IDEA OSG 1: PRELAUNCH STATUS REPORT

Masahiko Uetsuhara, Kohei Fujimoto, and Mitsunobu Okada

Astroscale PTE. LTD., 6 Battery Road, #38-04 Singapore, 049909
Email: {m.uetsuhara, k.fujimoto, nobu}@astroscale.com

ABSTRACT

Sub-millimeter sized debris can cause fatal damage to spacecraft. Unlike trackable space debris, however, which are 10cm or larger, spacecraft cannot always make collision avoidance maneuvers against them because they are too small to detect using ground-based observation systems. Orbital debris models such as ESA's MASTER and NASA's ORDEM help manufacturers to properly design spacecraft to protect them from sub-millimeter size debris. Unfortunately, there are large discrepancies between modeling tools available on the market, leaving room for improvement using more accurate information on debris flux. Currently available methods to measure the sub-millimeter size debris environment via returning ISS cargo lacks in spatiotemporal resolution, especially in an ever more congested, contested, and competitive orbital environment. The IDEA project, initiated by Kyushu University, aims at developing in-situ debris environmental awareness by constructing a constellation of small satellites carrying impact detectors developed by JAXA. IDEA OSG 1, the first of the IDEA series, is expected to launch in early 2018. The satellite will detect sub-millimeter size debris in orbit and provide timely data about the size and spatiotemporal distribution of sub-millimeter size debris. This data aims at improving models of the LEO environment and, ultimately, spaceflight safety.

Key words: Sub-millimeter size space debris; In-situ measurements; On-orbit impact detectors; IDEA OSG 1.

1. INTRODUCTION

Timely mapping and tracking capabilities for space debris in the sub-millimeter size regime are essential to modeling the low earth orbit (LEO) environment as well as improving spaceflight safety. This paper aims to update our progress on the development of IDEA OSG 1: a sub-millimeter size debris monitoring system which consists of an in-situ impact sensor on board a microsatellite plus a ground-based data processing platform to communicate with the satellite and to process the impact data.

Millimeter and sub-millimeter size debris objects are too small to detect and track using ground-based observation systems, making collision avoidance maneuvers against them very difficult. Despite their small size, however, due to their high velocity, such objects have the capacity to cause critical damage to operating spacecraft. Therefore, sampling the sub-millimeter size debris environment with impact sensors and extrapolating the data to the millimeter or larger size regime will help us better understand the LEO environment.

Sub-millimeter size debris data were originally gathered by scanning the surfaces of returned spacecraft such as NASA's Long Duration Exposure Facility (LDEF) and Space Shuttles. After the end of the Shuttle program, there has been limited availability to measure the sub-millimeter size debris environment by means of returned materials via ISS cargo. The data from returned objects is cumulated during the whole mission, and thus the accuracy of the time and location of the collected data is low. Continuous sampling is paramount to understanding the dynamic evolution of the LEO environment. Microsatellites are advantageous in this scenario as they can access space frequently and at low cost by utilizing piggyback launch opportunities. The combination of a microsatellite bus carrying an impact sensor has the potential to be a cost efficient way to maintain a sub-millimeter sampling scheme and to have accurate spatiotemporal data.

The IDEA project, initiated at Kyushu University, aims at developing in-situ debris environmental awareness by constructing a constellation of microsatellites 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 20 kg-class microsatellite with an outer dimension of 400 mm by 400 mm by 600 mm. Launch of IDEA OSG 1 is scheduled in early 2018 as a piggyback launch. IDEA OSG 1 will be put on an elliptic polar orbit with an apogee altitude of 800 km and perigee altitude of 600 km at launch. IDEA OSG 1 will sample the sub-millimeter size debris environment for 2 years after launch.

