Development of a New Type of Sensor for In-Situ Space Debris Measurement

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Abstract

The importance of measuring large debris particles (larger than 100 μm) has increased, especially from engineering viewpoints (e.g. space system design and operations). However, it is difficult to measure the impact flux of these large particles because of the low spatial density of large particles (larger than 100 μm). Sensor systems to monitor these sizes must have a large detection area, while the constraints of a space environment deployment require that these systems be low in mass, low in power, robust and have low telemetry requirements. The in-situ measurement data are useful for; 1) verifications of meteoroid and debris environment models, 2) verifications of meteoroid and debris environment evolution models, 3) real time detection of unexpected events, such as explosions on an orbit (Ex. ASAT: Anti Satellite Test). JAXA has been developing a simple in-situ sensor to detect dust particles ranging from a hundred micrometers to several millimeters. Multitudes of thin, conductive strips are formed with fine pitch on a thin film of nonconductive material. A dust particle impact is detected when one or more strips are severed by the impact hole. The sensor is simple to produce and use and requires almost no calibration as it is essentially a digital system. The authors have developed prototypes of the sensors and performed hypervelocity impact experiments. As a result, prototype models have been manufactured successfully and the projectile diameter (debris diameter) is able to be estimated from the number of broken strips.

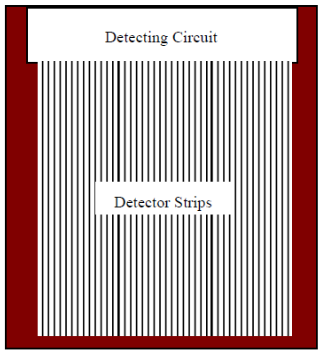
1. Introduction

Space debris environment models are used for debris impact risk assessments for spacecraft. The comparison of representative models revealed that there is a large difference in the flux value of the size range from a hundred micrometers to several millimeters. The uncertainty of models is caused by the lack of measurement data. Although large size objects (larger than several cm) can be detected by ground based observations, and small size debris (smaller than a hundred micrometers) is measured by spacecraft surface inspections, the size range of a hundred micrometers to several millimeters cannot be detected by ground observations and not enough data can be obtained from spacecraft surface inspections. However, the importance of measuring these large particles has increased, especially from engineering viewpoints. JAXA has been evaluating the risk of micro-debris from the ADEOS- II (Midori-II) satellite anomalies. As shown in a collision experiment carried out by JAXA on the harness for the satellite's power systems, 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 resulting in a short circuit as a result of carbonization [1]. The results showed the damage on the wire harness and other equipment even when the impact of the micro-debris was due to particles in the range of 100 μm to several millimeters. It is difficult to obtain data on the environment in space required to evaluate the frequency of impact on a satellite by micro-debris, and currently, we are unable to get real time data. Under these circumstances, it is urgent that environmental data be measured to understand the effect of impact by micro-debris on the safe operation of a satellite and to accurately evaluate the frequency of these impacts. In this paper, we describe the issues related to the impact on a satellite by micro-debris and the technology for measuring micro-debris. The in-situ measurement data are useful for; 1) verifications of space debris environment models, 2) verifications of space debris environment evolution models, 3) real time detection and evaluation of the influences on space environment by unexpected events, such as explosions on an orbit (ex. ASAT (Anti-Satellite Test) and satellite collisions). Many micro-debris monitoring sensors have been developed to enable the observation of meteoroids, and more than ten types are available [2]. Conventional systems are not necessarily suitable for the measurement of debris that is >100 μm in size. In addition, many hypervelocity impact tests are required to correlate the changes produced on sensors and in impact parameters (velocity, particle diameter, and material). For these reasons, we are currently developing a sensor that works on the basis of the principle proposed by the Institute for Q-shu Pioneers of Space (iQPS) and IHI Corporation (patent pending).

