ANALYSIS OF FIRST DATA FROM ATOMIC OXYGEN MONITOR SYSTEM ONBOARD SLATS

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ABSTRACT

JAXA has proposed a brand-new concept 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 adopt a "super low orbit" at an altitude lower than 300 km. Higher resolution optical observation and the reduced emission power of such active sensors as radar are expected in future Earth observations from super low altitude orbits. Launched on December 23, 2017 from the Tanegashima Space Center, SLATS successfully completed its critical operation phase.

The Atomic oxygen MOnitor (AMO) is one of the mission sensors of SLATS. It consists of two mission sensors—the Atomic Oxygen Fluence Sensor (AOFS) and the Materials Degradation Monitor (MDM). The AOFS will obtain AO environment data in SLATS's orbit. It consists of eight sensor heads (AOFS-Hs) and one set of readout electronics. For AO measurement, six Thermoelectric Quartz Crystal Microbalances (TQCMs) with polyimide sensors (AOFS-Hs) were mounted at several positions of the satellite. Two non-coated TQCM sensors were also mounted next to the AO sensors for measuring the contamination background. Two AOFS-Hs have shutter mechanisms that control incident AO fluence on the front of the AOFS-Hs. The MDM will observe the degradation of candidate materials selected for future use in super low altitude satellites. It consists of a sample control unit (MDM-S) and a CCD camera unit (MDM-C). Thirteen temperature-controlled samples were fixed at MDM-S. The samples are thermal control films, power cables, and an AO monitor material. MDM-C will take an image once a week with LED lights that illuminate from the front and back of the material surface. Such AMO data will be used for a design standard and material usage guidance on future satellites in super low altitude orbits. This paper presents the flight data of both the AOFS and MDM from January 1, 2018 to the middle of July 2018.

1. INTRODUCTION

One of the problems in low Earth orbit is the degradation of materials used on the satellite's surface by atomic oxygen (AO). The oxygen molecules in the upper air are dissociated by ultraviolet rays from the sun, and the tendency toward a high concentration means that low altitude AO collides with exposed materials at high velocities of about 8 km/s, thereby eroding their surfaces. Such AO attacks transform the exposed surfaces of polymer materials into a needle-like form[1]. Polymers used for spacecraft suffer chemical and physical damage from this space environment, which alters surface characteristics and degrades mechanical properties.

Meanwhile, JAXA has proposed a brand-new concept of LEO satellites, namely, the Super Low Altitude Test Satellite (SLATS). High resolution optical observation and the reduced emission power of active sensors such as radar are expected in future Earth observations from super low altitude orbits. Super low altitude satellites are designed to operate in orbits of less than 300 km in altitude, where air drag can no longer be considered negligible. However, the high propellant efficiency of ion thruster systems allows air drag to be compensated and maintains the satellite's altitude throughout the entire mission.

However, AO fluence in a super low altitude orbit is expected to far exceed that in LEO, hence the severe material degradation from AO. Moreover, it is very difficult to evaluate the materials used in these satellites because it takes so long to irradiate AO on the ground. Regarding the AO environment, there are very few examples of direct AO detection made in a super low altitude orbit, and such precious survey data are needed to help design super low altitude satellites.

JAXA is now developing SLATS as a unit intended to demonstrate technology while in a super low altitude orbit below an altitude of 300 km[2-4]. The results obtained from satellite operations will then be leveraged when designing a future low altitude orbit satellite. The Atomic Oxygen Monitor (AMO) is one of the missions of SLATS. It comprises two missions; the Atomic Oxygen Fluence Sensor (AOFS) and the Materials Degradation Monitor (MDM). The AOFS will obtain AO environment data in the SLATS orbit, while the MDM will observe the degradation of candidate materials for super low altitude satellites in the future. This paper presents a summary of the AMO mission development status and flight data.

2. SLATS[2-4]

Proceedings of the 14th ISMSE & 12th ICPMSE, Biarritz, France, 1 to 5 October 2018.