IDEA OSG 1 equips a pair of impact sensors called the Space Debris Monitor (SDM), developed by the Japan Aerospace Exploration Agency [3]. SDM is a simple in-situ sensor designed to detect dust particles ranging from 100 μm to about 1 mm. 3,300 conductive stripes (Ni-Au coated Cu material, 50 μm width) are formed

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

with 100 μm separation on a nonconductive thin film (polyamide material, 12.5 μm thick). A dust particle impact is detected when one or more stripes are severed by the perforation. The length of each conductive stripe is 300 mm; thus, the total detection area of one SDM is 300 mm by 350 mm, or approximately 0.1 m^2. The two SDM units are distinguished by name as "SDM-1" and "SDM-2," and are located on the outer body structure of IDEA OSG 1.

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

In this paper, we present a status update on the IDEA OSG 1 mission, with a particular focus on the development of the DeOrbiting Device (DOD) and the Mission Control Center (MCC). The DOD is a lightweight deployable / retractable sail that controls the orbit decay rate of the spacecraft due to atmospheric drag. Performance analysis shows that a drag inducing sail like the DOD can enable small spacecraft at high altitudes to adhere to the 25 year deorbiting guidelines, as well as shift the phase of the spacecraft by a distance of 1 km in-track over 1 week for collision avoidance purposes. The MCC, on the other hand, is a graphical user interface for all Ground Station (GS) operations. Both systems are in final development and testing at Astroscale Japan Inc. We also recap the overall ConOps and hardware of IDEA OSG 1.

2. IDEA OSG 1 MISSION OVERVIEW

2.1. Mission Architecture

This section describes the overall 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 the ground in near real-time. To this end, IDEA OSG 1 records the mission telemetry data to on-board non-volatile memory at a regular time period, T, and downlinks them to Astroscale's Mission Control Center (MCC) daily. IDEA OSG 1 has 1 downlink channel in S-band, whose downlink speed is up to 64 kbps.

The mission scheme is depicted in Figure 1. One set of the mission telemetry data consists of a GPS time stamp, spacecraft (SC) location, SC velocity, SC attitude, SDM raw data from SDM-1 and 2, and SDM differential data. The SDM raw data is the conductive line status of one SDM unit, which is expressed as a 0 or 1 (1 bit) for each conductive line in dead (= severed) or active state, respectively. Since one SDM unit has 3,300 conductive lines, the SDM raw data for one unit is comprised of 3,300 bits. The SDM differential data (M_k) is the number of severed conductive lines of the 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 the SC's on-board computer in real-time by taking the XOR of the raw SDM data at 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 had occurred during this time frame.

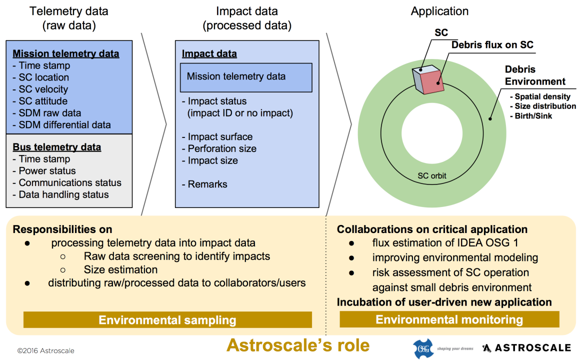

Figure 1. IDEA OSG 1 mission architecture.

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

2.2. Spacecraft Hardware

Figure 2 shows the hardware components of IDEA OSG 1, whose designed hardware lifetime is two years. The structure consists of the SDMs installed on two adjacent sides (defined as the +X and +Y sides) of the spacecraft. The internal space is divided diagonally into two so as to separate the pair of sides with and without the SDMs, with bus hardware installed in the space opposite the SDM. In the space on the same side as the SDM, the Information Mix Camera (IMC) is installed. The satellite bus consists of the following:

Communications S-band transceiver

Power Supply Power control unit (PCU), 30 W GaAs solar cell arrays (SCA), 10 Ah rechargeable (NiMH) batteries (BATT)