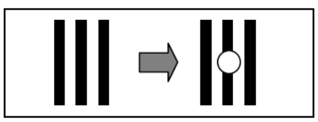
2. Micro-Debris Measurement Technology

2.1 Basic Principal

The sensor consists of a pattern of parallel, thin conductive strips (hereafter called the detector strips) formed on a layer of thin film of nonconductive material such as polyimide as shown in Fig. 1. These are realized by etching or a micro-printed thin film. For further details the reader is referred to the patent. Detector strips with less than 0.1 mm of spatial pitch on a film less than 0.05 mm thick are planned. When debris with an effective diameter larger than or around the spatial pitch of the detector strips impacts the sensor, one or more of the strips are severed and become nonconductive. Debris impact can be detected by monitoring the state of the detector strips as though they were on-off switches. The functions of this system are 1) the detection of the number of broken detection strips, and 2) the determination of the time at which the detector strips break. We can estimate the time of impact and approximate size of meteoroids and debris particles using this sensor.

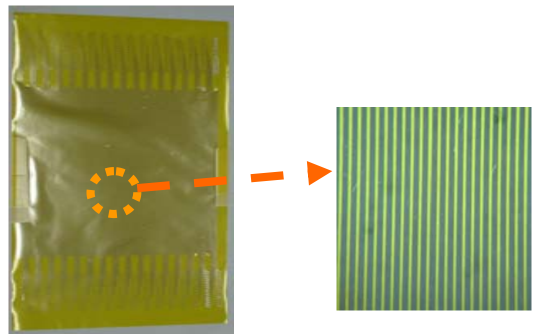


(a) Detector strips on a thin film



(b) A strip is severed by debris

Fig. 1. Concept of the detector



Sensor Surface

(Material: Aluminized polyimide film, t=25um, 12.5um)

Fig. 2. An example of sensor prototype model

2.2 Detecting Circuit

The detection circuit determines the number of simultaneously nonconductive strips (broken conductive strips). The authors have adopted a combination method of digital and analog for minimization of the area of the circuit. As debris impacts occur only quite infrequently, it is possible to switch from constant monitoring of the impact time using the analog method to the acquisition of the impact position using the digital method after the impact has been observed. Fig. 3 shows the schematic of this method, in which an analog, current-monitoring circuit is connected to each row input. During the continuous-monitoring mode, all the column-output bits are held high, and the impact is detected as the current decrease at one or more row input bits. After the impact, the mode is changed to the digital method in which each column-output bit is held high successively to check the existence of the input current at each row-input bit. This method is suitable when both the impact time and position must be measured.

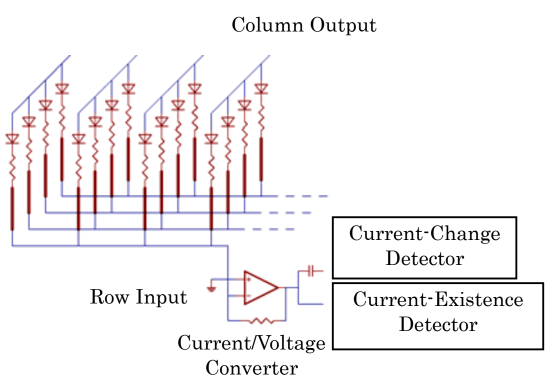


Fig. 3. Detecting circuit

3. Hypervelocity Impact Experiments on Prototype Sensors

Hypervelocity impact experiments on sensor prototypes were performed using JAXA's two-stage gun facility [3] (Fig. 3). The objectives of the experiments are 1) confirmation of signals produced when strip lines are broken up by projectile impacts, 2) obtaining data of the relation between the projectile diameter and the perforation hole diameter. Table 1 shows experiment conditions and Fig. 3 shows a set up configuration of the hypervelocity impact experiment on the prototype sensor. For the prototype sensor, the authors did not make detecting circuit equipment suitable for real time use under vacuum conditions. The detecting circuit equipment was switched off under vacuum conditions, although the equipment was set in the chamber. The signal (existence of a fracture of a lead) was detected from comparison of the electrical connection examination before and after the experiment. As a result of the experiments, breakup signals were detected successfully. Breakup signals corresponding to the number of broken strips were acquirable. Fig. 4 shows an example on a perforation (one strip line is broken) on a sensor surface. Fig. 5 shows the relation between the projectile diameter and the perforation diameter of the sensor, and it shows that a projectile diameter is able to be estimated from a perforation diameter (the number of broken wires).

