DESIGN AND INITIAL CALIBRATION OF MICROMETEOROID/SPACE DEBRIS DETECTOR (MDD)

Guy Spencer[1,5], Frank Schäfer[1], Makoto Tanaka[2], Mike Weber[1], Robin Putzar[1], Rolf Janovsky[3], Indulis Kalnins[4]

[1]Ernst-Mach Institute, Eckerstraße 4, 79104 Freiburg, Germany, Email: spencer@emi.fhg.de, schaefer@emi.fhg.de, putzar@emi.fhg.de, weberm@emi.fhg.de
[2]Visiting scientist at EMI from Tokai University, 1117 Kitakaname, Kanagawa, 259-1292 Japan, Email: makoto@cc.u-takoi.ac.jp
[3]OHB-System AG, Universitaetsallee 27-29, 28359 Bremen, Germany, Email: janovsky@ohb-system.de
[4]Cosmos International GmbH, Email: cosmos@fuchs-gruppe.com
[5]Visiting scientist at EMI from Air Force Office of Scientific Research, United States Air Force, 875 N. Randolph St., Suite 325, Room 3112, Arlington, VA 22203

ABSTRACT

The space debris and micrometeoroid environment poses an increasing threat to operations in space due to the escalating quantity of debris in orbit. Particle impact detectors provide a low cost means to monitor and study this environment. EMI and OHB-System have developed an impact detection system to be launched in 2005 into a sun-synchronous orbit at an altitude of 680 km. The experiment consists of an impact detection system and a data transfer system. The detector utilizes three independent systems to detect impacts and provide coincidence verification of an impact event, while the data transfer system uses low-cost means to transfer data over an already existing communications network to end-users via the internet. This paper presents the mission, provides a description of the impact detector and data transfer systems, explains the detection techniques employed, and discusses initial functional and calibration testing setup, as well as outlines future plans.

1. INTRODUCTION

With the increasing amount of space debris posing a threat to space missions, it is becoming increasingly important to understand how this environment is changing and the threat it creates for future space endeavors. There have been many attempts to study this changing environment, which have primarily been done through the development of micrometeoroid and space debris impact detectors. Such detectors attempt to measure real-time impacts and their effects on structures or make use of recoverable systems to study the in situ effects of impacts on structures. Low Earth Orbit (LEO) instrumentation used to detect and evaluate space debris and micrometeoroid impacts include Long Duration Exposure Facility (LDEF) (Singerl, 1991) and DEBris In-orbit Evaluator (DEBIE) (Kuitunen, 2001). Geostationary Orbit Impact Detector (GORID) is another example of a particle detector, although its operating location is in Geosynchronous Earth Orbit (GEO) (Drolshagen, 2001).

The Micrometeoroid and space Debris Detector (MDD) is a small, inexpensive approach to monitor the space environment for debris and micrometeoroids. The detector consists of a thin aluminum target plate onto which three independent measurement systems have been integrated. The MDD is shown in Fig. 1. The three detection systems have fundamental differences to ensure true coincidence verification of impacts. For the first system, presently two options are under consideration: either Polyvenylidene Fluoride (PVDF) sensors or Ultrasonic transducers will be used for monitoring acoustic waves in the plate that are generated during impact. The second system consists of a pair of photo diodes monitoring the front side of the target plate for impact-flashs generated during a particle impact. The final system consists of a radio-frequency (RF) antenna used to detect electro-magnetic (EM) radiation emitted during impact.

