ENVIRONMENTAL ESTIMATION ON SUB-MILLIMETER-SIZE DEBRIS USING IN-SITU MEASUREMENT DATA

Masahiro Furumoto(1), Shin'ya Nakano(2), Koki Fujita(3) , Toshiya Hanada(4)

(1) Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan, Email: f.masa@aero.kyushu-u.ac.jp
(2) The Institute of Statistical Mathematics, 10-3 Midori-cho, Tachikawa, Tokyo 190-8562, Japan, Email: shiny@ism.ac.jp
(3) Nippon Bunri University, 1727-162 Oaza Ichigi, Oita-shi, Oita 870-039, Japan, Email: fujitakk@nbu.ac.jp
(4) Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan, Email: hanada.toshiya.293@m.kyushu-u.ac.jp

ABSTRACT

Space debris smaller than 1 mm in size still have enough energy to cause a fatal damage on a spacecraft, but such tiny debris cannot be followed or tracked from the ground. Therefore, Kyushu University has initiated IDEA the project for In-situ Debris Environmental Awareness. This project aims to measure the sub-millimeter-size debris with a constellation of small satellites. This study proposes a statistical model that estimates the population of sub-millimeter-size debris using in-situ measurement data. This paper demonstrates and validates this estimation by impact simulations based upon MASTER-2009. This paper also investigates characteristics of the proposed estimation, which suggest effective strategies to improve the environmental estimation.

1 INTRODUCTION

The risk of being impacted with space debris is one of the most major problems on humankind's space development and activity. An impact of an orbital debris larger than 10 cm on a spacecraft can cause a catastrophic breakup, but operational spacecraft can make collision-avoidance maneuvers because such debris are tracked by ground-based observations. By contrast, pieces of debris smaller than 2 mm are too small to be tracked or detected by ground-based observations [1]. However, an impact of a piece of sub-millimeter-size debris also can cause a fatal damage on a spacecraft. Nitta et al. have reported that a simulated debris particle with a size of approximately 0.3 mm fractured power cables [2]. This kind of damage might result in power loss, which is believed to have happened to ADEOS 2 spacecraft in October 2003 [3]. Spacecraft cannot avoid sub-millimeter-size debris, so that spacecraft must be protected against them. To design satellites properly in terms of debris protection, some space agencies have developed engineering models that define debris environment, such as NASA ORDEM 3.0 [4] and ESA MASTER-2009 [5].

Krisko et al. have reported that ORDEM 3.0 and MASTER-2009 orbital debris fluxes for several test cases showed quite significant differences, however [6]. Differences in philosophy between ORDEM 3.0 and MASTER-2009 may be a major reason but not all. Knowledge on sub-millimeter-size debris was obtained from scanning the surfaces of returned objects such as LDEF, SFU and US Space Shuttles. However, returned spacecraft and in-situ measurements are quite limited in terms of orbital regime and not continuously available yet. Therefore, the current definition of orbital debris environment does not include any knowledge on sub-millimeter-size debris from recent major breakups such as Chinese Anti-satellite Test using Fengyun-1C in January 2007 and US Iridium 33 and Russian Cosmos 2251 accidental collision in February 2009. This situation may also account for the differences in the orbital debris flux between ORDEM 3.0 and MASTER-2009.

Therefore, Kyushu University has initiated IDEA, the project for In-situ Debris Environmental Awareness, to construct an in-situ debris measurement network using a constellation of small satellites. The measurement satellites of the IDEA project will detect impacts of sub-millimeter-size debris using Space Debris Monitor (SDM) that JAXA has developed based upon the joint patent by IHI Corporation and Institute for Q-shu Pioneers of Space [7]. SDM consists of a lot of conductive lines on a thin film. By periodically confirming the conductivity of the conductive lines, the measurement satellites equipped with SDMs can record the time and location at impact. Besides, the size of the hole on the film is substantially the same as the size of the impacted debris. The estimation of the impacted debris size is based on the number of the conductive lines without the conductivity.

