RESEARCH AND DEVELOPMENT ON IN-SITU MEASUREMENT SENSORS FOR MICRO-METEOROID AND SMALL SPACE DEBRIS AT JAXA

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ABSTRACT

The Japan Aerospace Exploration Agency (JAXA) has been conducting R&D into in-situ sensors for measuring micro-meteoroid and small-sized debris (MMSD) since the 1980s. Research into active sensors started with the meteoroid observation experiment conducted using the HITEN (MUSES-A) satellite that ISAS/JAXA launched in 1990. The main purpose behind the start of passive collector research was SOCCER, a late-80s Japan-US mission that was designed to capture cometary dust and then return to the Earth. Although this mission was cancelled, the research outcomes were employed in a JAXA mission for the return of MMSD samples using calibrated aerogel and involving the space shuttle and the International Space Station. Many other important activities have been undertaken as well, and the knowledge they have generated has contributed to JAXA's development of a new type of active dust sensor. This paper reports on the R&D conducted at JAXA into in-situ MMSD measurement sensors.

1 Introduction

Solid particles present in the near-Earth environment are either natural or artificial in origin, with the former being referred to as "meteoroids" and the latter as "space debris" (or "orbital debris"). Meteoroids are considered to originate from comets, asteroids, or planets, and the origins of some meteoroids—known as "interstellar dust particles" (or "interstellar grains")—lie outside the solar system (Grün *et al.*, 1993[1]). Since meteoroids are thought to be closely related to the evolution of the solar system, study of these materials provides us with crucial information on the solar system's primitive materials. Space debris is the product of normal satellite operations, the deterioration of satellites, and the fragmentation or breakup of satellites (Johnson and McKnight, 1991[2]). The distribution and composition of small-sized debris are not well known, as these particles are too small to be observed with ground-based telescopes or radars.

For the measurement of micro-meteoroid and small-sized debris (MMSD), a number of technologies have been developed by many researchers over the last five decades. McDonell[3], Liou *et al.*[4][5], Hőrz *et al.*[6][7], Kuitunen *et al.*[8], Menicucci *et al.*[9], Bauer *et al.*[10], and Matsumoto *et al.*[11] have introduced many kinds of important sensors and related technologies. Depending on the type of sensor, these can be roughly classified into passive collectors and active collectors.

Mainly used for sample returns of MMSD, passive collectors have a simple structure and usually need neither electrical power nor means of communication. The passive collector is exposed to space for a certain period of time, and then brought back to the Earth. The cumulative number (impact flux) of MMSD collisions on the collector can be measured, and the material properties (e.g., composition) of the captured (or residual) material in the collector can be analyzed at the ground laboratory in Post Flight Analysis (PFA). Active

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

sensors, on the other hand, usually measure the number of MMSD collisions on the sensor in real time (or quasi-real time). In other words, the active sensor can detect MMSD impacts with a time resolution. Some types of sensors can measure the physical, chemical, and dynamical characteristics (composition, mass, velocity, trajectory, and charge) of MMSD based on ground calibration experiments.

The Japan Aerospace Exploration Agency (JAXA) has been researching and developing in-situ measurement of MMSD for about 30 years. This paper reports on the R&D into in-situ MMSD measurement sensors at the JAXA-Aerospace Research and Development Directorate (JAXA/ARD).

2 Passive Collectors

2.1 Overview of Development History

The main reason behind the start of passive collector research was SOCCOR (Comet Coma Sample Return Mission), a late-80s Japan-US mission that was designed to capture cometary dust and then return to the Earth[12]. Hypervelocity impact experiments and simulations were performed by Fujiwara[13] on many kinds of low-density materials that were candidates for use as meteoroid capturing materials in the SOCCER research mission. The mission proposal was not accepted, however, because no comets with an encounter velocity of less than 6 km/sec were found at that time. In addition, the SOCCER mission concept was replaced by the US STARDUST[14] mission. Although the SOCCER mission was cancelled, the research outcomes were employed in a JAXA mission for the return of MMSD samples using passive collectors and involving the space shuttle and the International Space Station (ISS).

