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著者	Faure Pauline, Masuyama Shingo, Nakamoto Hiroshi, Akahoshi Yasuhiro, Kitazawa Yukihito, Koura Takao
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Space Dust Impacts Detector Development for the Evaluation of Ejecta

Pauline Faure[a]*, Shingo Masuyama[a], Hiroshi Nakamoto[a], Yasuhiro Akahoshi[a], Yukihito Kitazawa[b], Takao Koura[a]

[a]*Kyushu Institute of Technology, 1-1 Sensui-cho, Fukuoka 804-8550, Japan*
[b]*IHI Corporation, Tokyo 135-8710, Japan*

Abstract

This paper aims at a) introducing the space dust impacts detector developed at Kyushu Institute of Technology (KIT), b) presenting the detector utility for the evaluation of ejecta, and c) raising awareness of the space community regarding the risk represented by orbital debris. The space dust impacts detector introduced into this paper belongs to the in-situ detection systems and has for purposes to be a) light, 30g, b) low cost, about EUR200, c) low power consuming, 0.01W, d) easily adaptable on-board of spacecraft, and e) able to detect impacts of debris with a diameter ranging from 100 µm to 600 µm. The detector is mounted on the nano-satellite, Horyu-II, developed at KIT and launched on May 18, 2012. The data received will be very helpful to identify the detector's strengths and weaknesses to improve it and create a second version that will aim at evaluating ejecta fragments produced during hypervelocity impact testing. An accurate evaluation of ejecta is critical for orbital debris risk assessment and mitigation. If all space activities were stopped, debris will still be created by chain reaction. The number of debris could then become so large, that the access to certain LEOs will be quasi-impossible, which will jeopardize the space exploration as well as scientific, educational, and security missions that benefit to all mankind. Debris is therefore a serious issue that should be taken into consideration at every step of the development of a small or large spacecraft.

Keywords: Space environment, Debris, Hypervelocity impact, Modeling

1. Introduction

Spacecraft are used for many purposes such as scientific, educational, and security missions, and despite the fact that space seems to be abstract and far, the researches that are conducted in space have a tremendous impact in our lives. So, what if these services became unavailable in the future?

This might sound an unrealistic scenario, but with 5,800,000,000,000 debris from 100 µm in diameter orbiting the Earth as estimated by Gelhaus in 2005 [1] with a velocity approximating 10 $km.s^{-1}$, the scenario becomes more realistic every day. As a matter of fact, Kessler and Cours-Palais warned and predicted [2] that around the year 2000, a threshold will be reached for which the number of debris will be so important that they will start colliding each other. This is known as the Kessler syndrome [3].

The notion of debris regroups two main categories: the catalogued objects and the other debris. Catalogued objects are debris that can be tracked by ground observations whereas the other debris are untraceable i.e., with a diameter smaller than 10 cm in low Earth orbit (LEO) and smaller than 1 m in geostationary Earth orbit (GEO). In this paper, the authors investigated LEO's untraceable debris and more precisely ejecta that count for 2 to 3% of the debris population in LEO [4], which makes them a major contributor to the small size debris population (Fig. 1).

* Corresponding author. Tel.: +81-93-884-3151; fax: +81-93-871-8591.
E-mail address: m584103r@tobata.isc.kyutech.ac.jp.

