

ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik



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experiment using small optical transponder (SOTA) equipment –
Optical Antenna***

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icso proceedings



On-orbit Evaluation of Satellite-ground Laser Communication Experiment using Small Optical TrAnsponder (SOTA) Equipment –Optical Antenna

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I. INTRODUCTION:

Recently, the sensors ability of remote sensing satellites are offering much better resolution, higher quality, etc. [1] The gathered data size by the satellite has become larger. However, generally, downlink transfer capacity from the satellite to a ground station using RF (Radio Frequency) communication is limited, due to the internal balance of resources (power consumption, size capacity, mass, placement, etc.) in the satellite, and allocation of bandwidth by frequency regulation arrangement.

On the other hand, laser communication technologies attract attention because of the large capacity in data transfer. The size and the mass of an optical terminal could be smaller than communication equipment used in RF communications. Since the restriction of satellite resources is tighter for smaller satellites, the combination of optical communications and small satellites is regarded as suitable for applications generating large amount of data. Our challenge is to provide a small optical communication terminal for a 50 kg-class small satellite, where the data rate is more than 1 Mbps. [2]

An optical communication terminal has been developed by National Institute of Information and Communications Technology (NICT), which is named SOTA. [3-5] The mass of the terminal is less than 6 kg including the optical and the electrical part. The terminal was mounted on a 50 kg-class piggy-bag satellite “SOCRATES” [3,4] of H2A launch vehicle. SOCRATES has been launched and injected into 650 km-SSO on 24th of May, 2014. Until June 2015, at the OSG (Optical Ground Station) in NICT Koganei, we succeeded in receiving the mission data of SOCRATES via 10 Mbps communication speed link with 1.5 μm wavelength laser, FEC (forward error correction) and LDGM (Low-Density Generator Matrix) coding for relaxing the atmospheric fading.

In this project, we tried to reduce the weight and the components of SOTA for extremely limited resources, as available in a small satellite. Although, in general, the optical antenna is a critical part to establish the communication link, for weight reduction and easy processing, we tried to reduce the weight of the main antenna of SOTA.

In an actual wireless communication system, it is essential to evaluate the characteristics of the antenna. In measurement of the characteristics of an optical antenna which is an aperture antenna with large ratio of diameter and wavelength, a long range distance is needed. [6] In addition, when designing the antenna, a computer simulation is utilized, the error is occurred due to limitations of simulation performance and fabrication process errors. Therefore, For the system demonstrated and proven, it is important to compare validate the design value and the measured value of the actual antenna. Although it is very difficult to evaluate the characteristics of the mounted optical antenna to LEO satellites like SOTA because of the influence of the atmosphere between the satellite and the ground station. In this report, we tried to obtain the gain of SOTA TX4 optical antenna from the result of the detected power at the OGS in a satellite-ground laser communication experiment demonstrations under limited circumstances.

II. Small Optical TrAnsponder (SOTA):

A. Overview of SOTA

The features of SOTA are that three laser sources with wavelengths of 0.8 μm , 0.98 μm and 1.5 μm , are installed to perform different experiments with optical ground stations. The wavelengths of 0.98 μm and 1.5 μm are used to perform data downlink from the satellite to the ground. The BER (Bit Error Rate) and the atmospheric influences on propagating light will be measured on those wavelengths. The coding technique will be imposed onto those transmitted lights so that the effect of the mitigation of atmospheric influences can be observed. The wavelength of 0.8 μm is employed in a preparative measurement for a QKD (Quantum Key Distribution).

The development progress and the photograph of SOTA are shown in Figure 1. The first stage of SOTA development was the SOTA-BBM (Breadboard Model). Some functional modifications took place as a result of SOTA-BBM evaluation activities, and the SOTA-EM (Engineering Model) was developed. After SOTA-EM evaluation, the design of SOTA-PFM (Proto Flight Model) was fixed as shown in Fig. 1. Table 1 shows the main specifications of SOTA-PFM. SOTA has four optical transmitters of TX-1, TX-4, TX-2 and TX-3, which operate at 980 nm, 1550 nm and 800 nm band respectively, and the each of the optical paths are shown in Figure 2

SOTA can use either TX-1 or TX-4 for the downlink to perform the conventional laser communication demonstrations, while, in the basic experiment for QKD, TX-2, TX-3 and TX-4 are turned on simultaneously. For the downlink, SOTA can select one of the two data rates of 1 Mbps and 10 Mbps.

