**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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International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 1056247 · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296107



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# SOTA OPTICAL DOWNLINKS TO DLR'S OPTICAL GROUND STATIONS

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ABSTRACT

Optical Satellite Downlinks have gathered increasing attention in the last years. A number of experimental payloads have become available, and downlink experiments are conducted around the globe. One of these experimental systems is SOTA, the Small Optical Transponder, built by the National Institute of Information and Communications Technology (NICT).

This paper describes the downlink experiments carried out from SOTA to the German Aerospace Center's Optical Ground Stations located in Oberpfaffenhofen, Germany. Both the Transportable Optical Ground Station (TOGS) as well as the fixed Optical Ground Station Oberpfaffenhofen (OGS-OP) are used for the experiments. This paper will explain the preparatory work, the execution of the campaign, as well as show the first results of the measurements.

## I. INTRODUCTION

Optical communication downlinks from low Earth orbit (LEO) satellites may be a solution to overcome the existing bottleneck in transmitting e.g. Earth observation data to the ground. The high data-rates offered by optical communication technologies, and the low size, weight and power (SWaP) required by optical terminals, make them an attractive solution in a number of applications.

After decades of research, and with exhaustive use of optical technologies in terrestrial applications, the first space applications of optical communication links are becoming a reality, as is e.g. shown by the optical links employed in the European Data Relay System (EDRS) [1], or the Lunar Laser Communication Demonstration (LLCD) [2].

Since about ten years, experimental optical downlinks from LEO-spacecraft to Earth have been performed as well. Probably the first downlinks were performed with the KIRARI satellite by JAXA, NICT and others [3–5]. In the recent years, a number of further experimental payloads have been launched. NASA-JPL had great success with OPALS, the Optical PAyload for Lasercomm Science [6], [7], which has been installed aboard the ISS and performed successful experiments between ISS and ground.

Furthermore, NICT has developed SOTA, the Small Optical TrAnsponder, which has been embarked on the SOCRATES satellite and is the main subject of this paper. SOCRATES has been launched on 24th of May, 2014, and a number of experiments to NICT's optical ground station in Tokyo have been performed [8], as well as to international partners [9].

Besides that, the German Aerospace Center (DLR) has been developing experimental optical communication payloads within its OSIRIS project as well. The second OSIRIS generation, which has been embarked aboard DLR's BIROS satellite [10], has been launched on 22nd of June, 2016, and will be tested in-orbit in Fall 2016.

## II. SMALL OPTICAL TRANSPONDER

The National Institute of Information and Communications Technology (NICT) in Japan has developed a Small Optical TrAnsponder (SOTA), which has been mounted on the Space Optical Communication Research Advanced Technology Satellite (SOCRATES), launched on 24th of May, 2014 [11]. The SOTA mission has reached full mission success level in June, 2015 and as a part of the extra success activities NICT has started several international collaborations for experiments between SOTA and different optical ground stations (OGS) around the Globe [12].



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*A. SOTA Interface*

The SOTA interface is shown in Fig 1 and the downlink characteristic of SOTA are shown in Table 1. SOTA is equipped with four laser sources, Tx2 and Tx3 are reserved for polarization measurements related to future satellite-to-ground QKD experiments and are part of the extra success mission. The main wavelength, used for international experiments is 1549 nm (Tx4) since it allows atmospheric propagation measurements on the main wavelength of interest for future missions. Optional wavelength is 976 nm (Tx1) but in this case only the coarse tracking is available (marked as "Acquisition and tracking sensor" in Fig 1) since the fine tracking is within the Tx4 module (marked as "Rx" in Fig 1). The beam parameters for both wavelengths are shown in Table 1.

