Sub-millimeter size debris monitoring system with IDEA OSG 1

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ABSTRACT

The 20-kg class microsatellite carrying debris impact sensors IDEA OSG 1 contributes to timely mapping and tracking capabilities for space debris in sub-millimeter size regime are essential to model the low earth orbit (LEO) environment and to improve spaceflight safety. IDEA OSG 1 will sample the sub-millimeter size debris environment in one of the most congested region in LEO by detecting impacts of sub-millimeter size debris and provide key data about the size, the time, and the location of impacted sub-millimeter size debris in near real time.

1. ISSUES AND MOTIVATIONS

Timely mapping and tracking capabilities for space debris in sub-millimeter size regime are essential to model the low earth orbit (LEO) environment and to improve spaceflight safety. This paper introduces the sub-millimeter size debris monitoring system, which consists of the in-situ monitoring of sub-millimeter size debris using impact sensors on board a microsatellite called IDEA OSG 1, and the ground-based data processing platform to communicate with the satellite and to process the impact data.

Sub-millimeter size debris is too small to detect and track using ground-based observation systems. Unlike trackable space debris, which are 10cm or larger, spacecraft cannot always make collision avoidance maneuvers. Despite its small size, due to its high velocity, millimeter to sub-millimeter size debris has the capacity to cause critical damages to operating spacecraft. Sampling the sub-millimeter size debris environment with impact sensor and extrapolating to millimeter or larger size regime will help understand the LEO environment.

Sub-millimeter size debris data were originally gathered by scanning the surfaces of returned objects such as Long Duration Exposure Facility (LDEF) and the US space shuttles. After the end of the Shuttle program, there was limited availability to measure the sub-millimeter size debris environment through returning materials by ISS cargos. The data from returned objects is cumulated during the whole mission, therefore the accuracy of the collected data, time and location, is low. Continuous sampling is, thus, needed to understand evolution of LEO environment. The microsatellite can access to space frequently at low cost by utilizing piggyback launch opportunities. The combination of microsatellite and impact sensor will be the cost efficient way to maintain the sub-millimeter sampling scheme and to have accurate data in location and time.

IDEA project, initiated at Kyushu University, aims at developing in-situ debris environmental awareness by constructing a constellation of micro satellites carrying impact sensors. Based on the mission concept of Kyushu University [1], IDEA OSG 1, the first of the IDEA series, is developed by Astroscale with the sponsorship of OSG corporation [2]. IDEA OSG 1 is a 20kg-class microsatellite with the outer dimension of 380mm by 380mm by 600mm. Launch of IDEA OSG 1 is scheduled from end of 2016 to early 2017 as a piggyback launch. IDEA OSG 1 will be put on the elliptic polar orbit with the apogee altitude of 800km and perigee altitude of 540km at launch. As the mission period, IDEA OSG 1 samples the sub-millimeter size debris environment for 2 years after the launch.

IDEA OSG 1 equips the impact sensor developed by Japan Aerospace Exploration Agency (JAXA), the Space Debris Monitor (SDM) [3]. SDM is a simple in-situ sensor to detect dust particles ranging from a hundred micrometers to several millimeters. 3300 conductive stripes (Ni–Au coated Cu material, 50um width) are formed with 100um separation on a nonconductive thin film (polyimide material, 12.5um thick). A dust particle impact is detected when one or more stripes are severed by the perforation. Length of each conductive stripe is 300um, thus total detection area of one SDM accounts for 300mm by 350mm (~0.1m^2). The IDEA OSG 1 mounts two SDMs, distinguished by SDM-1 and SDM-2, on the outer body structure of the IDEA OSG 1.

IDEA OSG 1 will sample the sub-millimeter size debris environment in one of the most congested region in LEO by detecting impacts of sub-millimeter size debris and provide key data about the size, the time, and the location of sub-millimeter size debris. Data gathered from IDEA OSG 1 are transmitted to the ground-based data processing platform in near real time. The ground-based data processing platform identifies impacts of space debris from the satellite telemetry and transfers the information via the Internet. This information will contribute to update space debris models, provide space debris mapping capabilities [4][5], and eventually allow spacecraft manufacturers to use enhanced information for spacecraft shielding designs.

