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EXPERIMENTAL RESULTS OF SATELLITE-TO-GROUND LASER COMMUNICATIONS LINK THROUGH ATMOSPHERIC TURBULENCE USING SOTA

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I. INTRODUCTION

In recent years, the performance of observation equipment mounted on satellites has improved to such levels that it can obtain significant amount of data from a single observation [1]. Radio waves are used as a method for transmitting large volumes of data acquired by satellites to the ground. However, currently operational radio frequencies make it difficult to improve the communication speed, owing to interference problems and the carrier frequency. Space optical communication is expected to be a solution to this problem.

The National Institute of Information and Communications Technology (NICT) developed the small optical transponder (SOTA) for the Space Optical Communications Research Advanced Technology Satellite (SOCRATES) project, which was launched in 2014 [2]. Establishing an optical communications link is the main objective of this project. The SOTA is equipped with four lasers and employs Reed–Solomon and low-density generator matrix (LDGM) error-correcting codes [3]. The international SOTA experiments campaign started in April 2015.

In this paper, the experimental configuration is introduced in Section 2. The overview of the SOTA including the specification of the error-correcting codes, the success criteria, and link establishment protocol are described. Section 3 shows the experimental results. We show result of the international SOTA experiments campaign Between April of September of 2016, and ccomparing the scintillation indices and the spectrum analysis of the 1m telescope and 2-inch photo detector.

II. SOTA configuration

The 1550-nm band laser technology is considered to become mainstream in the future of space optical communications, and a project to perform a space laser communications experiment in order to get the propagation data of 1550-nm band has been ongoing since 2010[4]. The NICT developed the SOTA to be used on board of small satellites. The SOTA was expected to be equipped on board of a 50 kg-class small satellite called the Space Optical Communications Research Advanced Technology Satellite (SOCRATES) project [5]. Figure 1 shows this configuration, including the laser communication terminal. The satellite bus of SOCRATES was developed by Advanced Engineering Services Co., Ltd (AES). SOCRATES was launched on May 24, 2014 as a piggyback satellite of ALOS-2. The SOTA has been operating normally in orbit since then.

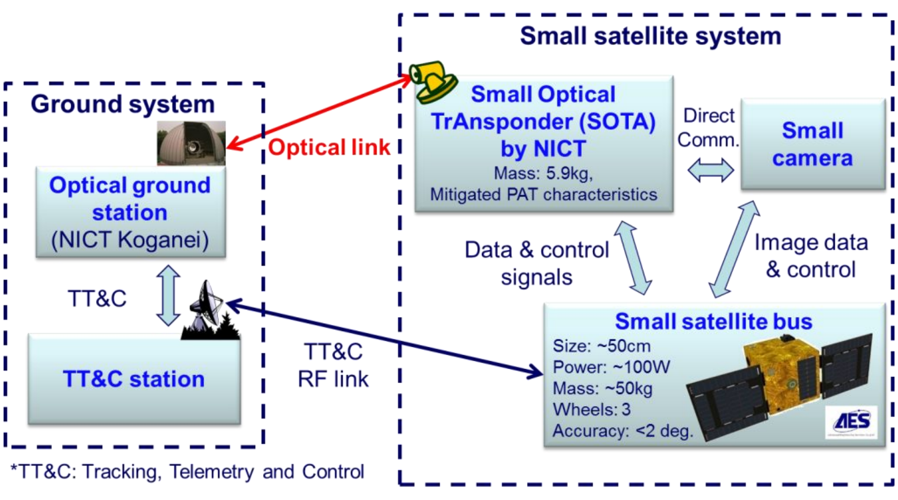


Fig. 1. Configuration of Space Optical Communications Research Advanced Technology Satellite (SOCRATES).

SOCRATES embarks a camera and sensors in addition to the SOTA. The optical ground station was developed for the space laser communications experiment by using telescopes in NICT located in Koganei-city, Tokyo. Radio frequency (RF) communication for the satellite operation is conducted from the ground station developed by the AES Corporation. Telemetry data of the satellite and the SOTA are sent via RF during the experiments.