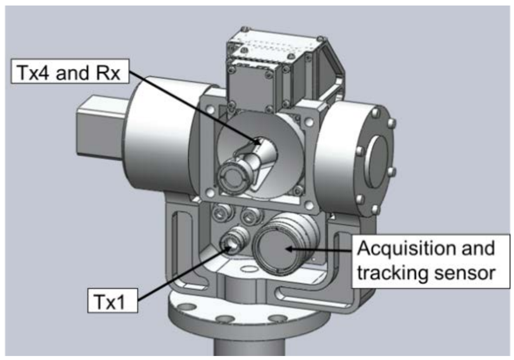


**Fig 1.** Scheme of the transmitter and coarse tracking sensor positions

**Table 1.** SOTA downlink characteristics

| Parameter | Tx1 | Tx4 | Others |
|---|---|---|---|
| Wavelength (nm) | 976 | 1549 | at 25degree Celsius, 0.1nm/deg |
| Polarization | Random | RHCP | |
| Data rate (Mbps) | 10 or 1 | 10 or 1 | Selectable |
| Intensity (MW/sr) | 0.89 | 0.57 | |
| Divergence angle (μrad) | 500 | 223 | -3dB Full width |
| Pointing loss (dB) | -3.4 | -5.7 | |
| Atmospheric loss (dB) | -5.6 | -3.9 | at NICT OGS |
| Irradiance (nW/m$^2$) | 112 | 63 | at ground, 1000km distance |
| Modulation | OOK | OOK | NRZ, PRBS-15, the generating polynomial is X^15+X^14+1. |

For transmission PBRS-15 signal with a rate of 10 Mbps has been chosen.

The uplink beacon should be at 1064 nm wavelength in order for SOTA to be able to detect it (Table 2). Careful calculation of the beacon divergence angle and the transmit power is necessary in order to guarantee irradiance levels that are enough for smooth beacon acquisition. Furthermore, the beacon light must hit SOTA for several seconds so that SOTA gimbals can point to the OGS station and start successful tracking. This is necessary due to the very slow gimbal movement in order not to affect the satellite orbit.

**Table 2.** SOTA uplink (tracking and acquisition) characteristics

| Issues | Acquisition and coarse tracking | Fine tracking |
|---|---|---|
| Wavelength (nm) | 1064 ± 3 | 1064 ± 3 |
| Required irradiance (μW/m$^2$) | 11~209 | 11~209 |

The experiment flow is shown in Fig 1. First, the laser diode of SOTA is switched on and both SOTA and the OGS are in open pointing mode – SOTA is pointing to the supposed position of the OGS, and the OGS is tracking SOCRATES based on orbital information in TLE format. Then, the beacon from the OGS is switched



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on. When its light is registered in the SOTA QD sensor, coarse tracking (gimbal moving) and, if available, fine tracking takes place and as a result the SOTA signal will be received in the OGS and data receiving will take place.

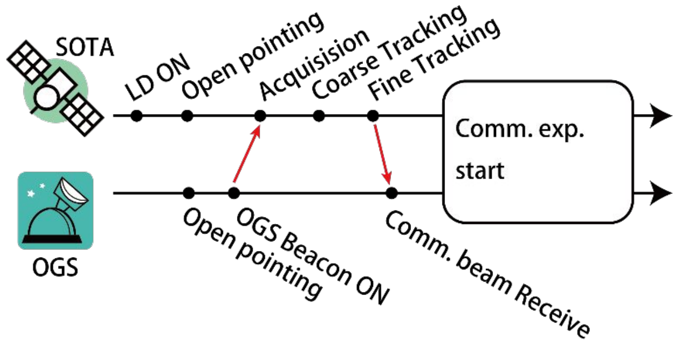


**Fig 2.** Experiment flow (Image source: NICT)

III. Description of ground segment

The ground segment for SOTA-downlinks to Oberpfaffenhofen consists of two optical ground stations, namely DLR's Transportable Optical Ground Station (TOGS) and DLR's Optical Ground Station Oberpfaffenhofen (OGS-OP). TOGS has been equipped with the required beacon laser system and was responsible for link acquisition with SOTA. OGS-OP focused on recording atmospheric measurements.

