Downlink communication experiments with OSIRISv1 laser terminal onboard Flying Laptop satellite

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Received 25 October 2021; revised 7 February 2022; accepted 7 February 2022; posted 8 February 2022; published 3 March 2022

Downlink measurement campaigns from the optical downlink terminal *OSIRISv1* onboard the LEO satellite *Flying Laptop* were carried out with the French Observatoire de la Côte d'Azur and with two Optical Ground Stations of the German Aerospace Center. On/Off keyed data at 39 Mb/s was modulated on the laser signal and according telecom reception was performed by the ground stations. The pointing of the laser terminal was achieved by open-loop body pointing of the satellite orientation, with its star sensor as attitude control signal. We report here on the measurements and investigations of the downlink signal and the data transmission.

1. Introduction

In the race of high data rate transmission for the Space-Ground link, optical data transfer, or *lasercom*, is a promising candidate which may replace classical RF technology in certain applications through the following features: large bandwidth with high data-rate, license free transmission spectrum, less power consumption and low mass requirements [1]. Feasibility of lasercom downlink has been demonstrated at high data-rate through the atmosphere in various missions: From first demonstrations at 1024 Mbps with an 830nm data signal in the 1990s [2], and 50 Mbps at 847nm in the 2000s [3], lasercom has been demonstrated successfully at higher data rate up to 5.625 Gbps bidirectional and with coherent phase-modulation between the NFIRE satellite and an Optical Ground Station (OGS) at 1064 nm [4]. Recently the 1550nm wavelength is employed for several small downlink terminals [5] [6]. Despite of the great potential of lasercom, its performance in satellite-to-ground links is still limited by the adverse effects of the atmospheric channel (absorption, scattering and index-of-refraction turbulence [7]), by intermediate cloud blockage, and by the challenges of extremely precise pointing during a link pass with high angular speed. Both effects increase mean bit-error-ratio (BER) and thus reduce overall signal quality. However, rapid improvement on optical power of modulated laser source, pointing and tracking strategy onboard satellite, and specialized error correction coding together with strong interleaving allow integration and reliable use of laser communication terminals in small satellites at Low Earth Orbit (LEO) [8].

The technique employed for the measurements presented here allows a simplified setup of the space-part, avoiding dedicated opto-mechanical pointing assemblies as well as elaborate optical tracking of a ground-beacon, and even the generation of this beacon signal by the OGS. Instead, by rotating the whole satellite-body during downlink, controlled by its attitude-knowledge from onboard star-cameras, a fixed laser emitter can be directed onto an OGS. Similar technique has been shown by [9] for cube-sats at 1064nm signal wavelength. The proceeding described here allows application of high-speed optical data downlinks by standard nano-sats (50cm / 100kg class satellites) with only little modifications.

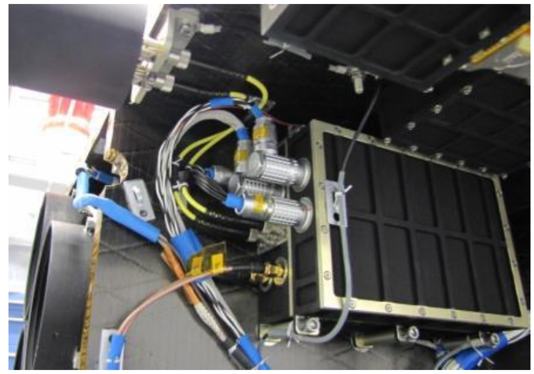
At the end of December 2018, three successful links between the MeO (Metrology and Optics) telescope and the laser terminal OSIRISv1 (Optical Space Infrared Downlink System version 1) were established. This is the first time a downlink beam from a body-pointing lasercom satellite has been detected in Grasse station. Data downlinks with OSIRISv1 were also performed to DLR's OGS-OP (Optical Ground Station Oberpfaffenhofen) and TOGS (Transportable Optical Ground Station) located at Oberpfaffenhofen near Munich.

This paper reports on the performances of these successful links. After describing the Spacecraft and the OGSs, we give a description of the lasercom experiments. The last parts is dedicated to the experimental results including detailed analysis of the optical power received at OGSs and performances in terms of BER.

2. Spacecraft- and OGS'-description

A. Satellite and Laser Terminal – general Description

The OSIRISv1 laser communication terminal has been designed for the Flying Laptop satellite (FLP) [10]. The laser terminal operates in the 1550nm-range and uses body pointing of the satellite to direct the laser beam towards the optical ground station. FLP with OSIRISv1 on board has been launched on July 14th 2017 from Baikonur into a near-circular Low Earth Orbit of 586 x 604 km with 97.5° inclination (NORAD-/Spacetrack-#: 42831). FLP is a small satellite that was developed and built by graduate and undergraduate students at the Institute of Space Systems of the University of Stuttgart with support by space industry and research institutions. The satellite mission is operated by the University of Stuttgart and has the main goals of technology demonstration, education, and Earth observation. Besides OSIRISv1, FLP has a multi-spectral imaging camera system, an Automatic Identification System (AIS) receiver for ship-tracking, and a wide-angle camera. The mission is currently in the second extended operations phase until July 2023. The attitude control system which is used to point the satellite body is based on Star Cameras and Fiber-Optic Gyroscopes and uses Reaction Wheels as actuators. The components of OSIRISv1 installed on FLP are shown in fig. 1. The OSIRISv1-payload consists of two boxes where one is the power supply and the other contains the laser sources Tx1 and Tx2 (laser transmitters 1 and 2). Both laser sources are connected to separate collimators, which have been referenced to the Earth observation imaging system of the satellite to be able to have a starting point for the search patterns during commissioning phase.



