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Analysis of upper atmospheric effects on material per onboard atomic oxygen monitor system of SLATS

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JAXA has proposed an innovative idea for satellites in Low Earth Orbit (LEO). The Super-Low Altitude Test Satellite (SLATS), also known as TSUBAME, is the first Earth observation satellite to occupy a Super-Low Orbit (S-LEO) or Very Low Earth Orbit (VLEO), below 300 km. The purposes of SLATS are 1) testing the maintenance of the satellite's altitude with its ion engine against high atmospheric drag at a super-low altitude, 2) acquiring data on atmospheric density and atomic oxygen (AO), and 3) testing optical Earth observation. SLATS was successfully launched on 23 December 2017. SLATS was then altitude-controlled for 636 days to 271.7 km using chemical thrusters, aerodynamic drag, and ion engine propulsion. SLATS finally maintained its orbit of 167.4 km for 7 days and finished its operation on 1 October 2019. All the SLATS and Atomic oxygen MOnitor (AMO) data was acquired during these operations. The AMO is one of the mission sensors that monitor AO and its effects on spacecraft materials. The data from the AMO contributes to the choice of materials in future S-LEO satellite design. The data obtained by the AMO are valuable in that they provide considerable knowledge on AO fluence and its effects on space materials. A precise atmospheric density model and atmospheric composition model are indispensable for predicting the trajectory or re-entry of debris in orbit. Atmospheric models such as NRLMSISE-00, JB 2008, and DTM2013 have been developed, but few studies compare these models and the actual atmospheric environment in LEO. The average atmospheric density obtained from SLATS is lower than the value predicted by the atmospheric models (NRLMSISE-00, JB 2008, and DTM 2013). Understanding the model's accuracy will contribute to the orbit control of future S-LEO satellites and the orbit prediction and control of debris in LEO.

KEYWORDS

SLATS, AMO, atomic oxygen, VLEO, atmospheric density

Introduction

Recently, the number of missions has been increasing in Low Earth Orbit (LEO, at altitudes between 300 and 2000 km). Attention is focused on a mission called S-LEO or VLEO, which operates below LEO. Lower altitudes will benefit Earth observation, such as higher resolution optical imaging, a higher signal/noise ratio of Synthetic-Aperture Radar (SAR), and more significant cost reduction of compact, lightweight satellite sensors and launch services (Kawasaki et al., 2018). Additional benefits include improved geospatial position accuracy, improved communications-link budgets, and greater insertion capability of launch vehicles. The radiation environment and the risk of colliding with orbital debris will be improved over conventional LEO spacecraft (Crisp et al., 2020).

Another big issue of satellites in LEO is the degradation by AO of materials used on the satellite's surface. Ultraviolet rays from the sun dissociate oxygen molecules in the upper atmosphere. Low-altitude AO collides with exposed materials at about 8 km/s, leading to a tendency toward high concentration, eroding satellite surfaces. Such AO attacks transform exposed polymer surfaces into a needle-like form. Polymers used on spacecraft exteriors suffer chemical and physical damage from this environment, altering surface characteristics and degrading mechanical properties. Moreover, AO fluence in S-LEO is expected to be far higher than in normal LEO, leading to severe material degradation. There have been few examples of direct AO effects in S-LEO, and such critical data are needed to design better S-LEO satellites (Kimoto et al., 2021a).

SLATS (Kawasaki et al., 2018)

The SLATS mission aims to evaluate orbit-control techniques and demonstrate the ability of high-resolution optical imaging from super-low altitudes. Supplementary Figure S1 shows an overview of SLATS, and Supplementary Table S1 lists general information about SLATS.

Supplementary Figure S2 shows the orbit transition profile of SLATS. SLATS was launched from the Tanegashima Space Center together with its main satellite, GCOM-C. First, GCOM-C was injected at an altitude of 798 km. Second, the upper part (ejection section) of the SLATS onboard adapter, which had carried SLATS inside, was separated. Third, altitude and orbit inclination control were carried out by the second and third firing of the second stage engine by the H-IIA altitude enhancement function. Finally, SLATS was separated at an apogee of 643 km, perigee of 450 km, local sun time (LST) of 10:30, and orbit inclination of 98.3° in a non-sun-synchronous orbit. Then it moved to about 400 km using its chemical thrusters (Reaction Control Subsystem: RCS). Over the next year, it transferred to an altitude of 271 km using air drag and chemical thrusters. It maintained its orbit at several altitudes (271.5, 250, 240, 230, 216.8, and 181.1 km) *via* ion propulsion or both ion and chemical thrusters in a hybrid configuration until it reached 167.4 km. SLATS maintained this orbit for 7 days and was certified as having the "Lowest altitude by an Earth observation satellite in orbit" by Guinness World Records®. SLATS successfully ended its operation on 1 October 2019.