*A. Transportable Optical Ground Station (TOGS)*

The Transportable Optical Ground Station (TOGS) features a pneumatically deployable telescope with a main mirror diameter of 60 cm [13]. It is a Cassegrain-Telescope in Ritchie-Chrètien configuration with main and secondary mirror. Both mirrors are manufactured from aluminum for robustness, and the telescope mount itself is manufactured of carbon fiber to make it light-weight, robust and stiff. It is supported on the ground by four manually mounted supports that provide levelling of the station and compensation for ground roughness. The TOGS telescope can be automatically folded in and out of the transport box within few seconds to achieve a short installation and setup time. In addition, the body of the TOGS itself contains all necessary control units for calibration and operation.

A picture of TOGS and its optical system, which is embarked behind the telescope, is shown in Fig 3. The optical signal received at the telescope is collimated with a lens. The collimated signal is splitted using a 90/10 optical splitter. 10% of the signal is sent to the tracking sensor for closed-loop tracking, while 90% of the power is guided to the receiver front-end (RFE) that converts the received optical signal to electrical and provides data to the transceiver for decoding the received data.

For the SOTA experiments, two beacon laser sources with 1064 nm were installed aside the telescope. The placement on the left and right sight of the telescope, respectively, ensured a higher average power as well as transmitter diversity for reduced fading at the satellite.



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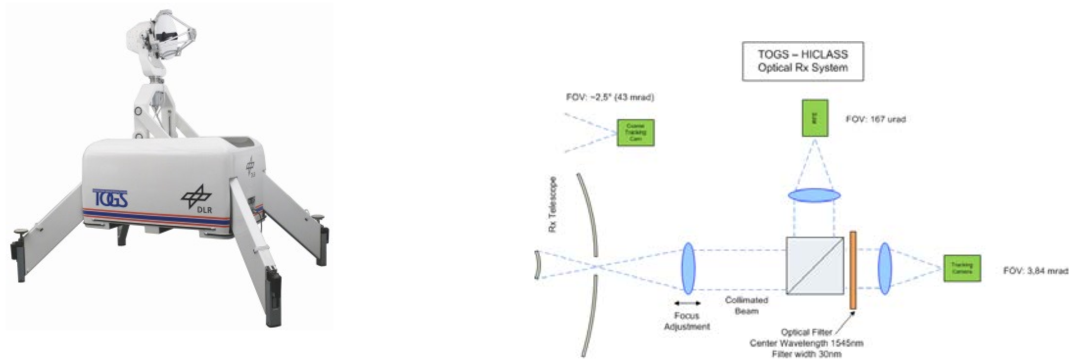


**Fig 3**. Left: Transportable optical ground station (TOGS); Right: Optical System of TOGS (Image source: DLR)

In order to achieve good pointing, acquisition and tracking (PAT), control software for the TOGS is written in C++ and installed in a PC with real-time linux kernel. The PAT process in TOGS can be explained with the help of Fig 4. For initial pointing, TOGS uses its own GPS position and the orbit information of the satellite (which, in the case of SOTA, is in two line element (TLE) format) and the current time to calculate the pointing angle and commands the telescope mount to point towards the satellite. This process is named open-loop or blind pointing. The blind pointing accuracy of the TOGS must be sufficient to hit the satellite within the beacon laser's divergence. Once the satellite terminal acquires the beacon signal, it starts close-loop tracking and transmits the signal. TOGS then acquires the signal and as soon as the signal is detected on the tracking camera, closed-loop tracking is activated on the TOGS.