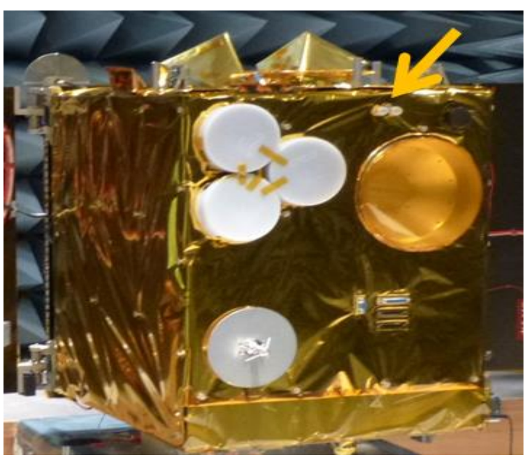


Fig. 1. Satellite-hardware: Up: Flying Laptop satellite with the two laser transmitter collimators on the upper right indicated by an arrow; down: the OSIRISv1 power supply and laser source boxes installed on Flying Laptop.

The pointing requirement for OSIRISv1-downlinks was matched between the transmitter-collimators' divergence angle and the precision from the satellite's attitude control system. The later again was defined through the camera-payloads of FLP as 150 arcseconds (727 µrad). Accordingly, 1.0 mrad FWHM (Full-Width at Half-Maximum) divergence was used for the gaussian beams from OSIRISv1, leaving a small margin to the given pointing precision goal of FLP.

Tx1 is based on a seed-laser with a subsequent optical amplifier (Erbium-Doped Fiber Amplifier, EDFA) with 1W optical output power, while Tx2 is based on a directly modulated High-Power Laser Diode (HPLD) [11]. Both lasers are connected to optical collimators with a FWHM divergence angle of 1.0 mrad each. Based on the selected orbit, the beam divergence, and optical output power, Tx1 can apply various data rates up to 622 Mb/s while Tx2 can transmit 39 or 78 Mb/s. Only Tx1 was used in the experiments described here. Fig 2 and Table 1 give an overview of the technical specification of OSIRISv1. With its maximum transmission power of 1W during a downlink, the payload consumes 26W at a system weight of 1.3kg.

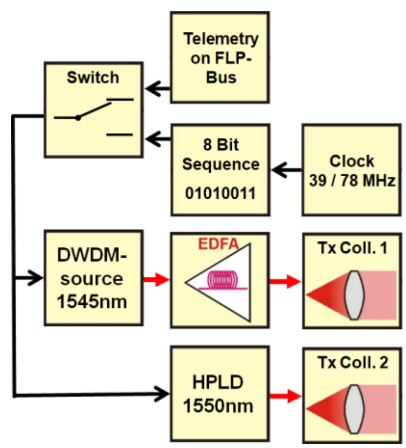


Fig. 2. Functional diagram of the OSIRISv1-module on Flying Laptop satellite.

OSIRISv1	Tx1 (EDFA)	Tx2 (HPLD)
wavelength	1545 nm	1550 nm
Polarization	random	random
Data rate options	39 to 622 Mb/s in steps of factor two	39 or 78 Mb/s
Optical Power mean	1 W	0.10 W
Divergence FWHM	1.0 mrad	1.0 mrad
Pointing loss	<3 dB	< 3 dB

Table 1. Design-Specifications of OSIRISv1 downlink terminal.

With the parameters stated in table 1 (and regarding an internal Tx-loss of -1.5dB), we calculate an axial intensity at 20° elevation of 328 nW/m² at the distance to DLR-IKN station (no atmospheric turbulence effects regarded, only average power considered). When also regarding the atmospheric losses we derive 233 nW/m² in front of the telescope. This would result (after OGS-internal loss by splitting to the tracking-path) in a maximum power onto the data detector in the 60cm TOGS of 39nW. Table 2 shows this link budget estimation. Later we measure a power of 15 nW, fitting with these estimates after considering residual pointing loss.

Link Budget Component	unit	value
Tx-power	dBm	+30
Tx-internal loss	dB	-1.5
Divergence FWHM	mrad	1.0
Tx antenna gain	dB	+70.4
circular orbit height	km	595
Distance at 20° elevation	km	1381
Free-Space loss	dB	-261,0
Atmospheric loss	dB	-1.5
on-axis intensity at Rx	nW/m²	233
Rx telescope area (60cm TOGS)	m²	0.26
Rx-aperture gain	dB	+121.2
Rx-internal loss and splitting	dB	-2
Power onto detector	nW	39

Table 2. Link budget for OSIRISv1 at 20° elevation (no pointing error).

B. Grasse Optical Ground Station – General information

The MeO (Metrology and Optics) telescope of Grasse station (France, 43.7546° N 6.9216° E, 1323.1m) was designed by the end of the seventies in the framework of a laser-ranging program dedicated to the Moon. Since the beginning of 2000, a new organization has been set up permitting to enlarge the initial scientific objectives of the station and to make research and development activities on laser links in general. The station is located in the hinterland of Grasse, France at 1270 meters above sea level. The station is based on a 1.54 m Ritchey Chretien telescope installed on an Alt-Az mount (Fig. 3 and 4). The telescope is able to track any targets in the sky at a maximum speed of 5°/s. The mount works with direct drive motors and direct encoders for both azimuth and elevation axes. The pointing accuracy is < 2 arcsec RMS, obtained through a calibration process using absolute position of stars.

