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Orbital plane constraint applicable for in-situ measurement of sub-millimeter-size debris

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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, IDEA the project for In-situ Debris Environmental Awareness, which aims to detect sub-millimeter-size debris using a group of micro satellites, has been initiated at Kyushu University. First, this paper reviews the previous study on the nature of orbits on which debris may be detected through in-situ measurements proposed in the IDEA project. Second, this paper derives a simple equation that constrains the orbital plane on which debris is detected through in-situ measurements. Third, this paper also investigates the nature and sensitivity of this simple constraint equation to clear how frequently impacts have to be confirmed to reduce the measurement error. Finally, this paper introduces a torus model to describe the collision flux observed from the previous study approximately. This collision flux approximation agrees rather well with the observed collision flux. It is concluded, therefore, that the simple constraint equation and collision flux approximation introduced in this paper can replace the analytical method adopted by the previous study to conduct a further investigation more effectively.

Keywords: Space debris; Environmental modeling; Small satellite; In-situ measurement

1. Introduction

The risk of space debris is one of the biggest problems on long-term sustainability of outer space activities. Space debris larger than 10 cm in size are tracked so that operational spacecraft may be able to maneuver away from those debris (Mehrholz et al., 2002). On the other hand, space debris between 2 mm and 10 cm in size are observable (e.g. Haystack radars) but not tracked. They are too small to predict their orbits accurately. Therefore, operational spacecraft cannot avoid being hit with space debris smaller than 10 cm in size. Even spacecraft cannot maneuver away from tiny debris, Nitta et al. (2010) reported that a simulated debris particle with a size of approximately 0.3 mm fractures power cables for spacecraft. This kind of damage might be the cause of loss of power, which is believed to have happened to ADEOS 2 spacecraft in October 2003 (Neish et al., 2005). Impacts on spacecraft with sub-millimeter-size debris in space are not new in these days. In fact, the US Space Shuttle Endeavour and Atlantis have

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received flesh scars caused by sub-millimeter-size meteoroid or debris impacts on their radiator panels (Hyde et al., 2007; Lear et al., 2008). Another example is sub-millimeter-size meteoroid or debris impacts on Window 2 of the Cupola module of the International Space Station. Therefore, knowledge on sub-millimeter-size debris, especially larger than 0.1 mm, should be incorporated in design of spacecraft to minimize the damage done by impacts with such tiny debris.

Knowledge on sub-millimeter-size debris is available from existing space debris environmental models such as NASA ORDEM 3.0 (Krisko, 2014) and ESA MASTER 2009 (Gelhaus et al., 2010). However, Krisko et al. (2015) has reported that ORDEM 3.0 and MASTER 2009 space debris fluxes for several test cases showed quite significant differences. Differences in philosophy between ORDEM 3.0 and MASTER-2009 may be a major reason but not all. Measurements of space debris smaller than 2 mm in size are nearly impossible from the ground, so that knowledge on sub-millimeter-size debris was obtained from returned spacecraft (US Space Shuttle windows, LDEF, ...) and in-situ measurements (GORID, DEBIE, ...). However, returned spacecraft and in-situ measurements are quite limited in terms of orbital regime and not continuously available yet. Therefore, current definition of space 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 some differences in the space debris flux between ORDEM 3.0 and MASTER 2009.

Kyushu University has initiated IDEA the project for In-situ Debris Environmental Awareness. This project aims at a prompt and clear understanding of the current and future sub-millimeter-size debris environment in the low Earth orbit region. Thus, this project proposes to deploy a group of micro satellites, which conduct in-situ and near real-time measurements of sub-millimeter-size debris, into any orbital regimes to be monitored. To define the current and future sub-millimeter-size debris environment from measurement data Ae et al. (2013) have investigated the nature of orbits on which debris may contribute to the collision flux into a measurement satellite. For this investigation they applied an apogee-perigee filter to known objects in the catalogue to eliminate objects that never approach a measurement satellite. Then, they investigated the collision flux into the measurement satellite due to the objects not eliminated by the apogee-perigee filter. Finally, they picked up contributors to the collision flux.

This paper derives a simple equation that constrains the orbital plane with which debris a measurement satellite impacts. This simple constraint equation can apply for contributors that Ae et al. (2013) picked up. This can also account for the outcome of Tasaki et al. (2014) and Fujita et al. (2016). Tasaki et al. (2014) and Fujita et al. (2016) have investigated how to identify a major breakup from measurement data. They have concluded that at least two measurement satellites are necessary to properly estimate the orbital parameters of a broken-up object.

This paper also investigates the nature and sensitivity of this simple constraint equation to clear a requirement on the frequency of sampling for in-situ measurement proposed in the IDEA project. Furthermore, this paper introduces a torus model to approximate the collision flux into a measurement satellite. The collision flux approximation agrees rather well with the observed collision flux of known objects in the catalogue. Therefore, the simple constraint equation and collision flux approximation introduced in this paper can replace the analytical method adopted by Ae et al. (2013) to conduct a further investigation more effectively.

2. IDEA the project for In-situ Debris Environmental Awareness

As explained in Section 1, impacts on spacecraft with sub-millimeter-size debris are unavoidable and the cause of fatale damage on spacecraft. Therefore, knowledge on sub-millimeter-size debris should be incorporated in protection design of spacecraft. However, the current sub-millimeter-size debris environment has not been defined well because measurements are quite limited in terms of orbital regimes and not continuously available yet. Knowledge is necessary to be dynamically updated based on measurements of sub-millimeter-size debris in the actual environment.

Against the aforementioned background Kyushu University has initiated IDEA the project for In-situ Debris Environmental Awareness, aiming at the following three major objectives.

1. In-situ measurements of sub-millimeter-size debris
2. Establishment of dynamic environmental modeling
3. Recognition of environmental change due to a major breakup

The first objective is to conduct in-situ and near real-time measurements of sub-millimeter-size debris using a group of small satellites deployed into any orbital regimes to be monitored. Japan Aerospace Exploration Agency (JAXA) has developed Space Debris Monitor (SDM) based on a patent jointly held by IHI Corporation and Institute for Q-shu Pioneers of Space (Nakamura et al., 2015). As schematically illustrated in Fig. 1, SDM consists of approximately 3500 conductive lines with a width of 50 μm, which are equally spaced on a non-conductive thin film with a gap of 50 μm. A debris particle punches out a hole on the film at impact to break some conductive lines on the film, so that the impact can be detected by periodically confirming the continuity of the conductive lines on the film. Besides, the size of the hole on the film is substantially the same as the size of the debris impacted. One can estimate the size of the debris impacted by counting the