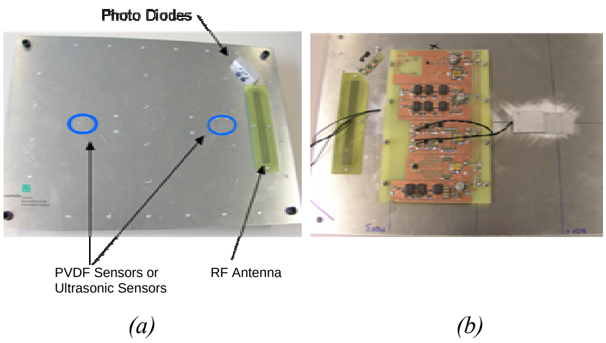


Figure 1. Photo of MDD (a) top side of target plate with Photo diode and antenna assemblies (b) rear side of detector plate with electronics

2. MISSION DESCRIPTION

The MDD detector plate is a 2 mm thick aluminum plate which is 360 mm long and 250 mm wide. The complete detector has a total height of 28 mm, with a total weight of approximately 1.1 kg. The active detection surface has an area of approximately 0.1 m^2. There are four fixation points used to secure the detector

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

to the Cosmos upper stage, which are located in the four corners of the target plate, centered at 15 mm from both edges of the plate. The circuit board is suspended on the rear side of the target plate on 8 posts, providing a centimeter distance between the target plate and electronics. In the gap between the target plate and the electrics, a layer of Kevlar material has been inserted. The Kevlar is joined to the 8 posts supporting the electronics and providing a layer of impact protection against penetrating debris generated during an impact event that causes fragment ejection inside the MDD housing.

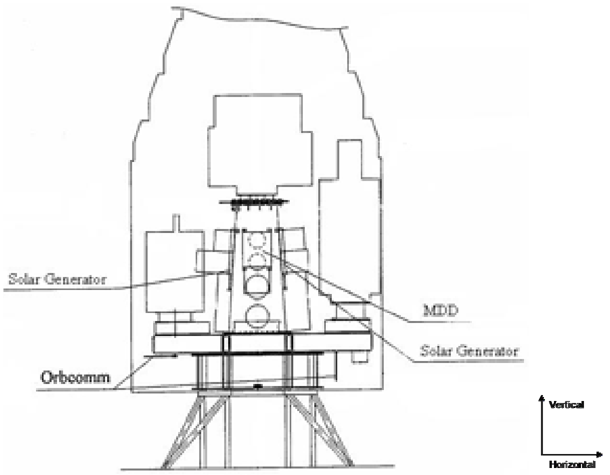


Figure 2. MDD integration onto Cosmos Upper stage

The MDD will be launched on a Russian Cosmos rocket into a Sun-Synchronous Orbit (SSO) of 680 km at an inclination of 98.2°.

The detector will be positioned at the base of the payload adapter, which is located above the Cosmos upper stage, which is shown in Fig. 2. Based upon its position, the MDD will have a substantial field of view between 98° and 127° in the vertical direction, including shadowing by upper stage satellite adapters. The field of view of in the horizontal direction is 180°. The Cosmos upper stage is also equipped with GPS capability for determining position in orbit, as well as an on-board 3-axis magnetometer for determining the upper stage's attitude in orbit. Combining all this information will provide useful data to roughly determine the direction of impact.

Power will be supplied to the detector and the data transmission system via two solar generators, which are an additional technology experiment of ESA ("Asolant") to be flown on the Cosmos upper stage. The solar generator surfaces are also located on the payload adapter (Fig. 2). The MDD will draw its power from its connection cable to the data transmission system. The data acquisition system monitors the signal output channel of the MDD with a sampling frequency of about 500 Hz.

The data transmission system takes advantage of an already existent communications system, ORBCOMM, to relay data to users. ORBCOMM is a commercial satellite system composed of 34 satellites in a LEO orbit of approximately 750 km. Data is uplinked to the ORBCOMM satellite network and downlinked to a ground station, where it is automatically forwarded to users. Data transmission after the detection of an impact event consists of a 200 Byte message, containing MDD data, Cosmos position and attitude information. This message is transferred from the ORBCOMM-modem at the Cosmos upper stage to one of the ORBCOMM-satellites, from where it is downlinked to one of the gateways in the ORBCOMM-network. Finally, the message is transferred as a standard E-mail via the internet to the operators of the MDD-experiment. A sketch of the data transmission principle is shown in Fig 3. This low-cost, innovative means of data transmission provides for a user friendly option for data acquisition.