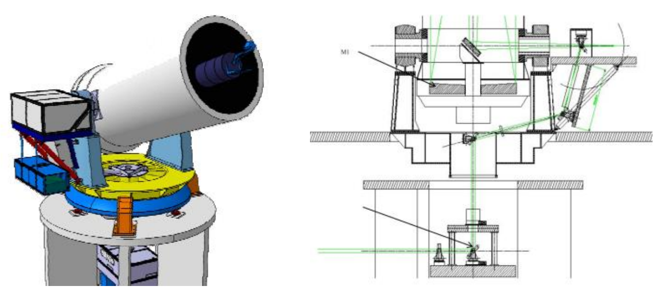


Fig. 3. Grasse station (France) with 1.54 m MeO telescope (Ritchey Chretien telescope installed on an Alt-Az mount).

Since 2014, the Grasse station, has been upgraded in order to be able to take part in lasercom experiments [12]. Several campaigns have been successfully performed since 2015 between Grasse station and lasercom terminal at low Earth orbit, SOTA (Small Optical Transponder) onboard SOCRATES satellite [13], OPALS (Optical PAyload for Lasercomm Science) integrated on the International Space Station (ISS) [14]. Atmospheric turbulence effects, downlink wavefront, lasercom link performances (pointing, tracking, link budget, bits errors rate) have been analyzed [15], [16]. To prepare for OSIRIS' satellite mission, the lasercom optical bench is moved from Nasmyth (mechanically connected to the Alt-Az gimbal of the telescope) to the Coudé focus (located underneath the telescope) in order to integrate more auto-tracking system and measurement instruments. In order to establish the lasercom at higher data-rate (Gbps), the ground lasercom detector needs to have a high bandwidth and high sensitivity. Those requirements lead to use a very small detector narrowing the field of view. Particularly, it causes difficulty for maintaining the downlink signal on the small detector during the satellite pass. Thus, for maintaining the laser spot on small detectors, a fine auto-tracking system, performed by a TipTilt mirror and a camera, is integrated at the input of the optical bench. In addition, the displacement of the optical bench from Nasmyth to Coudé allows creating three sub-apertures, or three independent measurement channels (for telecom detection, Adaptive Optical bench and wavefront analyzer), from 1.54 m full aperture of the telescope while maintaining sufficient signal power for each measurement channel. These additional measurement devices will be analyzed in a later step.

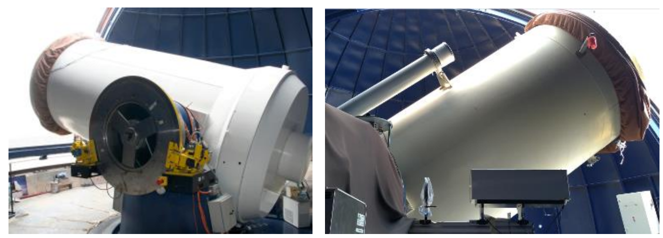


Fig. 4. MeO telescope (left side with motor and right side with refracting telescope used for tracking).

C. DLR-IKN Optical Ground Stations – General information

DLR-IKN has used two optical ground stations to conduct experiments with OSIRISv1, namely the Optical Ground Station Oberpfaffenhofen (OGS-OP, located at 48.0848° N, 11.2780° E, 653 m height) and the Transportable Optical Ground Station (TOGS, located nearby) [17], [18]. Fig. 5 gives an impression of the situation on the rooftop of DLR-IKN.

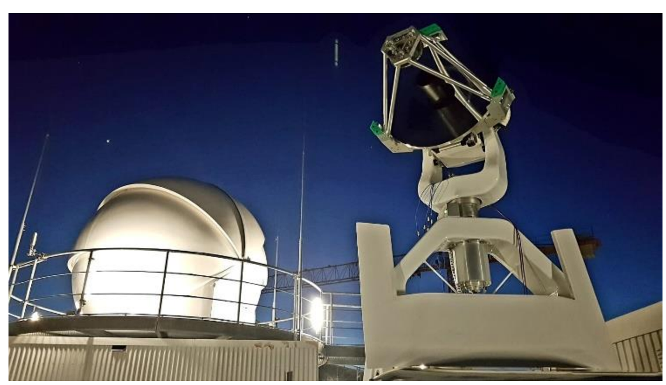


Fig. 5. DLR-TOGS (60cm) on the rooftop of IKN-building (right), with the closed dome of OGS-OP (40cm) to its left.

In the scope of the experiments with OSIRISv1, a PIN diode was installed in the primary focus of OGS-OP, allowing measuring the received power.

DLR's Transportable Optical Ground Station (TOGS) with its 60 cm telescope had an APD receiver front end installed within the optical system in order to test data reception from OSIRISv1.

3. Lasercom experimental setup

A. Grasse station – Optical bench

The downlink beam from satellite is received through MeO telescope coudé, coupled to the optical test bench. The collected beam is then split in several parts in order to perform multiple measurements (Fine tracking camera, telecom detector, wavefront analyzer and adaptive optics bench – ONERA). Because of link budget limitations (loss in MeO Coudé ~ 7 dB) for multi measurements, 3 sub-apertures (diameter of 40 cm and 50 cm, "Beam-Distribution" in Fig. 6) are created from the full aperture of MeO telescope. After the beam splitter, the first beam is dedicated for telecom signal detection. The second part is dedicated for a Shack Hartmann wavefront sensor (SHWFS) to characterize atmospheric turbulence effect during experiment. The other is dedicated to LISA bench (developed by ONERA - French Aerospace Lab) for fiber coupling test using adaptive optics. The architecture of the optical bench and the characterization of each component are detailed in [19]. Evaluation of Shack-Hartmann and Adaptive-Optics performance shall be done in a later publication.