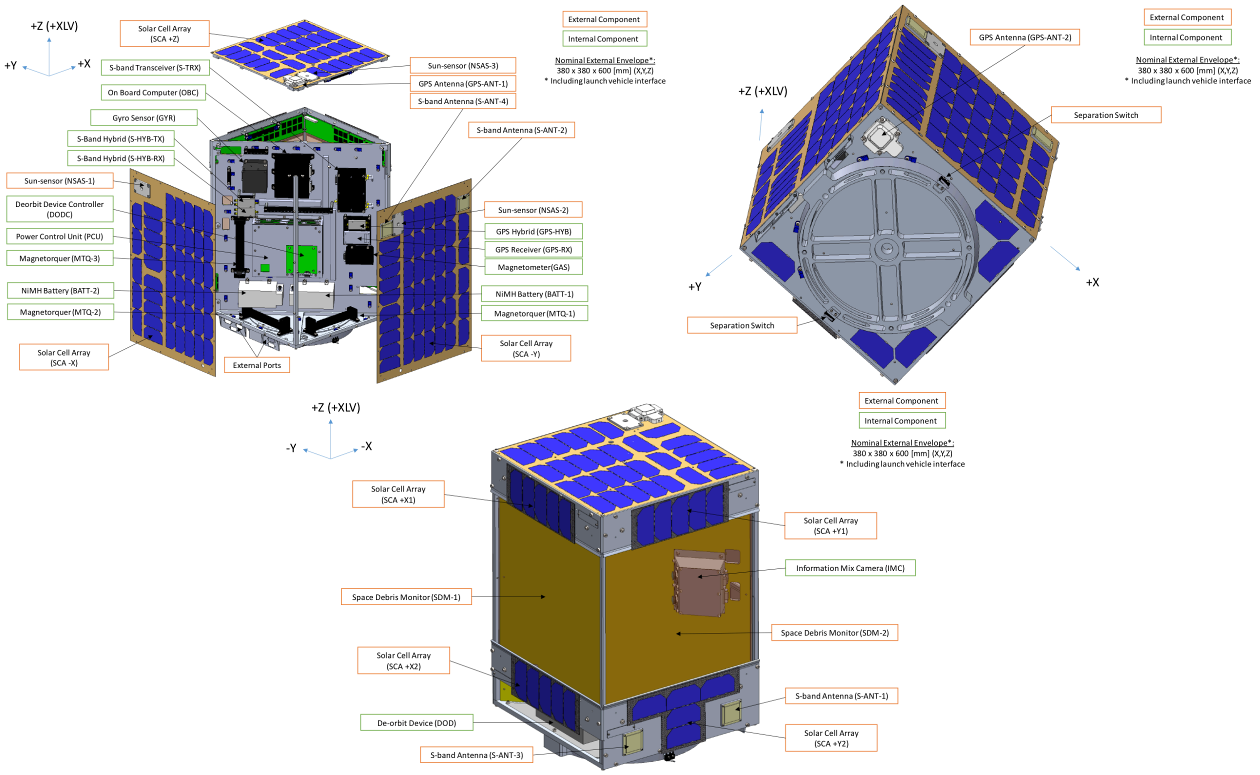

Figure 2. Hardware components of IDEA OSG 1.

Command and Data Handling SH4 bus on-board controller (OBC), FPGA mission OBC, PIC watch dog

Attitude Determination and Control Sun sensors (NSAS), magnetometer (GAS), MEMS control gyro (GYR), magnetorquers (MTQ) for 3-axis control

Timing and Orbit Determination GPS antennas and receiver (GPS)

DeOrbiting Device (DOD) A lightweight deployable / retractable sail

In the following section, we discuss in detail the system requirements that lead to the addition of the DOD to IDEA OSG 1, the operational scenarios of the DOD, and its components. Then, we present results from an orbit decay analysis when a generic drag inducing sail similar to DOD is deployed from a small spacecraft.