One of the advantages of the IDEA project is that measurement data can be transmitted down to the ground in near-real time. This advantage allows us to continuously update knowledge on sub-millimeter-size debris. Therefore, the IDEA project aims to establish an innovative environmental model that can describe the continuously changing environment. This model can provide a better definition of space debris environment to contribute to long-term sustainability of outer space

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activities.

The measurement satellite records the position at impact but not the impact velocity. Hence, the orbit of the debris cannot be determined directly. Therefore, the previous study has investigated the nature of the orbit on which debris may contribute to the collision flux into a measurement satellite, and has revealed that the orbits of debris detected through in-situ measurements are constrained by a simple equation [8]. In addition, a torus model has been introduced to describe the collision flux approximately as a function of the angle between two orbital planes of the measurement satellite and the debris. This knowledge can be applied to the environmental estimation of this paper.

This paper proposes the model based on the particle filter and the constraint equation to estimate the environment of sub-millimeter-size debris. In this paper, the proposed model estimates the debris distribution with measurement data simulated by MASTER-2009. Moreover, a comparison with the environment defined by MASTER-2009 validates the model.

2 METHOD

2.1 Impact Data Simulation

This paper simulated impacts that a measurement satellite may experience based upon outcome of MASTER-2009. Tab. 1 summarises conditions of the simulation.

Table 1. Conditions of the Simulation

Initial Epoch	2007/04/01
Final Epoch	2009/04/01
Semi-major axis [km]	7176.130
Eccentricity	0.0
Right ascension of ascending node [deg]	212.226
Inclination [deg]	98.6
measurement area [m^2]	0.1225

The measurement satellite was put into a sun-synchronous orbit (SSO) with an altitude of 798 km. MASTER-2009 provides "Cell Passage Event (CPE)" file that defines the positions at which debris may contribute to the collision flux into the measurement satellite. Some collision positions sampled randomly depending on the collision flux is considered as the simulated mission data of the measurement satellite. As a simulation result, 106 pieces of debris impacted the measurement satellite within two years. Figs. 1 and 2 plot right ascension and declination at impact, respectively. It can be observed from Fig. 2 that impacts occur often at higher declination.

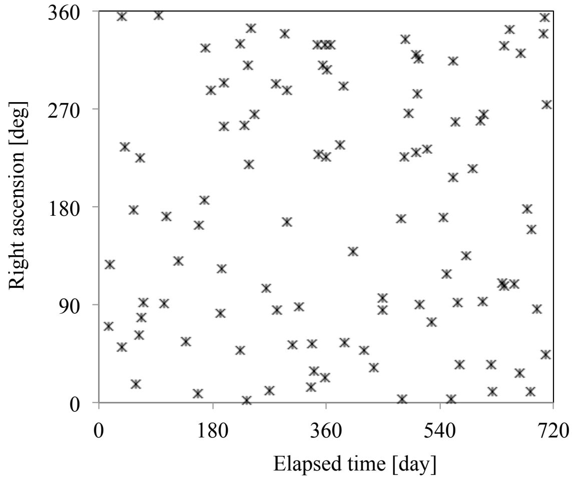

Figure 1. Right ascension of the Collisions

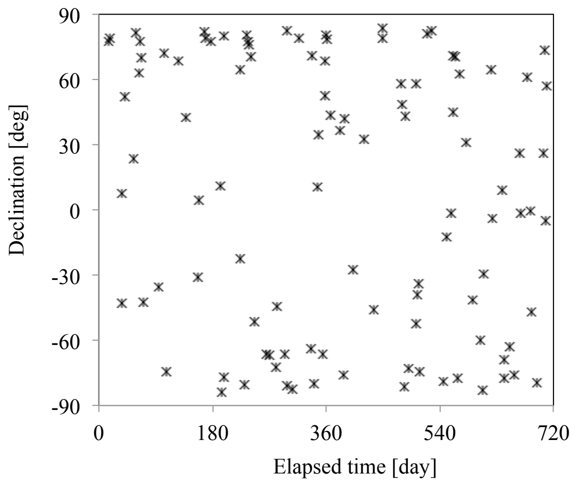

Figure 2. Declinations of the Collisions

2.2 Orbital Plane Constraint

As mentioned previously, the measurement satellite can record the position at impact but not the impact velocity. Therefore, the debris orbit cannot be determined directly.