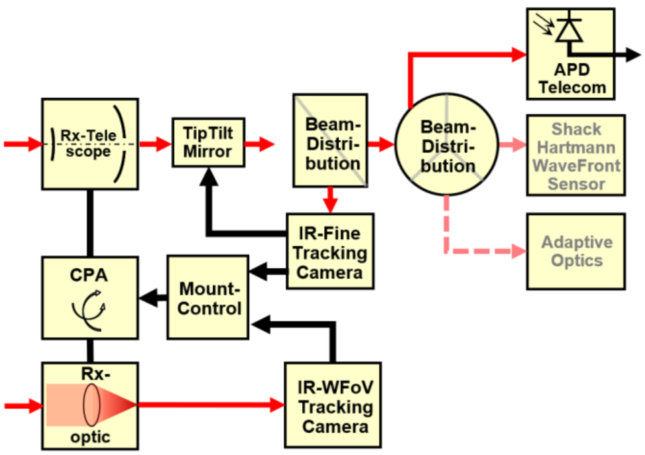


Fig. 6. Functional diagram of Grasse station as configured during FLP downlinks.

The TipTilt mirror system serves for fine tracking with a dynamic of ±30 arcsec. The coarse tracking is performed by a Wide Field of View camera (IR-WFoV) and a 200 mm refracting telescope mounted on MeO telescope. The very large FoV of 2200×1760 arcsec^2 allows to have a performant system for satellite finding and coarse tracking.. When the downlink beam is detected in the wide FoV camera, the autotracking software of MeO telescope tracks the satellite (coarse tracking by sending correction signal to MeO telescope) and brings the downlink beam into the IR-Fine Tracking Camera in order to enable fine tracking through the TipTilt Mirror. The coarse and fine tracking maintain the downlink beam coupled in all detectors in spite of satellite prediction error during the satellite pass [19].

The free space telecom detector is based on the detector APD Telecom - STH301-000-005 (bandwidth of 26 MHz) developed by SigmaWork and a digitizer CSE123G2-GS (configured at 500 MS/s and synchronized to a 10 MHz H-Maser clock) from Gage. The photodiode used in the detector module is a commercial 200µm InGaAs-APD, providing a field of view of 30 arcsec. The optical power level is measured also from the telecom detector. The digitalized signal (500 MS/s) is down-sampled to 2 kS/s for scintillation measurement. The noise of scintillation measurement (at 2 kS/s) is 1.8 pW RMS that adapts our need on optical level (from -70 dBm to -40 dBm).

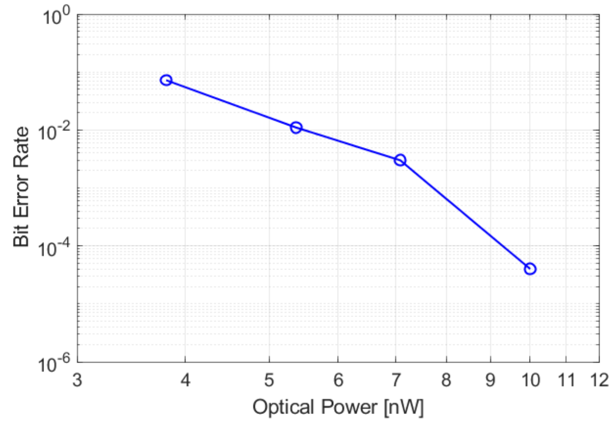


Fig. 7. Lab sensitivity verification of APD Telecom - STH301-000-005 , as used by Grasse MeO station during FLP-downlinks.

During OSIRISv1 experiment, three independent instruments are used to observe the atmospheric turbulence effects: MeO optical bench observes the lasercom downlink beam of OSIRISv1; PBL observes the Moon limbs; GDIMM observes the stars. The comparison between experiment data recorded of these instruments allows us to understand the turbulence effects on lasercom downlink beam flux fluctuation and wavefront error.

B. DLR-IKN-Stations – experiment setup

Both DLR ground stations were employed for FLP-downlinks: the fixed installed OGS-OP and the transportable TOGS. The OGS-OP performs acquisition and tracking with the separate WFoV telescope, and performs calibration with visible targets through an additional daylight-telescope. OGS-OP bears several measurement instruments to analyze downlink quality and channel influences. It also provides a fine tracking stage (FPA) to avoid any influence from miss-tracking errors with aeronautical targets, which but was not necessary with the smooth satellite movements during FLP-downlinks [20].

An optical power sensor with 1mm detector diameter was used to monitor the received intensity strength during FLP-downlinks. through the OGS-optics. This was translated into a sensor FoV of 1.2 mrad for this detector.

Although a Data Receiver Frontend (Data-RFE) can be installed in OGS-OP, the data reception during these FLP-downlinks was performed only by TOGS.

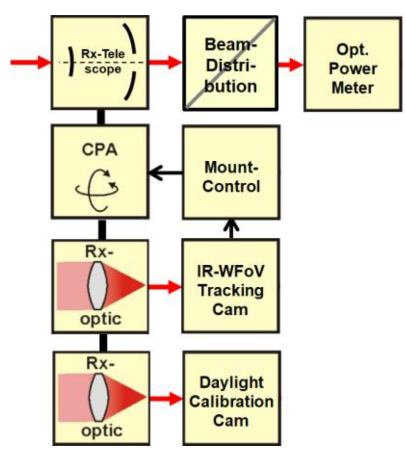


Fig. 8. Diagram of DLR's OGS-OP (40cm) as configured during FLP-downlinks.

In contrast to OGS-OP, the TOGS performs complete tracking through the camera inside the optical telescope. The separate WFoV-telescope and -camera is used for monitoring and calibration with visible targets only. Also, no dedicated measurement devices are installed at TOGS (Fig. 9). Focus is on pure binary-data reception, but an additional monitor from the RFE allows analog sampling of the data signal's amplitude. The FoV of the receiver APD is 167 µrad.