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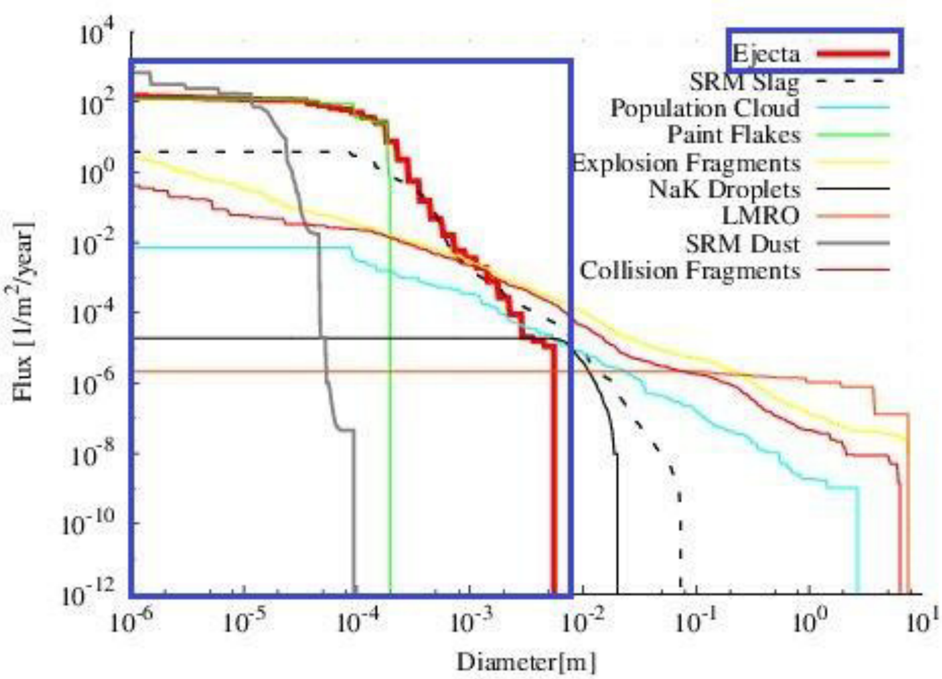


Fig. 1. MASTER-2009 simulation of debris diameter vs. impact flux for Horyu-II orbit (alt. = 680 km, I = 98.2°) showing that ejecta are a major contributor to the small size debris population.

Ejecta are secondary debris ejected upon hypervelocity impact (HVI) of primary debris on a spacecraft's surface. Their size varies from a few micrometers to a few millimeters. Ejecta might seem harmless due to their smallness, yet Kitazawa et al. [5] and Klinkrad [6] demonstrated that they can significantly damage a spacecraft, especially if they impact solar panels or optical elements such as mirrors. Moreover, every year, a few satellites experiment power loss or communication troubles with no apparent reason. These phenomena could be explained by small debris impacts, such as ejecta, which impact can create plasma, disturbing the on-board electronics.

Due to their dangerous potential and the lack of data, ejecta are being investigated by the authors at the Kyushu Institute of Technology (KIT). In this paper are reported KIT's past and undergoing researches on ejecta. The past research section focuses on the development of the space dust impacts detector and the undergoing research section focuses on the improvement and implementation of the detector for the evaluation of ejecta fragments' velocity, size, and/or impact angle during ground-based HVI testing.

2. Space dust impacts detector

2.1. Overview

Between 2010 and 2012, a space dust impacts detector has been developed at the KIT. The detector is a square printed circuit board (PCB) with a side length of 90 mm. On the front face are 128 copper lines (Fig. 2.a), which composed the detection area and on the rear face (Fig. 2.b) are the electronic components that verify the state of each copper line. HVI tests were performed by using KIT's two-stage light gas gun (TSLGG). Projectiles were alumina particles (Fig. 3.a) with a diameter ranging from 212 μm to 300 μm. The impact velocity was about 5 $km.s^{-1}$ and it can be seen from Figs. 3.b and 3.c that despite their small size, alumina particles could cut the copper lines and damage the board. HVI tests demonstrated that to be able to detect debris, the copper lines need to be fully cut. The detector's working principle, development, and testing have been previously reported in more details [7, 8].

The flight model of the detector was mounted on the nano-satellite Horyu-II (Fig. 2.c) that was launched on May 18, 2012, by the Japanese Aerospace Exploration Agency (JAXA) on a H-IIA rocket. The satellite is on sun-synchronous orbit at an altitude of 680 km and an inclination of 98.2°. Horyu-II's main mission is to produce 300 V using spherical micro solar cell and if it succeeds, this will be the world highest voltage ever generated in space.