The downlink lasers of TX-1 and TX-4 transmit either pseudo noise code or image data of a camera installed on the satellite. Besides, coding technologies such as the RS and LDGM code can be superimposed to see the effect of error correction. The wavelength of an uplink beam for acquisition and tracking is 1064 nm.

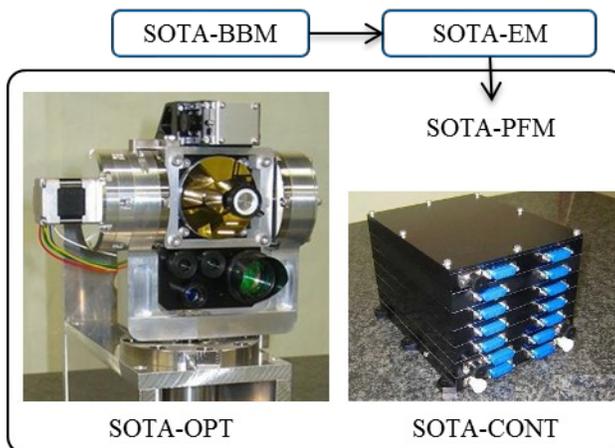


Fig. 1. The developmental progress and the photograph of SOTA

Table 1. SOTA specifications (PFM model, final)

Mass	5.86 kg (incl. both the optical part & electric part)			
Dimension	Optical part: 178(W) × 114(D) × 268(H) mm Electric part : 146(W) × 146(D) × 107(H) mm			
Power consumption	Sleep mode	Stand-by	TX-1	TX-2,3,4
	1.7 W	2.0 W	15.7 W	12.6 W
Tracking system	Tracked by InGaS QD (Quadrant Detector) sensor			
Gimbal range	Az: >±50deg, El: -22deg~+78deg			
Link range	Less than 1000 km			
Wavelength	TX-1: 976 nm / TX-2 and Tx3 : 0.8 μm-band / TX-4 : 1549 nm			
	RX: 1064 nm, Acquisition/Tracking: 1064 nm			
Angle of divergence (FWHM)	TX-1 : 442 μrad / TX-4 : 191 μrad @23°C, 1 atm			
	TX-1 : 500 μrad / TX-4 : 223 μrad @0°C in vacuum (estimated)			
Data Rate	1 Mbps / 10M bps (selectable)			

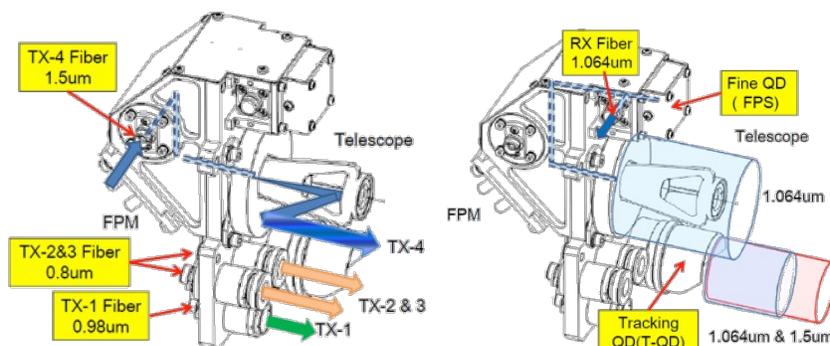


Fig. 2. The optical paths of SOTA optical part, the transmitter system (left), the receiver system (right)

B. Experimental plan and success criteria of SOTA project

Figure 3 shows the experimental plan chart and success criteria of SOTA project. Each row shows the stage of success criteria. The first row from left is minimum success stage. In this stage, the functional verifications are confirmed, for example, the health check of Laser diodes, gimbals, and the other discrete components.

The second row from left is success stage. In this stage, on first place, the acquisition and tracking function are confirmed. To confirm the function, mainly, the cooperative system control between SOTA, SOCRATES satellite bus system, and OGS system is checked. Next, the propagations through the air are measured using downlink laser, 976 nm and 1549 nm wavelength from SOTA TX-1 & TX-4, and uplink laser 1064nm beacon beam from OGS. Finally, BER under 1549 nm, 976 nm wavelength is measured.