3. UPDATES ON THE DEORBITING DEVICE (DOD)

3.1. Requirements and Concept of Operations

There are two system-level safety requirements regarding the operations of the IDEA OSG 1 spacecraft:

1. If there is sufficient probability that IDEA OSG 1, during its operations, will collide with an uncontrollable resident space object, then IDEA OSG 1 should control its own orbit to the best of its ability to avoid the collision. IDEA OSG 1 shall conduct an operational demonstration of this feature.
2. IDEA OSG 1 should, after termination of its mission, attempt to deorbit in order to meet the 25 year debris mitigation guideline. The deorbit sequence should be "active," meaning that a deorbiting device shall be deployed to reduce the orbital lifetime. IDEA OSG 1 shall conduct an operational demonstration of this feature.

As such, two operational scenarios are considered for the DOD:

1. Collision avoidance by temporarily changing the deployment state of the DOD
2. Orbital lifetime reduction by maintaining the DOD in its deployed state

In particular, after the end of the extended operations phase, the mission enters the deorbit phase, during which Astroscale will conduct tests on the sail deployment / retraction. As a preliminary test, the DOD sail will transition between deployed and retracted on a weekly basis over three weeks. After the second full state change, we

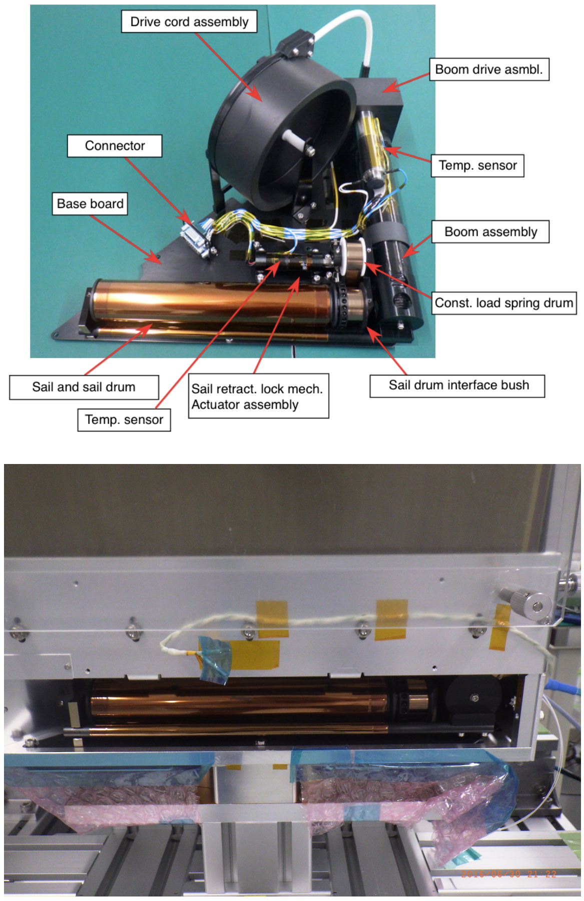

Figure 3. The DeOrbiting Device (DOD) on the flight model with component call outs (top), and as viewed from the exterior of the spacecraft in its retracted state (bottom).

will determine whether to conduct additional tests based on the project's overall status.

3.2. Components

Figure 3 is a picture of the DOD as fabricated on the flight model. The DOD is comprised of the following:

Sail Increases the cross-sectional area of the spacecraft. The sail is 3 meters long and 20 cm wide when fully deployed.

Sail Boom A multi-segment rod that provides structural rigidity to the Sail.

Drive Cord Conveys rotation of the Boom Drive Motor to the Sail Boom when the Sail is deployed / retracted.

Boom Drive Motor Deploys and retracts the Sail Boom via the Drive Cord.

Boom Drive Motor Encoders Used to estimate the state of the Sail Boom by counting the number of rotations made by the Boom Drive Motor.

Interlock Motor Ensures that the sail retraction mechanism does not engage during launch. The lock is disengaged after launch.

Zero-Point Detection Switch Detects when the end segment of the Sail Boom is retracted, meaning that the Sail has been fully retracted.

DOD Controller The DOD is actuated via the DOD Controller (DODC). The spacecraft's PCU, based on commands from the OBC, controls the DODC. DOD-related commands from the OBC to the PCU are issued from the ground via the OBC.