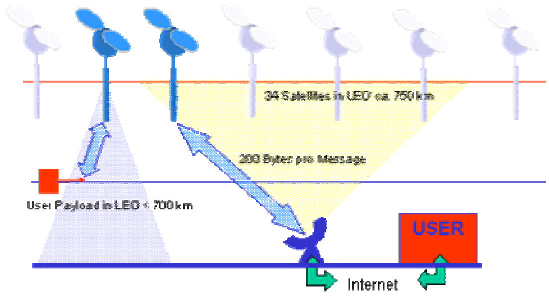


Figure 3. MDD-experiment data transmission concept

The target SSO is considered very critical with regard to expected debris flux. This is due to the fact that it is used quite frequently for Earth observation tasks and the debris released within this orbit remains for long time.

3. IMPACT DETECTION METHODOLOGY

There are three independent measurement systems utilized on-board the MDD. Each system is unique in that it represents a distinct methodology of detection, which measure different physical parameters created during an impact. The three independent systems are based upon the detection of mechanical, optical and EM signatures of a hypervelocity impact.

3.1. Mechanical System

In the case of a hypervelocity impact on a thin plate, stress waves are generated that can be detected by acoustic sensors. For the mechanical detection system, presently two options are under consideration. The first option is detection of stress waves through PVDF sensors; the second option is ultrasonic transducers. The final choice will be based on sensitivity considerations.

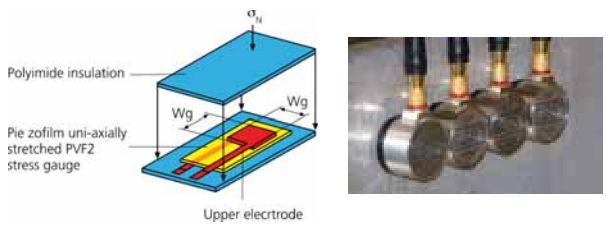
The first option under discussion consists of two commercial-off-the-shelf (COTS) uni-axially stretched PVDF sensors (Dynasen, 2004). The PVDF sensors, shown in Fig. 4 (a), are thin-film, piezoelectric gauges. The primary function of these sensors is to detect disturbances, or waves, induced into the target plate from impacts. These sensors are glued to the rear side of the target plate (Fig. 5) and then secured with a thin aluminum cover plate, which is bolted over the sensor.

As can be seen from Fig. 4 (a), the PVDF gauges consist of a set of leads and electrodes, where the electrode width is given by W_g. Both the leads and electrodes are vapor-deposited on either side of a uni-axially stretched polymer film. This portion is then sandwiched between two thin layers of insulation (Kapton). In the MDD application, the sensors detect the normal stress component of longitudinal stress waves, which results in the generation of an electric field across the sensing element. Thus, the output is expressed as the amount of charge per unit area that is generated by the normal stress, σ_N, in the sensing element.

These gauges are extremely small, with a thickness of roughly 80 μm and an active sensing element that is only 3.18 mm × 3.18 mm, or 0.1 cm^2. Both PVDF sensors are positioned on the centerline of the minor axis. Along the major axis, the sensors are positioned one-quarter from each end. The sensing element of each gauge is centered upon this intersection, positioning it 90 mm along the major axis and 125 mm along the minor axis from any corner. Fig. 5 depicts the positioning of the gauges on the rear side of the target plate, integrated on a prototype.

The second option under discussion is ultrasonic transducers. The transducers foreseen for application are from Vallen GmbH, type VS150M (Fig. 4 (b)). The transducers are high-sensitivity, broadband transducers (100-450 kHz) having a diameter of 20.3 mm. These transducers have been demonstrated to be a suitable monitoring system for impact-induced acoustic waves (Schäfer, 2004).

