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Hannah Tomio

Toshinori Kuwahara

Shinya Fujita

Yuji Sato

et al.



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Hannah Tomio^a, Toshinori Kuwahara^a, Shinya Fujita^a, Yuji Sato^a, Morokot Sakal^a, Hiroo Kunimori^b,
Toshihiro Kubooka^b, Hideki Takenaka^b, Yoshihiko Saito^b, Morio Toyoshima^b,
^aTohoku University, Aramaki Aza Aoba 6-6-11, Sendai, Japan 980-8579
^bNational Institute of Information and Communication Technology, Nukui Kitamachi 4-2-1,
Koganei, Japan 184-8795

ABSTRACT

The Rapid International Scientific Experiment Satellite (RISESAT) is a 50-kg-class Earth observation microsatellite that is currently being developed at the Space Robotics Laboratory (SRL) of Tohoku University, with a planned launch data in 2018. Intended to demonstrate a cost-effective and reliable microsatellite bus system, RISESAT features various scientific payload instruments from institutions and organizations around the world. Among the payloads are the Very Small Optical Transponder (VSOTA), a compact, dual-band (980 nm, 1550 nm), lightweight laser signal transmitter developed by the Japanese National Institute for Information and Communications Technology (NICT), and the High Precision Telescope (HPT), a multi-spectral, high-resolution Cassegrain telescope developed by Hokkaido University and intended for Earth and astronomical observations. Using these two payloads, RISESAT can demonstrate satellite-to-ground one-way laser communication. This experiment is intended to demonstrate optical communication capability within the scope of the available hardware resources on a microsatellite dedicated to numerous other scientific endeavors. Hence, VSOTA is lighter, less power intensive, and more simplified than other optical transmitter terminals. Internal gimbal mechanisms for fine pointing have also been eliminated, thus the tracking of the optical ground stations will be achieved using body pointing of the satellite. Recently, end-to-end electrical configuration and communication tests have been conducted for both the engineering model (EM) and the flight model (FM) of the VSOTA assembly. This paper provides an overview of VSOTA and its space-to-ground optical communication demonstration, and describes the current status of the RISESAT optical communication subsystem assembly and integration.

Keywords: microsatellite, body pointing, space optical communication

1. INTRODUCTION

The Rapid International Scientific Experiment Satellite (RISESAT, shown in Figure 1) is a 50-kg-class Earth observation microsatellite that is currently being developed at the Space Robotics Laboratory (SRL) of Tohoku University. Also known as Hodoyoshi-2, RISESAT was originally part of the “New Paradigm of Space Development and Utilization Opened by Micro/Nano-satellites with Reasonably Reliable Systems ‘Hodoyoshi’ Concept,”¹ a Japanese FIRST (Funding Program for World-Leading Innovative R&D on Science and Technology) project under the direction of Professor Shinichi Nakasuka at the University of Tokyo.² Currently, it has been selected to be part of the “Innovative Satellite Technology Demonstration Program” run by the Japanese Aerospace Exploration Agency (JAXA), with a planned launch data in 2018 on the Epsilon rocket.