3.3. Performance Analysis

We conducted simulations to ascertain the deorbiting and collision avoidance – i.e., orbit phasing – abilities of a generic drag inducing sail like DOD for a small spacecraft. First, we employed the analytic propagator in NASA's Debris Assessment Software (DAS) 2.0 to compute the orbit lifetime of the spacecraft, as a numerical approach would take an impractical amount of time. The initial orbital elements, corresponding to an elliptic orbit with and 800 km apoapsis altitude and 600 km periapsis altitude, are:

$$(a, e, i, \Omega, \omega, M) = \\ (7078.138 \text{ km}, 0.01428, 97.60\text{deg}, 337.5\text{deg}, 0, 0) \quad (1)$$

and the analysis epoch is set to January 1, 2018 00:00 UTC. The dynamical model includes secular and long-term perturbations due to a 4×0 Earth gravity field, lunisolar gravity, atmospheric drag, and solar radiation pressure. The coefficient of drag C_d and solar radiation pressure C_r are set to 2.2 and 1.25, respectively. Atmospheric density from the Jacchia-Roberts model is fed into the analytic drag theory by King-Hele.

Both atmospheric drag and solar radiation pressure are proportional to the area-to-mass ratio (A/m). Prior to deploying the sail, we assume that the spacecraft is rotating about an arbitrary axis and thus take the average cross-sectional area to compute A/m, which is set to 1/4 the total surface area of the spacecraft. After deploying the sail, the surface area increases by twice the sail's physical area, which we assume, including margins, has a width of 0.2 m and a length of 3.0 m. Additional parameters of the dynamical model are summarized below:

Dimensions 0.38 m × 0.38 m × 0.6 m cuboid

Sail Width 0.2 m

Sail Length 3.0 m

Mass 26.0 kg

Average cross-sectional area (Total surface area)/4

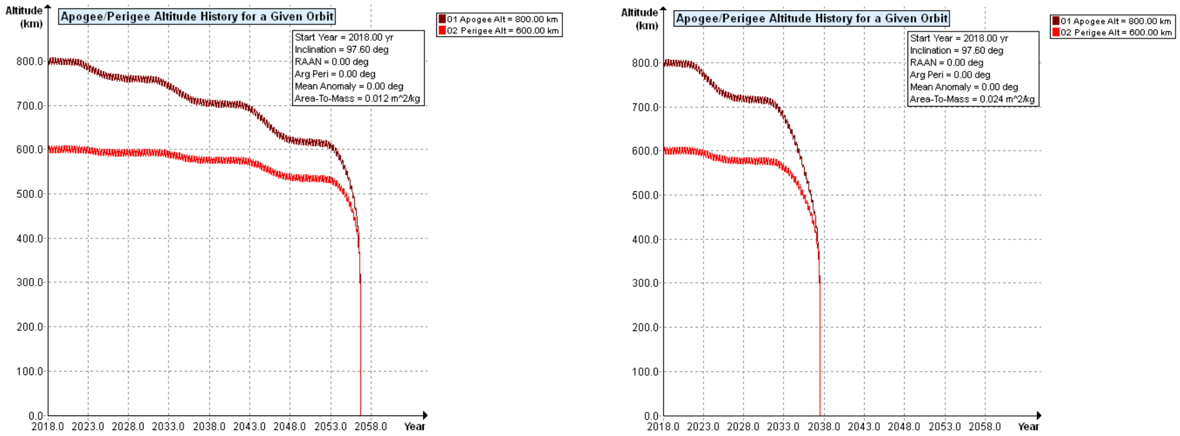

Figure 4. Orbit periapsis (red) and apoapsis (brown) altitudes as a function of time when a drag inducing sail is retracted (left) and deployed (right).