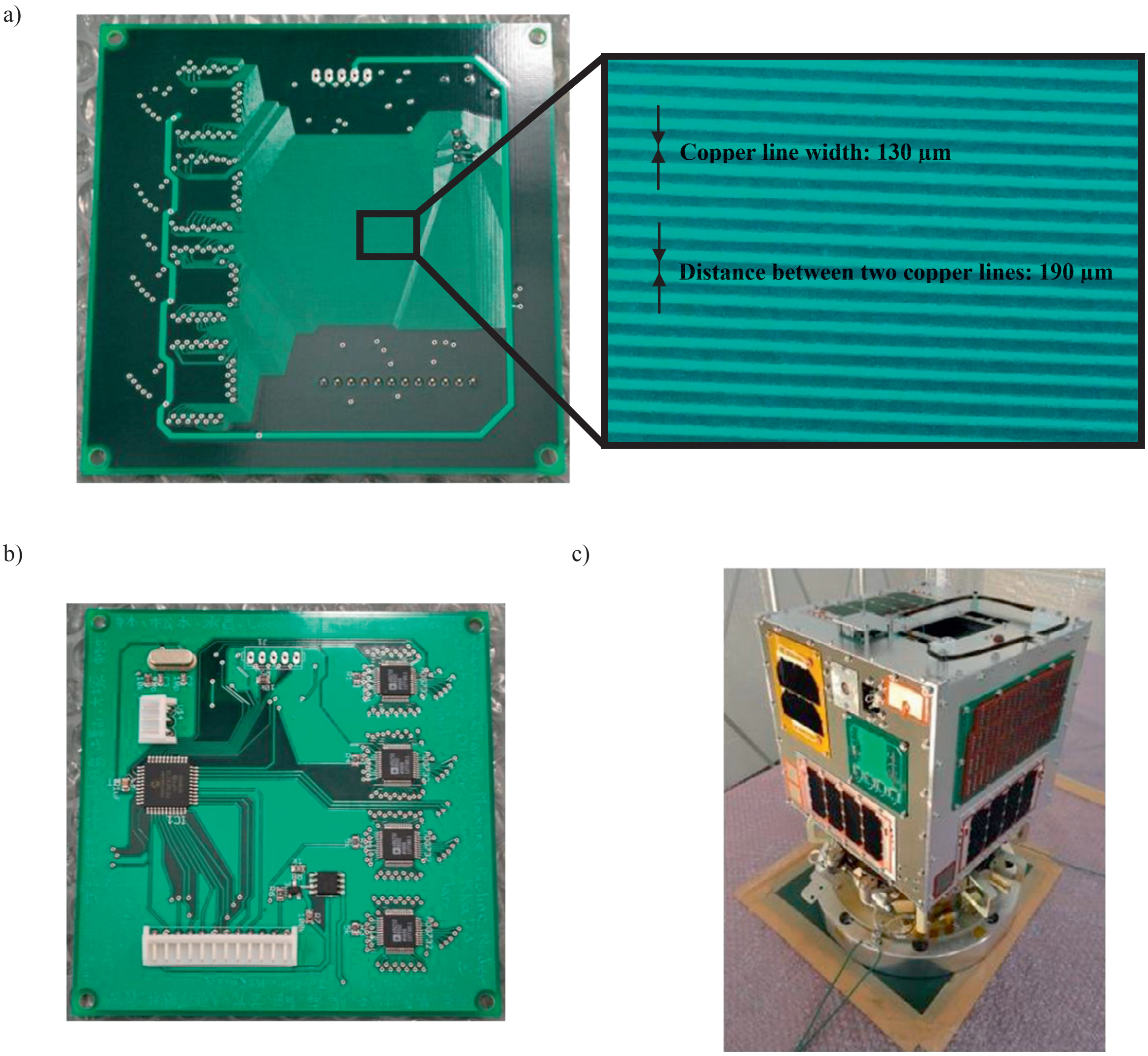


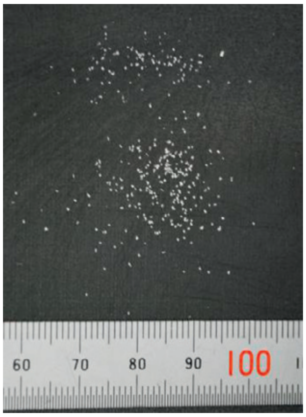
Fig. 2. KIT's space dust impacts detector flight model. a) Front face with the 128 copper lines exposed to the space environment. b) Rear face with the electronic components to control the state of each detecting line. c) Horyu-II with the detector mounted on the –Y panel.