The previous study has derived a simple equation that constrains the orbital plane with which debris a measurement satellite gets impacted [8]. Since the debris and the measurement satellite must be at the same position at impact, the angular momentum vector of the debris must be normal to the position vector of the measurement satellite. Therefore, Eq. 1 can be derived as the constraint equation with the unit vector of the angular momentum vector of debris $\boldsymbol{e'}_W$ and the unit vector of the collision position $\boldsymbol{e}_R$.

$$\boldsymbol{e}_R \cdot \boldsymbol{e'}_W = 0 \tag{1}$$

The measurement simulation with MASTER-2009 provides the position at impact with right ascension α and declination δ. Thus, the unit vector $\boldsymbol{e}_R$ is expressed as Eq. 2. On the other hand, the unit vector $\boldsymbol{e'}_W$ is determined by Eq. 3 with right ascension of the ascending node Ω' and inclination i'. Finally, the constraint equation can be reduced to Eq. 4.

$$\boldsymbol{e}_R = \begin{bmatrix} \cos\delta\cos\alpha \\ \cos\delta\sin\alpha \\ \sin\delta \end{bmatrix} \tag{2}$$

$$\boldsymbol{e'}_W = \begin{bmatrix} \sin\Omega'\sin i' \\ -\cos\Omega'\sin i' \\ \cos i' \end{bmatrix} \tag{3}$$

$$\cos\delta\sin i'\sin(\Omega'-\alpha) + \sin\delta\cos i' = 0 \tag{4}$$

For example, Fig. 3 demonstrates the constraint equation with a measurement data of α = 69.72 [°] and δ = 77.27 [°]. The measurement satellite can detect only debris on orbital planes specified by solid line in red in Fig. 3.

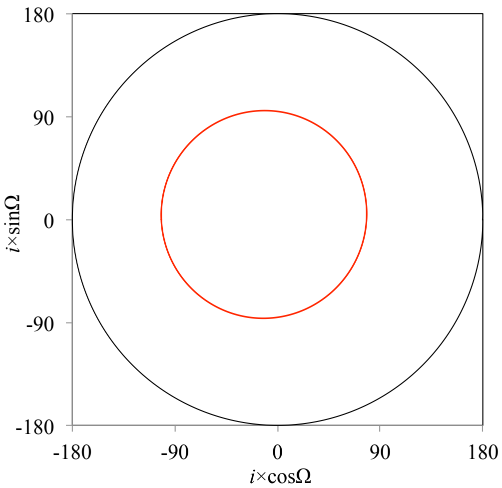

Figure 3. Constrained Orbital Planes

2.3 Estimation method

The environmental model proposed by this study estimates the environment of sub-millimeter-size debris using both orbital propagation and in-situ measurement data. The method that combines measurement data with a simulation to estimate a state is called "data assimilation". Kalman filter, which is extensively used in astronautics, is one of the data assimilation methods. Estimations with Kalman filter require an observation matrix that translates a state vector into a measurement vector. However, the observation matrix applicable to the problem of this study cannot be defined because a debris environment is not transformed into an in-situ measurement data linearly. Therefore, this study proposes an environmental estimation with the particle filter [9] that can be applied to non-linear systems.

In the proposed model, the debris distribution is approximated with an ensemble of many orbital planes. Each orbital plane is propagated through J_2 perturbation. To express the uncertainty of orbital propagation and determination, white noise is added to right ascension of the ascending node and inclination.

To estimate the environment with the particle filter, the probability with which measurement data is obtained in an environment must be calculated. The collision flux calculated by the torus model provides this probability. Torus model proposed in [8] can approximate the collision flux of an object in a circular orbit into the measurement satellite.

The environmental model with the particle filter estimates the debris environment depending on the aforementioned definitions. The estimated environment is updated every 5 days in this paper.