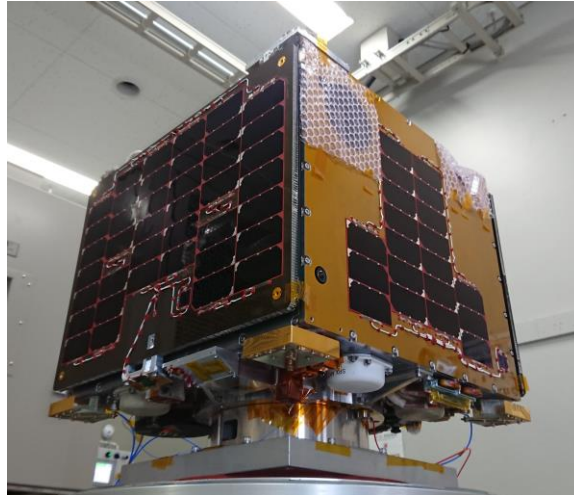


Figure 1. Flight Model of RISESAT during a vibration test

As the fourth 50-kg-class microsatellite developed by Tohoku University, RISESAT is preceded by SPRITE-SAT³ (renamed RISING-1 after launch), which was launched in 2009, RISING-2⁴ (launched in 2014), and DIWATA-1⁵ (launched in 2016), in addition to numerous CubeSats. Intended to demonstrate a cost-effective and reliable microsatellite bus system, RISESAT features various scientific payload instruments from institutions and organizations around the world. To facilitate their development and integration, the Space Plug and Play Avionics (SPA) standard was referenced for the payload instrument-to-satellite bus system interface.⁶

Among the payloads are the Very Small Optical Transponder (VSOTA, shown in Figure 2), a compact, dual-band (980 nm, 1550 nm), lightweight laser signal transmitter developed by the Japanese National Institute for Information and Communications Technology (NICT), and the High Precision Telescope (HPT, shown in Figure 3), a multi-spectral, high-resolution Cassegrain telescope developed by Hokkaido University and intended for Earth and astronomical observations. Using these two payloads, RISESAT can demonstrate LEO-to-ground one-way laser communication.



Figure 2. VSOTA pre-manufacture illustration of VSOTA-COL and flight model of VSOTA-E

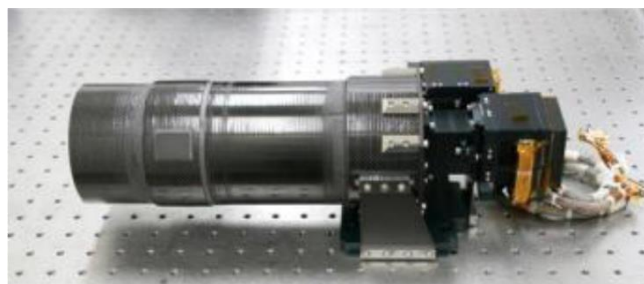


Figure 3. Flight model of HPT

Due to the weight and volume constraints of the microsatellite, VSOTA lacks an internal gimbal mechanism and fine pointing mechanism, and thus the transmission direction is fixed with the orientation of the satellite structure. Therefore, the optical ground stations must be tracked using the attitude control of the entire satellite body (“body pointing”). The requirement for tracking NICT’s optical ground stations is an accuracy of 3σ . This will be facilitated by a 532nm satellite laser ranging (SLR) guide signal transmitted from ground that will be detected using the HPT and used as a feedback signal by the Attitude Control Unit (ACU).^{7 8 9}

This paper provides an overview of VSOTA and its space-to-ground optical communication experiment, and describes the current status of the RISESAT optical communication subsystem assembly and integration.

1.1 Related works

NICT has previously conducted bi-directional optical communications experiments between satellite and ground station using laser communications systems aboard Optical Inter-Orbit Communications Engineering Test Satellite (OICETS, also known as KIRARI), launched in 2005, and Space Optical Communications Research Advanced Technology Satellite (SOCRATES), launched in 2014. SOCRATES, in particular, carried the Small Optical Transponder (SOTA), upon which the design of VSOTA is based. The basic structure of the laser collimator and the laser diode driver are the same in SOTA and VSOTA for two of the laser transmitters (980 nm and 1550 nm), though SOTA features two additional laser transmitters in the 800 nm band in order to take polarization measurements for satellite quantum key distribution. SOTA has a mass of 5.9 kg and supports a downlink data rate of up to 10 Mbps. For pointing, SOTA has an internal gimbal mechanism consisting of a 2-axes gimbal.^{10 11}