2. IDEA OSG 1 MISSION ARCHITECTURE

This section describes the overview of mission architecture of IDEA OSG 1. The mission concept is to sample the sub-millimeter size debris environment in space and to analyze the sampled data on ground in near real time for understanding the current environment of interests.

To realize the mission concept, IDEA OSG 1 records the mission telemetry data to on-board non-volatile memory in a regular time period, T, and downlinks them to the Astroscale's mission control center (ASMCC) in every day basis. IDEA OSG 1 has 1 downlink channel in S-band, whose downlink speed is up to 64kbps.

The mission scheme is depicted in Fig. 1. One set of the mission telemetry data consists of time stamp, spacecraft (SC) location, SC velocity, SC attitude, SDM raw data of SDM-1 and 2, and SDM differential data. The SDM raw data is the conductive line status of one SDM, which is expressed by 1-bit for each of conductive lines in active or dead(=severed) state. One SDM has 3300 conductive lines so that SDM raw data of one SDM is expressed by 3300bits as depicted in Fig. 2. The SDM differential data (M_k) is the number of severed conductive lines of two SDMs measured at time t_k since the last sampling at t_{k-1}. The calculation of the SDM differential data M_k is done by SC on-board computer in real time by taking XOR of SDM raw data of t_k and t_{k-1}

and counting the number of true bits. Thus, the SDM differential data instantly indicates whether or not new impacts occur.

At every downlink operation, a time series of the mission telemetry data except for SDM raw data are downlinked to the ASMCC first. If $M_k \geq 1$ is detected at the time stamp t_k, the SDM raw data of t_{k-1} and t_k are downlinked to the ground immediately. By analyzing the SDM raw data according to a screening guideline on ASMCC, the impacted SDM (SDM-1 or SDM-2) and one-dimensional (1-D) size of impact hole are identified as one impact data. The impact data is also registered to the ASMCC database as a subset of the mission telemetry data at t_k.