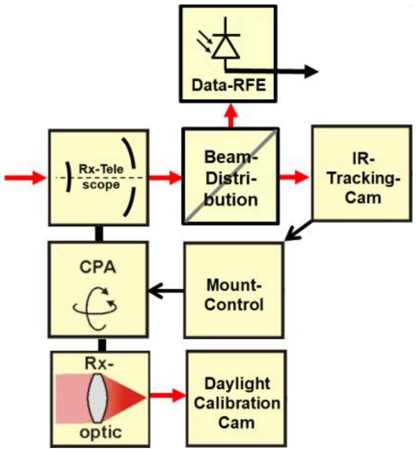


Fig. 9. Diagram of DLR's TOGS (60cm) as configured for FLP-downlinks.

Both OGS' were placed 10 meters apart on the roof of the IKN building. This allows distinguishing effects from index-of-refraction turbulence (IRT) on intensity, from such caused by satellite-pointing: Intensity-pattern from IRT are only sized several centimeters to decimeters and change in milliseconds, thus they do not correlate between both OGSs. Miss-pointing of the beam from the satellite, however, does cause large-scale and slower variations of the beam-pattern, and thus their received-power fluctuations do correlate between both OGSs. A later evaluation of these different power alterations will allow identification of the direction of pointing and thus will help optimizing beam-pointing.

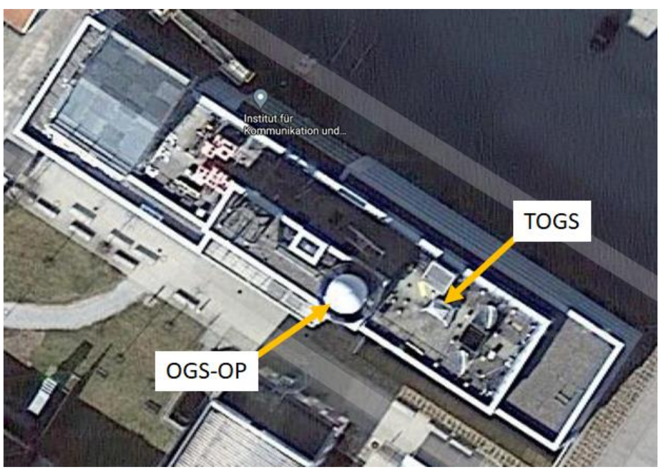


Fig. 10. Geometrical situation of both DLR-OGSs placed 10m apart on the rooftop of the IKN building. *(Image:* Google */ 2021 GeoBasis-DE/BKG)*

Results of optical OOK data reception are obtained via the receiver frontend based on an avalanche photo diode. This APD-RFE-100 shows a sensitivity according to the figure 11 at a data rate of 100Mb/s and test pattern PRBS=2^7-1.

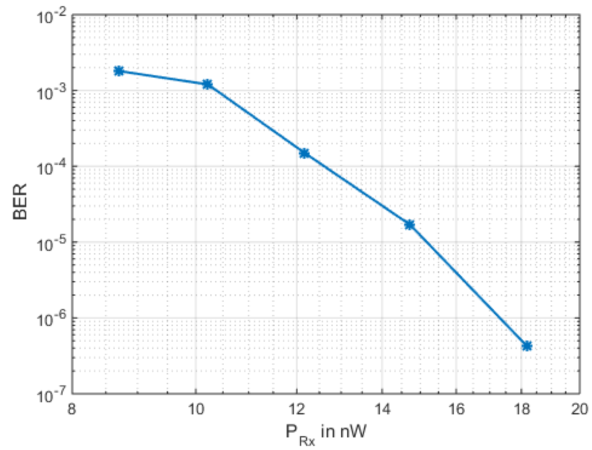


Fig. 11. Lab sensitivity verification of APD-RFE-100., as used by DLR in TOGS data reception during FLP-downlinks.

The parameters of all three OGSs are summarized in table 3

	MeO-OGS	OGSOP	TOGS
aperture diameter	50 cm (after splitting)	40 cm	60 cm
inner obscuration by secondary (diam.)	NA	13 cm	16 cm
detector diameter	data-APD: 200 µm	power sensor: 1 mm	data-APD: 200 µm
Field-of-View of data detector	142 µrad	NA	167 µrad
splitting between data-det. / tracking-cam	70 / 30	NA	90 / 10
FoV of tracking cam (diagonal)	300 µrad	15.4 mrad	3.84 mrad

Table 3. Specifications of the three optical ground stations

4. Experimental results

A. Grasse station – experimental results

Three passes of OSIRISv1 on Dec. 18, 19, 20 2018 have been provided to Grasse station of OCA. The first downlink signal of OSIRISv1 has been detected by MeO telescope on Dec.18, during 90 seconds. The spot of the downlink laser appeared on the Wide Field camera at 7.° elevation during 2 secs, and then it disappeared during 10 seconds and re-appeared at 9.0 deg elevation (Fig. 12 a), while the transmit source had to be switched-of after 20° of elevation. For Dec.19 pass, stray light from the Moon was clearly visible on the background of the Wide FoV camera (Fig. 12 b). A dynamic pointing bias from OSIRISv1 (on the ascending part) was observed. Very low optical level was detected at culmination of satellite, on the descending part the optical power detected was higher but there were large and slow fluctuations at 0.1 – 0.3 Hz. These fluctuations were not correlated to spot position variations detected by the TipTilt camera and they were common in all detectors (APD photodiode and 3 cameras). Thus, we conclude that all strong fluctuations 0.1-0.3 Hz observed in the downlink signal relate to satellite pointing bias.