Other technology demonstrators of microsatellite optical downlink systems include those of DLR’s OSIRIS Program, such as OSIRISv1 on Flying Laptop, launched in 2017, and OSIRISv2 on Bispectral Infrared Optical System (BiROS), launched in 2016. OSIRISv1 has a mass of 1.3 kg, a power consumption of 26 W, and supports a downlink data rate of up to 200 Mbps, while the OSIRISv2 has a mass of 1.65 kg, a power consumption of 37 W, and supports a downlink data rate of up to 1Gbps. Both satellites use body pointing to track optical ground stations, but while Flying Laptop uses open-loop body pointing, BiROS is equipped with a tracking sensor that can receive a beacon signal from the ground station in order to perform closed-loop body pointing.^{12 13}

VSOTA differs from these projects in that its primary motivation is to demonstrate optical communication capability within the scope of the available hardware resources on a microsatellite dedicated to numerous other scientific endeavors. Hence, it is lighter, less power intensive, and more simplified than other optical transmitter terminals. This is also the rationale for the usage of body pointing, with closed-loop control facilitated by HPT.

2. SPECIFICATION OF VSOTA

VSOTA consists of the optical collimator “VSOTA-COL” and the electronics unit “VSOTA-E.” Additionally, there is the control and interfacing unit “VSOTA-CNT.” VSOTA-COL contains the two collimators, precisely aligned in the same direction, and an alignment cube mirror to facilitate the light axis measurement, critical to determining the relative alignment angle between the collimator assembly and HPT. VSOTA-E contains the laser diode driver electronics and has a fiber optic connection to VSOTA-COL. VSOTA-CNT contains a Remote Terminal Unit (RTU) that controls VSOTA-E, performs the data handling related to VSOTA, and interfaces with the Science Handling Unit (SHU). VSOTA-CNT receives commands and executes from the SHU to control VSOTA-E, e.g. turning on and off the laser transmitters, and setting the downlink parameters such as data rate and modulation rate. VSOTA-CNT also monitors the temperatures of VSOTA-E and VSOTA-COL, and the voltage levels of VSOTA-COL, and sends this telemetry as housekeeping data to the SHU. Both VSOTA-COL and VSOTA-E were developed by NICT, while VSOTA-CNT was developed by Tohoku University.

The position of the VSOTA assembly in the internal structure of RISESAT is shown in Figure 4. The optical collimators, along with the cube corner retroreflector (CCR), on RISESAT FM are shown in Figure 5. The downlink specifications, listed alongside those of SOTA for comparison, are shown in Table 1.

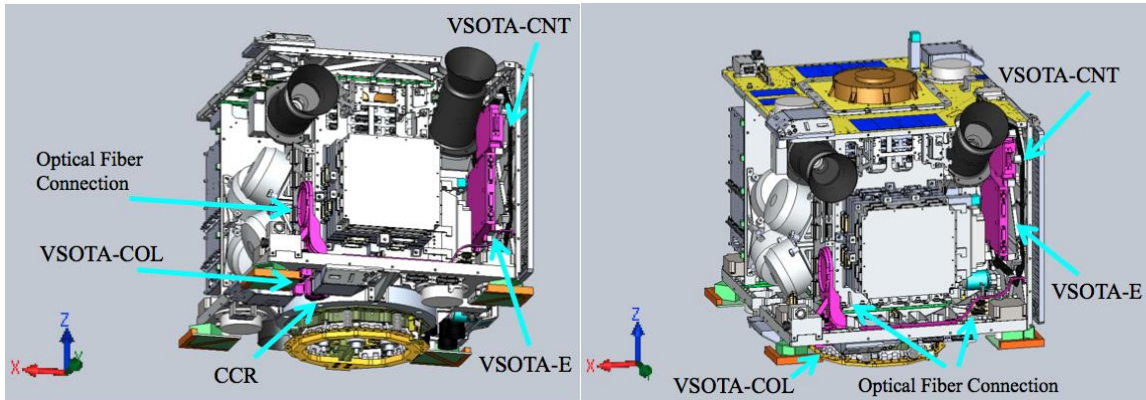


Figure 4. Position and configuration of VSOTA in the RISESAT structure.



Figure 5. VSOTA-COL and CCR shown on the flight model of RISESAT

Table 1. VSOTA and SOTA downlink specifications.