2.2. On-orbit results

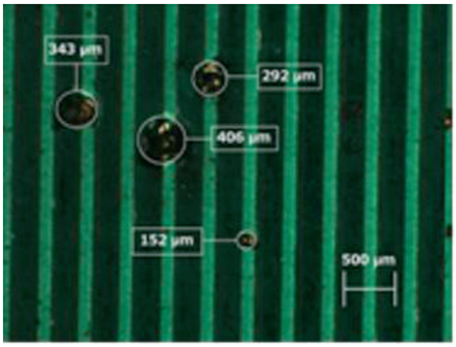
The launch of Horyu-II on May 18, 2012, was successful and the first telemetry data were received. After almost one week, no impacts were recorded by the detector as shown on Fig. 4.

The results are not surprising since the probability of impact, q, of debris with a diameter ranging from 100 µm to 600µm was previously estimated to be 72 impacts.m^{-2}.$year^{-1}$ by using ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER-2009), which corresponds to 0.16 impacts per year for the 22 cm^2 detecting area of the detector. However, when the impact probability is calculated for orbital debris with a diameter ranging from 1 µm to 100 µm (Fig. 5), MASTER-2009 estimated that two impacts will occur for the 22 cm^2 area considered. Therefore, even if no impacts are recorded by the detector, it will not mean than no impacts occur but that the impacting debris was out of the detecting range.

a)



b)



c)

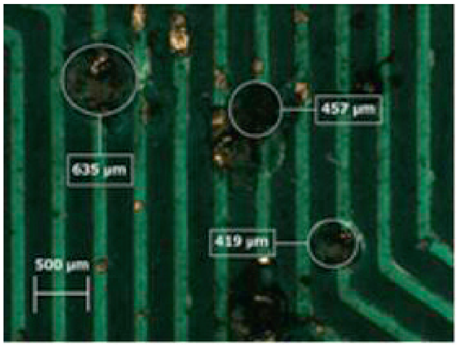


Fig. 3. a) HVI tests projectile: Al_2O_3 particles with a diameter ranging from 212 μm to 300 μm were launched at 4.7 $km.s^{-1}$. b) Copper lines cut by the projectile. If several lines are cut (c), the size of the impacting debris can be estimated.

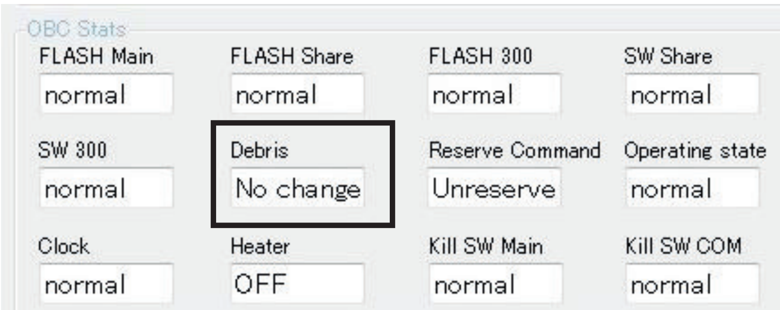


Fig. 4. Telemetry data received on May 21, 2012. No debris in the range 100 – 600 μm in diameter impacted the detector.

In case of success of the impacts detector, the data will help us to better estimate the small debris population for Horyu-II's orbit. The obtained data could be compared with the predictions of engineering space environment models such as NASA's Orbital Debris Engineering Model (ORDEM) and MASTER to observe whether the simulation data are consistent with the real space environment data. Moreover, the results will help us to identify the strengths and weaknesses of the detector especially regarding its ability to withstand the real space environment and give accurate data on the space dust population.