Table 1. Experiment conditions

(Vacuum level: < 5 Pa, Temperature: Room temperature)

Target thickness (um)	Projectile diameter (um)	Projectile material	Impact velocity (km/s)
25	**300**	**SUS**	**5.9**
25	**100**	**Glass**	**5.1**
25	**50**	**Glass**	**4.9**
12.5	**100**	**Glass**	**5.1**
12.5	**50**	**Glass**	**5.5**

Two-stage light gas gun (JAXA/ISAS)

Prototype sensor in the target chamber

Fig. 3. Set up configuration of the hypervelocity impact experiment on the sensor prototype.

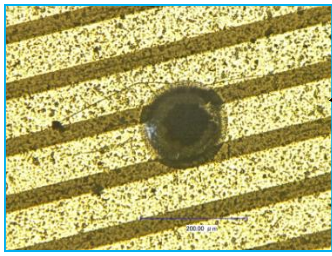


Fig. 4. An example of a perforation.

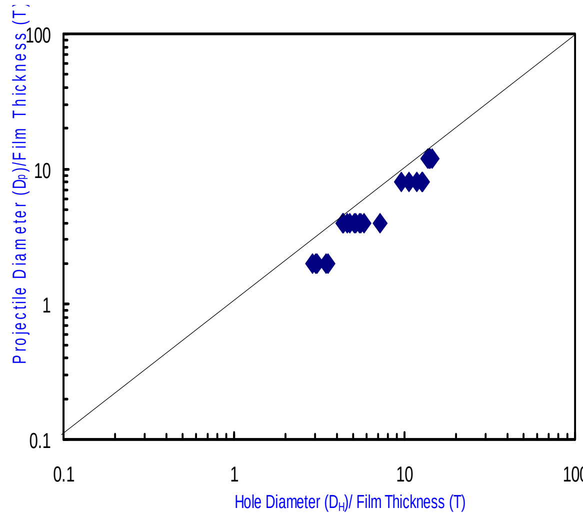


Fig. 5. Relation between the projectile diameter and the perforation diameter.

4. Discussion

4.1 Hypervelocity Impact Data Analysis

From the studies by Kitazawa *et al.* [4], Niesh *et al.* [5][6] and Hörz *et al.* [7][8][9], when particles impact a thin film at hypervelocity, and when the ratio of particle size/film thickness is greater than 10, the diameter of the hole on the film and the particle diameter are equal. However the sensor surface is not flat exactly, as there are conductive strip lines on the surface. Fig. 5 shows good agreement with previous works. It is thought the sensor film can be considered the same as a sufficiently thin film.

4.2 Size Detection Error

However conductive strips are formed on a sensor surface, the perforation diameter is almost equal to the projectile diameter i.e. debris diameter. The measurement error in the sizes of meteoroids and debris particles can be determined using the pitch width of conductive strips. Fig. 6 shows the dimensions of a conductive strip with the pitch of the conductive strip ***p***, and the conductive strip width ***d***. There is no particular restriction regarding the conductive strip's length. The size of the perforation when ***n*** detection conductive strips are broken simultaneously, i.e. the debris size, is approximately ***np*** when ***n*** is sufficiently large. However, the debris size is not constant considering uncertainty of distributions, and the probability is given by **kp**+***d*** (*k*: the number of wires broken simultaneously). As shown in Fig. 7, the distribution is triangular with a peak, and the size at the peak indicates the average size. Fig. 7 shows an example in which ***p***=0.1 mm and ***d***=0.05 mm. Even if the value of ***d*** is different, the probability distribution has the same triangular shape; only the position of the peak shifts.