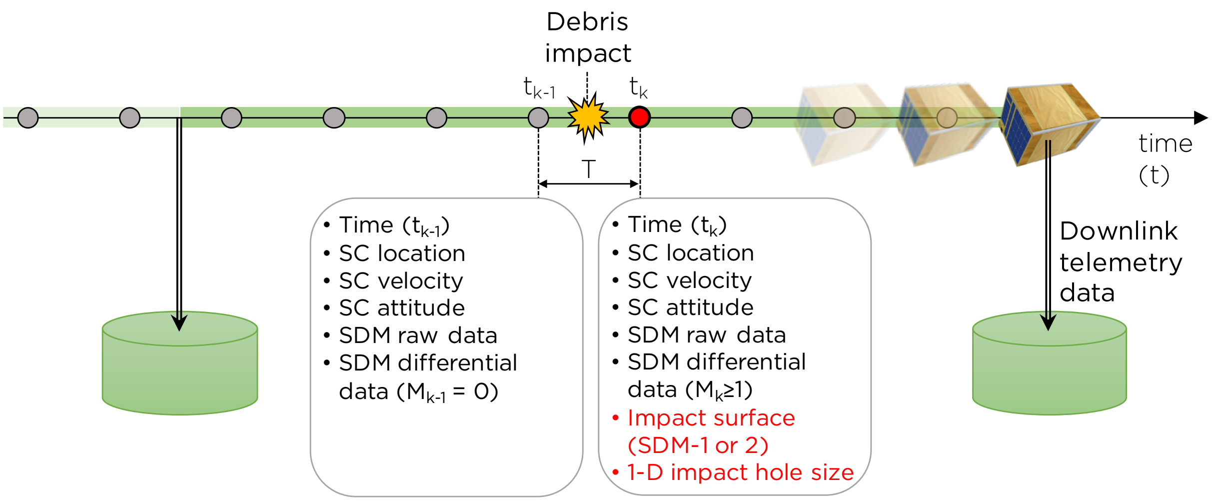

Fig. 1. IDEA OSG 1 mission architecture

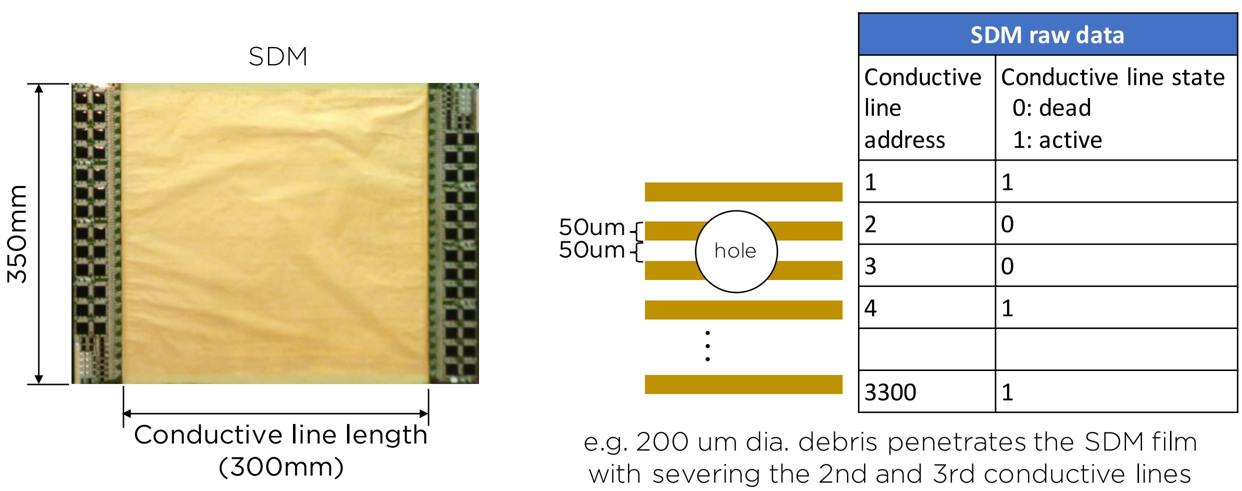

Fig. 2. SDM raw data definition

2.1 Impact data screening guideline

A guideline is needed to identify one impact from the XOR analysis result of SDM raw data and to estimate the perforation size of one impact. Adjoining lines of true bit status (i.e., newly severed lines of an adjoining part) is identified as a single impact. If newly severed line addresses are adjoining to the existing severed line addresses, it is still regarded as a single impact but the situation must be noted to a remark column of the impact data.

1-D size of perforation, D, is bounded by $d+(N-1)p \leq D < d+(N+1)p$, where N is the number of severed lines in one impact, d is the conductive line width, and p is the conductive line pitch. The SDM has d=50um and p=100um. The 1-D perforation size D is essential to estimate the impacted debris size (D_p) for better understanding of size distribution of debris in space. Upper limit of D_p is bounded by the upper limit of 1-D size of perforation, thus, $Np+d+p$. The actual size range of D_p will be modeled by a probability distribution conditioned by debris impact angle probability distribution, SC attitude, and SC orbit at the impact.

2.2 Sampling resolution and effectiveness

Sampling time period, T, is fixed to 15sec unless any SC system anomalies occur during the mission period. This time period corresponds to 1deg true latitude resolution in SC orbit which is enough within the spatial resolution of the existing sub-millimeter size debris map models built in MASTER series [6] and ORDEM series [7]. Thus, the sampled data is easily handled in combination with existing models and also applicable to precise modeling. The time, SC location, and SC velocity at every sampling are determined by onboard GPS sensor. SC attitude is determined by multiple onboard sensors consisted of sun sensor, magnetometer, and gyro sensor in combination with extended Kalman filtering algorithms. The attitude determination error is designed to be less than several degrees for each of the angles in Z_{SC}-Y_{SC}-X_{SC} Euler angle definition.