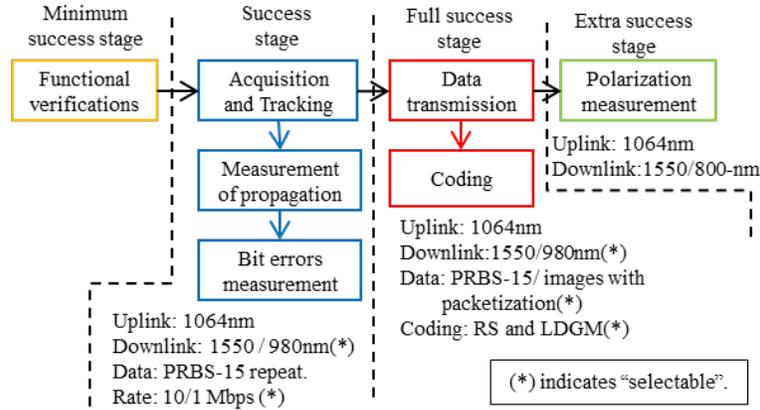


Fig. 3. The experimental plan chart and success criteria of SOTA project

III. Design and measurement results on the ground test of SOTA Optical antenna

Figure 2 shows the optical paths of SOTA. The left one is the transmitter path, the right one is receiver path. The diameter of the optical antenna (main reflector) for FPM tracking sensor and TX-4 transmitter is 50 mm. For weight reduction and easy processing, the base material of main and sub reflector is aluminum with aurum coating (overlaid with gold). To avoid the eclipse of the sub reflector and the support parts, the radiated beam of TX-4 is reflected by a part of the main reflector. The divergence angle of SOTA-TX4 is 191 μ rad in full width at half maximum (FWHM), which is measured on the ground in a room condition. On the orbit, the divergence of SOTA TX-4 is changing by the temperature and the atmospheric pressure, the corrected value in the vacuum, 0 $^{\circ}$ C is 223 μ rad.

In general, the antenna gain is defined as the ratio of the maximum radiation intensity at the peak of the main lobe to the radiation intensity that would be produced by an isotropic radiator fed with the same input power. A gain of an optical aperture antenna, G_t is obtained by Equation (1), approximately, [8]

$$G_t = 8(\pi w_0 / \lambda) = 8 / \theta_0^2 \quad (1)$$

where, G_t is the gain of transmitter antenna, w_0 is the radius of beam waist, θ_0 is the divergence angle of the Gaussian beam pattern on far field in half width at $1/e^2$ maximum (HWE²M). According to the measured result, the divergence of SOTA TX-4 in HWE²M is 189 μ rad, which is converted FWHM into HWE²M. The estimated gain of SOTA TX-4 antenna is 83.5 dBi.

IV. On-orbit evaluation of SOTA optical antenna

In this chapter, we describe cases of the communication experiment results. Figure 4 shows the captured whole sky image at the time of the experiment by a whole-sky visible camera. The camera is located on a housetop of NICT Koganei OGS's backyard. A red and yellow arrow shows the SOTA trajectory at the time. On December 9th, 2015, in this trajectory (Fig. 4), the maximum elevation is 42.3 $^{\circ}$, at 13:52:26. The weather condition is clear, the temperature is 6 $^{\circ}$ C. The relative humidity is 79 %. The slant range between SOTA and the OGS is of the order of 1300 km to 875 km. During the experiment, we tried to confirm the data transmission function from the satellite with SOTA modulator and OGS systems, via 1.5 μ m wavelength laser beam, BER (Bit Error Rate), 10 Mbps link speed.

Figure 5 shows the detected and estimated received power during the experiment at the OGS. The solid line show detected power at the power meter, the sampling time is 1.0 sec. The dotted line is the estimated power, P_r , which is obtained by Equation (2), (3), (4) and (5).

$$P_r = P_t \cdot \tau_t \cdot G_t \cdot L_r \cdot G_r \cdot \tau_r \cdot L_p \quad (2)$$