2.1 Overview of SLATS

The purpose of the SLATS mission is to evaluate orbit control techniques and demonstrate the ability of high-resolution optical imaging from super low altitudes. Figure 1 shows an overview of SLATS, and Table 1 lists general information about SLATS.

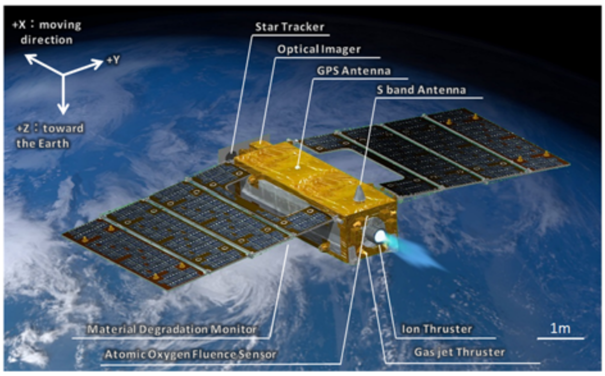


Fig. 1. Overview of SLATS

Table 1. General information about SLATS

Mission	1) Technological demonstration at super low altitudes 2) Atomic oxygen monitoring 3) High-resolution optical imaging
Size (Orbit)	2.5 m (X) × 5.2 m (Y) × 0.9 m (Z)
Power	~ 1.1 kW @EOL
Orbit	Orbit transfer from 392km orbit to 268km by mainly air drag. Keep orbit by an ion thruster from 268 to 180 km. Use gas-jet as well as 180km.
Lifetime	2 years (designed)
Launch	Aboard H-IIA F37 on 23 December 2017

2.2 Orbit transition plan

Fig. 2 shows the orbit transition profile plan of SLATS.

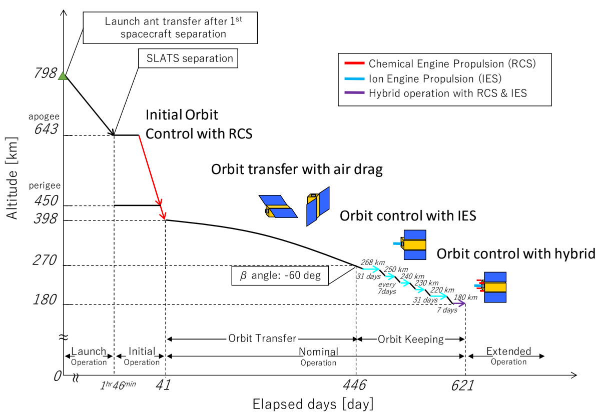


Fig. 2. Orbit transition profile plan of SLATS

After SLATS is injected into orbit at an altitude of 643 km by the H-IIA launch vehicle, it transfers to a lower altitude of 400 km by using its hydrazine thrusters. Then it transfers toward an altitude of 268 km by using its own air drag over the course of one year. SLATS uses an ion engine for maintaining its orbit to compensate for air drag. It will maintain its orbit at several altitudes (268, 250, 240, 230 and 220 km) step-by-step via ion engine propulsion, and use both ion and chemical thrusters in a hybrid configuration at 180 km.

3. AMO

The Atomic oxygen MOnitor (AMO) is one of the mission sensors of SLATS. It consists of two mission sensors—the Atomic Oxygen Fluence Sensor (AOFS) and the Materials Degradation Monitor (MDM). The AOFS will obtain AO environment data in SLATS's orbit. The MDM will observe the degradation of candidate materials selected for future use in super low altitude satellites.