During the mission, IDEA OSG 1 stabilizes its attitude to increase the debris sampling efficiency. Debris impacts are mostly expected from the ram direction in polar low earth orbits. Fig. 3 depicts mission attitude mode of IDEA OSG 1. Two SDMs are mounted on the outer surface of IDEA OSG 1 in the $+X_{SC}$ and $+Y_{SC}$ body axes directions and the median of $+X_{SC}$ and $+Y_{SC}$ axes is pointed toward the along-track direction with a rough 3-axis control by using magnetorquer. $+Z_{SC}$ axis, defined perpendicular to the launch vehicle separation plane, is oriented toward the orbit normal direction.

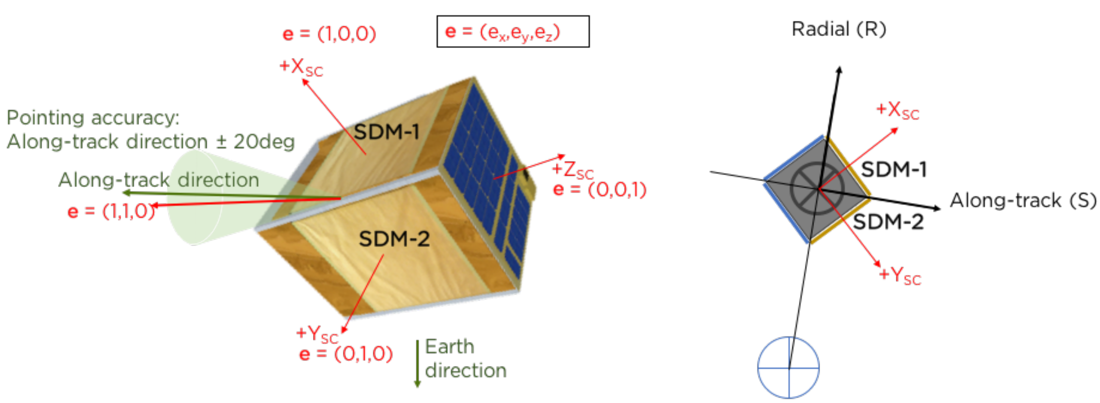

Fig. 3. IDEA OSG 1 mission attitude mode

According to the prediction of impact angles in the mission orbit using MASTER2009, debris impact angle range is wide in azimuth direction and very narrow in elevation direction which are evaluated in Fig. 4. A perforation due to impact can shape elliptic and its aspect ratio can be varied by impact azimuth angles. The minor axis of the perforation will correspond to actual size of impacted debris [3]. Thus, in the mission attitude mode, the direction of SDM conductive lines are aligned to Z_{SC} axis for better estimating the debris size from the number of severed SDM conductive lines.

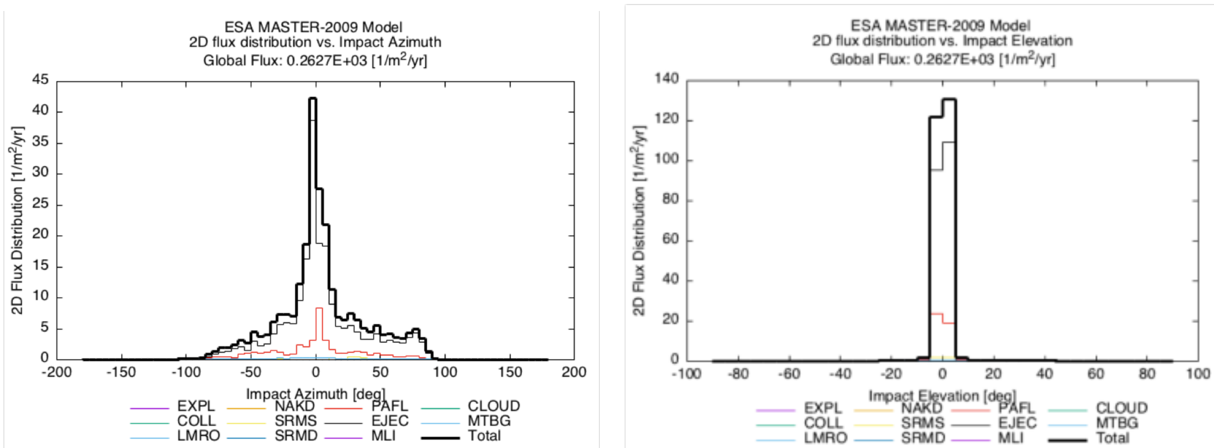

Fig. 4. Prediction of impact angle in mission orbit by using MASTER2009

It is important to break down the cases where miss detection and false detection of debris impact occur. Miss detection means that debris impact makes a perforation on SDM sensor film but no impact (M_k=0) is detected. On the other hand, the false detection means that the detection result by impact data screening is different from the actual impact state.