3 ESTIMATION RESULT

This section shows the distribution estimated by the proposed model with the simulated measurement data shown in Figs. 1 and 2.

First, Fig. 4 shows the inclination vector distribution before estimation starts to explain that the initial distribution is uniform. To start the estimation from uniform distribution, the ensemble of the orbital planes is put randomly.

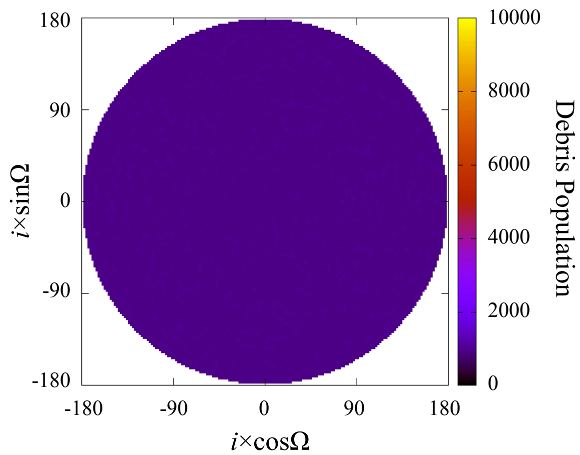

Figure 4. Distribution Before Estimation Starts

Next, Fig. 5 depicts the estimated distribution after the first measurement at α = 69.72 [°] and δ = 77.27 [°]. The constraint equation demonstrated in Fig. 3 is also appeared in Fig. 5 clearly. This fact indicates that the particle filter with the constraint equation can find orbital planes on which the measurement satellite can detect debris.

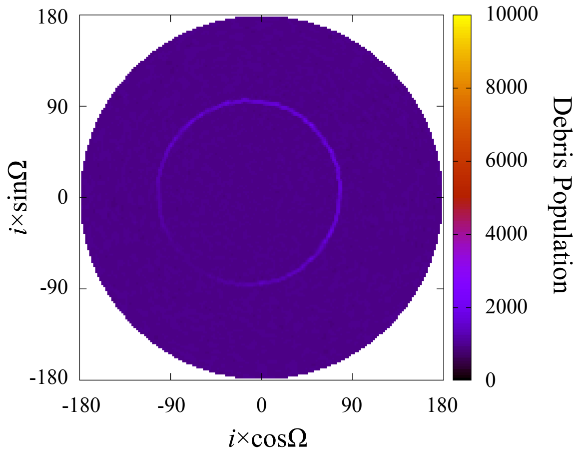

Figure 5. Estimated Distribution after 1st Impact

Finally, Fig. 6 provides the final result of the environmental estimation. Comparing with the initial distribution in Fig. 4, debris population around polar orbital region was increased and the population in other region was decreased. In terms of inclination, the highest peak of the population is at SSO. On the other hand, the peak is around 45˚ in terms of right ascension of the ascending node. Particle on those planes collide head-on into the measurement satellite at Ω = 212 [˚].

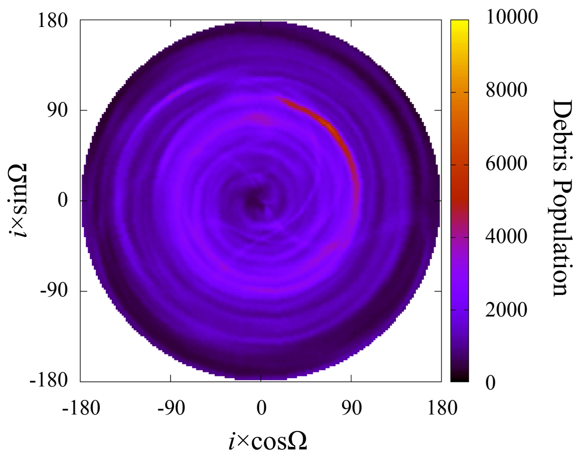

Figure 6. Final Estimated Distribution

4 COMPARISON WITH MASTER-2009

This section compares the distribution estimated by the proposed model and the environment defined in MASTER-2009 to evaluate how accurately the model estimated the debris distribution.