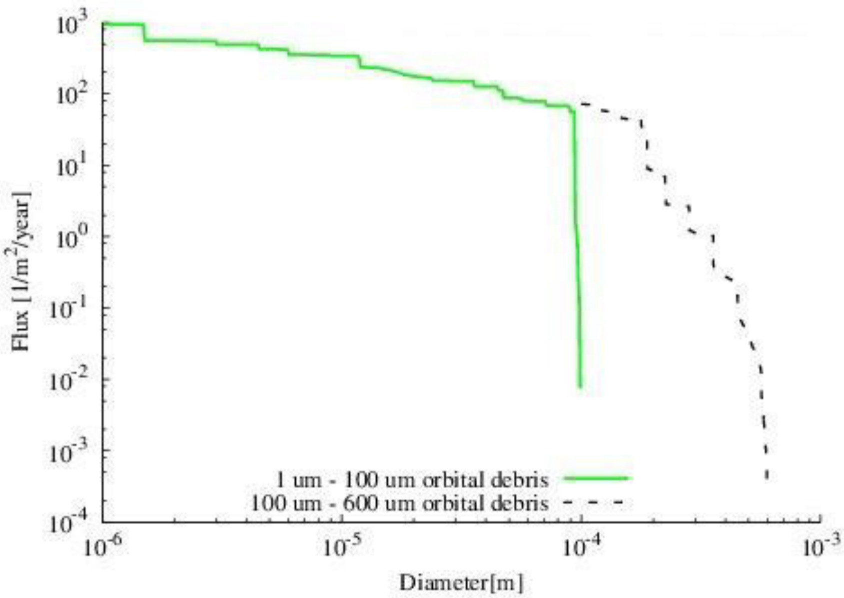


Fig. 5. Orbital debris diameter vs. impact flux. The plot shows that the probability of impact on the 22 cm^2 detecting area of the detector is much higher for debris smaller than 100 µm.

3. Ejecta impacts detector

The development and mounting of the space dust impacts detector on the nano-satellite Horyu-II was the first step to develop a detector able to evaluate the ejecta fragments generated upon HVI. In the future research, the space dust impacts detector will be improved for the evaluation of ejecta fragments' size, velocity, and impact angle.

3.1. Requirements for the ejecta impact detector

The estimation of the impact flux with MASTER-2009 shows that debris smaller than 100 µm are more likely to impact. Moreover, from Matsumoto et al. experiments [9], most of the ejecta fragments generated upon HVI tests on spacecraft materials have a diameter ranging from 25 µm to 150 µm. This indicates that the detector should be functional within this range. To achieve this requirement, the use of a PCB is inappropriate because the minimum line width is limited to about 120 µm and the minimum pitch to about 190 µm. Hence, polyimide film in association with polyvinydilene fluoride (PVDF) film is considered. Francesconi et al. [4] used successfully PVDF film in their method to evaluate ejecta fragments. However, in this study, only the average velocity and size of the ejecta cloud could be obtained and not the velocity and size of each ejecta fragments. From the previous study, the impact angle of the ejecta fragments was not investigated. On the other hand, Kitazawa et al. [10] propose to use a two layers flexible sensor made of 1,000 conductive lines to evaluate space dust impact angle. Therefore, in this study, we propose to combine both ideas to obtain a detector able to evaluate each ejecta fragment's size, velocity, and impact angle.

Following the development of the ejecta impacts detector, HVI tests will be performed on spacecraft materials i.e., solar array coupons, aluminum honeycomb, and carbon fibers reinforced plastic (CFRP)/aluminum honeycomb.

3.2. Ejecta model

The data acquired during the different HVI tests will be used to build an ejecta model. The model is expected to be able to give the size, velocity, and impact angle distribution of the ejecta fragments generated upon HVI. After its development, the ejecta model will need to be validated by using other laboratories' results. If validated, the authors expect to propose the ejecta model to the International Organization for Standardization (ISO). The different research phases are summarized in Fig. 6 in which an example of the possible results layout is also given.