A. Specification of SOTA

Figure 1 shows a photograph of the SOTA and control device. Table 1 shows the SOTA specifications. The mass of the SOTA is 5.9kg, and the power consumption during the communication operation is less than 16W, which allows its mounting on a 50kg-class small satellite. Table 1 lists the parameters for the transmitter (TX) and receiver (RX). The SOTA is equipped with four lasers: TX1, TX2, TX3 and TX4. TX1 and TX4 operate at wavelengths of 976 nm and 1549-nm for optical communication link. Both TX2 and TX3 use the 800-nm-band for polarization measurements [2]. The experiments were conducted using the 976-nm and 1549-nm lasers for TX and a 1064-nm laser for RX. The SOTA can track a 1064-nm laser using a quadrant detector (QD) and a fast-pointing mirror (FPM) during the experiments.

The functions onboard the SOTA are listed in Table 2. The modulation method of the SOTA is the on-off-keying (OOK) and the non-return-to-zero (NRZ), and has a function of error correction codes. Error correcting code can be selected from the LDGM and Reed–Solomon. The source data to be used for optical communication can be generated PRBS-15 data, a camera image or a sample image that is previously recorded on the SOTA. The PRBS of generating polynomial is

$$T_p = X^{15} + X^{14} + 1. \quad (1)$$

The wavelength of course pointing (CP) sensor and FPM sensor of the SOTA is 1064-nm.

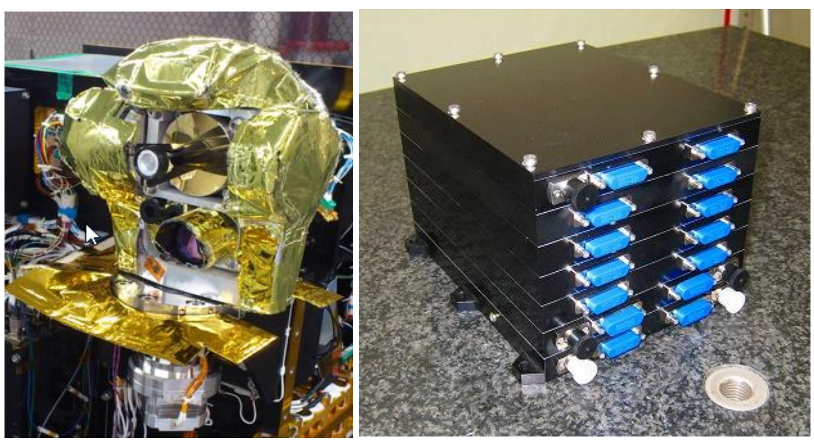


FIg 2. The optical (left) and electrical (right) part of the SOTA mounted on the SOCRATES

Table 1. Major specification of the SOTA[2]

Mass	5.9 kg (incl. both the optical part & electric part)			
Power consumption	Sleep mode	Stand-by	Tx1	Tx2,3,4
	1.7W	2.0W	15.7 W	12.6W
Gimbal range	Az: >±50deg, El: -22deg~+78deg			
Link range	1000 km			
Wavelength	TX1: 976 nm			
	TX2 and TX3 : 800 nm band			
	TX4 : 1549 nm			
	RX: 1064 nm, Acquisition/Tracking: 1064 nm			
RX antenna diameter	4.5 cm			
Data Rate	1Mbps / 10Mbps (selectable)			
Modulation	OOK-NRZ			

B. Success criteria of the space-to-ground laser communication experiments

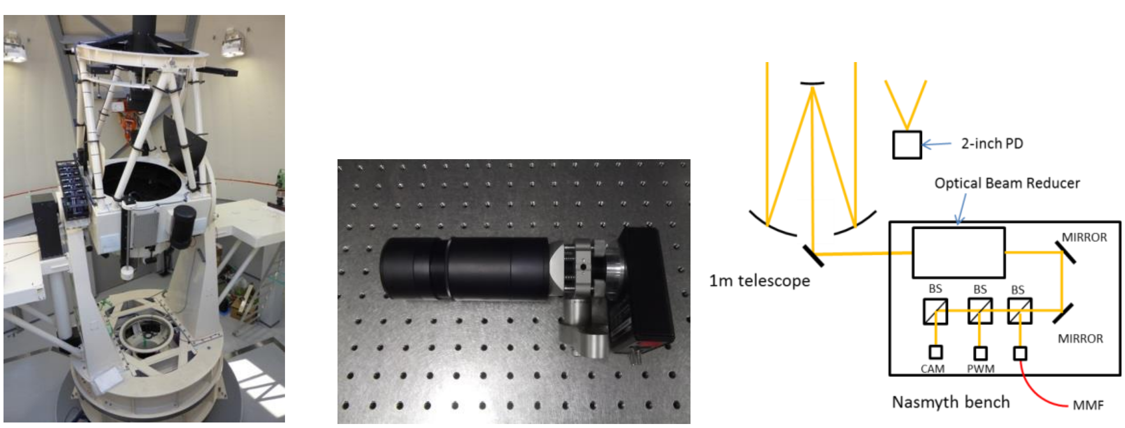
Table 3 shows success criteria of the space-to-ground laser communication experiments using the SOTA. The success criteria has been defined from the minimum success level to the extra success level. The underlines indicate those which were already successfully conducted. Additional experiments are planned for completion of the list.