To obtain a sufficient blind pointing accuracy for TOGS has been one of the challenges during ites development. Reliable timing accuracy, improved tracking algorithms and a good referencing based on a star calibration made the experiment successful. Calibration of the TOGS was one of the crucial aspects, as the TOGS consists of both mechanical structure and optical elements, which are not perfectly aligned and introduces some errors in different directions. Such errors could be azimuth- or elevation offsets, non-perpendicularity of azimuth and elevation axis, non-perpendicularity of optical axis, tilt of axes etc. Such errors cannot be compensated by adding simple offsets and therefore require good star calibration and derivation of pointing model parameters which can compensate those errors. In addition, the timing behavior of the software was significantly improved by using an additional GPS time reference and a real-time kernel for the operating system. During the experiment, SOTA and TOGS were able to acquire the signal immediately and track their optical signals throughout the link.

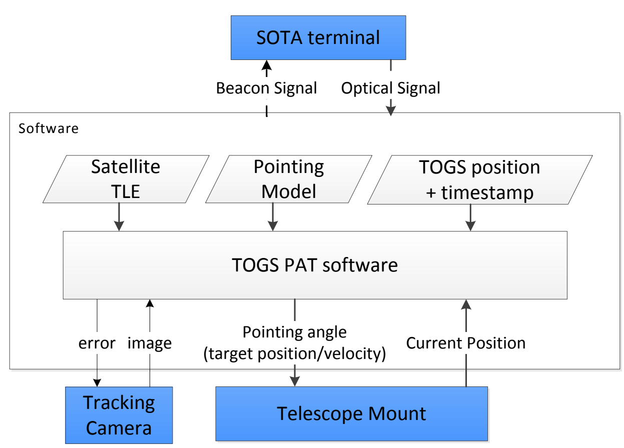


**Fig 4**. Block diagram showing pointing, acquisition and tracking of the TOGS (Image Source: DLR)

*B. Optical Ground Station Oberpfaffenhofen*

The OGS-OP is the stationary partner lab of the TOGS with a higher focus on research experiments and flexibility [14]. The station is designed in a way to easily integrate and exchange measurements devices and laser systems. The generic functional block diagram is shown in Fig 5. The incident beam enters the telescope.



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The collimations optics collimate and compress the beam for further processing. An optional fine pointing assembly (FPA) stabilizes the beam by use of signals from the NFoV camera (Narrow Field of View) and FPA control. The free-space coupling systems splits the signal and distributes it to the measurement devices, receiver front-end (RFE) and NFoV camera. The black vertical bar denotes components that are assembled on the telescope mount and therefore mechanically coupled. The mount is controlled by using signals from the WFoV camera (Wide Field of View). Two 2 inch side telescope focus light on a PIN diode or APD for separate power measurements. The laser and beacon telescopes are not installed for the SOTA experiments since the TOGS is used for link acquisition. The installed measurement devices behind the 40 cm telescope are a PIN diode for power measurements and a pupil camera for characterization of irradiance and power scintillation.