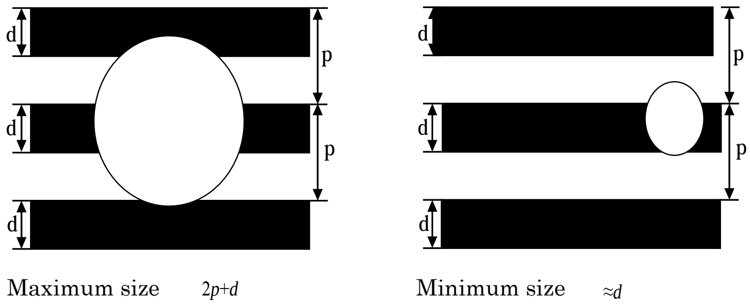


Fig. 6. Debris hole size when one detector strip is broken.

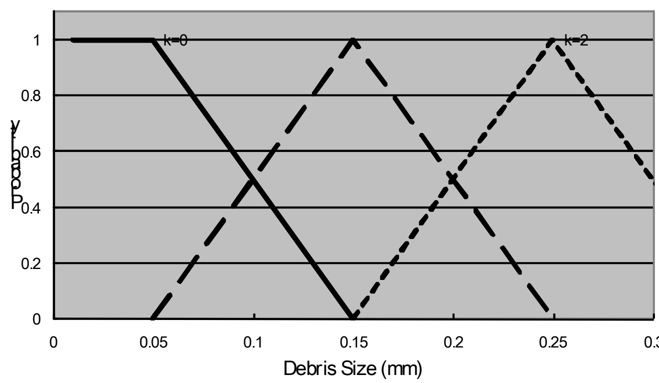


Fig. 7. Probability of detection by sensor (***p***: 0.1 mm, ***d***=0.05 mm).

4.4 Detection Frequency

Hits by debris occur at a specific frequency within a certain time period. The frequency is described using a Poisson distribution [10]. The probability of occurrence of hits ***k*** in period ***t*** is given as

$$P(k) = e^{-\lambda t} \frac{(\lambda t)^k}{K!} \quad \cdots\cdots (1)$$

Here, λ is a constant representing the frequency at which the designated event occurs within one unit of time. Assuming the flux of debris is ***q*** (times/m^2/y) and the sensor area is ***A*** (m^2), the frequency is

$$\lambda = qA(times / y) \quad \cdots\cdots \quad (2)$$

Fig. 6 shows the Poisson distribution of the events and the probability of the number of actual impacts. The abscissa represents the average number of hits expected to occur within a certain period when the flux and sensor area are determined. However, the actual number of impacts is not the same as the mean hit number; it is distributed around the mean value. For example, if the expected value is 1, the case (***k***=0) in which no hits occur has the same probability as the case for one hit (***k***=1), which is 0.37. Furthermore, two hits occur at a probability of 0.18. The curve for ***k***=0 shows the change in zero-hit probability with respect to the average hit number. With a small flux value, a small area, and a short period, the average number of hits is small, and the probability of zero hits predominates. For a high hit probability, for example, ***k***=10, the probability is large at 10 on the abscissa (expected value). In reality, the curve for ***k***=10 is very similar to the normal distribution with a center value of 10; in this case, the standard deviation is $\boldsymbol{k}^{-2}$. The hit detection frequency obtained using this sensor is proportional to the sensor area and the flux of the debris particles. The impact number itself increases in proportion to time. Accordingly, when the number of hits is small, the actual flux cannot be determined accurately. We study how to determine flux values for practical situations, in particular when the hit number is small, and including the case of no hits. From the curve for ***k***=0 in Fig. 8, even in the absence of hits in a short period, the actual flux can be identical to that in an environment in which 1-2 times the number of average hits occurs.

