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THE TESAT TRANSPORTABLE ADAPTIVE OPTICAL GROUND STATION AND THE OPERATIONAL EXPERIENCES

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I. INTRODUCTION:

Optical communication in space is already in its operational phase. Nevertheless, laser communication is not only of interest between satellites, but also from and towards ground. The applications are not only ground to GEO-S/C links (feeder-links), direct LEO-S/C to ground links, links with hubs and UAVs but also quantum key distributions from space platforms towards the ground.

Tesat has been contracted by the German Space Agency DLR to build, test, and operate a transportable adaptive optical ground station (TAOGS). The adaptive optics corrects the wavefront within the receive channel and the receive aperture can be large compared to the Fried parameter of the atmosphere while still obtaining diffraction limited receiver performance, necessary for binary phase shift keying (BPSK, as used in the TESAT laser communication terminal, LCT) and differential phase shift keying (DPSK) based laser communication systems. For the down link channel a transmit power from 5W is sufficient for 2.8Gbps BPSK homodyne communication. For the up-link channel the atmospheric influences are mitigated by higher uplink power up to 50W with reduced beam diameter.

Since September 2015 the TAOGS, co-located with the European Space Agency (ESA) Optical Ground Station on Tenerife, is operating and performing links with a LCT on the geostationary S/C Alphasat. During several campaigns up-, down-, and bidirectional links have been performed. The Alphasat TDP1 LCT has the special capability to record and downlink LCT internal telemetry with a sampling rate of 25 kHz. Especially the direct detection of the acquisition sensors and of the coherent tracking sensors are useful information for channel modeling. Also the TAOGS can record the received light using direct detection and coherent detection both with 5 kHz sampling rate as well as several other parameters like the derived Fried parameter. This allows correlating the uplink and downlink channel data.

Together with external partners, the TAOGS serves as test setup for feasibility tests on quantum key distribution (QKD) and for tests of innovative codes optimized for atmospheric links. Furthermore characterization of the uplink channel, which is not corrected by the adaptive optics will be used to derive specialized acquisition and tracking strategies for the space segments.

II. OPERATION OF THE TAOGS:

A. Link Planning and Success Statistics

Several campaigns with different goals have been performed. Typically up to 10 links per day were planned, each with a duration of 20min; including the spatial acquisition, frequency acquisition and communication phases. For specific tests, where communication is not the goal, the 20min of the optical link have been used in a different way. In every campaign at least one link is dedicated to TAOGS alignment setting verification.

Overall statistics on the campaigns so far show that significant more links than required need to be planned in advance.

The reasons for reduced link availability are:

- Weather conditions: high clouds, humidity, dust, heavy winds
- Priority or operational issues of the space segment
- Priority or operational / technical issues of the ground segment

Weather conditions lead to availability reduction of ~25%. It has to be considered that no weather prediction was done when planning the optical links.

The availability reduction is depending of the concept of operation:

Firstly, the links were planned in a one hour interval. Thus a single issue causes loss of consecutive links. For example weather issues (“if the weather is bad at the moment, it will be bad the next hour as well”); but also some kind of priority, operational or technical issues (“if there is an operational or technical problem, it can’t be solved within the 40min before the next planned link.”). Observed technical problems include power outages, operational problems include cancelling links in space for a full day.

Secondly, link planning is performed one week in advance for a period of a full week. I.e. the links of the last day within the planning cycle had been planned 11 days before. This is a typical timeline for activity planning cycles.



Fig. 1. Weather conditions causing link losses or degradation. Left: one week of closed roads due to snow (March 2016) causing 50% link loss during that campaign. Right: high clouds influencing the links from degradation (1-3dB) to loss (>3dB).

III. RESULTS OF UPLINKS

A. Far Field Beam Profile of TAOGS

With a dedicated experimental link we measured the beam profile of the TAOGS as it appears at the space segment. During this measurement the TAOGS was in the nominal configuration, which is: receive the light using the large aperture of the Coarse Pointing Assembly CPA270 and transmit the light using the separate CPA (CPA100) with a beam diameter of 35 mm [1], [2]. This beam has a $1/e^2$ diameter of 31.2 mm which would lead to a nominal divergence angle of 22 μrad ($1/e^2$ radius). Together with a truncation diameter of 35 mm, the designed and expected divergence angle is 26 μrad , which should be slightly broadened by the atmosphere.