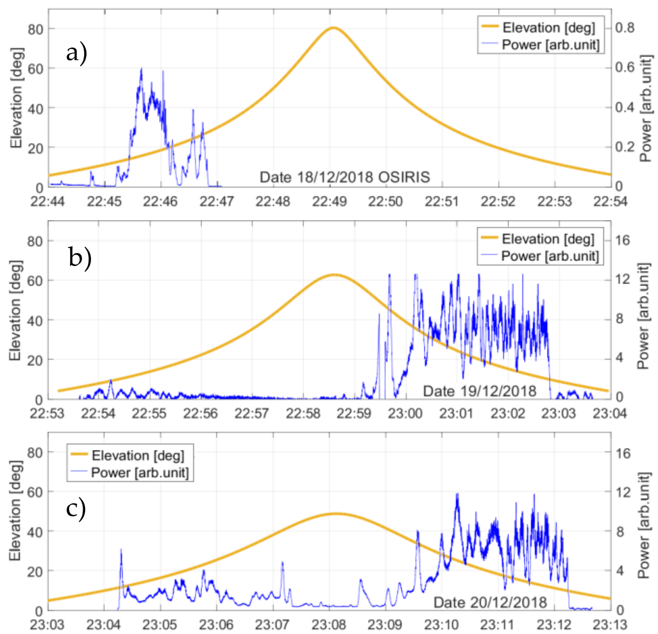


Fig. 12. Signal recorded by wide FoV Camera – 200 mm telescope (2220×1760 arcsec) for the 3 passes. (a) Dec.18.2018; (b) Dec.19.2018; (c) Dec.20.2018. Note that optical powers (blue curves) in these figures are not at same scale.

For the third pass (Dec.20, Fig. 12 c), the downlink beam was detected by MeO at lower power during ascending and peak elevation, while it was well observed in the descending phase. The prediction error of OSIRISv1 (from TLE) is estimated to be roughly 100 arcsec peak-to-peak in elevation and 220 arcsec peak-to-peak in azimuth. Note that several parasites have been detected in foregoing trials [15], [6]. Such parasites (10 Hz to 200 Hz) in optical fluctuation data falsified and complicated the scintillation index estimation. During OSIRIS campaign however, no oscillation relating to vibration was observed in the spectrogram of flux fluctuation. This allowed to correctly characterize the optical power fluctuation caused by atmospheric turbulence. The normalized spectrogram Fig. 13 (below) shows a larger frequency range when the satellite elevation increases.

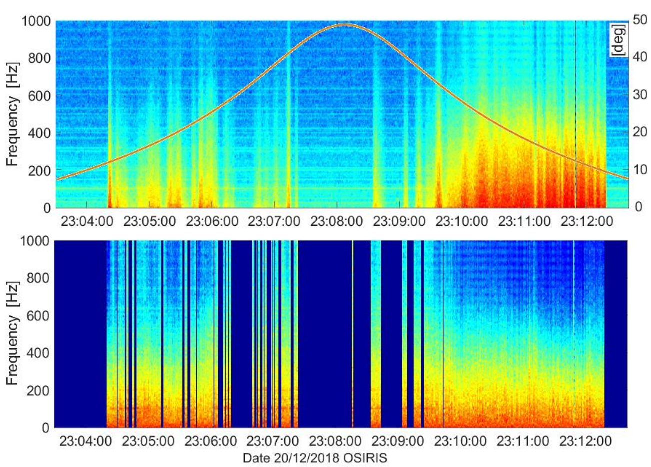


Fig. 13. Power Spectral Density (PSD) spectrogram of flux fluctuation (up), and normalized PSD of flux fluctuation spectrogram (below) estimated from PSD for OSIRISv1 to MeO (Dec.20.2018).

The sensitivity of the telecom detector is 1.7 mV/nW and performance is $BER < 10^{-4}$ for power $P_{opt} > 10$ nW. Fig. 14 presents an example of the telecom data detected by MeO telescope, 8 bits repetition 11001010 at 39 Mbps, digitalized at 500 MS/s.

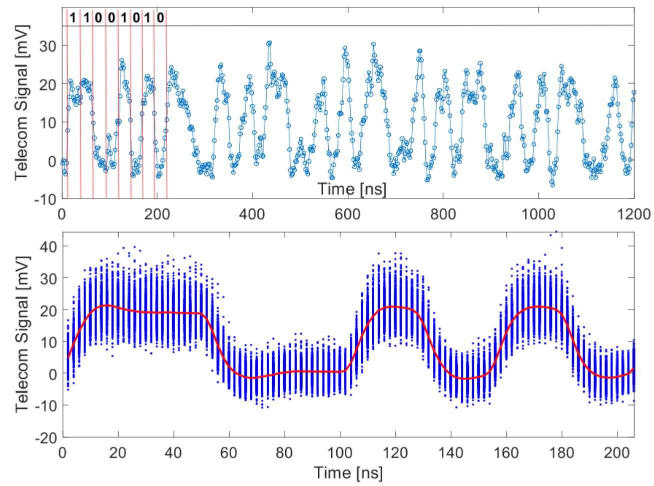


Fig. 14. Raw telecom signal from OGS detected at OGS (a) and zoom on the 8 bit sequence (b).

The Bit Error Ratio (BER) of the downlink telecom signal is calculated from collected telecom data by using frame-synchronization recovery and bits comparison. BER is estimated on every 82552 bits sequence - or 2 ms duration data (equivalent to 10^6 samples on recorded data at OGS). The synchronization process is performed by sweeping 400 synthetic bits (sampled at 500 MS/s) on recorded data for each 82552 bits sequence. Then, bit recovery process is performed, regarding the Doppler effect caused by radial velocity of the satellite. Fig. 15 shows measured BERs and corresponding average optical powers (each 2 ms duration) for the pass of Dec.20.2018.