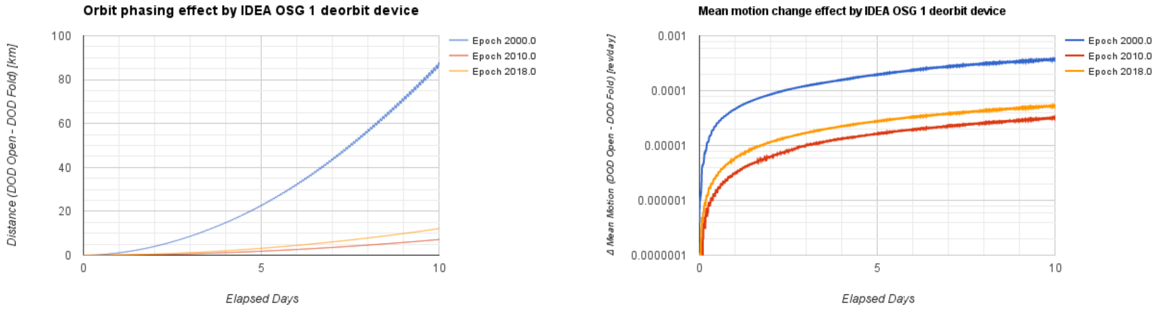

Figure 5. Distance (top, km) and mean motion (bottom, rad/s) between spacecraft trajectories with and without the DeOrbiting Device deployed as a function of time elapsed from deployment. Each color corresponds to a different simulation epoch. The nominal mean motion at epoch is 0.00106 rad/s.

Therefore, the average cross-sectional area prior to sail deployment is computed as

$$\frac{1}{4}(0.38 \times 0.38 \times 2 + 0.38 \times 0.6 \times 4) = 0.3192\,\mathrm{m}^2, \quad (2)$$

and after sail deployment is

$$\frac{1}{4}(0.38 \times 0.38 \times 2 + 0.38 \times 0.6 \times 4 + 0.2 \times 3.0 \times 2)$$
$$= 0.6192\mathrm{m}^2. \quad (3)$$

Starting from an epoch date of January 1, 2018 00:00 UTC, we simulated the orbital evolution of the spacecraft until re-entry, defined as when the orbit altitude becomes 0. The periapsis and apoapsis altitudes of the spacecraft with and without a sail is in Figure 4. Compared to when the sail is not deployed, deploying the sail halves the orbit lifetime from 38.6 years to 19.4 years. Thus, the drag inducing sail will ensure that the spacecraft analyzed will meet the 25 year LEO deorbit guidelines, whereas the spacecraft by itself will not.

We next determine the change in the spacecraft's in-track position (i.e., orbital phase) that is induced when the sail is deployed. For this analysis, we use a variable step numerical integrator (RK89) in a.i. Solution's FreeFlyer to ensure sufficient accuracy. The dynamical model and any associated parameters are the same as before, except the Earth's gravitational field includes sectoral and tesseral terms up to degree and order 4. We compare the distance and mean motion between the spacecraft trajectories over one week with the sail fully deployed or fully retracted. The analysis timespan was set to 10 days as we expect the earliest conjunction assessment reports to come in at about one week from the time of closest approach. The trajectory for three different epochs (January 1 at 00:00 UTC in 2000, 2010, and 2018) are computed, each corresponding to solar maximum, solar minimum, and IDEA OSG 1's proposed mission timeframe.

Figure 5 are the results. Although there is an order of magnitude difference in the displacement distance between solar min. and max., the sail is able to induce an in-track position change on the order of 10^0 km even at solar min, which is sufficient for collision avoidance. Furthermore, with nearly a 10% change in mean motion accumulated over 10 days, these results suggest that the effect of orbit phasing using a drag inducing sail could be corroborated via the public two-line element (TLE) data set provided by the Joint Space Operations Center (JSpOC).

4. UPDATES ON THE MISSION CONTROL CENTER

Once IDEA OSG 1 is launched, it will communicate with our Ground Station (GS) via S-band, as mentioned in Section 2.1. The Mission Control Center (MCC) is a graphical user interface for all GS operations, including command uplink, telemetry and mission data downlink, and link modulation / demodulation. After the operation engineer sets up commands for the spacecraft, the MCC translates them into standard Space Packet Protocol and interfaces with the GS communication system to establish an uplink. Figure 6 is a block diagram of the IDEA OSG 1 MCC architecture.