Parameter	VSOTA Value	SOTA Value
Mass (including the optics and electronics)	< 1 kg	5.9 kg
Power Consumption	Sleep mode: 0 W Standby mode: 1.82 W TX1 only: 4.33 W TX4 only: 2.73 W	Sleep mode: 1.65 W Standby mode: 1.96 W TX1 only: 15.74 W TX4 only: 12.54 W
Link Distance	< 2000 km	< 2000 km
Wave Length	Transmitter 1: 980 nm Transmitter 4: 1550 nm	Transmitter 1: 980 nm Transmitter 4: 1550 nm
Divergence	Transmitter 1: 3.3 mrad Transmitter 4: 1.2 mrad	Transmitter 1: 500 urad Transmitter 4: 223 urad
Polarization	Transmitter1: Arbitrary Transmitter 4: Linear	Transmitter 1: Arbitrary Transmitter 4: Linear
Modulation	OOK-NRZ, PPM	OOK-NRZ
Data Rate	1 kbps ~ 1 Mbps (variable)	1 Mbps / 10 Mbps (selectable)

Error Correction Codes	Reed-Solomon	Reed-Solomon, Low-density generator matrix (LDGM)
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Apart from the mass and power consumption, the primary difference between VSOTA and SOTA is the divergence. To account for the pointing accuracy of the satellite using the body pointing method, the transmit divergence of VSOTA has increased. Other differences are in the method of modulation and the usage of error correction codes. SOTA's modulation method is non-return-to-zero on-off keying (OOK-NRZ), while VSOTA has two modulation methods: OOK-NRZ and pulse position modulation (PPM). PPM is necessary to fulfill the extra success condition of optical communication experiment. On SOTA the error correction code can be selected from Reed-Solomon or LDGM, while for simplicity VSOTA utilizes only Reed-Solomon.

For the VSOTA demonstration, the source data to be downlinked can be selected from either the pseudorandom binary sequences (PRBS) PRBS-15 or PRBS-11, or a sample image that was saved and stored in the memory of VSOTA-CNT.

3. SPECIFICATION OF BODY POINTING SYSTEM

3.1 Specification of HPT

HPT is a multi-spectral, high-resolution Cassegrain telescope. The specifications of HPT are shown in Table 2.

Table 2. HPT specifications.

Parameter	Value
Observation Band	630 bands (420 nm – 1050 nm)
Ground resolution	5 m (at 700 km LEO)
Field of View	0.2°
Data update frequency	10 Hz
CCD Area	659 x 494 pixels
Diameter	100 mm
Focal Length	1000 mm

Using two Liquid Crystal Tunable Filters (LCTFs), HPT can obtain measurements from 630 bands in the 420-1050nm range. Each LCTF is combined with a charge-coupled device (CCD) matrix image sensor with a pixel resolution of 5 m while in LEO. Using these devices, HPT can take multi-spectral images for Earth and astronomical observations. In addition to this functionality, HPT implements a laser detection system to support the optical communication demonstration. By using HPT to detect the SLR laser guide beam, the tracking error of the system can be measured accurately. It can calculate a laser incident direction by measuring the position of a light spot on a charge-coupled device (CCD sensor), though it is limited to the case when the distance between the satellite and the ground station is less than 1000 km. This functionality is used to both implement the attitude control method and evaluate it from ground. The position of HPT in the internal structure of RISESAT is shown in Figure 6.⁹

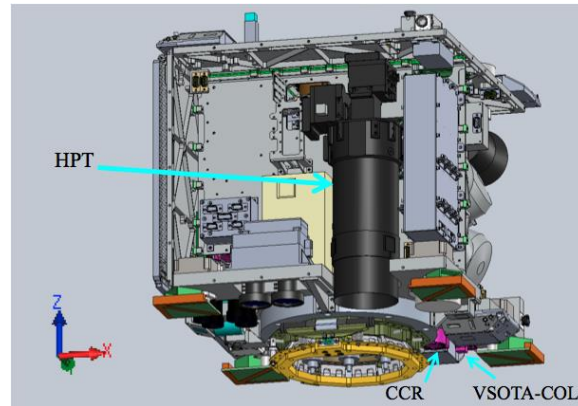


Figure 6. Position and configuration of HPT in the RISESAT structure.