AMO

The Atomic oxygen MOnitor (AMO) is a SLATS sensor unit. It consists of two mission sensors—the Atomic Oxygen Fluence Sensor (AOFS) and the Materials Degradation Monitor (MDM). The AOFS obtains AO environment data in SLATS' orbit, and the MDM observes the degradation of candidate materials for future use at super-low altitudes.

AOFS

We adopted a method of calculating and measuring the amount of collision with AO from the microscopic mass change accompanying the AO erosion of a substance. The sensor uses a quartz oscillator microbalance (Thermoelectric Quartz Crystal Microbalance: TQCM), which quantitatively measures micro-changes in the mass of substances adhering to a quartz electrode at a controllable temperature.

When the temperature of the sensor mounting surface is 20°C, it can be adjusted to −25°C to +80°C by active control of a Peltier element. The number of AO collisions is measured using the mass loss phenomenon. A polyimide coating is applied to the side of the crystal oscillator electrode of the TQCM and reacts with AO. Since the amount of erosion of polyimide reflects the information on the reaction efficiency (3×10^{-24} cm^3/atom), AO fluence can be calculated by the loss of polyimide mass measured by the TQCM. A sensor using polyimide as an erodible material has been proven an effective system by the JAXA AO irradiation facility (Miyazaki and Shimamura, 2007). Telemetry data reflects the change of mass as frequency changes. However, the mass of the coating of the TQCM when the sensor is exposed has a limit of 1.0×10^{20} atoms/cm^2. It is impossible to observe the number of AO collisions in a SLATS mission (predicted to be 2.6×10^{22} atoms/cm^2 for + X). Therefore, the sensor is designed as a structure that features a shutter at the front of the TQCM to limit the number of AO collisions (Supplementary Figure S3). Two sets

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of shutters are settled. There are no-coated TQCM sensors for contamination monitoring next to these sensors. The other four TQCMs with polyimide-coated sensors are positioned on and inside the SLATS structure—Supplementary Table S2 lists where the eight TQCM sensors are located. All the AOFS sensor heads are kept warm to prevent contamination due to adhesion, as shown in Supplementary Table S2.

MDM (Kimoto et al., 2021b)

The MDM is a system that qualitatively monitors the extent of material deterioration by AO through visual observation. It comprises two components: MDM-C (Supplementary Figure S4A), which has a camera system, and MDM-S (Supplementary Figure S4B), which mainly carries material samples. Both components are mounted on the +Z side panel of the SLATS. The material sample mounting side is faced toward the +X side, which is in the direction of satellite movement. At the same time, MDM-S evaluates material degradation based on AO collisions from the direction of satellite movement. More detailed information is described in reference (Kimoto et al., 2021b).

Operation and analysis results from AMO

SLATS was launched aboard the H-IIA rocket from the Tanegashima Space Center on 23 December 2017, along with the GCOM-C satellite. The experiments on space material exposure done so far had shown that the influence of on-orbit contamination inhibits the influence of AO. For this reason, all temperatures of the AOFS-Hs are regulated to above 50°C. This temperature was confirmed in a ground facility experiment. The MDM was launched with the sample holder's temperature control off, and the sample holder's temperature control was turned on by a stored command 1 hour after the launch. It is assumed that no contamination adhered to the sample holder during periods of uncontrolled temperature. The temperature at the sample holder of the MDM-S is monitored and controllable from 50 to 60°C. After the initial checkout, the AOFS has continuously acquired data, and the MDM has taken pictures with front and back lights once a week.