Miss detection can be classified into two types as follows.

(A.1) Debris impact makes a perforation on conductive lines of dead state only

(A.2) Debris impact makes a perforation on a conductive line of active state but the 1D perforation size, D, is within one conductive line width, d.

Assuming that the probability of debris impact occurrence is uniform on any points of SDM sensor film, the occurrence of the miss detection of type (A.1), defined as P_{miss}, can be described by the following relations:

$$P(n,j) = \frac{j}{N}P(n-1,j) + \left(1 - \frac{j-1}{N}\right)P(n-1,j-1) \quad (1)$$

$$P_{miss}(n) = \sum_{j=1}^{n-1} \frac{j}{N}P(n-1,j) \quad (2)$$

where n is the accumulated number of severances on conductive lines due to perforations regardless of the active/dead states, j is the number of conductive lines of dead state, and $P(n,j)$ is the probability of having j conductive lines of dead state at n-th severance. In Eq.(1), the range of n is $n \geq 2$, and the range of j is $1 \leq j \leq n-1$. At the n-th severance, the probability of severing a conductive line of dead state, $P_{miss}(n)$, is evaluated in Fig. 5. For example, 400 severances will be expected during 2 years since the launch if the expected number of debris impacts on the single SDM sensor film is 100 per year and the average number of severances of conductive lines due to one debris impact is 2.0. At the 400th severance, the probability of miss detection becomes $P_{miss}(400)$=11.39%.

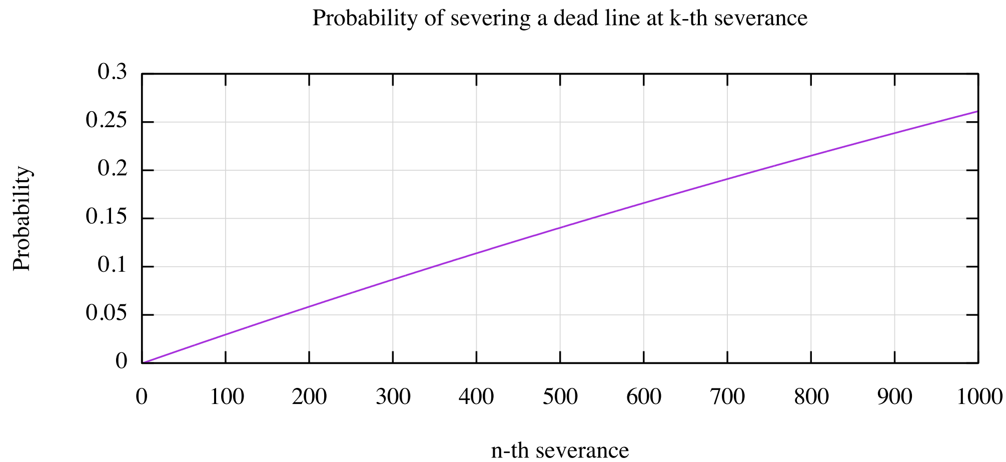

Fig. 5. Probability of miss detection of type (A.1) at n-th severance
(assuming the total number of conductive lines (N) on SDM sensor film is 3300)

The expectation of miss detections of type (A.1) at n-th severance, $P_c(n)$, can be described by the following relation.

$$P_c(n) = n - \sum_{j=1}^{n} jP(n,j) \quad (3)$$

Eq.(3) is evaluated in Fig. 6. For example, 23.24 of miss detection of type (A.1) is expected by the 400th severance.