3.2 Attitude control modes

The attitude control method for body pointing consists of two modes. The first mode is used during the initial phase of the optical ground station tracking. During this mode, the guidance laser is not used due to the possibility that the tracking error exceeds the field of view (FOV) of HPT or that the satellite is at too great a distance from the ground target to detect the laser. Instead, open-loop tracking control towards an estimated position of a ground station is carried out with a required tracking accuracy of 3σ (0.1°), which is constrained by the size of the FOV of HPT. The second mode begins when the guidance laser is transmitted by the primary optical ground station to the satellite. Using the position of the light spot on the CCD sensor, the laser incident direction can be found, which becomes the basis of the feedback. In this mode, guide laser-based feedback control is combined with the open-loop tracking control of the first mode with a required tracking accuracy of 3σ (0.04°).¹⁴

The body pointing system and its optical ground station tracking algorithms have been evaluated using the Model based Evaluation and Verification for Integration of u-Satellite (MEVIuS) hardware-in-the-loop (HILS) simulator that was developed by SRL.¹⁵

4. OPTICAL COMMUNICATION DEMONSTRATION

The primary ground station to be used in RISESAT's optical communication demonstration is NICT's 1.5 m diameter optical ground station, located in Koganei, Tokyo. In addition, 0.3 m diameter mobile optical ground stations have also been developed by Tohoku University and will be used as part of the extra success criteria.

All of the success criteria of RISESAT's space-to-ground optical communication experiment using VSOTA are shown in Table 3.

Table 3. VSOTA mission success criteria.

Mission Success Level	Item	Objective
Minimum Success	M1	Demonstrate the capability of lightweight, compact optical communication on a scientific microsatellite.
	M2	Acquire data on the effect of atmospheric scintillation noise on the laser communications link.
Full Success	F1	Evaluate the HPT image of the SLR guide signal from ground
	F2	Evaluate the downlink beam divergence and ACU accuracy using the primary ground station
Extra Success	E1	Evaluate the downlink beam divergence and ACU accuracy simultaneously using the primary ground station and mobile ground stations to consider the beam spread.

	E2	Be used as a reference source for verifying the adaptive optics of the optical ground stations intended for future high-throughput satellites, etc.
	E3	Be used as a reference source for verifying the superconducting nanowire single-photon detector (SSPD) to be used for a PPM-based deep space communication method.

The minimum success condition is to demonstrate the optical data downlink, regardless of the baud rate, and allow for the acquisition of atmospheric scintillation noise data.

The ability to evaluate the optical communication tracking performance constitutes a full success. The first step is the confirmation of SLR guide signal from the ground station by HPT. While the evaluation of the attitude control unit will primarily be done using HPT, RISESAT's passive CCR sensor (shown in Figure 7) can also be used as an evaluation method. In particular, the CCR is capable of detecting RISESAT when the attitude of the satellite shifts from the nominal position by over several degrees, due to its large FOV (15°).

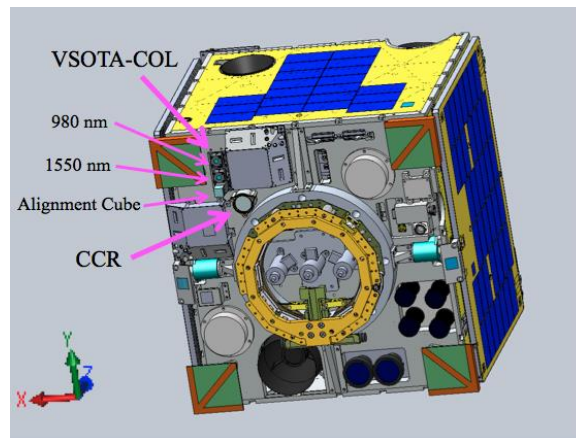


Figure 7. Position and configuration of VSOTA-COL and CCR in the RISESAT structure.