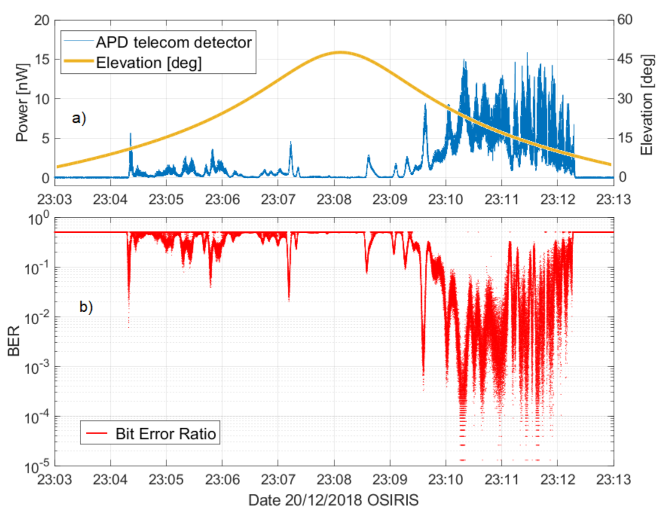


Fig. 15. Values for Dec.20.2018 (by sub-aperture 50 cm) from 5° satellite elevation to 49° at highest point, back to 5°. a) Averaged optical power and satellite elevation (not in scale); b) BER-estimation.

Fig. 16 shows the variation of BER as a function of detected average optical power at 0.5 m aperture. The lower boundary is close to the detector performance curve (blue curve). BER reaches to 'Error Free' (BER < $\mathbf{10^{-6}}$) when the optical power is close to -49 dBm (13 nW) despite the presence of optical fluctuation caused by atmospheric turbulence and satellite bias pointing. In the optimal case, BER reaches to 'Error Free' when optical power $\boldsymbol{P_{opt} > 13}$ nW and reaches to 'Good channel', $\boldsymbol{BER < 0.01}$, when $\boldsymbol{P_{opt} > 5}$ nW. In Fig. 15, there are several sequences where the optical power level is enough to achieve a good BER but the synchronization fails. The issue happens when there is a strong fluctuation (caused by satellite bias pointing) on optical power in one data sequence.

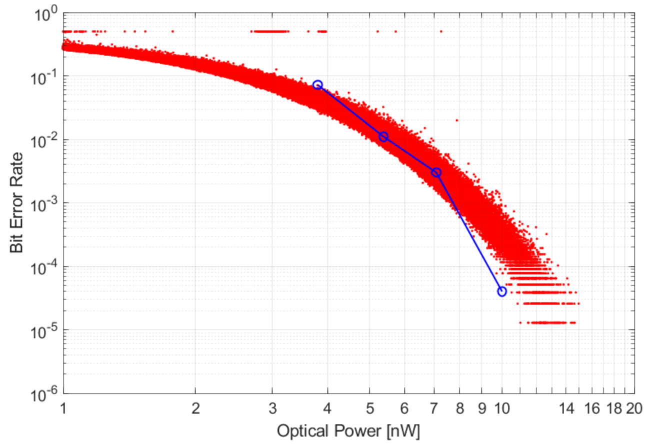


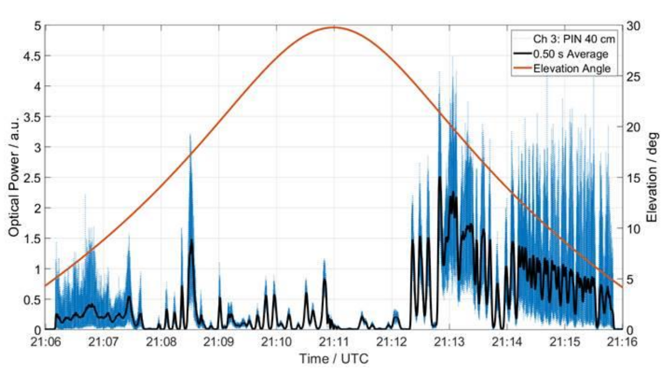
Fig. 16. MeO telescope Dec.20.2018 pass - Bit error ratio vs optical power level detected by APD telecom photodiode (red dots) compared to laboratory characterization (blue circles).

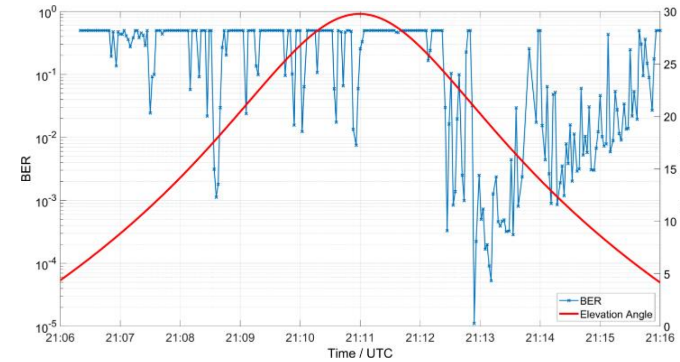
When zooming on BER for ascending and descending part one finds the following behavior: the BER very well matches to received power (just indicating few synchronization locking losses in the BER-measurement as the dots at BER=0.5 in Fig. 16). However, also elevation-dependent pointing quality reduction from the satellite can be seen at the sections of ascending and highest elevation, due to deflections form celestial bodies and coordinate offsets which causing more fading at higher elevation due to smaller laser spot size.

B. DLR IKN stations – experimental results

We concentrate our analysis on the link on 26 Oct 2019 starting at 21:04:58 UTC. Optical power into the 40cm telescope of OGS-OP was recorded and in parallel TOGS sampled the OOK telecom-signal into its 60cm aperture. Additionally, the amplitude of this data signal was analyzed.

The high sampling rate (10 kS/s) of the received power (blue line in fig. 17 top) reveals fast power variations stemming from atmospheric IRT scintillations, which are typical in the range of ~10ms. The thicker black line shows the 0.5s means which average out such scintillations and only show the run of the longer-term intensity. It is again disturbed by variations from the satellite's body pointing of the laser beam.