It can be seen (Fig. 2) that the beam is slightly elliptical. Fitting an elliptical Gaussian beam on the data, the resulting divergences angles are 22 μrad and 28 μrad ($1/e^2$ radius).

The result shows that the divergence angle measured in space has the expected value. The manufacturing and alignment tolerance could lead to beam opening angle variations, especially if the truncated aperture is a little larger than designed. The elliptical shape is caused by the TAOGS itself. The beam shape after the first collimator already shows a slightly elliptical beam shape.

Fig. 3 shows the raw data of the beam profile measurement. After a permanent link was achieved the point ahead angle of the TAOGS was performing a slow spiral scan with the point ahead mirror, while the received power on the tracking sensor in space was measured. During the measurement the TAOGS as well as the LCT on Alphasat were able to maintain the link as pointing reference. Thus the size of the spiral scan is limited to a displacement equal to the tracking margin of the link budget.

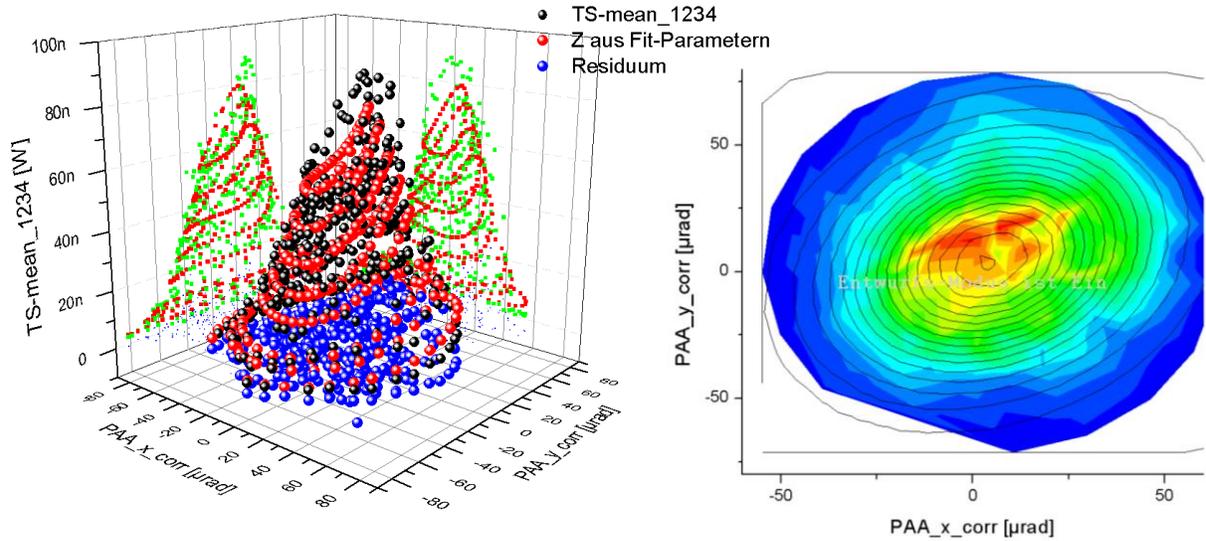


Fig. 2. TAOGS beam profile as measured by the tracking sensor (TS) of the LCT on Alphasat.