There are three extra success criteria, the first of which is to evaluate the optical tracking performance using the mobile ground stations. The following extra success criteria are related to the usage of VSOTA as a reference optical downlink signal to evaluate ground receivers for future applications. One such criterion is to be a part of an adaptive optics (AO) experiment. Optical ground stations with AO are planned for communication with Engineering Test Satellite-9 (ETS-9) and other future high-throughput satellites. Using VSOTA as a reference enables the examination of the wavefront fluctuation and the sending wavefront to create a wavefront compensation algorithm. Another such criterion is to be a part of a quantum communication experiment. Using its PPM functionality, VSOTA can be used to demonstrate the high sensitivity reception of a superconducting nanowire single-photon detector (SSPD).

5. STATUS OF ASSEMBLY AND INTEGRATION

Recently, end-to-end electrical configuration and communication tests have been conducted for both the engineering model (EM) and the flight model (FM) of VSOTA and its related subsystems. A diagram of test configuration is given in Figure 8. Images from the actual test set-up are shown in Figure 9.

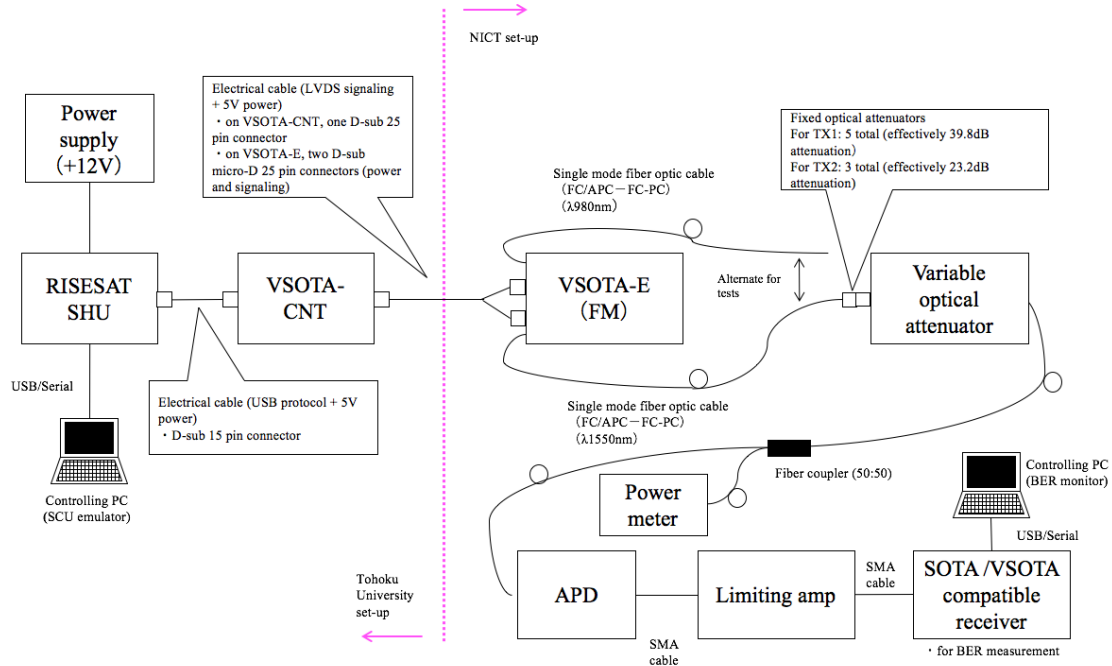


Figure 8. VSOTA end-to-end test configuration connection diagram.