$$L_r = (\lambda / 4\pi R)^2 \quad (3)$$

$$L_p = \exp[-2(\Delta\theta/\theta_0)^2] \tag{4}$$

$$G_r = (\pi D/\lambda)^2 \tag{5}$$

where, P_r is the transmitted power, τ_t is the efficiency of transmitter, $\Delta\theta$ is the error of pointing angle, L_r is the loss of free space, G_r is the gain of receiving antenna, τ_r is the efficiency of receiver, L_p is the loss of pointing, R is the slant range between a transmitter and a receiver, and D is the diameter of receiver. In the demonstration setting, P_r is a 15.4 dBm, τ_t is 0.3 dB, R is the changing of the slant range during the demonstration, G_r is 99.8 dBi, τ_r is 0.3 dB, and D is 48.3 mm. For simple analysis, random losses, which are the atmosphere losses between SOTA and the OGS are not taken into account. To neglect the loss of pointing at the OGS, a highly sensitive InGaAs PIN detector with a wide FOV (Field of View) telescope is used. The FOV of the telescope is 5.0 m rad (17.2 arc minute). The detected power is around 65 dBm and stabilized. The difference between the estimated and the detected optical power is in the range of 4 dB to 6 dB, which is assumed to be the loss of the atmosphere. The loss of the atmosphere is depended by the elevation of the telescope, the air turbulence and the air conditions at during the experiment, mainly. According to a rough calculation, the loss of the atmosphere is in order of 5 dB, the estimated gain of SOTA TX4 value is considered to be a reasonable value.

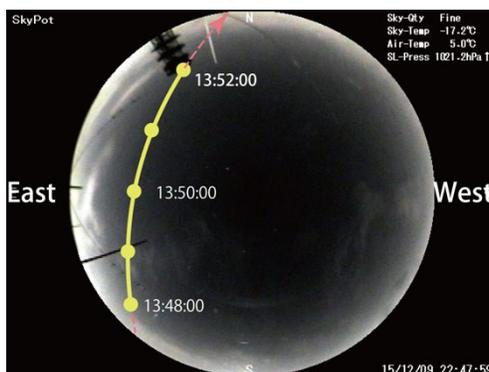


Fig. 4. The captured whole sky image at the time of the experiment by a whole-sky visible camera (located on a housepot of NICT Koganei OGS’s backyard). Captured at 13:47:59, 9th December, 2015, in UTC.

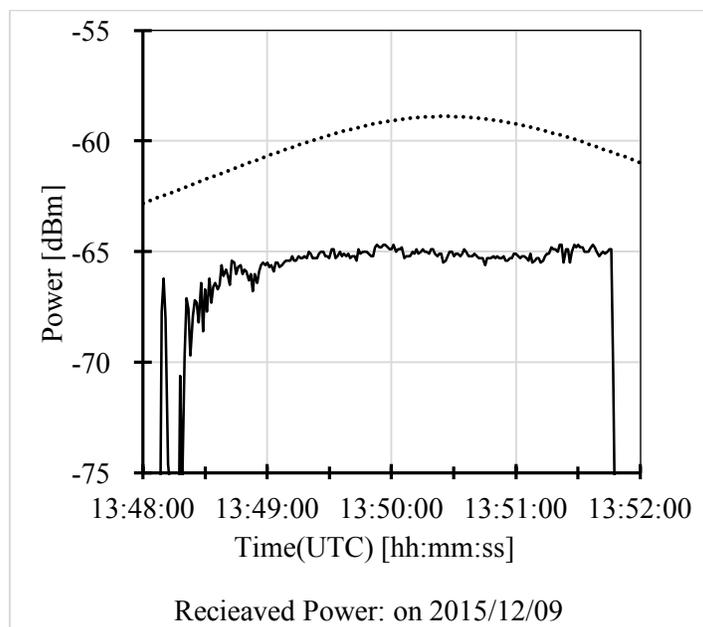


Fig. 5. The detected and estimated received power during the experiment at NICT Koganei OGS. The receive timing is 13:48:00 to 13:52:00 9th December, 2015, in UTC. (Solid: detected, Dotted: estimated, without the loss of atmosphere)

V. Conclusion

In this report, we described initial overview of the satellite-ground laser communication experiment demonstrations between the ground station and LEO, and on-orbit evaluation of SOTA equipment, then, to obtain the gain of SOTA TX4 optical antenna from the result of the detected power at the OGS in a satellite-ground laser communication experiment demonstrations. After that, the estimated gain of SOTA TX4 value is considered to be a reasonable value under limited circumstances.

In future, to obtain the gain of SOTA antennas, we will continue the detailed analysis by taking into account the influence of the atmosphere.

ACKNOWLEDGEMENT

We are grateful to Dr. Dirk Giggenbach and Dr. Florian Moll in DLR-IKN (Institute of Communications and Navigation, German Aerospace Center) for the support of the highly sensitive detector.

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