2.2 Passive Collector Mission by JAXA/ARD

Passive collectors developed by JAXA/ADR include silica aerogel (“aerogel”), polyimide foam, aluminum alloy (Al) plates, and gold (AU) plates. The main purpose of the first two collectors was the intact capturing of MMSD. The latter two items are polished metal plates that were developed mainly for measuring the impact number and residual material.

1) “Calibrated” aerogel collector

Based on the SOCCER research, the development of aerogel dust collectors began in 1995. The characteristics of the aerogel are as follows. 1) Since aerogel is a very low-density material (up to 0.03 g/cm^3), it is effective for the intact capturing of MMSD. 2) Aerogel is transparent, so it is easy to locate the MMSD that it captures. 3) Aerogel mainly consists of pure silicate (SiO_2), and it is a robust material in a space environment. Furthermore, an excellent feature of JAXA’s aerogel is that it allows "calibrated" impact parameters to be roughly estimated from the shape parameters of penetrations on the aerogel based on hypervelocity impact experiments.

2) Polyimide foam collector

The bulk density of the polyimide foam is 0.011 g/cm^3, and the density is lower than that of aerogel. However, the pore size of the foam is several tens of micrometers, which is much larger than the aerogel pore size of a few to several nanometers. Although the large pore size is not suitable for the intact capturing of MMSD, the low density portion is sufficient to enable MMSD fragments to be captured. The foam costs much less aerogel, and the foam is very easy to handle.

3) Metal witness plates (Al plate and Au plate)

The polished metal plates (6061-T6 aluminum alloy plate and/or pure gold plate) are used to obtain detailed estimates for the impact flux of MMSD. The morphological features of impact-induced craters and residual materials can be observed.

2.3 Evaluation of Collector Performance

Laboratory hypervelocity impact experiments were conducted to verify the performance of collectors. The experiment results have been described by Kitazawa *et al.*[15][16][17]. Here, we briefly mention these experiments to verify (“calibrate”) the performance of aerogel collectors and derive the relationships among the various parameters characterizing the projectile through the morphology of tracks left by the penetrating projectile captured in the aerogel collector.

Aerogel collectors were impacted at velocities ranging from 1 to 14 km/s using projectiles of aluminum oxide, olivine, or soda-lime glass that had diameters ranging from 10 to 400 µm. Fig. 1 shows the measurement parameters. Data from the laboratory experiments used in the aerogel experiment comprised 149 hypervelocity impact data points. Of these, 141 were from the plasma-gun of the Hypervelocity Impact Facilities (HIF) of the Space Power Institute, Auburn University, 4 were from the two-stage light-gas gun of the Institute of Space and Astronautical Science (ISAS), JAPAN, and the remaining 4 were from the electro-thermal gun of IHI Corporation, Japan. The impact velocity covered by the three data sets ranged from 3 to 14 km/s with the plasma-gun, 1 to 5 km/s with the light-gas gun, and 1 to 2 km/s with the electro-thermal gun.

In the results of the hypervelocity impact experiments, the shapes and dimensions of the penetration tracks left in the aerogel collector were correlated with the impact parameters. Details of the experiments have been described by Kitazawa *et al.*[15]. The dimensions and features of the penetration tracks caused by projectile impacts are correlated with the projectile size and the impact velocity (Fig. 2). The aspect ratio (T/D_{ent}) and the track features correspond to the impact velocity of the projectile, where T is the track length and D_{ent} is the track diameter. At velocities lower than about 5 km/s, T/D_{ent} is greater than 10 and the tracks are "carrot shaped". Between 12 and 13 km/s in particular, these values are very small and a spindle-shaped or crater-shaped track becomes dominant. When T/D_{ent} is greater or equal to 10, the track is spindle-shaped and there are sometimes several branches at the bottom of the track.