Due to the size and cost-effective means implemented within the MDD, there is limited capability for data acquisition on-board the detector, i.e. there is no possibility for measuring the delay time between signal arrivals at both sensor/transducer locations. Therefore, peak magnitude of impact events will be captured from both sensors/transducers, which will provide a ratio of the peak magnitudes resulting in the ability to determine the approximate impact location on the target plate. With only 2 sensors, every impact will provide two likely impact locations on the target plate. In addition to this, the peak magnitude information obtained from



(a) *(b)*

Figure 4. (a) PVDF stress gauge representation (b) ultrasonic transducers

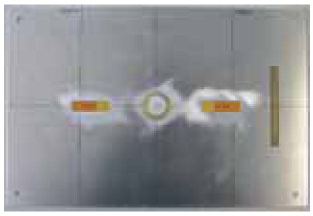


Figure 5. PVDF gauge positioning (Note: the ultrasonic transducers presently under discussion as a second option for the mechanical system will be mounted in the same location as the PVDF gauges shown above)

impact events will also be used to determine the order of magnitude of transferred momentum.

There are two stages to the electronics in this detection system. The first stage consists of two amplification steps, which combined amplifies the signal 1000 times. The second stage is a signal preparation step, in which the signal is latched high in order to provide sufficient time for the peak magnitude to be sampled, which is sampled at 500 Hz.

3.2. Optical System

The second technique is based on the optical detection of the impact flash generated during an impact event. The moment a hypervelocity impact occurs between target plate and projectile, there is an intense flash of light generated. This phenomenon has been investigated by Jean (1966), Eichhorn (1975, 1976), Ang (1990), Weber (1983), as well as many others trying to understand the formation of this flash and its dependence on such parameters as particle velocity, mass, and material composition of both target and projectile. Duration and intensity are important characteristics of impact flash. Eichhorn (1975) observed that the duration of the flash could range up to tens of microseconds, which is dependent upon impact velocity and material composition of the target and projectile. Intensity on the other hand, is difficult to generally quantify due to its dependency on many factors, to include particle mass and velocity, as well as material compositions (Eichhorn, 1975). For the optical detection system used for the MDD, intensity will be the basis for determining whether an impact event has occurred.

This system makes use of Avalanche Photo Diodes (APD). The APDs selected have an active detection area of 0.196mm^2, a rise time of 550 picoseconds and maximum wavelength sensitivity between 760 and 910 nanometers. The APDs are mounted next to one another, perpendicular to the target plate surface in one corner to ensure the widest field of view, as shown in Fig. 6. There are two photo diodes connected in parallel to provide redundancy in case one fails during the mission.

Figure 6. APD assembly mounted on target plate

Fig. 7 represents a typical signal obtained during preliminary testing using the APD selected for the MDD. Although the phenomenon of impact flash has many interesting attributes, the photo diode selected for this application will not be able to distinguish them during the monitoring of an event.

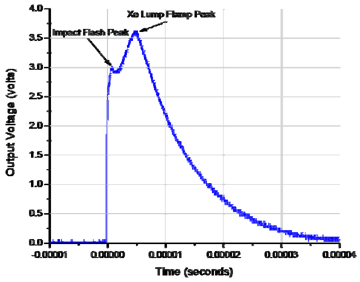


Figure 7. Representative signal of impact flash

The electronics for the APD detection system is similar to that of the PVDF detection system. The major difference between the two circuits is the high voltage power supply required for the APDs. In this section, 12 volts is converted to 200 volts and regulated by 5 volts to provide a power signal with minimal disturbances.

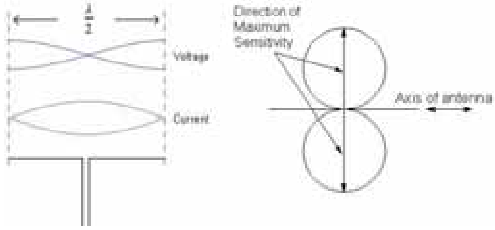
3.3. Electro-magnetic System

The final detection system utilizes a RF antenna to detect EM radiation emitted during impact. This phenomenon has also been the focus of many studies, e.g. Takano et al., 2002; Maki et al., 2004). Their experiments have shown that hypervelocity impact results in the emission of EM radiation.