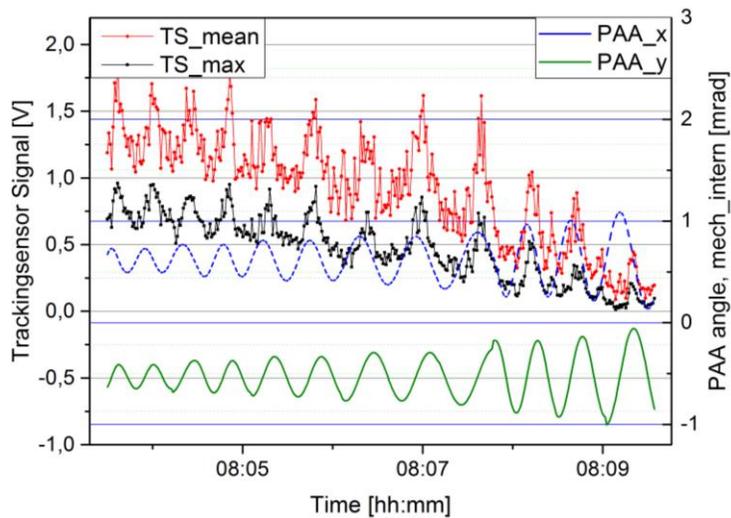


Fig. 3. Timeline of beam-profile measurement. While the point ahead angle (PAA) of the TAOGS was performing a slow spiral scan (blue and green data), the received power on the space segment, the LCT on Alphasat was measured. Given here as an average signal within 1sec (red, TS_mean) and as the maximum signal within 1sec based on 25kHz sampling rate (black, TS_max)

B. Thermal Alignment Drift

The transmitting and receiving paths of the TAOGS are separated from each other when performing GEO to ground links using the CPA100 for the transmit beam and receiving the light via the CPA270 [1].

While the optical container is water cooled and air conditioned, both coarse pointing assemblies CPA270 and CPA100 are exposed to the environment. This causes temperature changes due to air temperature and direct solar irradiation.

The data shown in Fig. 3 were also used to determine the thermal misalignment during a link. Applying a linear drift of $0.03\mu\text{rad/s}$ on both PAA axes, the data showed the lowest residuum during the Gaussian fit. This means that, during the 5min of measurement the cumulated thermal deformation was $\sim 10\mu\text{rad}$ on each axis.

Note that the above measurement was performed shortly after sun rise, i.e. during strong environmental changes such as increasing solar irradiance on one CPA side. Links at night showed much less thermal deformation once the TAOGS was operating for about 1h. The $10\mu\text{rad}$ per axis within 5min is thus an upper level of thermal deformation.

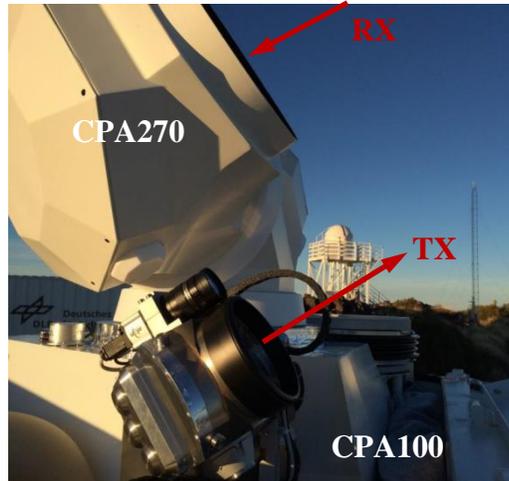


Fig. 4. The two coarse pointing assemblies (CPA) of the TAOGS on top of the optical container. CPA100 has an aperture of 100 mm and is used as CPA for the transmitted beam (here 35 mm diameter). CPA270 has a 270 mm receiving aperture.

C. Uplink channel fading

For an uplink a surge to fade ratio was calculated in the following way [3]. Using receiver diode signals (PD) sampled with 25 kHz maximum and minimum values with 1 sec periods were calculated:

$$Surge / Fade [dB] = 20 * \log_{10} \left(\frac{\sum_{i=1}^4 PD_{i,max}}{\sum_{i=1}^4 PD_{i,min}} \right) \tag{1}$$

Note that this surge / fade calculation is not based on the optical power but on the detector-signal. We used this formula, to compare the results with results derived from inter-satellite atmospheric links as shown in [3]

Fig. 4 shows the timeline a link where the surge / fade ratio of optical uplink is calculated on the intensity as measured with the tracking sensor of the LCT on Alphasat. During communication the surge / fade ratio is about 9dB. Compared with [3] the intensity fluctuations seen in this ground to GEO uplink are similar to low grazing inter satellite links this an grazing altitude of 40 km to 45 km. Note that the characteristic of low grazing links and ground links (here with an elevation angle of 34°) cannot be compared directly.