The relationship between D_{ent} and D_p obtained by the least squares fit is represented by:

$$D_{ent} = 8.0D_p \tag{1}$$

and the correlation coefficient (r) of the equation is 0.6.

The correlation results provided by Kitazawa *et al*.[15] suggest that it is possible to estimate projectile impact parameters from penetration track observations when PFA is performed for the collectors. In addition, a simplified analysis model, in a similar way to that of a meteoroid penetrating the atmosphere, can predict penetration the track lengths and the diameters of captured projectiles [15].

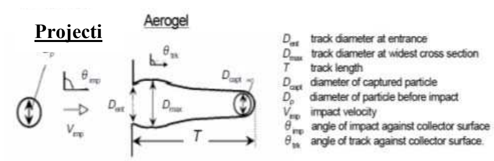


Figure 1. Measurement parameters at experiments

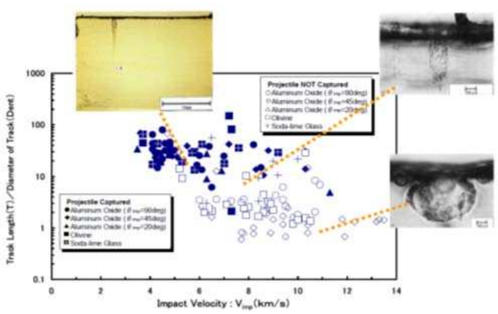


Figure 2. Relation of aspect ratio of the tracks (T/D_{ent}) with impact velocity

2.4 Flight of Experiments

In 1997, the "calibrated" aerogel dust collectors were sent aboard the space shuttle as part of the equipment for the Evaluation of Space Environment and Effects on Materials (ESEM) experiment. Details of the flight experiment have been reported by Kitazawa *et al.*[18] and NASDA[19]. The use of such collectors in this experiment demonstrated that they can be used in actual flight.

As part of an experiment named the Micro-Particles Capturer (MPAC) experiment, four sets of passive collectors have been sent aboard the ISS. Three of the passive collectors were for the Russian Service Module (SM) on the ISS, and the other one was for the Japanese Experiment Module Exposed Facility (JEM/EF) on the ISS (Fig. 3).

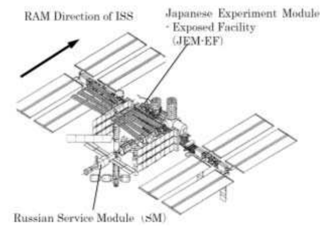


Figure 3. Location of JEM-EF and SM on the ISS

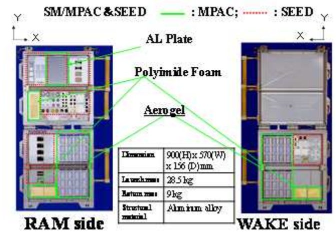


Figure 4. Configuration of SM/MPAC&SEED unit

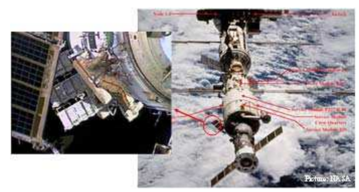


Figure 5. Three SM/MPAC&SEED units on the

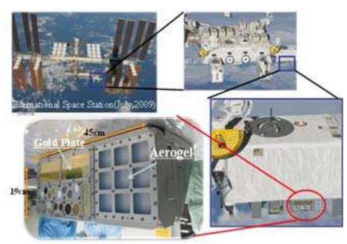


Figure 6. JEM/MPAC&SEED unit on the ISS

Table 1 Estimated MMSD impact flux [22]

	JEM	SM1(RAM)	SM2(RAM)	SM3(RAM)
Exposure Period (Days)	259	315	865	1403
D_p [um]	Flax [Number/m^2/year]			
<5	3.50E+03	-	-	-
5	4.90E+02	5.10E+03	-	-
10	3.60E+02	1.60E+03	-	-
20	6.00E+02	6.30E+02	3.90E+02	2.10E+02