4.5 Error Estimation of Flux Value from Measurements

When the number of hits of debris particles is measured during a given period, the flux value can be estimated using eq. (3).

$$q = k / At \qquad \cdots\cdots \quad (3)$$

Here, k, q, A, and t are the number of hits, flux, sensor area, and measurement duration, respectively. The number of hits can be increased by increasing the duration of the measurement or the sensor area; the accuracy in the measurement of the flux can be improved by these methods. Because the number of hits follows a Poisson distribution, the flux value can be obtained at a statistically desired confidence level. When the event is observed a total of k times during T time a unit time interval, the interval with a population mean μ at a significance level α can be obtained as

$$\chi^2_{2k}(1-\alpha/2)/2T \le \mu \le \chi^2_{2k+2}(\alpha/2)2T \qquad \cdots\cdots \quad (4)$$

Here, $\chi_n{}^2(\alpha)$ represents the α percentage point of a chi square distribution with $\boldsymbol{n}$ degrees of freedom. Generally, the lower and upper limits of flux values and the duration of their relative intervals can be obtained from a table. For example, when the significance level is set at 5% or 10% and only one hit is observed, the value obtained includes an error of ±200% or greater, compared with the value obtained using eq. (3) without compensation. In some cases, the value obtained may be more than 1 order of magnitude away from the actual observed values. However, if the number of hits is 5, the error is approximately ±100%, and the order of magnitude of the error does not exceed 1. For the measurement of more than 10 hits, the error is limited to approximately 50%, and the evaluation using only eq. (3) provides practically reliable values. Fig. 9 shows the change in error levels (percentage of duration of estimated interval) with respect to the number of hits measured.

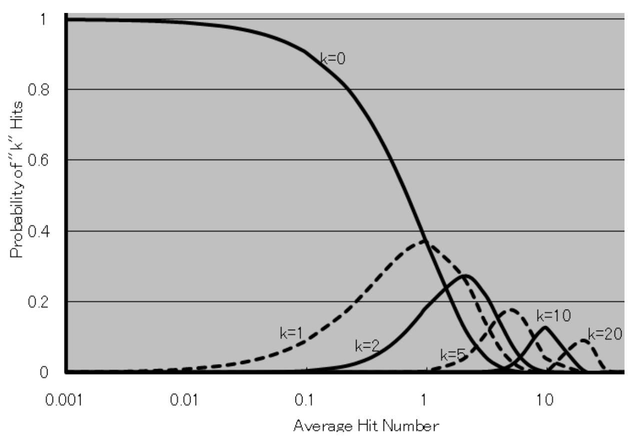


Fig. 8. Probability of occurrence of hits

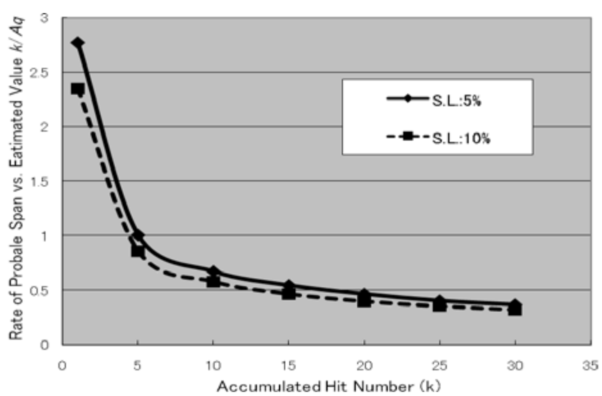


Fig. 9. Relationship between number of hits and change in the width of the estimated interval. The percentage of the width of the estimated interval with respect to the number of impacts estimated using eq. (3). The higher the number, the narrower the width.

6. SUMMARY

The authors have been developing the in-situ measurement sensor to detect dust particles ranging from a hundred micrometers to several millimeters. The sensor consists of multitudes of thin and conductive strips which are formed with fine pitch on a thin film of nonconductive material. A dust particle impact is detected when one or more strips are severed by the impact perforation. Since the sensor has a simple mechanism, the sensor has superior features (high reliability, flexible configuration, low weight, low power and low cost). The authors have developed prototypes of the sensors and performed hypervelocity impact experiments. As a result, prototype models have been manufactured successfully and the projectile diameter (debris diameter) is able to be estimated from the number of broken strips. The authors estimated error of flux values from measurements as low spatial density of large particles (larger than 100 μm). As a result, for the measurement of more than 10 hits, the error is limited to approximately 50%.

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