A half-wavelength, dipole antenna was selected to monitor and detect EM emissions produced by hypervelocity impacts. The dipole antenna consists of two terminals, or poles. The lengths of the terminals are determined by the desired frequency at which the dipole resonates. Their lengths can be calculated with the following equation:

$$c = f * (2\lambda) \tag{1}$$

where λ is the antenna wavelength, c is the speed of light, and f is the desired reception frequency. For the MDD, a 2.0 GHz, center fed antenna was chosen. Using this value in equation (1) shows that the required length of the antenna should be 7.5 cm, with each terminal being 3.75 cm.



(a) *(b)*

Figure 8. Dipole antenna characteristics (a) current and voltage distribution pattern, (b) horizontal polar diagram

Fig. 8 shows the representative characteristics of the dipole antenna. Fig. 8 (a) illustrates how current and voltage are distributed across a half-wavelength, λ/2, dipole antenna. Here, current is a maximum in the center and voltage is a maximum at the terminal extremes. As is shown Fig. 8 (b)b, the dipole antenna has maximum sensitivity along the axis that is perpendicular to its terminals. Along the axis of the antenna, the sensitivity declines to zero. A dipole antenna is omni-directional, only in azimuth.

Knowing the antenna's maximum sensitivity is perpendicular to the antenna axis, the antenna was positioned parallel to the minor axis, within a narrow slit created in the detector plate, so that the antenna is approximately level with the top surface of the detector plate. This orientation permits the maximum sensitivity axis to extend along the center of the minor axis, and provide maximum reception from an impact on the target plate. The antenna is secured into place by two plastic covers, which allow for transmission of RF radiation.

The electronics for the antenna detection system is again identical to that of the PVDF system. Based on future testing, this circuit may be slightly modified in order to add a filter to protect the op amps already present. Future testing will show whether the input signal from this antenna is too fast for the electronics to adequately process.

3.4. Life Monitor System

Along with the three coincidence measurement systems, two other components have been integrated into the electronics for on-orbit functional testing. This system provides a predetermined input, providing the opportunity to monitor the mechanical and optical measurement systems on orbit to ensure they are fully functional.

The first component is a piezoelectric element, which is glued to the rear-side of the target plate between the two mechanical sensors/transducers. When supplied a 5 volt TTL signal, this element vibrates, which results in a pulse being transmitted across the target plate. This vibration induced into the target plate results in a signal obtained on the sensors/transducers, which will indicate whether they are operational and functioning as expected.

The second life monitor consists of two light emitting diodes (LEDs) connected in parallel, which are mounted through two small holes from the rear side of the target plate. Each LED is positioned at the base of one APD and mounted perpendicular to the APD's orientation. The LEDs are also supplied with a 5 volt TTL signal, and in-turn emit a light source to test the operational capability of the APDs. The LEDs have a wavelength at peak emission of 880 nanometers, which corresponds to the peak wavelength sensitivity of the APDs selected. They also have an emission angle of 40 degrees, which produces a large enough light emission footprint to trigger the APDs in this configuration.

4. INITIAL FUNCTIONAL TESTING

Initial characterization has been conducted on the MDD at EMI. The MDD was tested under various conditions in order to evaluate the functionality and estimate the sensitivity of the detection system. The two major test campaigns conducted were air cannon tests for the mechanical system and flash lamp tests for the optical system. Each test campaign will be discussed here, giving an overview of test objectives, setup and results.