SM/MPAC consisted of three identical MPAC units (numbered #1 to #3)—each containing calibrated aerogels, polyimide foams and an Al plate—that were deployed on the exterior of the SM. MPAC was mounted on an approximately 1-m long frame that it shares with the Space Environment Exposure Device (SEED), which is used for a materials exposure experiment (Fig. 4). Three SM/MPAC&SEED units were launched aboard Progress M-45 on 21 August 2001, and these were attached side-by-side to a fixture mechanism on a handrail outside the SM via extravehicular activity (EVA) on 15 October (Fig. 5). The first unit ("SM1/MPAC&SEED") was retrieved via EVA after 315 days' exposure, and then brought back to Earth on board Soyuz TM-34. SM2/MPAC&SEED was retrieved after 865 days' exposure and SM3/MPAC&SEED was retrieved after 1403 days' exposure. All SM/MPAC&SEED units were retrieved safely. Details of the SM/MPAC&SEED experiment plan and the preliminary PFA results have been reviewed by Neish *et al.*[20] and Kitazawa *et al.*[21]

The JEM/MPAC was also mounted on SEED to form JEM/MPAC&SEED, and installed in the outboard platform of KIBO (JEM) on the ISS (Fig. 6). In addition, JEM/MPAC&SEED was expected to encounter a different artificial space environment than SM/MPAC&SEED, because the SM is located at the rear of the ISS while JEM was attached at the front (see Fig. 3). Aerogels and Au-plates of MPAC samples had been exposed to space for about 8.5 months (259 days between 23 July 2009 and 9 April 2010). Waki and Kimoto[22] reviewed the PFA results for the JEM/MPAC experiment. Here, we briefly introduce a few matters with regard to PFA.

(1) Estimated impact flux on calibrated aerogel

Using the measuring results on D_{ent} for aerogels in PFA and Eq. (1), we estimated the impact flux during each mission. Kitazawa *et al.* [17] obtained the impact fluxes at each of the three SM/MPACs and Waki and Kimoto[22] obtained the impact flux at JEM/MPAC. Table 2 shows the numerical results for the flux on the RAM side. Due to the surface alteration of aerogels caused by contamination, it is difficult to inspect small tracks, and it was not possible to estimate the fluxes for diameters less than 10 μm for the SM2 and SM3 aerogels. In addition, Fukushige *et al.*[23] compared the impact flux estimated from an inspection of the SM's aerogels and calculated the results from MASTER-2001, MASTER-2005 and ORDEM 2000. They concluded that the impact fluxes of aerogels are greater than the model results.

(2) Material analysis of captured MMSD

Detailed analysis is still underway as a lot of material has been captured. Noguchi *et al.*[24][25] published important PFA results. Fig. 7 shows a captured particle in the aerogel retrieved in 2004 (SM2/MPAC). After extraction from the silica aerogel, the particle was investigated by SR-XRD. The particle proved to be a mixture of silver oxide and sulfide. TEM observation of the grain revealed that it has a continuous rim (< 500 nm thick) and a quite porous interior. The rim is composed of an S-rich amorphous material and silver sulfide (Ag_2S). Its crystal structure is the same as that of acanthine. It is quite interesting that the particle contained a 2-μm-wide low-Ca pyroxene crystal near one of the edges of the particle. As this particle is comprised of a mixture of natural and artificial materials, this particle is secondary debris that was formed by a collision of a micrometeoroid with an artificial object[24]. One of the most important research topics with regard to PFA is the world's first discovery of an extraterrestrial material captured from the ISS. According to research by Noguchi *et al.*[25] MPAC&SEED has captured a new extraterrestrial material with unprecedented mineralogical characteristics. The material has been named "Hoshi" (which means "star" in Japanese).