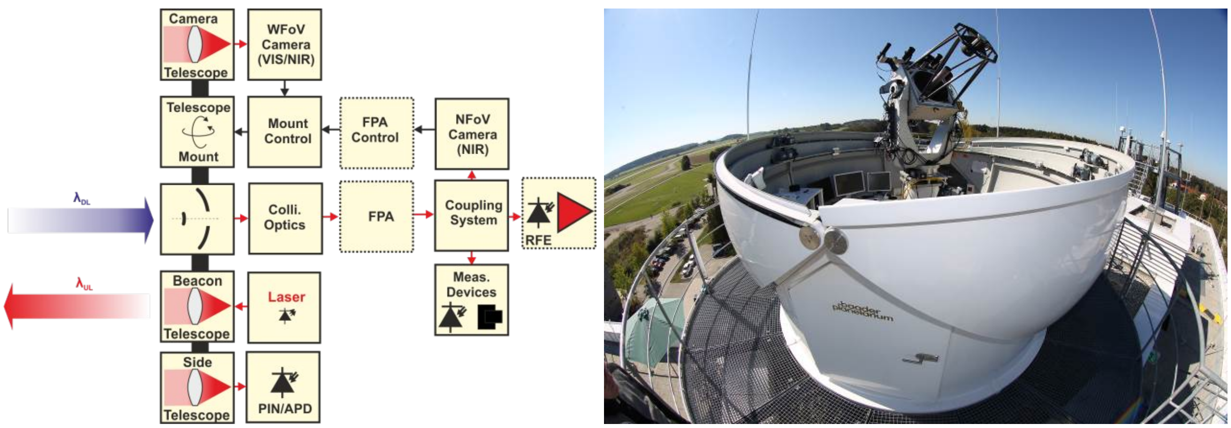


**Fig 5**. Left: generic functional block diagram of OGS-OP; Right: Image of open dome with 40 cm Cassegrain telescope (Image Source: DLR).

IV. Conducted Experiments & Results

On May 6th, 2016, a downlink between SOTA and TOGS as well as OGS-OP was set up. The most important parameters of the satellite overflight are shown in Table 3.

**Table 3.** Characteristics of SOTA downlink to Oberpfaffenhofen

| Parameter | Value | Comment |
|---|---|---|
| Start time of experiment | 22:54:00 | UTC |
| Start elevation of experiment | 26.7° | |
| End elevation of experiment | 22:55:45 | UTC |
| End elevation of experiment | 54.6° | |
| Maximum elevation of overflight | 56° | |

In Fig 6 we show the telemetry data for the received optical power in the coarse pointing quadrant detector (QD). The necessary count level for smooth tracking and acquisition of SOTA is 300 and it must be maintained for up to several seconds. We can see that we have a stable and strong signal through the whole pass. SOTA cannot operate under daylight due to QD sensor saturation; this is the reason to have shorter pass only up to the equinox.



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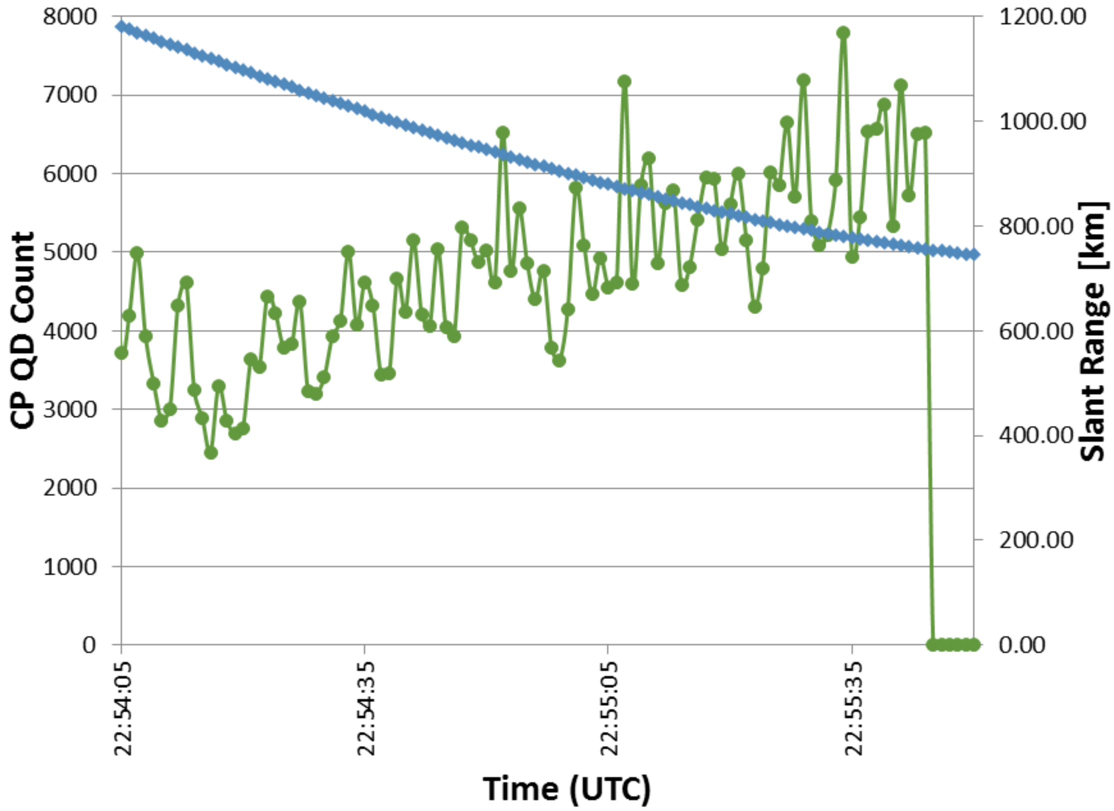