AOFS

Supplementary Figure S5 shows the time dependence of AOFS sensor output frequency from 1 January 2018 to 30 June 2019 (Kimoto et al., 2021b). All AOFS sensors continued to operate normally, except for the intermittent instability of AOFS-H3 from September to December 2018. Regarding the sensors coated with polyimide, except for AOFS-H4 installed inside the satellite structure, there is a tendency for the thin polyimide film to be scraped off by orbital AO exposure and for the frequency to become gradually lower. The AO flux striking a sensor depended mainly on the SLATS′ attitude. As the satellite was often in the sun-oriented mode, the AO flux at AOFS-H3 (satellite -X plane) was the highest until March 2019. After that, SLATS changed its attitude [orbit keeping phase (+ X plane in the direction of movement)] from around March 2019, so the tendency of AO exposed to each sensor changed. After March 2019, the AOFS-H7acquired the data for calculating the AO fluence, mainly on the + X plane (the satellite's plane of motion). Supplementary Figure S6 shows the AO fluence striking the + X plane, measured by AOFS-H7 from April 1 to 30 June 2019 (Kimoto et al., 2021b). During this period, the shutter on the AOFS-H7 was operated twice a day (about 180 min) with an open/closed ratio of 0.148% to obtain AO fluence. Since the shutter calibration test was conducted and the AOFS-H7 shutter was closed during period A, no data is shown. The value measured by AOFS-H7 was about 50% on average, smaller than that of model (NRLMSISE-00 (Picone et al., 2002)) in the period analyzed. However, daily changes and the timing of the measurements agreed well with the model. The NRLMSISE-00 is an empirical model of the atmospheric that extends from the ground to the exobase. This model is useful for predicting changes in satellite orbit due to aerodynamic drag and the amounts of gaseous components (e.g., atomic oxygen and nitrogen) that degrade spacecraft materials. The model is populated with the date, time, orbital information, average F10.7 solar flux, F10.7 solar flux of the previous day, and magnetic index during the SLATS operation to predict the density of AO during the AOFS-H7 measurement. As Banks et al., Banks et al. (2004a), Banks et al. (2004b) mentioned, factors influence the flow, such as the angle of incidence), and the reference model (e.g., point in the solar cycle and geomagnetic conditions) affect AO estimates.

MDM (Kimoto et al., 2021a)

An initial check was performed to confirm the operation of the MDM. MDM images obtained from orbit were presented in another paper (Kimoto et al., 2021a). The images of the material in S-LEO were successfully acquired until the end of SLATS' nominal operation. Our goal for future work is to understand the degree of material degradation and its correlation with AO fluence.

Atmospheric density analysis results from SLATS

To show how much the atmospheric drag differed from the predicted values, a comparison of average atmospheric density derived from the SLATS orbit determination results, the SLATS aerodynamic model, and the atmospheric model (NRLMSISE-00) in November 2018 are shown in Supplementary Figure S7 (Kimoto et al., 2021b). The SLATS orbit determination values were calculated from onboard GPS positioning point data and attitude angle data. The SLATS aerodynamic model is based on the CDS database with SLATS altitude, elevation, and skid angle. The average atmospheric density was calculated for each orbit. The atmospheric model value is input to SLATS' orbit operations. However, the atmospheric model value is higher than SLATS orbit determination results and the SLATS aerodynamic model with +30–40%. This average positive bias continued until the end of the operation, and SLATS was less likely to descend than expected. In response to commands from the ground, the RCS was backfired every month, and air drag control was continued as long as possible during orbit transfer. Supplementary Figure S8 also shows average atmospheric densities derived from SLATS and NRLMSISE-00 (MSIS) data and JB 2008 (Bowman et al., 2008) and DTM 2013 (Bruinsma, 2015) atmospheric models in April 2019. The average atmospheric density obtained from SLATS was about 30% lower than predicted by the atmospheric model (NRLMSISE-00) in Supplementary Figure S8. [1]These results suggest that the atmospheric models overestimated the atmospheric density. Solar activity during the 2018 and 2019 periods when SLATS was operational were relatively moderate. The relationship between solar activity levels and detailed SLATS attitude variations will be analyzed in a future paper.

Conclusion

AMO onboard SLATS was the first satellite to measure data on the effects of AO in orbit at 300 km or less for more than 6 months. AOFS data evaluation showed that the AO flux was about 50% lower than the atmospheric model (NRLMSISE-00). This result may indicate the need to apply more relaxed environmental conditions to extend the service life of low-altitude satellites. Image data showing material degradation by AO were analyzed for the first time. AOFS and MDM data are valuable because they reveal considerable new knowledge of AO fluence, which will aid in avoiding material degradation, and of material changes under large AO fluence. The data are expected to significantly contribute to the material design of S-LEO satellites. In addition, the atmospheric model density derived from SLATS orbital data is higher than the density calculated from SLATS orbit determination results and the SLATS aerodynamic model by +30–40%. The accuracy of these models has been verified through SLATS operation, which has enabled us to achieve highly accurate tracking control of SLATS. Understanding the model's accuracy will contribute to the orbit control of future S-LEO satellites, orbit prediction, and control of debris in LEO.

1 https://www.mext.go.jp/kaigisiryo/content/000034536.pdf

Author contributions

TY, EM, AG and KY contributed to conception and design of this study. SI organized the SLATS system. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frspt.2022.891753/full#supplementary-material

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