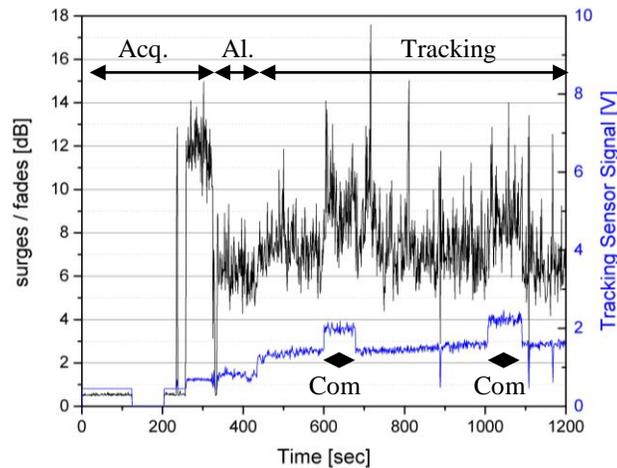


Fig. 4. Timeline of a link used fade to surge ratio analysis. Blue: Tracking Sensor Signal of the LCT on Alphasat. Black: surge / fade as indication of atmospheric influence. The link starts at t = 0 sec with spatial acquisition followed by a TX/RX optimisation. From t ~ 450 sec the LCT in space is tracking on the light from ground. The link has two time spans with communication, which can be seen at the 3dB increase of the tracking sensor signal.

To derive a general surge to fade ratio based on true received optical power, the detector characteristics of the tracking diode is eliminated by using a calibration function.

This ratio of the optical signal, calculated accordingly to Equ. 1 is shown in Fig. 4. during a tracking time span. The intensity fluctuations are mainly between 10 dB and 15 dB.

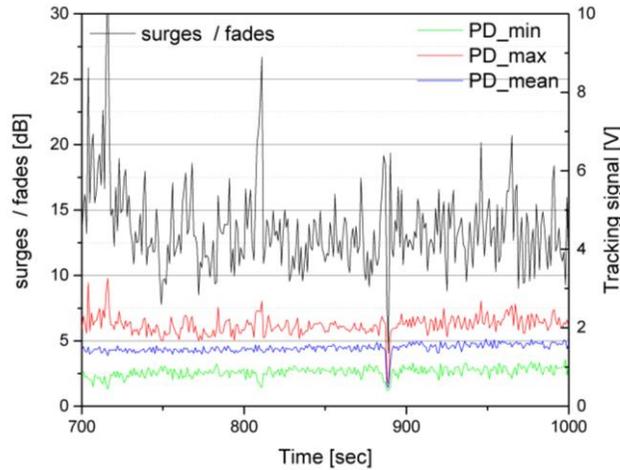


Fig. 5. Surge to fade ration calculated on the optical signal of the LCT on Alphasat during tracking. Black: surge to fade ratio. Red, blue, green: max, mean, min signal during a 1 sec time periode.

D. Beam wander

The optical intensity fluctuation on the LCT in GEO orbit as shown above is related to several reasons. Besides atmospheric scintillation and TAOGS pointing jitter, there is the effect of the beam wander [4], an effect close to ground which changes the direction of the uplink beam. A fluctuating angular displacement will lead to fluctuating intensity reductions, which depends also on the transmit beam diameter.