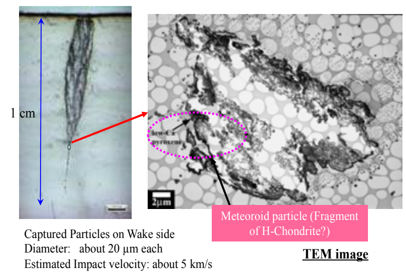


Figure 7. An example of captured particle in SM2

3 Active Sensors

3.1 Overview of Development History

Research into active sensors started with the meteoroid observation experiment on a satellite launched in 1990 by ISAS/JAXA called "HITEN (MUSES-A)," which had MDC (Munich Dust Counter) on-board sensors for the measurement of micro-meteoroids[26]. This research was a collaboration between Technische Universität München and ISAS/JAXA. The MDC was modified for a Mars Orbiter called "Nozomi (Muses-B)" and named the MDC (Mars Dust Counter)[27]. Different types of active meteoroid sensors were also developed, including the PVDF sensor for IKAROS[28] and the PZT sensor for BepiColombo[29].

From the perspective of risk assessment of MMSD collisions on spacecraft, it is important to investigate debris ranging in size from a hundred micrometers to a millimeter, the range within which the majority of debris particles lie. Collisions with debris of this size change the characteristics of spacecraft materials or of on-board parts. It was shown in a collision experiment carried out by JAXA on the harness for the satellite's power systems that the impact of an object larger than 300 μm at a velocity of 4 km/s damaged the second-layer harness, leading to a continuous electrical discharge and a short circuit caused by carbonization[30]. A comparison of representative space debris environment models, however, reveals that there is a large difference in flux value in the size range from a hundred micrometers to several millimeters[31]. It is said that uncertainty concerning models is caused by a lack of measured data. Although large-sized objects (larger than several centimeters) can be detected by ground based observations and small-sized debris (smaller than a hundred micrometers) can be measured by spacecraft surface inspections, the size range from a hundred micrometers to several millimeters cannot be detected by ground observations and not enough data can be obtained from spacecraft surface inspections.

Conventional active sensor systems are not necessarily suitable for the measurement of debris of a size greater than 100 µm. In addition, a large number of hypervelocity impact tests are required to correlate the changes produced in sensors with the impact parameters (velocity, particle diameter, and material) in usual cases. Also, the distribution and flux of debris in that size range are not well understood and are difficult to measure using ground observations. However, it is important that the risk caused by such debris be assessed.

A new type of sensor using resistive networks was proposed in 1990 and its patent (utility model) was published in Japan in 1992 (Fig. 8) [32]. Thin resistive lines, all lying in parallel, are printed onto a suitable substrate plate. If the particle is large enough (e.g., larger than 50 um), one or more of the resistive grid lines will be destroyed as a result of hypervelocity impact. Measuring resistance increases for the sensor (i.e., between the bus lines) enables the number of destroyed resistive lines to be determined, and a measurement of the impacting particle's size can be estimated. This resistive network concept was very innovative at the time, although technical difficulties existed in the early 1990s. It is difficult to print multiple thin resistive lines with a fine pitch on a board (e.g., line width of 50 um and pitch of 50 um). Even if the lines can be printed, the actual manufacturing of the connections between the lines and the measurement circuit is difficult. Hypervelocity impacts produce "craters" and crater size is a function of the impact parameters (including dust size, impact velocity, and impact angle). As a result, many hypervelocity impact experiments are required to identify impact parameters based on the number of severed resistive lines, which reflects the crater size.

In the 2000s, however, an innovative idea and a breakthrough technology made the production of this resistive sensor system possible. In the next section, we describe a new type of sensor which is being developed by JAXA/ARD.