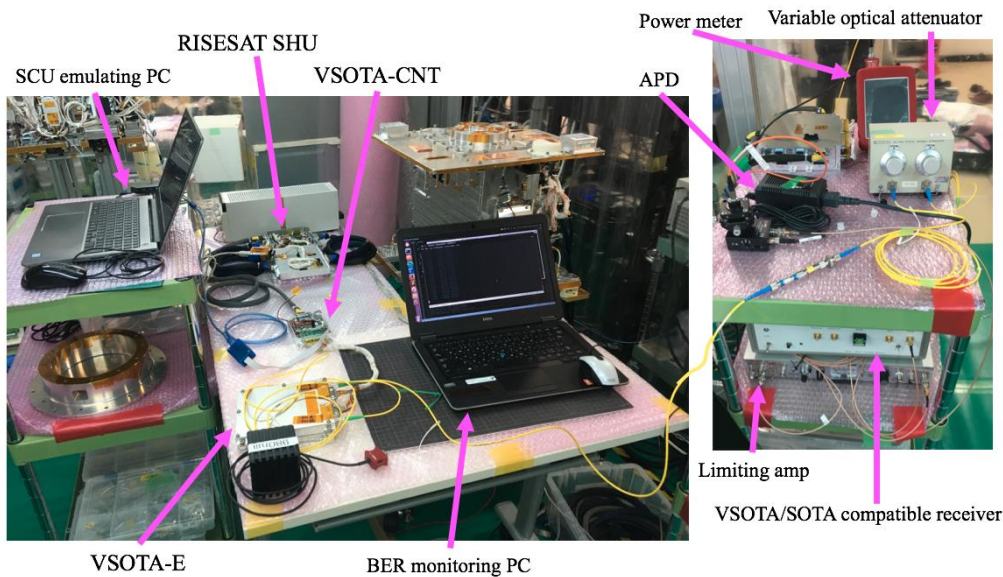


Figure 9. VSOTA end-to-end test set-up.

In this case, “end-to-end” refers to commands originating at RISESAT satellite central unit (SCU), which is being emulated on a laptop PC, that can be routed through the SHU to VSOTA, where they are implemented, and the veracity of the implementation is confirmed using the optical ground station receiving set-up. In the ground station receiving setup, transmission and reception of the optical signal in space is omitted in favor of a fiber optic connection with a variable attenuator. Using a coupled power meter, the power can be monitored while the light signal is attenuated, before the signal goes to the receiver. The receiver consists of avalanche photodiode (APD) and a DC limiting amplifier. This connects to a BER measurement and recoding apparatus, which can be controlled and monitored over a serial interface. Using this test configuration, the correct operation of both laser transmitters in continuous wave mode, PRBS-11 mode,

and PRBS-15 mode was checked and confirmed. For the PRBS modes, data rates were varied and confirmed as well. Particular test items were used to prove that the requirements for the mission success criteria can be met. Table 4 shows the test items and the mission success criteria to which they correspond.

Table 4. VSOTA mission success criteria.

Test Item	Test Item Description	Mission Success Criteria
T1	Achieve a BER of 0 for PRBS-15 on TX4 at 1 Mbps for 1 minute, while recording power consumption and temperature telemetry	F1, F2
T2	Achieve a BER of 0 for PRBS-11 on TX4 at 100 kbps for 1 minute, while recording power consumption and temperature telemetry	F2
T3	Achieve a BER of 0 for PRBS-11 on TX1 at 100 kbps, while recording power consumption and temperature telemetry.	M1, M2, F2
T4	Simultaneously power TX1 and TX4 in CW mode, while recording power consumption and temperature telemetry.	M2, E2
T5	Check that a low duty cycle bit pattern (0x01) can be sent just by modifying the software	E1, E3

6. CONCLUSION

The paper presented an overview of RISESAT's optical terminal VSOTA and its space-to-ground optical communication demonstration, including the specifications of VSOTA and HPT, a description of the optical ground station tracking implementation using body pointing, and the mission success criteria of the demonstration. An update on the current status of the RISESAT optical communication subsystem assembly and integration was also given, focusing on the end-to-end electrical configuration and communications tests that have been performed recently.

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