4.1. Air Cannon Tests

A low pressure air cannon owned by EMI, which has a maximum air pressure of 10 bars, was used during initial evaluation of the MDD. The barrel is small

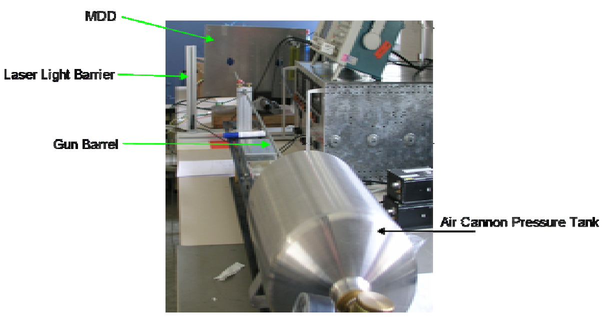


Figure 9. Air Cannon Test Setup

caliber, capable of shooting spheres up to 3 mm in diameter. A laser light barrier was used at the end of the barrel to obtain a time signal, which is in-turn used to calculate the velocity. Fig. 9 shows the details of the test setup.

Three test series were conducted during this campaign. The first two test series were used to characterize the MDD with the first mechanical option (PVDF sensors), where the aim point for each five shot series was one of the two sensing elements. The signals registered by each sensor were recorded and compared. Plastic spheres, with a diameter between 1.0 mm and 2.0 mm, were used as projectiles. With the distance between target and barrel at 30 cm, the velocity range for testing was between 20 to 250 m/s. The third test series consisted of air cannon shots, where the aim point was moved to different positions around the detector plate to determine how the magnitude of signals acquired from the sensors is dependent upon location of impact.

The same test campaign was repeated using Ultrasonic transducers instead of PVDF gauges. The MDD still has considerable more characterization testing to go through, but initial results have shown that the sensitivity of the ultrasonic gauges selected is higher than that of the PVDF gauges.

4.2. Sensitivity Determination

Sensitivity is crucial in determining the frequency in which an impact is expected to occur on the MDD target plate. Due to lack of funding, the detector presently cannot be calibrated appropriately under realistic impact conditions e. g. by shooting micron-sized particles at hypervelocity on the detector using plasma-drag accelerators or dust accelerators. Hence, simple assessments of the sensitivity of the mechanical system are made only assuming that the minimum detectable impact momentum is independent of impact velocity. To this purpose, the minimum detectable impact momentum has been determined from dropping millimeter-sized plastic spheres onto the detector plate from various heights and repeating with smaller and smaller spheres to the point where the PVDF sensors no longer detect an impact. The test with the smallest projectile producing a measurable impact signal was taken as the basis for MDD sensitivity calculations. Knowing the minimum detectable momentum at low velocity, this value was correlated to a hypervelocity impact, where the assumed impact velocity on orbit was 10 km/s. For the impacting particles, Al-spheres were assumed.

Hence, based on the momentum approach the projected sensitivity was determined to be high enough for detecting hypervelocity particles with a size of a few 10 microns. Taking this value and comparing it to the flux model predicted for the target orbit, the number of impacts expected per week can be estimated.

A predicted distribution of the number of impacting debris particles as a function of their size on a random tumbling plate in the target orbit is shown in Fig. 13. Based on this calculation, the number of expected impacts per week is 2 to 4.

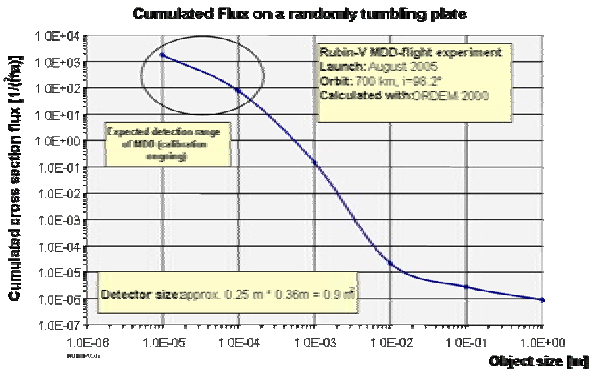


Figure 13. Predicted debris flux of desired orbit using ORDEM 2000

The actual number of impacts detected may be larger than what was estimated considering momentum enhancement effects and shockwave effects that may lead to higher signal amplitudes at the sensor positions.