Table 2. Success criteria of the space-to-ground laser communication experiments with the SOTA

No.	Experiment name	Others
Minimum success		
M1	Start-up check of equipment	Demonstration of COTS parts
M2	Confirmation of optical sensors etc.	Demonstration of COTS parts
Success		
S1	Tracking test	Confirmation of orbit, bus attitude control and mounted equipment
S2	Propagation data acquisition	Acquisition of the received signal, data acquisition at different wavelengths (Uplink: 1064nm / Downlink: TX1, TX4)
S3	BER measurement	Downlink: TX1, TX4
Full success		
F1	Data transmission experiment	Confirmation of data transmission function (Data: CAM / PRBS / Sample image) (Downlink: TX1, TX4)
F2	Error correcting code	LDGM and RS code
Extra success		
E1	Polarization measurement	
E2	Experiment with other optical ground station	The S1 and S2 experiments are conducted in an OGS except Koganei OGS.
E3	Command operative simulation by the uplink	The detection of the modulated optical signal from the OGS

C. Optical ground station configuration

The optical ground stations used in the experiment are shown in Figure 3. (A) of Figure 3 is the 1m telescope used in the experiment, and 2-inch photo detector shown in (B) is attached to the side of the telescope. The tracking accuracy of 1m telescope is 10 arc sec accuracy for LEO satellite and the pointing accuracy is 3 arc sec for celestial object higher than 30 deg [6]. (C) of Figure 3 is a graphical representation of the optical reception system of the 1m telescope. In the optical system, the received laser from the telescope is narrowed using an optical beam reducer and then split into the MMF, optical power meter, and camera.



(A) 1m telescope (B) 2-inch photo detector (C) Optical system

Fig. 3. Optical ground station and optical system

D. Link establishment protocol

Figure 4 shows the configuration of the experimental system using the SOTA. First, we determine the experiment parameters and send commands to the SOTA by RF. Image data is taken by the onboard camera and the error-correction data is generated from the image data in orbit prior to the experiment. When the experiment time comes at the optical ground station (OGS), a beacon light is transmitted to the SOTA. When SOTA detects the beacon light, it sends the data to the OGS by a laser communication link. During communications the satellite is always irradiated with the beacon light from the OGS, and the SOTA continuously tracks the beacon light. Telemetry data are sent to the OGS through the TT&C station in real time during the experiment.

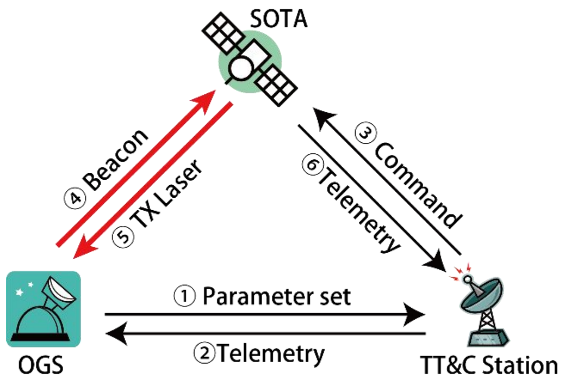


Fig. 4. Configuration of the experimental system

The sequence of events for the optical experiment with the SOTA is shown in Figure 5. First, from the predefined commands the laser diode (LD) is switched on and the QD sensors are prepared for tracking and acquisition. The beacon light from the OGS is started and coarse and fine tracking and acquisition are performed consequently on the SOTA side and the link is established.