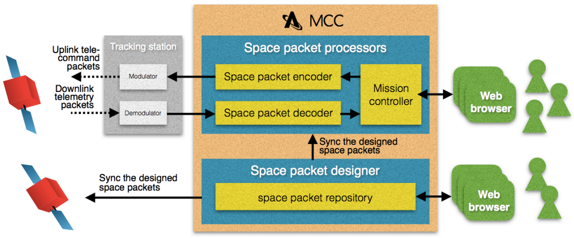

Figure 6. System block diagram of the IDEA OSG 1 Mission Control Center.

The MCC is currently being tested at our engineering facilities in Tokyo using the IDEA OSG 1 flight model and Hardware In-the-Loop System (HILS). A photograph of the development and testing environment is in Figure 7. Several prominent features include:

- The MCC is programmed entirely in JavaScript and runs on any modern web browser, meaning that it is both scalable and mobile-ready.
- The MCC is capable of both real-time operations as well as scheduled operations based on preset operation scenarios.
- The user can precisely tweak spacecraft commands through the space packet designer module.
- The MCC is designed to take inputs from multiple GS should they be added to the mission.

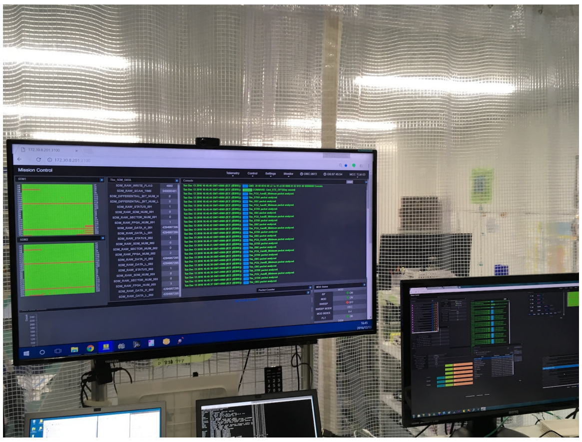

Figure 7. The IDEA OSG 1 MCC in development and testing at the Astroscale Japan Inc.

5. CONCLUSIONS

In this paper, we discussed updates on two components of the IDEA OSG 1 mission, which aims to conduct near real-time in-situ detections of sub-millimeter sized debris in low Earth orbit. One is the DeOrbit Device, which is a deployable and retractable drag inducing sail. Simulations using generic parameters show that such a device is capable of halving the orbital lifetime of small spacecraft as well as avoiding collisions predicted over timescales of several days to a week. The other is the Mission Control Center, a browser-based ground station graphical user interface. IDEA OSG 1 is under active development and integration to prepare for its planned launch in early 2018.

6. ACKNOWLEDGEMENTS

The DOD was jointly developed by Astroscale Japan Inc., RYOKEISO Corporation, and the Institute for Q-shu Pioneers of Space, Inc. We thank our partners for their support.

REFERENCES

1. Doi, A., et al. (2013) "IDEA: In-situ Debris Environmental Awareness." *Innovative Ideas for Micro/Nano-satellite Missions*, IAA Book Series 1(3), pp. 76-87.
2. The IDEA OSG 1 official website (2016). Retrieved from `http://www.ideaosg1.com` in September 2016.
3. Nakamura, M., et al. (2015) Development of In-Situ Micro-Debris Measurement System. *Advances in Space Research* 56(3), pp. 436-448.
4. Furumoto, M., Fujita, K., and Hanada, T. (2015). "Dynamic Modeling on Micron-size Orbital Debris Environment." *Proceedings of the 30th International Symposium on Space Technology and Science (ISTS)*, Paper ISTS-2015-r-10.
5. Fujita, K., et al. (2016). An Orbit Determination from Debris Impacts on Measurement Satellites. *Advances in Space Research*, 57(2), pp. 620-626.