5. FUTURE PLANS

The desired test matrix for evaluating the MDD has not been completed as of yet. In the coming weeks, the MDD will undergo further evaluation as to the calibration of the three detection systems. The sensitivity will also be further investigated in order to make the best approximation as to the size and number of impacts that are to be expected.

Along with continued calibration and sensitivity testing, a number of environmental scenarios will be used to subject the MDD to simulated environmental conditions that it may experience on-orbit. These tests include vibration testing to ensure launch survivability, temperature cycling and vacuum testing. The expected completion of the test matrix is May 2005.

6. ACKNOWLEDGEMENTS

This project was the result of a cooperative effort by EMI and OHB System, in which both parties contributed in-house funding and development efforts for their respective contributions. As a visiting officer from the United States Air Force, I would like to thank EMI for the opportunity to supervise this in-house research program. In addition to the co-authors, the contributions of Mr. Wolfgang Grafmüller of EMI to the construction of the MDD are acknowledged.

7. REFERENCES

Ang J. A., Impact Flash Jet Initiation Phenomenology, *Int. J. of Impact Engng*, Vol. 10, 23-33, 1990.

Drolshagen G., Svedhem H., Grün E., Measurements of Cosmic Dust and Micro-Debris with GORID Impact Detector in GEO, *Proc. 3rd Europ. Conf. on Space Debris,* ESA SP-473, 177-184, 2001.

Eichhorn G., Measurements of the Light Flash Produced by High Velocity Particle Impact, *Planet Space Science,* Vol. 23, 1519-1525, 1975.

Eichhorn G., Primary Velocity Dependence of Impact Ejecta Parameters, *Planet Space Science,* Vol. 26, 469-471, 1977.

Jean B. and Rollins T. L., Radiation from Hypervelocity Impact Generated Plasma, *AIAA Journal,* Vol. 8, 1742-1748, 1970.

Kuitunen, J., Drolshagen, G., McDonnell, J.A.M., Svedhem, H., Leese, M., Mannermaa, H., Kaipiainen, M., Sipinen, V., DEBIE – First Standard In-Situ Debris Monitoring Instrument, *Proc. of 3rd Europ. Conf. on Space Debris*, ESA SP-473, 185-190, Darmstadt, Germany, 2001.

Maki K., Takano T., Fujiwara A., Yamori A., Radio-wave Emission Due to Hypervelocity Impacts in Relation to Optical Observation and Projectile Speed, *Advances in Space Research,* Vol. 34, 1085-1089, 2004.

Schäfer F., Janovsky R., Impact Sensor Network for Detection of Hypervelocity Impacts on Spacecraft, 55th International Astronautical Congress, Vancouver 4–8 October 2004 IAC-04-IAA.5.12.2.04, 2004

Singerl, S.F., LDEF Interplanetary Dust Experiment: Techniques for the Identification and Study of Long-Lived Orbital Debris Clouds, *Proc. of 42nd I.A.F. Congress,* Montreal, Canada, 1991.

Takano T., Murotani Y., Toda T., Fujiwara A., Hasegawa S., Yamori A., Microwave Emission Experiment with Hypervelocity Impacts and Applications of Its Results, *Proc. of 3rd Europ. Conf. on Space Debris*, ESA SP-473, 569-575, Darmstadt, Germany, 2001.

Takano T., Murotani Y., Maki K., Toda T., Fujiwara A., Hasegawa S., Yamori A., Microwave Emission due to Hypervelocity Impacts and its Correlation with Mechanical Destruction, *J. of Applied Physics,* Vol. 92, 5550-5554, 2002.

Weber, K., Hohler, V., Stilp, A.J., Impact Flash and Debris Could Expansion of High-Pure Metal Foils, *Int. J. of Impact Engng,* Vol. 14, 797-808, 1983.