3.1 AOFS

We adopted a method of calculating and measuring the amount of collision with AO from a micro mass change accompanying the erosion of a substance by AO. As the sensor, a measuring method with a quartz oscillator micro balance (Thermoelectric Quartz Crystal Microbalance: TQCM) is utilized. TQCM is a sensor that quantitatively measures micro changes in the mass of substances adhering to the electrode surface of quartz, with the temperature of the crystal being controllable. When the sensor mounting surface temperature is 20°C, it can be controlled in the temperature range of -25°C to + 80°C by active control of the Peltier element. The number of AO collisions is measured using the mass loss phenomenon, whereby a polyimide coating is applied to the crystal oscillator electrode side of TQCM, following a reaction with AO. Since the amount of erosion at the time of one oxygen atom colliding with polyimide includes data on "reaction efficiency [$3x10^{-24}$ cm^3/atom]," AO fluence can be calculated by the loss of polyimide coating mass, as measured by TQCM. A sensor using such polyimide as the material to be eroded has been established as a proven system within the JAXA AO irradiation facility. As for the change of mass, telemetry data are obtained as changes of frequency. However, a limit applies when the mass of the polyimide coating is applied to TQCM, and TQCM is exposed to measurement until only $1.0x10^{20}$ [atoms/cm^2] when the unadornment sensor is exposed. It is impossible to observe the number of AO collisions in a SLATS mission period (predicted as $2.6x10^{22}$ [atoms/cm^2] in terms of +X). The sensor is therefore designed as a structure that features an opening-and-closing type shutter mechanism at the front of TQCM to limit the number of AO collisions (Fig. 3). Two sets of shutter mechanisms are settled. No coated TQCM sensors are installed for contamination monitoring next to these sensors. The other four TQCMs with a polyimide-coated sensor are positioned on and inside the SLATS structure. Table 2 lists information about all eight TQCM sensor positions. All the AOFS sensor heads are kept warm at a high temperature rather than ambient temperature, to prevent contamination due to adhesion. The specific temperatures also listed in Table 2.

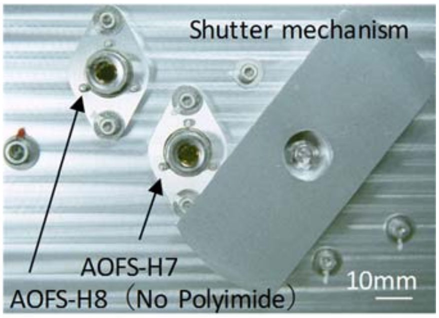


Fig. 3. AOFS sensors (AOFS-H7 and AOFS-H8) with shutter mechanism (installed on the X surface of SLATS)

Table 2. Description of AOFS sensors

Sensor number	Position	Polyimide coated	Temp. [deg.]	Shutter mechanism
		AO measurement		
AOFS-H1	+Z	○	55	N/A
AOFS-H2	−Y	○	55	N/A
AOFS-H3	−X	○	55	N/A
AOFS-H4	Inside of +Y	○	55	N/A
AOFS-H5	MDM +X	○	70	○
AOFS-H7	+X	○	55	○
		Contamination measurement		
AOFS-H6	MDM +X	Nothing	70	N/A
AOFS-H8	+X	Nothing	55	N/A

Ground calibration experiments were conducted in the Combined Space Effects Test Facility at JAXA's TKSC [5]. The AO source of this facility is the laser detonation type. The change in output frequency during AO irradiation was monitored, and the sensitivity coefficient (AO fluence when changing 1 Hz) of all the flight sensors was obtained from the frequency shift and the AO fluence value from the monitor material.

3.2 MDM

The MDM is a system that qualitatively monitors the extent of material deterioration by AO through visual observation. It comprises two components: MDM-S (Fig. 4), which mainly carries material samples, and MDM-C (Fig. 5), which has a camera system. Both components are carried in the +Z side panel of the SLATS satellite body structure (Fig. 6). A material sample mount side is carried toward the +X side, which is in the direction of satellite movement, while MDM-S evaluates material degradation based on AO collisions from the direction of satellite movement.