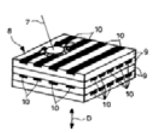


Figure 8. Primitive design using resistive networks was submitted in 1990[32]

3.2 New Type Sensor by JAXA/ARD

Using an innovative idea and a breakthrough technology to facilitate resistive networks, JAXA/ARD and its partners took up the challenge of developing a new type of sensor that is focused mainly on measurements in the range of 100 µm to several millimeters. The idea behind this development was to use a thin film instead of a plate, and the technology used was the flexible printed circuit (FCP) board manufacturing technique.

In-situ measurement of MMSD that is larger than 100 µm is useful for 1) verifying MMSD environment models, 2) verifying debris environment evolution models, and 3) the real time detection of explosions, collisions and other unexpected orbital events.

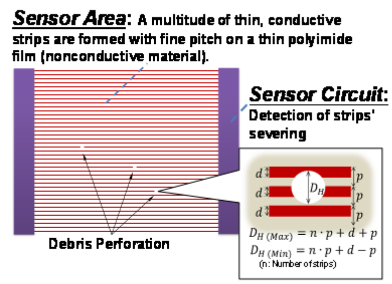
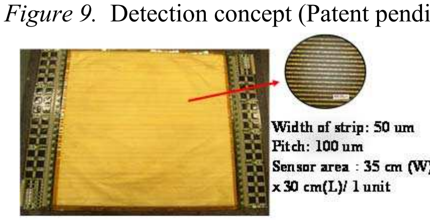


Figure 9. Detection concept (Patent pending, 2008)



Figurer 10. Sensor EM (Engineering Model)

Table 3 Experiment condition

Environmental conditions	Vacuum level (Pa)	<5
	Temperature	Room temperature
Impact conditions*	Projectile material	SUS304, Glass
	Projectile diameter (µm)	50 – 516
	Impact velocity (km/s)	1.9 – 7.0
	Impact angle (°)	90, 60, 30,15 (Measured from surface(=0))

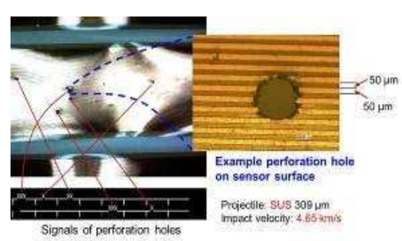


Figure 11. An example of a perforation hole on the sensor surface, together with the signal.

The basic design requirements are low power, low weight, and a large area. The sensor detection principal has been described by Kitazawa *et al.*[33][34] Here, we give a brief description of the measurement method.

The sensor consists of a pattern of thin, parallel conductive strips formed on a thin layer of nonconductive film that consists of materials such as polyimide, as shown in Fig. 9 and Fig. 10. When debris with an effective diameter that is larger than or approximately equal to the spatial pitch of the detector strips impacts the sensor, one or more of the strips are severed and become nonconductive. Debris impact can therefore be detected by monitoring the state of the sensor strips as though they were on-off switches. The system detects the number of broken detection strips and determines the time at which the strips break. Using this sensor, we can estimate the time of impact and approximate size of the MMSD.

A large number of thin, conductive copper strips are formed at a fine pitch of 100 um on a nonconductive polyimide film that is 12.5 um thick. An MMSD particle impact is detected when one or more of the strips are severed by being perforated by such an impact. This sensor is simple to produce and use, and it requires almost no calibration as it is essentially a digital system, and the sensor and connections between the lines and the measurement circuit is marked up as one large, "flexible printed circuit board". As a result, there are no mechanical connections and fewer parts.

3.3 Sensor Performance

Hypervelocity impact experiments on the sensors were performed in order to evaluate their performance and to correlate the diameter of the perforation hole in the sensor with the physical parameters of the impacting particles. Details of the experiments have been described by Kitazawa *et al.*[33]

Here, we provide an overview of the experiments and describe the important results.

(1) Facilities and conditions

The experimental conditions are listed in Table 3. The experiments were conducted using the two-stage light-gas gun of the ISAS/JAXA

(2) Examples of the results

Fig. 12 shows an example of a perforation hole on the sensor surface, together with the signal. Complete detection and confirmation of breakup signals was achieved. It is considered that the debris diameter can be estimated from the number of signals.