Fig. 7 depicts the inclination vector distribution of orbital planes on which debris contributed to the collision flux into the measurement satellite in the simulation using MASTER-2009. Fig. 7 shows that SSO region has the largest population of debris in terms of inclination, and that the right ascension of ascending node is approximately uniform.

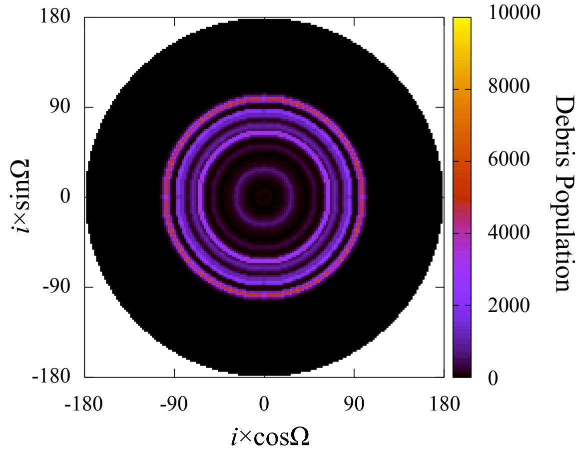

Figure 7. Distribution Defined in MASTER 2009

Figs. 8 and 9 compare the estimated inclination distributions with MASTER 2009 at Ω = 0 [˚] and 45 [˚], respectively. Both clearly demonstrate that the estimation model could find the highest peak at SSO. Especially, the debris population at Ω = 45 [˚] SSO was estimated accurately as shown in Fig. 9. Moreover, it was also estimated that the second largest population of debris is at inclinations between 60˚ and 90˚. In summary, the proposed estimation model provided the inclination distribution of debris population from in-situ measurement data sufficiently.

Fig. 10 depicts the debris distribution at i = 98 [˚] as a function of right ascension of the ascending node. This figure demonstrates that the debris population was estimated accurately around Ω = 45 [˚] and underestimated in other orbital regions. A possible explanation for this result may be that debris in counter orbit of the measurement satellite have higher collision flux into the measurement satellite and provide more impact data than in other orbits.

To evaluate the sensitivity for initial conditions, the estimation model was also run with several initial populations. As a result, the qualitative distribution could be estimated with any initial conditions, but the debris population estimation failed with some initial populations far from the true environment. This result suggests that a method to set a proper initial population is required.