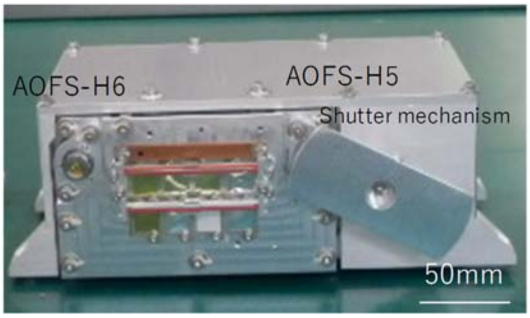


Fig. 4. MDM-S and AOFS-H (5 & 6; components also with a shutter mechanism)

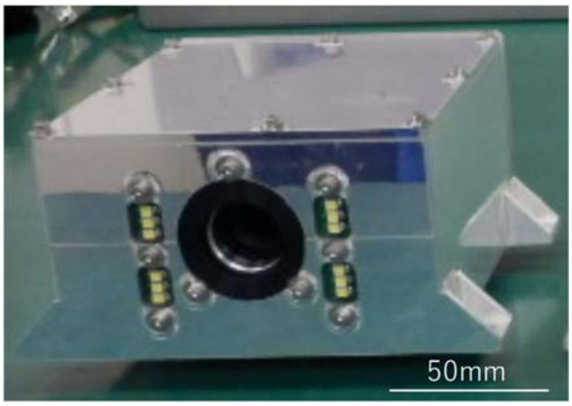


Fig. 5. MDM-C

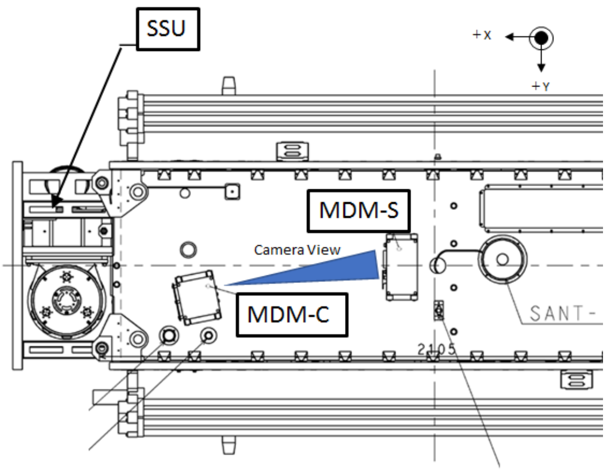


Fig. 6. Positions of MDM-S and MDM-C and the SSU (as viewed from the + Z side)

The material samples are illuminated by LED from the front and back to image details of the degradation situation. In order to protect material samples against contamination, the material sample holding part of MDM-S is regulated to maintain a high temperature (above 50 degrees Celsius) from launch time. Two AOFS sensors (AOFS-H5 and H6) are mounted near the material sample holding part. AOFS-H5 measures the AO fluence while controlling AO collisions with the same shutter mechanism as the SSU. AOFS-H6 is another sensor installed to monitor the effect of contamination on AOFS-H5 and the material samples.

Table 3. List of material samples on MDM

Mounting position	Material sample	Application
①	Vespel®	AO monitor
②	Atomic oxygen protective coating/polyimide (Apical-AH)/Al	MLI top surface
③	Polysiloxane block polyimide (BSF-30)/Al	
④	UV protective coating/polysiloxane block polyimide (BSF-30)/Al	
⑩	ITO coating/polyimide (Kapton®)/Al	
⑫	Beta cloth/Al	
⑤	Expanded PTFE cable (φ1.18 mm)	Cable
⑥	Expanded PTFE cable (φ1.35 mm)	
⑦	Expanded PTFE cable (φ1.58 mm)	
⑧	ETFE cable	
⑨	FEP film (1 mil)/Ag	OSR
⑪	FEP film (5 mil)/Ag	
⑬	ITO coating/FEP film (5 mil)/Ag	

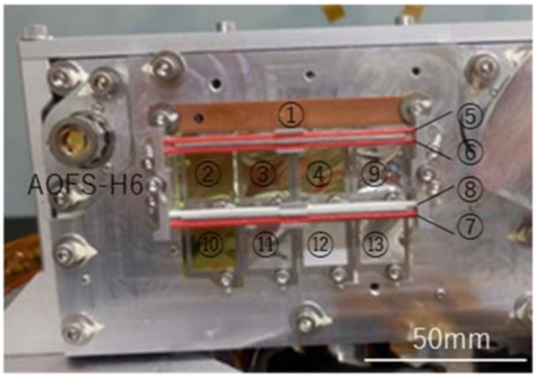


Fig. 7. Enlarged view of the MDM-S sample holding part and numbered mounting positions of material samples

Table 3 lists the material samples held on the material sample holding part of MDM-S and their application. Fig. 7 shows an enlarged view of the sample holding part where the mounting positions in Table 1 can be seen.