The expected value of the beam wander angle can be calculated using the Equ. (2) as derived within [5]

$$\sqrt{\langle \alpha_c^2 \rangle} = 0.73 \left(\frac{\lambda}{2\omega_0} \right) \left(\frac{2\omega_0}{r_0} \right) \quad (2)$$

For the TAOGS with a transmit beam of $2\omega_0 = 31.2$ mm and a wavelength of $\lambda = 1064$ nm, the expected beam wander is approximately $2 \mu\text{rad}$ for excellent atmospheric conditions of $r_0 = 25$ cm. For the design case of $r_0 = 10$ cm the beam wander is roughly $9 \mu\text{rad}$. This affects the uplink budget with less than 1 dB fades. It was possible to operate the TAOGS regarding down-link until atmospheric conditions of $r_0 = 5$ cm. This leads to beam wander effects within the uplink of $17 \mu\text{rad}$ and the corresponding intensity fluctuations.

E. Uplink Budget

Based on the knowledge of the non atmospheric losses and TAOGS characteristics it is possible to determine the atmospheric induced losses via the received light on the GEO LCT.

The table below shows a typical link with total atmospheric losses of 4.7 dB.

Tab. 1. Uplink budget

	Physical value	
TAOGS OPA signal power	50W	47.3 dBm
TAOGS transmit losses		-1.5 dB
TX output power		45.7 dBm
Free space propagation losses including TX and RX antenna gain		-83.2 dB
Atmospherical induced losses, 1sigma		-4.7 dB
Mean input power on LCT		-42.2 dBm

IV. RESULTS OF DOWNLINKS

A. Receiver performance

In the above sections the optical uplink channel is analysed. The optical down link channel is affected by similar intensity fluctuations. In Fig. 7 the TAOGS coherent detector signal of a 6 min optical communication downlink is shown. It has to be highlighted the communication is not lost although the minimum signal drops to almost zero during strong fades. Only at the end of the link a longer strong fade at ~00:35:28 leads to a loss of the homodyne phase lock loop, communication is lost and the coherent detector signal drops by 3dB.

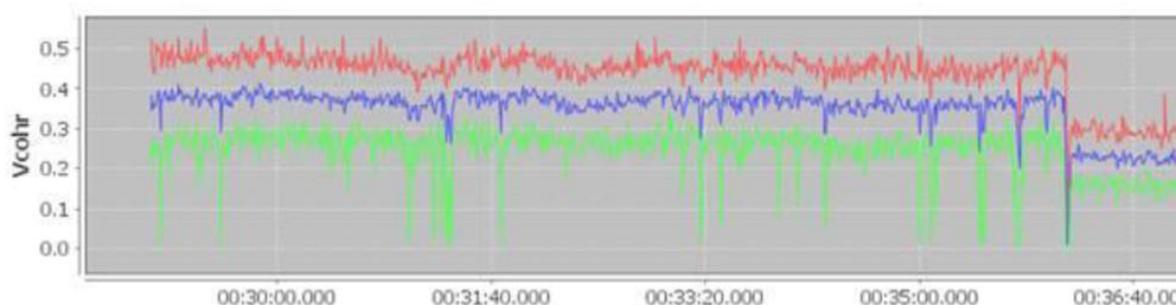


Fig. 7. TAOGS coherent detector signal during a communication down-link (V_{cohr}). The data are sampled with 5 kHz. Green: the minimum value with 0.5 sec. Blue: mean value within 0.5 sec. Red: maximum value within 0.5 sec. At 00:35:28 the communication was lost and the coherent detector signal drops by 3dB.

The TAOGS's receiver was characterised during a unit test with a constant input power. The characterisation curve (blue squares) is shown in Fig. 8. For a received signal of -45.5 dBm in the fiber, a raw bit error rate (BER) of 10^{-5} is observed (note that this BER is equal to 10^{-8} on the user data).

Bit error rates relative to received power during down-link communication are given in green, yellow and small blue dots in Fig.9. The analysis shows good consistency between the characterization measurement and the performance during an optical link with high intensity fluctuations. The horizontal shift between the green and the yellow data indicate the dynamical BER penalty, which is significant during optical links with high intensity fluctuations.