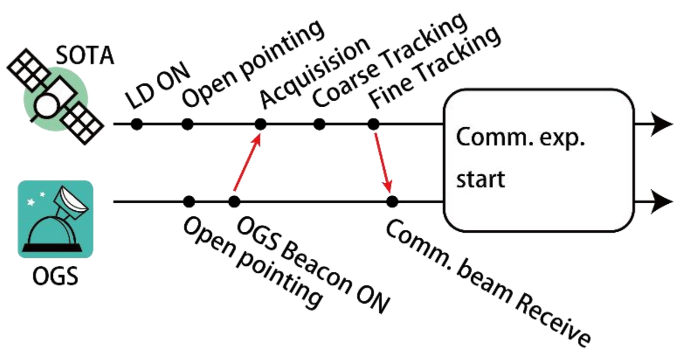


Fig. 5. Sequence of events for optical communication experiment

E. Progress of the SOTA experiments

Table 4 lists the main SOCRATES events that took place since the launch of 2014. From the launch in 2014 until July 2014, checkout of the satellite bus was performed. In approximately August 2014, the SOTA experiments began, and in April 2015 the international SOTA experiments campaign started. European Space Agency (ESA), German Aerospace Center (DLR), Centre National d'Etudes Spatiales (CNES) and Canadian Space Agency (CSA) are participating in the experiments [7,8]. In Spring 2016, we resumed the SOTA international experiment campaign.

Table 3. SOCRATES of events

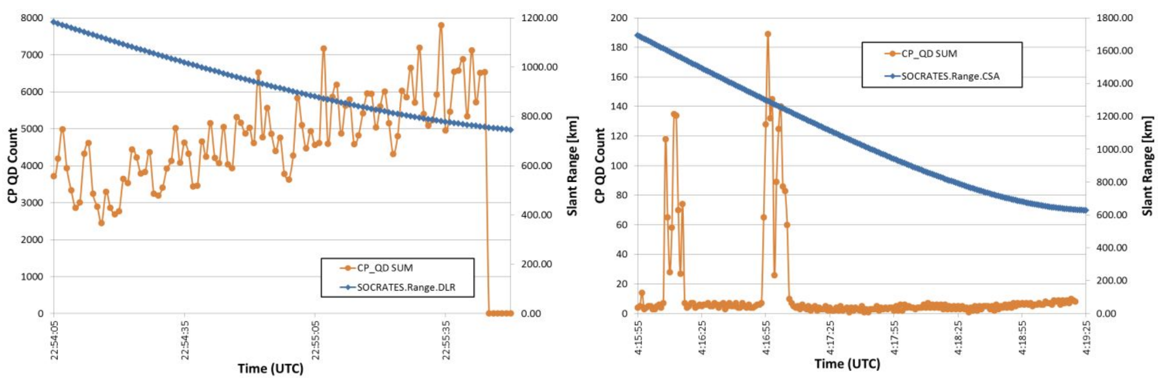
Date	Event
May. 24, 2014	SOCRATES Launch
~ July	Check out of the satellite
~ Oct.	Check out of the OGS and the SOTA
Nov. ~	Experiments for the NICT
May., 2015 ~	Start international experiment campaign
Spring, 2016~	Resumption of international experiment campaign

III. Experiment results

A. SOTA international experiment campaign

The SOTA international experiment campaign has been held since 2015. In 2015, ESA, CNES, and DLR performed experiments, and in June of 2015, CNES succeeded in an experiment. The SOTA international experiment campaign resumed around April of 2016.

During this campaign, DLR was able to receive a reception signal in May. Figure 6 shows the count levels of CP censors received by SOTA. As the level necessary to activate the SOTA tracking system is approximately 300, SOTA was able to receive enough laser to activate the tracking apparatus. Also, SOTA's laser signal was able to be detected in the ground station. In CSA, a beacon was detected by SOTA, and the laser of SOTA was detected in the ground station, but the communication link could not be established.