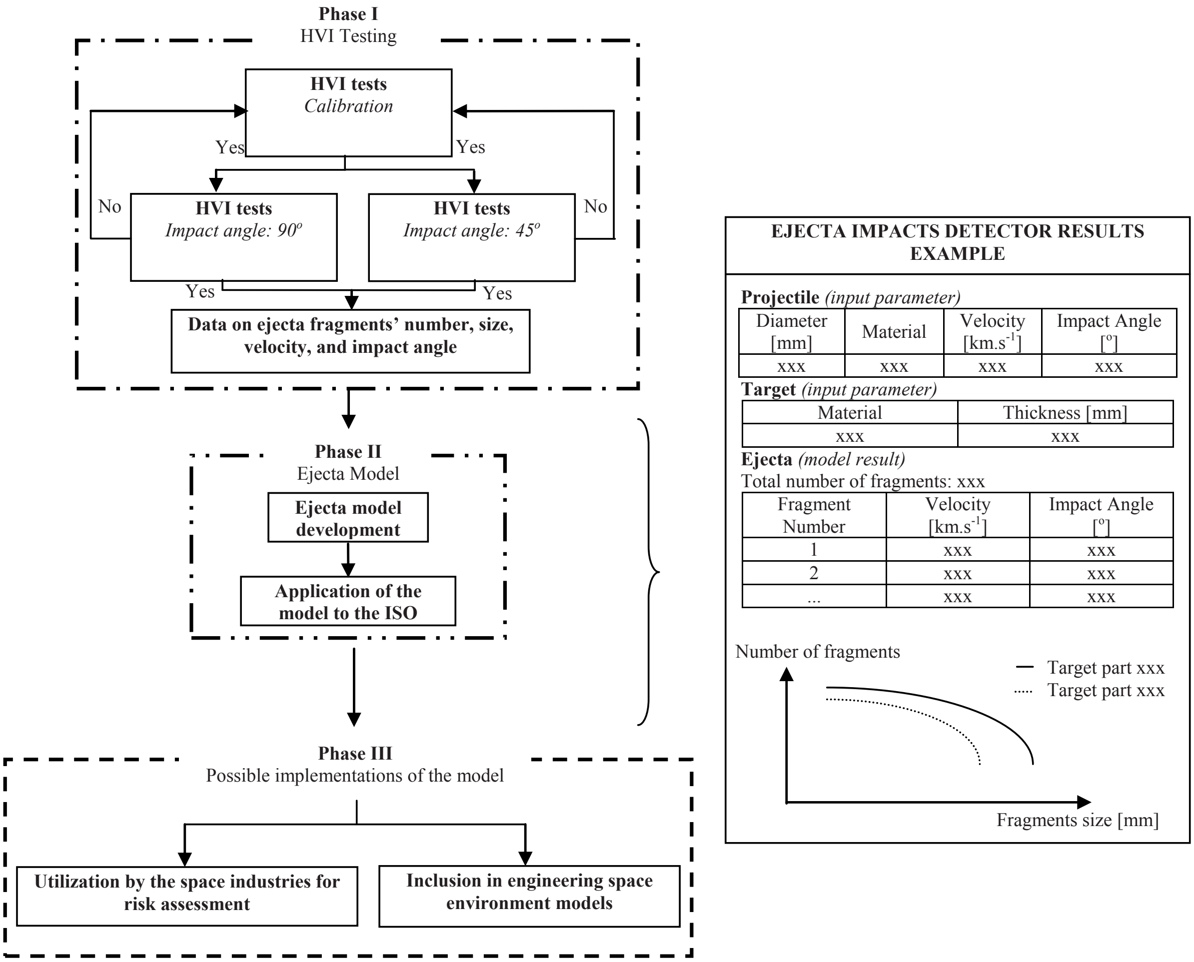


Fig. 6. Ejecta model development phases and possible layout of the results on ejecta fragments generated upon HVI tests.

4. Conclusion

In this paper, the space dust impacts detector developed at the Kyushu Institute of Technology was introduced and the first data after its launch on May 18, 2012, were successfully received showing that no space dust impacts were detected. However, on-ground testing demonstrated detector's ability to detect impacts of space dust with a diameter ranging from 100 μm to 600 μm. In the future research, this detector will be improved to become an ejecta impacts detector to be used during HVI testing. Ejecta fragments being much smaller than the previous range defined, polyimide film in association with polyvinylidene fluoride film is under consideration for the evaluation of each ejecta fragment's size, velocity, and impact angle. Following the results obtained during the experiments, an ejecta model will be built to give information on ejecta fragments' size, velocity, and impact angle distribution depending on the target material and projectile characteristics.

The ejecta model could be used by the space industries to better assess and understand the risk that small orbital debris represent to their large or small spacecraft. As a matter of fact, if no active actions against space debris are undertaken, the access to some LEOs will be impossible and in other LEOs or GEOs, scientific, educational, and security missions that benefit all mankind will be jeopardized.

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