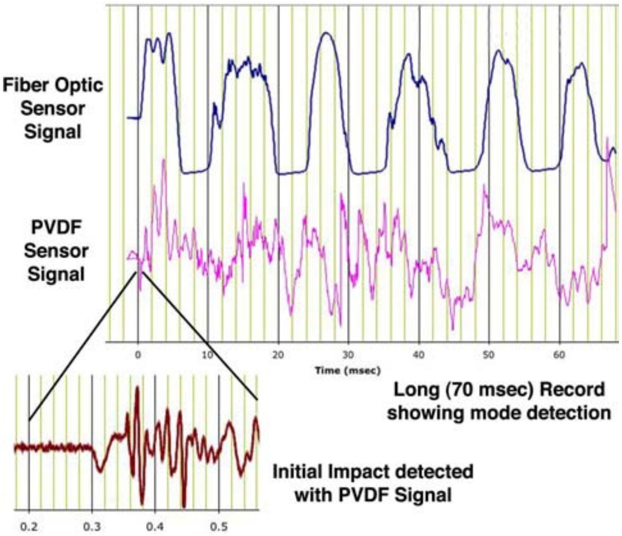

Figure 3. Preliminary signal analysis of an AIM hypervelocity impact test. PVDF provided the clearest indication of initial projectile impact, while the fiber optic sensor more clearly responded to the excitation of the modes of the thin film.

The final selection of ST9 instruments is expected to be made in mid-2005. Whether or not AIMS is selected, our proposed package to utilize the ST9 GTO solar sail represents a step forward in our attempt for a large area detector to better characterize the near Earth meteoroid environment.

3.2 Large Area Debris Collector (LAD-C)

The objectives of the Large Area Debris Collector (LAD-C) are to measure impact characteristics of meteoroids and orbital debris at ISS altitude and to return the collected samples after one year of deployment. This is a project led by Naval Research Laboratory with collaboration from NASA, Air Force Academy, and University of Florida.

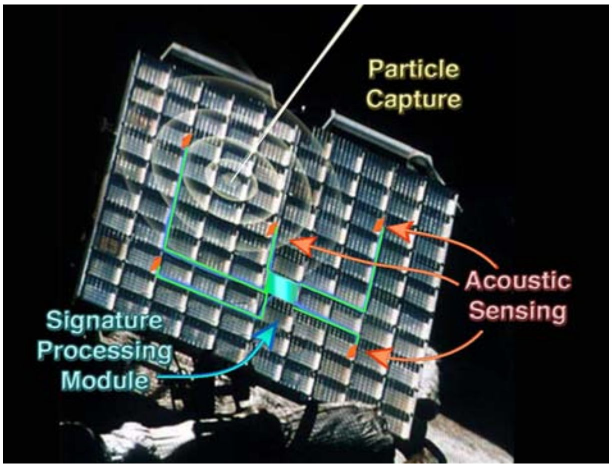

Figure 4. A simple illustration of the basic design of LAD-C. Acoustic sensors measure impact characteristics while aerogel preserves the samples for post-flight chemical analysis.

The basic design of LAD-C includes 10 sets of 1 m^2 panels for a total collection/detection area of 10 m^2. Fig. 4 illustrates the concept of the system. Each 1 m^2 panel is divided into one hundred 10 cm by 10 cm cells. The cells are filled with silica aerogel with a thickness of about 2 cm. Aerogel is known for its exceptional ability to capture cosmic dust, and has been flown on several missions (*e.g.*, Hörz et al., 1999, Tsou et al., 2003). In addition to aerogel, each LAD-C panel is equipped with multiple PIN-DROP acoustic sensors attached to the frame. When a meteoroid or orbital debris impacts the panel, the acoustic signals are received by the acoustic sensors and are recorded by the signal processing module. Impact time is measured directly. The signal threshold can be adjusted to filter out undesirable small particles. From the acoustic propagation model and signal triangulation method, the impact cell can be identified (Corsaro et al., 2004).

The combination of acoustic sensors and aerogel makes it possible to measure impact time, location, and chemical composition of the impactors. From the strength and rise time of the acoustic signals and the shape and length of the impact track embedded in the aerogel, impact velocity can be well-determined for some particles. Preliminary hypervelocity impact tests on an aluminum frame with aerogel cells have been conducted. To better calibrate the signals and to relate the information to impact characteristics, many more tests will be conducted in the future.

The significance of LAD-C is twofold. First, it will provide a much needed, updated environment definition for meteoroids and orbital debris 50 μm and larger in the low Earth orbit. Second, the measurements of impact timing, location, and velocity could lead to the determination of the impactor's orbit. A dynamical link between the samples and their parent bodies can be established. This will allow one to relate the chemical composition of the residuals extracted from the aerogel to their respective parents. The outcome of LAD-C will benefit meteoroid, orbital debris, and cosmic dust communities.

LAD-C has been scheduled for full integration by the DoD Space Test Program (STP) starting in late 2005. The deployment on the ISS could be as early as 2007. A successful LAD-C mission, and post-flight analysis and modeling, will improve our understanding of the near Earth meteoroid and orbital debris environment significantly.

4. SUMMARY

Large detection area (>1 m^2) and long mission duration are the keys for future *in situ* measurements. Several new and innovated instruments have been developed to meet the goals and to keep the mass, power, and cost requirements within practical constraints at the same time. The next step is to identify flight opportunities to carry out the proposed measurements. Without updated and improved data, one cannot model the meteoroid and orbital debris environment with a high level of confidence for reliable risk assessments. Due to the difficulties and limited resources available for any space experiments, collaborations may be the best option to support future *in situ* measurements.

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