Material samples mainly include films used for thermal control materials such as MLI and OSR. Wire cables such as photovoltaic paddles exposed to the outer surface of the satellite structure are also selected. Thirteen kinds of materials including an AO monitoring material were selected by a committee that was organized for this mission. Films are selected mainly for their expected use in future satellites in super low altitude orbits, including those used for SLATS. Data concerning the validity of the AO protective coating, AO tolerance of the base film itself, and other aspects are acquired. A reduced thickness of the wire cable covering material is also observed. These results can be used to determine the covering thickness required for the external exposure of electric wire in future satellites in super low altitude orbits, and the required examination of the effect against AO.

The AO monitoring material is used to determine the number of AO collisions other than on the experiment sample on the MDM (mounting position ①). The AO monitoring material is a bulk polyimide resin (VESPEL®) with several holes in the depth. The depth is designed so that it disappears sequentially by AO erosion. This monitors the number of AO collisions with the MDM samples on a semi-quantitively basis. VESPEL® has been proven as an AO monitoring material for the ISS / SM and JEM MPAC & SEED experiments[6,7]. A hole resembling a pinhole is initially expected due to AO material degradation, followed by a tear expanding from this starting point. For this observation with the MDM, we selected a CCD camera that can observe the state of such deterioration.

4. INITIAL DATA ANALYSIS RESULTS

4.1 Initial checkout and operation

SLATS was launched aboard the H-IIA rocket from the Tanegashima Space Center on Saturday, December 23, 2017, along with the GCOM-S satellite. The experiments on space material exposure experienced thus far have shown that the influence of atomic oxygen is inhibited by the influence of on-orbit contamination. There is a method of controlling the temperature as a means to prevent contamination. For this reason, all temperatures of the AOFS-Hs are regulated to exceed 50 degrees Celsius. Moreover, the MDM was launched in standby mode, with the material sample holding part in the temperature control off state, and after launch, the material sample holding part's temperature control was turned on by stored command.

After the initial checkout, the AOFS has continuously acquired data, and the MDM has taken pictures with front and back lights once a week.

4.2 AOFS

Fig. 8 shows the time dependence of AOFS sensor output frequency from January 1, 2018 to July 17, 2018. Regarding the sensors coated with polyimide, except for AOFS-H4 installed inside the satellite structure, there is a tendency for the polyimide thin film to be scraped off by orbital AO exposure, and for the frequency to gradually become lower. The amount of atmospheric incident to AOFS-H3 (satellite -X plane) thus becomes large, with the largest frequency change among all the sensors. The AO flux for each sensor mainly depends on the satellite's attitude at this stage. As the satellite is often in "sun-oriented mode," the AO flux in AOFS-H3 (satellite -X plane) is the biggest. AOFS-H7 mounted on the satellite + X plane (where AO radiation is also high) showed a smaller decrease in frequency than that of AOFS-H3, because the shutter mechanism is closed 100% until April 19, and then opened 1%, with a closed 99% duty ratio from April 20.

With regard to using AOFS-H6 and H8 for contamination measurement without a polyimide thin film, although temperatures are maintained at +55°C and +70°C, respectively, the frequency increased immediately from January (just after launch) to early February. This is the effect of adhesion from the contamination. And as the frequency later began to decrease, there is a high possibility of the deposition material having been scraped off by AO—the main atmosphere component at this altitude.

Given the fact that no influence of significant contamination has been seen since February, it is considered that there is no influence of contamination on the AO measurement and the MDM material samples.