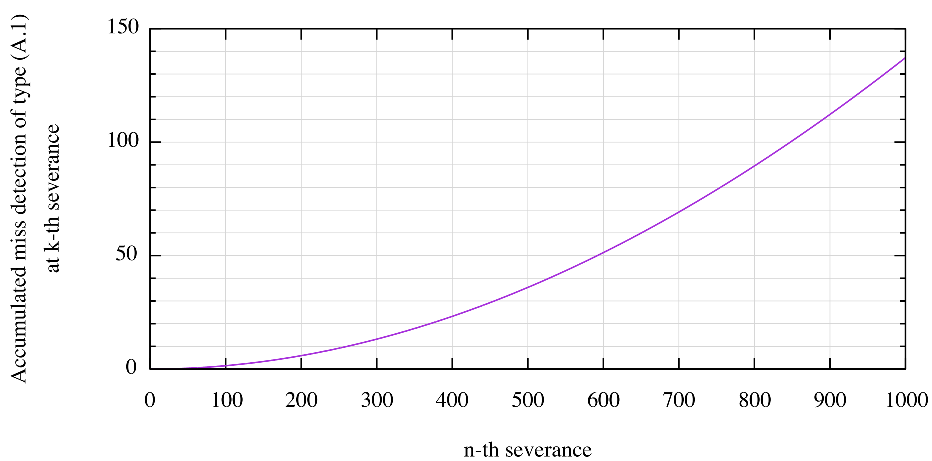

Fig. 6. Expectation of miss detections of type (A.1) at n-th severance
(assuming the total number of conductive lines (N) on SDM sensor film is 3300)

False detection can be classified into two types as follows.

(B.1) Debris impact makes a perforation on conductive lines of active state but system anomaly causes M_k=0 in SC or ground segment

(B.2) Debris impact does not occur on SDM sensor film but system anomaly causes $M_k \geq 1$ in SC or ground segment

Both of (B-1) and (B-2) are caused by the accidental reverse of bit status of SDM raw data. Such bit reverse can be mitigated by tuning timing of transferring SDM raw data from SDM to SC data storage, noise measures on SC system harness, mirroring SDM raw data on SC data storage, or inspecting the SDM raw data in time series.

2.3 Data distribution

To provide the mission telemetry data including impact data to data users timely, the data distribution timeline is summarized in Table. 2. The mission telemetry data (expect for SDM raw data) and bus telemetry data are downlinked to the ASMCC within the 24 hours since the last telemetry data sampling at IDEA OSG 1. First check of mission telemetry data will start in 1 week after the launch. The downlinked telemetry data will be released to the data users through the web interface of ASMCC in 1 month after the launch and within 24 hours after the downlink. The impact data screened to identify single impacts and SDM raw data will be released in half year after the launch and within 48 hours after new impact detection on the SDM differential data. The data users can process the telemetry dataset and each of the identified impact data for various types of needs.

Table. 2. Data distribution timeline

Data distribution direction	Item	Data distribution timeliness after the kickoff	The kickoff timing of data distribution (X: Launch)
IDEA OSG 1 to ASMCC (downlink)	Bus telemetry data (satellite bus status)	≤24 hours after sampling	≥X+1 day
	Mission telemetry data * except for SDM raw data	≤24 hours after sampling	≥X+1 week
ASMCC to data users	Bus telemetry data (satellite bus status)	≤24 hours after downlink	≥X+ 1 month
	Mission telemetry data * except for SDM raw data	≤24 hours after downlink	≥X+ 1 month
	Impact data (screened)	≤48 hours after impact	≥X+ 6 month
	SDM raw data	≤48 hours after impact	≥X+ 6 month

3. SUMMARY

This paper presented the mission architecture of sub-millimeter size debris monitoring system with IDEA OSG 1. IDEA OSG 1 will sample sub-millimeter size debris environment at 15-second interval by sensing the SDM and distribute the sampled data to the ground segment timely. The each of sampled dataset shows whether or not any new debris impacts occur in past 15 seconds. A single impact is identified on the ground by screening the SDM raw data. IDEA OSG 1 stabilizes the attitude in 3-axis control mode to point the SDM toward ram direction to increase the chance of debris impact detections. The data distribution service will start in one months after the launch. The screened impact data and its source data (SDM raw data) will be released in half year after the launch.

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