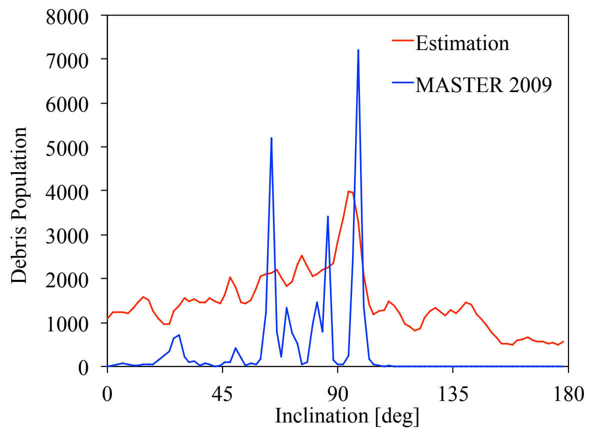

Figure 8. i-Distribution at Ω = 0°

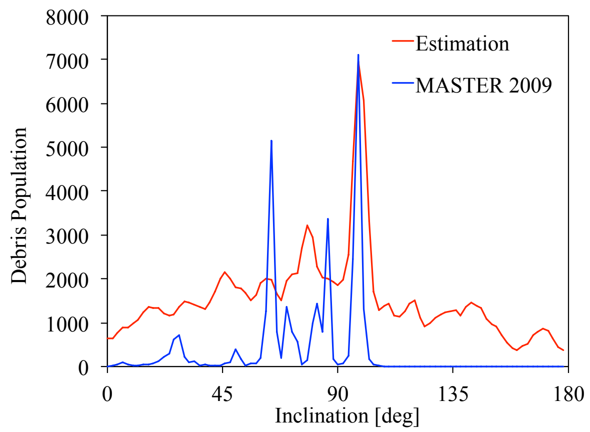

Figure 9. i-Distribution at Ω = 45°

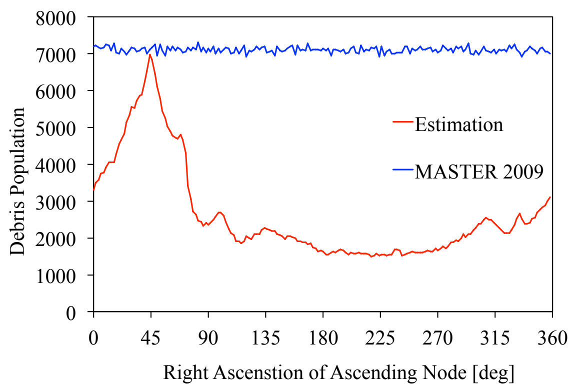

Figure 10. Ω-distribution at i = 98°

5 CONCLUSION

This paper proposed the environmental model to estimate the distribution of sub-millimeter-size debris with in-situ measurement data provided by the measurement satellite of the IDEA project. Validation of the estimation with impact simulation based on MASTER-2009 demonstrated that the proposed model could provide a sufficient environmental definition.

In addition, the characteristics of the estimation investigated in this paper suggest strategies to improve the environmental model. First, the estimation is sensitive to initial population of the model. Thus, the population of existing environmental models should be referred to set an initial value at the modeling with the actual measurement. Second, the orbital region at the right ascension of ascending node opposite to the measurement satellite is estimated most accurately. Therefore, a constellation of measurement satellite is very effective for better environmental modeling of the sub-millimeter-size debris.

6 REFERENCES

1. Mehrholz, D., Leushacke, L., Flury, W., Jehn, R., Klinkrad, H. & Landgraf, M. (2002). Detecting, Tracking and Imaging Space Debris. *ESA Bulletin* (0376-4265) 109, 128-134.
2. Nitta, K., Kawakita, S., Takeda, A. & Katayama, M. (2010). The response of Cable Harness Subjected to High Velocity Impact. *Trans. JSASS Space Tech. Japan* 8(ists27), Pr_2_55-Pr_2_62.
3. Neish, M. J., Takahashi, M., Maejima, H. & et al. (2005). Tests to Assess the Vulnerability of ADEOS-2 and ETS-8 to Debris and Micrometeoroid Impacts. *Proceeding of the Fourth European Conference on Space Debris*, 705-708.
4. Krisko, P. H. (2014). The New NASA Orbital Debris Engineering Model ORDEM 3.0. *AIAA/AAS Astrodynamics Specialist Conference,* (AIAA 2014-4227).
5. Gelhaus, J. & et al. (2010). Validation of the ESA-MASTER-2009 space debris population. *International Astronautical Congress* 61st, Vol. 4, p. 2996.
6. Krisko, P.H., Flegel, S., Matney, M.J., Jarkey, D.R. & Brau, V. (2015). ORDEM 3.0 and MASTER-2009 modeled debris population comparison. *Acta astronautica* 113, 204-211.
7. Nakamura, M., Kitazawa, Y., Matsumoto, H., Okudaira, O., Hanada, T., Sakurai, A., Funakoshi, K., Yasaka, T., Hasegawa, S. & Kobayashi, M. (2015). Development of In-Situ Micro-debris Measurement System. *Advances in Space Research* 56(3), 436-448.
8. Furumoto, M., Fujita, K., Hanada, T., Matsumoto, H. & Kitazawa, Y. (2017). Orbital plane constraint applicable for in-situ measurement of sub-millimeter-size debris. *Advances in Space Research* 59(6), 1599-1606.
9. Kitagawa, G. (1996). Monte Carlo filter and smoother for non-Gaussian nonlinear state space models. *J. Comp. Graph. Statist.* 5.1, 1-25.