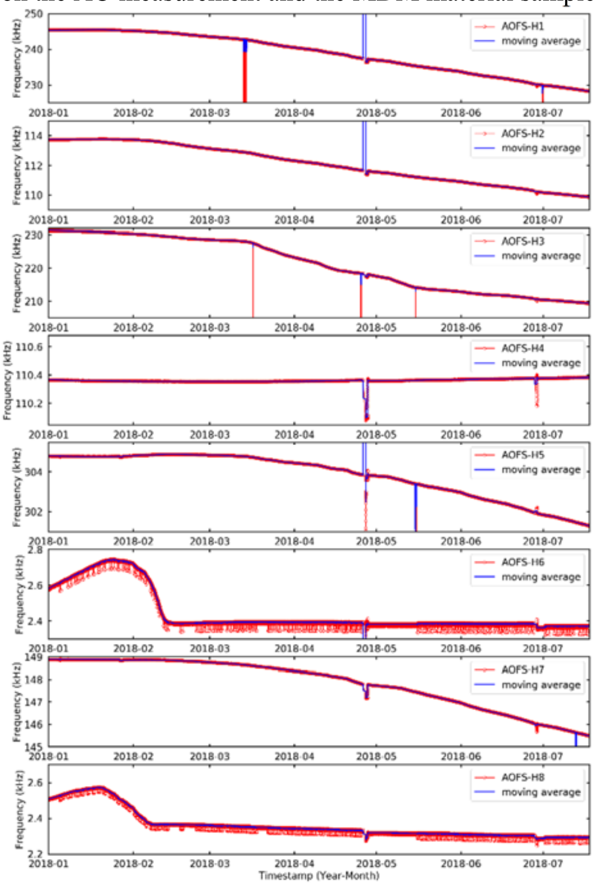


Fig. 8. Time dependence of frequency data from all AOFS-Hs (from January 1, 2018 to July 17, 2018)

Fig. 9 shows the time dependence of AO fluence per orbit (every 90 minutes) on the satellite -X plane using the data of AOFS-H3. The orbital altitude shown on the right X axis is the average for every orbit. The AO fluence at the position of AOFS-H3 (on the satellite -X plane) is calculated from the on-orbit AO density (MSIS) simulated from the neutral atmospheric model NRLMSISE-00[8] and then compared with the result of AOFS-H3. When comparing the AO fluence obtained from AOFS-H3 and NRLMSISE-00, respectively, the AO fluence obtained from the AOFS-H3 measurement value is 44% smaller than the value obtained by NRLMSISE-00, for example, on average for one week from April 1 to 7.

In SLATS orbit transition where SLATS reduces its altitude, we will continue to measure AO fluence at each sensor position.

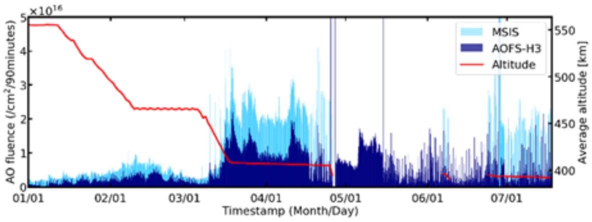


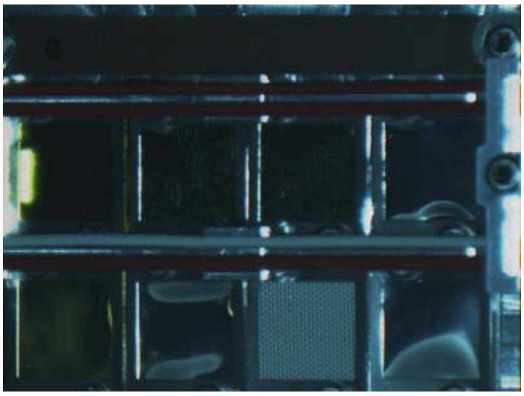
Fig. 9. Time dependence of AO fluence per orbit (every 90 min.) on the satellite -X plane using the data of AOFS-H3 and neutral atmospheric model NRLMSISE-00 (MSIS) (The average orbital altitude is also shown from January 1, 2018 to July 17, 2018.)