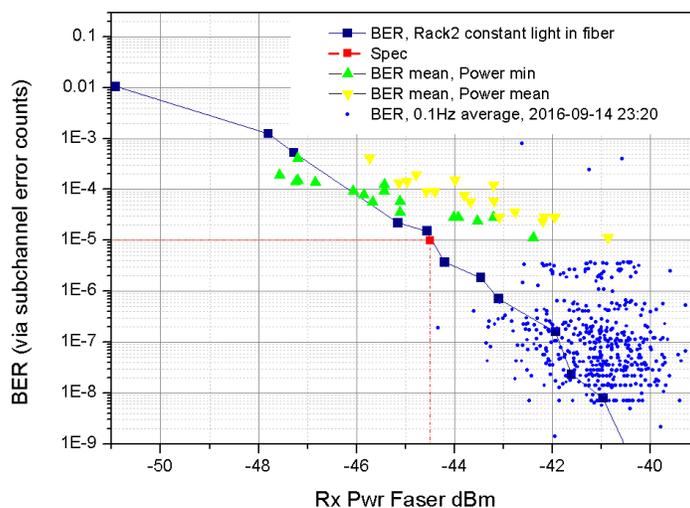


Fig. 8. Bit error rate on the optical data rate of 2.8 Gbps versus received light in fiber toward homodyne receiver unit. Blue bullets: characterization measurement in the factory, using constant light. Green, yellow, small blue points: evaluation of a two real down-links performed with the TAOGS at Izaña, Tenerife.

V. CONCLUSION AND OUTLOOK

This paper reports on the operational experience of an optical ground station used for laser communication in dedicated 2-3 week campaigns over several month. An outage analysis and measurements of beam parameters under changing environmental conditions have been presented,. These parameters are considered fundamental in the operational concept definition of future optical ground stations.

Ongoing campaigns are creating valuable measurement data for Quantum Key Distribution from GEO S/Cs [6] and optimized coding for atmospherically disturbed high data rate links [7].

REFERENCES

- [1] Fischer, E., Berkefeld, T., Ferencik, M., Ferencik, M., Kaltenbach, V. Soltau, D., Wandernoth, B., Czichy, R., Kunde J., Saucke, K., Heine, F., Gregory, M., Seiter, C., Kämpfner, K., “Development, Integration and Test of a Transportable Adaptive Optical Ground Station”, ICSOS 2012, New Orleans, Louisiana, U.S. (2015).
- [2] Saucke, K., Seiter, C., Heine, F., Gregory, M., Tröndle, D. Fischer, E. Berkefeld, T., Ferencik, M., Ferencik, M., Richter, I., Meyer, R., “The Tesat transportable adaptive optical ground station”, *Proc. SPIE 9739, Free-Space Laser Communication and Atmospheric Propagation XXVIII*, 973906 (15 March 2016)
- [3] Sterr, U., Dallmann, D.; Heine, F., Tröndle, D., Meyer, R., Lutzer, M., Benzi, E., “Planning constraints of low grazing altitude GEO-LEO laser links based on in-orbit data”, *Opt. Eng.* 55(11), 111608 (Aug 10, 2016)
- [4] Andrews, L., Phillips, R., “Laser Beam Propagation through Random Media”, SPIE Press, 2nd edition (2005)
- [5] Mata Calov, R., Becker, P., Giggenbach, D., Moll, F., Schwarzer, M., Hinz, M., Sodnik, S., “Transmitter diversity verification on Artemis geostationally satellite”, *Proc. SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI*, 897104, March 6 (2014)
- [6] Elser, D., Günthner, K., Khan, I., Stiller, B., Marquardt, C., Leuchs, G., Saucke, K., Tröndle, D., Heine, F., Seel, S., Greulich, P., Zech, H., Gütlich, B., Richter, I., Meyer, R. “Satellite Quantum Communication via the Alphasat Laser Communication Terminal, Quantum signals from 36 thousand kilometers above Earth”, *International Conference on Space Optical Systems and Applications (IEEE ICSOS Oct. 2015)*, *arXiv:1510.04507 [quant-ph]* (2015)
- [7] Orange Book CCSDS 131.5-O-1 „ERASURE CORRECTING CODES FOR USE IN NEAR-EARTH AND DEEP-SPACE COMMUNICATIONS“, Nov. 2014