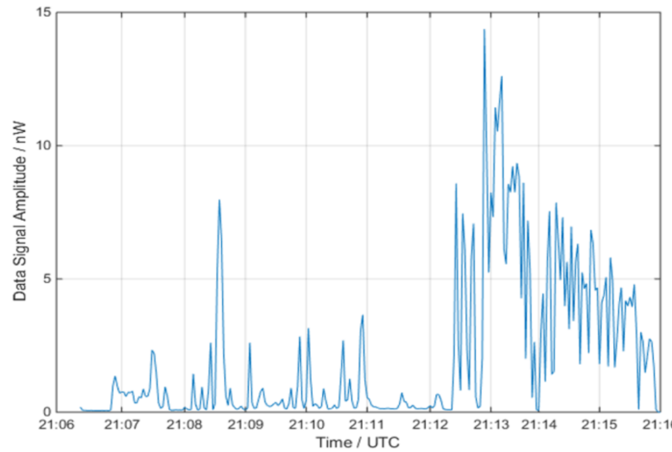


Fig. 17. Downlink on Oct26.2019 from 21:06 UTC on, to DLR's OGSs.
top: Received relative power into OGS-OP.
middle: BER measured by the data-receiver in TOGS, with 2 s resolution.
bottom: TOGS data-signal amplitude over link-time as derived from the data-receiver's analog data output, with the same 2 s resolution as the BER-

The different plots of Fig. 17 reveal gaps in the received power, due to the satellite's star-camera's limited absolute accuracy plus coordinate offsets, generating pointing offset of the beam. This effect becomes more dominant with high elevation, since the shorter link distance then reduces the spot diameter on ground. Other impairments are from the star-sensor's attitude information getting hampered by stray-light from sun and moon.

The telecom data signal from TOGS was sampled at 250MS/s and from these the according BER was calculated by comparison with the expected bit sequence at 39Mbps (Fig. 17 middle). The received signal strength from the telecom APD allows comparison of the intensities at both OGS' in parallel, where the absolute power-values were derived from the sensitivity-run of the RFE, see Fig. 17 bottom. BER=10^{-5} signifies 15nW signal power onto the data detector (compare Fig. 11). Some processing delay for this method is present when comparing middle and bottom plots. The difference from 15 nW to the 39 nW maximum value estimation at 20° elevation (Table 2) stem from residual miss-pointing, since we have to assume that the maximum measured power still was not the axial value.

We see mostly similar behavior of Rx-intensity at both OGSs in Fig. 17 top and bottom. However, also slight deviations can be observed, indicating different signal spot variations due to the satellite's pointing-jitter (compare the three peaks around 21:12:30). A wider separation of the OGS' and additional power-monitors shall enable an improved calculation of the centroid of this beam wander, allowing precise on-orbit calibration of the star cameras versus the laser collimators directions and the pointing precision in general.

5. Conclusion

Links between Flying-Laptop-OSIRISv1 and Grasse Station were successfully established. Acquisition and tracking were successfully performed from the moment of visibility of the laser-signal until the onboard laser was turned off. Channel data such as optical power level and fluctuation, corresponding frequency spectrum, telecom signal shape and BER were obtained. Maximum optical power levels detected at OGSs do match with theoretical link budget estimations., however beam wander from pointing errors cause frequent fading. Such frequency power fluctuations on optical power fluctuation relate to body-pointing offsets of the satellite. No high frequency variations related to vibration were detected. With the MeO OGS of 50cm aperture diameter, telecom data downlinks were measured at 39 Mbps. Detailed analysis (downlink flux level, flux fluctuation, BER performance and comparison to the theoretical expectation) on the collected data during three successful passes were presented.

DLR-IKN performed downlink measurements with a power meter in the 40 cm OGSOP, and BER-measurements with the 60 cm TOGS. The fast scintillations induced by atmospheric IRT, as well as the slower mis-pointing fades could be resolved by OGS-OP. The two ground stations simultaneously measured and accordingly calculated received power from FLP at DLR-Oberpfaffenhofen, where the OGS' were located several meters apart. These measurements reveal the movement of the beam spot and show a promising methodology to enable more precise pointing calibration of the satellite-attitude during open-loop downlinks based on star-sensors only. To increase the precision of this technique, the OGS' shall be placed further apart (~500m) and a third OGS shall be added to enable complete triangulation of the spot's center of gravity.

As a main result, the feasibility of open-loop optical data downlinks without opto-mechanical pointing assemblies, from LEO at 1550nm telecom-wavelength with a standard nanosat setup was demonstrated. Although pointing of the laser spot showed some deviations and thus transient signal interruptions at the OGSs, the reception quality allowed capturing several Gigabit of data during one downlink. Employing this technique in future missions will allow a major improvement of data downlink throughput from few Mbps to hundreds of Mbps at little extra satellite-hardware requirements.

Acknowledgments

The launch and operations of the Flying Laptop satellite has been supported by the Federal Ministry for Economic Affairs and Energy of Germany (BMWi) via the German Space Agency DLR and the ministry of economy, science and art of Baden-Württemberg. The OSIRISv1 measurements were obtained in a collaborative work of Observatoire de la Côte d'Azur (OCA), the French Space Agency (CNES), University of Stuttgart, and the German Aerospace Center (DLR). Funding for OCA was provided by CNES. The authors would like to express their appreciation to everyone who was involved in the measurement campaigns and their preparation.

Disclosures

The authors declare no conflicts of interest.

Data Availability Statement

Data underlying the results presented in this paper are available at the data repository website of University of Stuttgart in Dataset 1, Ref. [21].

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