4.3 MDM

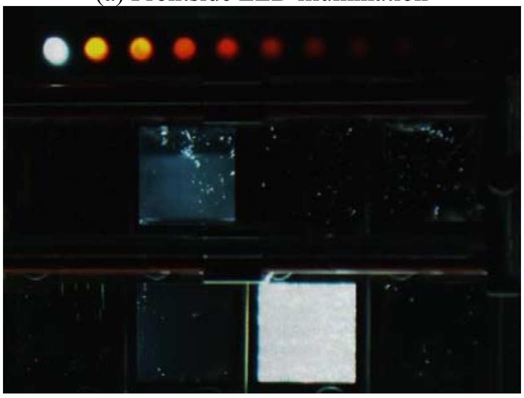
Fig. 10 shows the images acquired at the initial function check (taken on January 5, 2018). Fig. 11 shows the images taken on July 18, 2018. A comparison of all images of the whole period including both images (Figs. 10 and 11) shows a slight difference in shadow, although no fine damage due to AO or any clear material degradation can be seen.

Based on the data of AOFS-H6, contamination is considered not to affect the MDM material samples.

As for the AO monitor material, the thinnest pierce did not penetrate on July 18, 2018. The amount of AO collision required for the hole to penetrate is estimated as 5.7×10^{21} [atoms/cm^2], and the AO fluence at this time can be considered to be less than 5.7×10^{21}[atoms/cm^2]. Moreover, from the neutral atmospheric model NRLMSISE-00, the AO fluence (considered the attitude variation of SLATS) is 1.3×10^{20} [atoms/cm^2]. As the MDM is installed near the center of the + Z plane of SLATS depending on the attitude, it is affected by the satellite structure itself, which our estimation of AO fluence did not take into account.

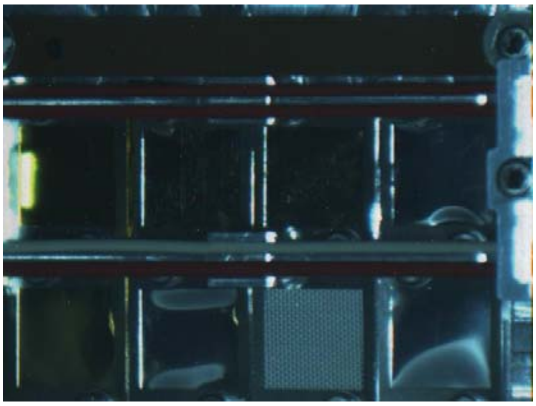


(a) Frontside LED illumination

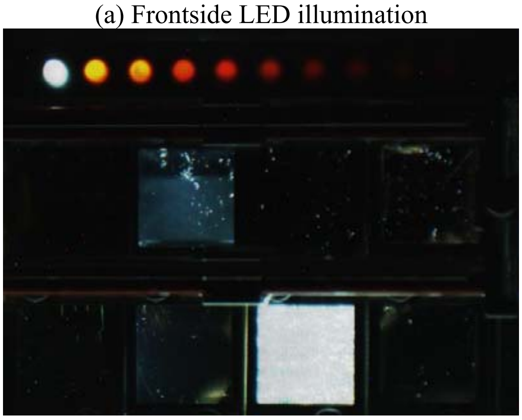


(b) Backside LED illumination

Fig. 10. Orbital image data (January 5, 2018)



(a) Frontside LED illumination



(b) Backside LED illumination

Fig. 11. Orbital image data (July 18, 2018)

5. CONCLUSIONS

SLATS was launched on December 23, 2017. The AOFS and MDM are steadily acquiring data. The AOFS continues to measure the AO fluence at each sensor position. In comparison with the neutral atmospheric model NRLMSISE-00, we have thus far obtained results that the model had overestimated. AO fluence obtained from the AOFS-H3 measurement value is 44% smaller than the value obtained by NRLMSISE-00, for example, on average for one week from April 1 to 7. It is considered that there is no influence of contamination. The MDM has taken pictures of the material samples once a week with front and back lights. At the present time, it is considered that there is no degradation of the material samples.

Data must be acquired over a long time in order to make it useful in a comparison with the atmospheric model and in material evaluation. We will continue our observations and accumulate data for future data acquisition during operation in a super low altitude orbit.

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