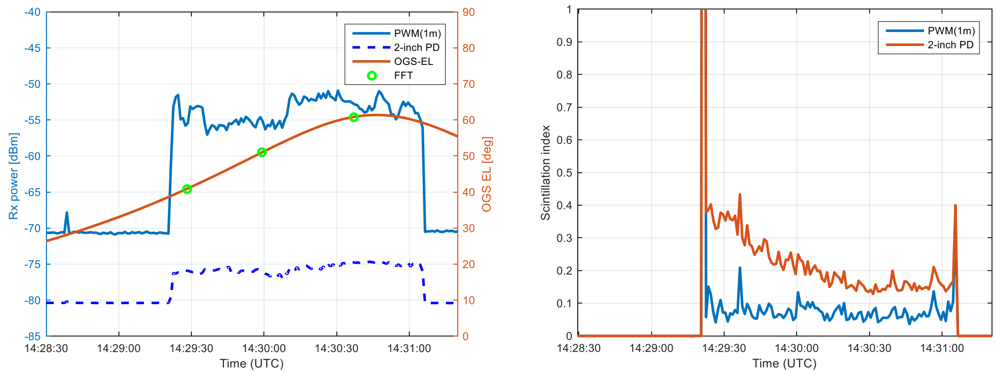


(A) DLR experiment (B) CSA experiment

Fig. 6. SOTA experiments of CP-QD count level

B. Analysis of the received data by the Koganei OGS

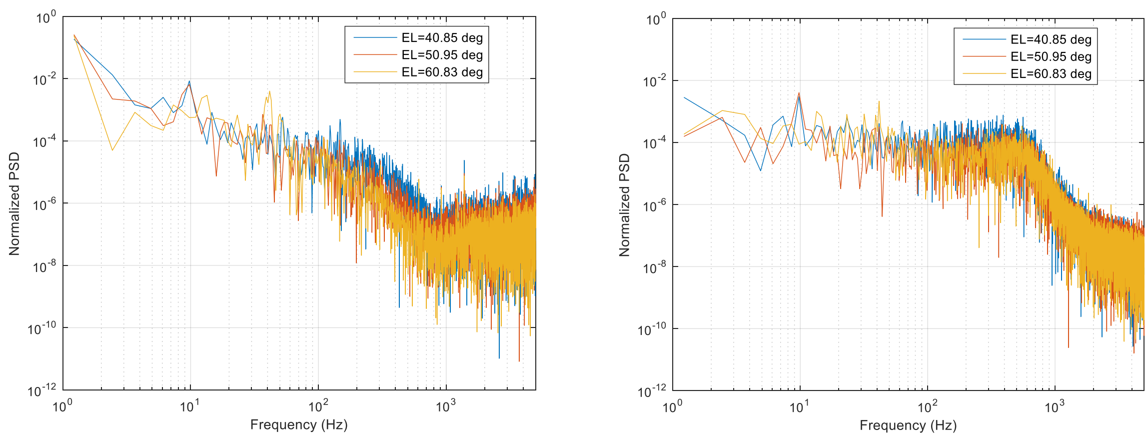
The results of the experiment preformed on May 5th, 2016 are shown in Figure 7. (A) of Figure 7 shows the data obtained by the 1m telescope and 2-inch photo detector, as well as the elevation angle of the telescope. The green circles indicate the locations as a result of FFT analysis on the data obtained during 1 second for that elevation angle and time. Also, the results of the scintillation index obtained from the received signals are shown in (B) of Figure 7. Comparing the scintillation indices of the 1m telescope and 2-inch photo detector, due to the aperture average effect, the scintillation index for the 1m telescope is lower.



(A) Receiving power (B) Scintillation Index

Fig. 7. Comparison of the receiving power and the scintillation index

The results of FFT analysis on the locations specified in Figure 7 are shown in Figure 8. In the 1m telescope FFT analysis in (A) of Figure 8, a trend of the frequency component decreasing as the elevation angle increases was observed. For the 2-inch photo detector shown in (B) of Figure 8, the differences based on the elevation angle tended to be small. Also, for the 2-inch photo detector, there is a big drop around 800Hz, but this is due to characteristics of photo detectors [9]. With this FFT analysis, filters to remove noise, disturbances of the tracking apparatus, and OGS tracking were not used. In the future, we would like to remove noise and analyse the effects of atmospheric fluctuation.



(A) 1m telescope (B) 2-inch photo detector

Fig. 8. Spectrum analysis of 1m telescope and 2-inch photo detector

IV. CONCLUSION

In this paper, the results of the SOTA international experiment campaign and their experiments were expressed, along with an introduction of SOTA. During this year's SOTA international experiment campaign, DLR succeeded, and CSA was also able to achieve detection using a camera. Also, analysis of the data obtained through SOTA experiments is ongoing, and current analysis results were expressed.

As current FFT analysis results include components outside of atmospheric fluctuation, such as noise, we would like to use filters to analyse the impact of atmospheric fluctuation.

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