**Fig 6**. SOTA telemetry measured during the downlink experiment. (Image source: NICT)

Fig 7 shows images of the tracking cameras of TOGS and OGS after link closure.

**Fig 7**. Tracking camera images of TOGS (left) and OGS-OP (right) after link acquisition and engagement of closed optical tracking loops. (Image source: DLR)

Fig 7 (left) shows the scintillation signal over elevation received by the OGS-OP sampled with 20 kS/s. Signal amplitude increases with elevation as expected. The signal shows that link lock was achieved between 32° and 55°. The right image shows an example record of the pupil camera at 54° elevation. The annular shape is caused by the secondary mirror of the Cassegrain telescope. The four cuts at the edges arise from the holder clamps of the primary mirror. The speckle pattern of the irradiance scintillation pattern is clearly visible. The vertical background lines are artefacts from the camera electronics.



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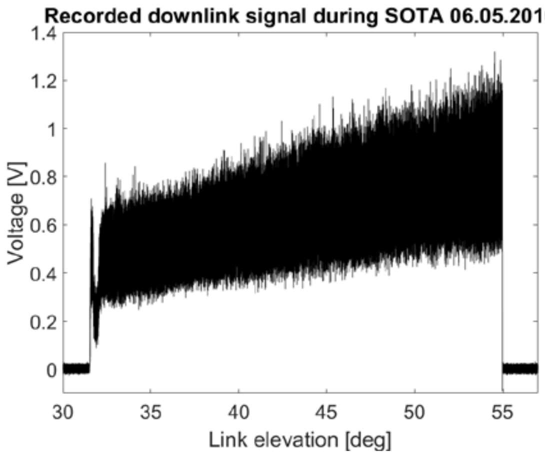


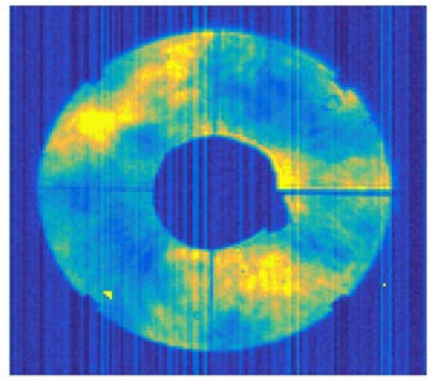

**Fig 8**. Left: recorded scintillation signal during SOTA downlink. Right: example of unprocessed pupil camera image of scintillation signal. (Image source: DLR)

V. Summary & Conclusions

The National Institute of Information and Communications Technology (NICT) and the German Aerospace Center (DLR) could demonstrate an optical downlink between NICT's Small Optical TrAnsponder (SOTA) and DLR's optical ground stations TOGS and OGS-OP in Oberpfaffenhofen, Germany. The main focus of the experiment was the gathering of atmospheric measurement data with the instruments of OGS-OP. The systems involved, both in the space- and ground-segment, as well as sensor data from both sides has been presented in this paper. Further evaluation of the measured data is currently ongoing and further SOTA downlinks with the goal of gathering more atmospheric measurement data might be conducted in Fall 2016.

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