(3) Evaluation of sensor performance

Fig. 12 shows the relationship between D_P and D_H using all of the experimental data for normal impacts on the sensor models. The relationship between D_P and D_H obtained by the least squares fit is given by:

$$D_P = 1.39\text{x}10^{-1} D_H \qquad (2)$$

and the correlation coefficient (r) of the equation is 0.98. When the D_H value is known, this relationship can be used to estimate D_P.

Fig. 12 also shows the dimensions of a conductive strip with pitch *p* and width *d*. No particular restrictions are used with regard to the length of the conductive strip. The size of the perforation when *n* conductive detection strips are broken simultaneously (i.e., the MMSD size) is approximately *np*. However, in consideration of the uncertainty of distribution, the MMSD size is not kept constant, and the probability is given by *np*+*d* (where *n* is the number of wires broken simultaneously). The uncertainty concerning the measurement of the sizes of MMSD particles can be determined using the pitch width of the conductive strips as deference between

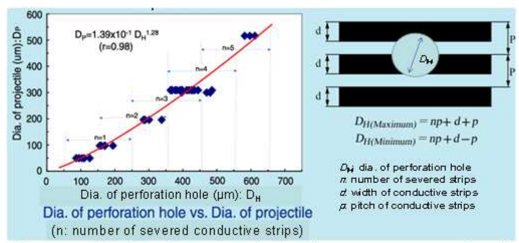


Figure 12. Perforation hole diameter vs. projectile diameter D_H*(Maximum)* and $D_{H(Minimum)}$.

3.4 Flight Demonstration Plan and Future Application Plan

Based on this sensor technology, the Kyushu Institute of Technology (KIT) has designed and developed an educational version of the sensor, which is currently on board the nano-satellite Horyu-II, which was built at KIT and launched on 18 May 2012[35]. Although the sensor has a very small sensing area, sensor data were nonetheless successfully received. This successful flight is intended to demonstrate that this new type of sensor can be used in space. Moreover, a laboratory model of a this sensor will be launched on a small satellite QSAT-EOS (KYUshu SATellite for Earth Observation Demonstration System) in 2013[36]. This laboratory model was manufactured by the Institute for Q-shu Pioneers of Space, Inc., JAPAN (iQPS). It was developed by iQPS under contract with JAXA through IHI Corporation with a view to evaluating the sensor's capability in hypervelocity impact experiments at JAXA.

JAXA have also been performing environment tests using Engineering Models (EMs). Fig. 13 shows an example view of the setting up of an acoustic test of JAXA's EM, which is to be employed on application satellites and/or the ISS. The EM will be ready for flight experiments in the 2013 Japanese Fiscal Year (JFY).

Two sensors
are attached.

FFigure 13. An example view of setting at an acoustic test

4 Summary

This paper reports on the R&D into in-situ MMSD measurement sensors at JAXA/ARD. JAXA/ARD have developed four types of passive collectors: “calibrated” aerogel, polyimide foam, aluminum alloy (Al) plates, and gold (Au) plates. Aerogel in particular is very useful for obtaining rough estimates of the impact parameters for MMSD based on the shape parameters of penetrations on the aerogels. JAXA/ARD is developing a simple in-situ sensor to detect dust particles ranging in size from a hundred micrometers to several millimeters. A large number of thin, conductive copper strips with a fine pitch (100 um) are formed on a thin film made from a nonconductive material (12.5 um thick polyimide). Dust particle impact is detected when one or more of the strips are severed by the perforation hole that the particle creates. This sensor is simple to produce and use, and it requires almost no calibration as it is essentially a digital system. This sensor will be ready for use in flight experiments soon.

Acknowledgements

The experiments described in 3.3 were conducted and supported by the Space Plasma Laboratory, ISAS, and JAXA.

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