Free-space optical communication outdoor demo

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1. Project and experiment description

The H2020 VERTIGO projects aims on the development and demonstration of the relevant key technologies for satellite communication to enable scalability of GEO-to-ground and vice versa optical feeder links towards and beyond 1 Tbps. Optical feeder links are considered as a promising technology to meet the future VHTS (Very High Throughput Satellites) system requirements instead of radio frequency (RF) links.

The following 3 concepts and technologies are addressed: 1. Higher capacity though advanced modulation format implementation (direct detection / coherent / analog modulation schemes), 2. High optical power generation for free space optical coms (high power amplifier / high power beams combination) and 3. High availability optic links though atmosphere (adaptive optics / multi-aperture / channel coding). More information on project and background is found in [1].

The feasibility of such optical feeder links has been demonstrated by implementing the developed technologies in 2 demonstrations in an unprecedented combination: The lab demo focuses on the combination of high capacity data transmission and high optical power generation, whereas the outdoor demo investigated the limits of data transmission in a free-space optical (FSO) link and atmospheric turbulence mitigation by either AO (adaptive optics) or MA (multi-aperture) optical ground stations.

For the AO experiments, a link setup between the Jungfraujoch and Zimmerwald was established, whereas the MA experiments were performed in parallel with another link setup between Thun and Zimmerwald. The Topology of the link setup is illustrated in Figure 2. The high level block diagram used for the AO link experiments and involved partners is found in Figure 1. Communication experiments have been only performed on the downlink in the optical C band (~1550nm), for beam alignment support, a weak uplink beacon in L band has been used.

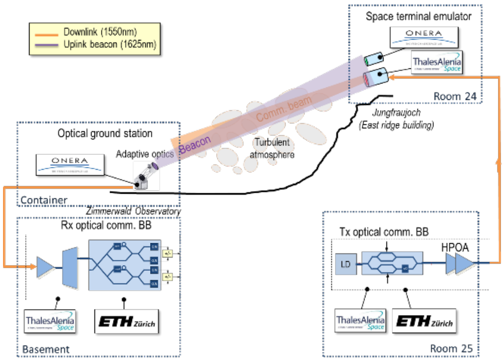

Figure 1. Test setup overview.

Figure 3 shows the installations in the valley site. The AO ground station [2] was installed inside a contained placed next to a dome of the Zimmerwald observatory (see Figure 3). The communication chain equipment was accommodated in the cellar of the observatory building (see Figure 4). Figure 5 shows the space emulator terminal (STE) installed in the east ridge building of the HFSJG facing north towards Zimmerwald. The transmitter equipment was located in a neighbouring room (see Figure 6).

The experiments have been performed in July 2022, starting with first equipment installation end of June.

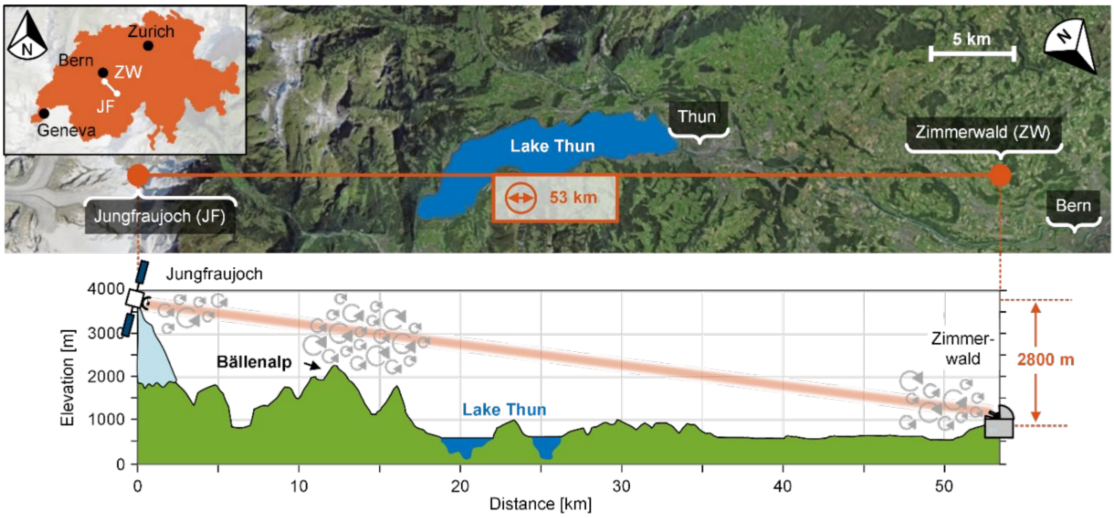

Figure 2. Link topology.

Figure 3. Installations at the Observatory Zimmerwald.

Figure 4. Adaptive optics optical ground stations placed inside a container in Zimmerwald.

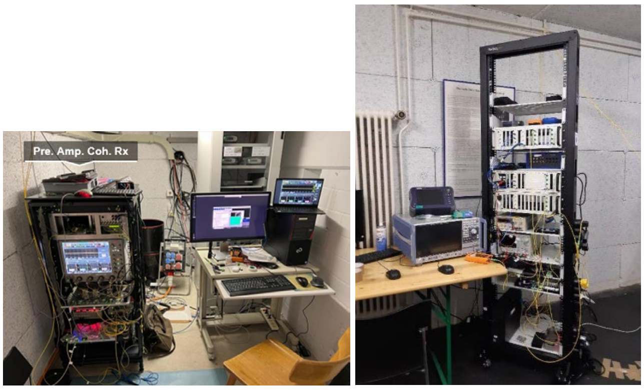

Figure 5. Receiver equipment (left: ETHZ, right: TAS-F) of the communication chain placed in the basement of the Zimmerwald Observatory.

Figure 6. Space Emulator Terminal (STE) with supporting equipment placed in room 24 of the east ridge building.

Figure 7. Transmitter equipment (left: ETHZ, right: TAS-F) of the communication chain placed in room 25 of the east ridge building.

2. Measurements and results

Once the equipment was installed on both sites, the first link was established with the help of visible cameras to find the counter-terminal on both sites (shown in Figure 8 and 9).

Figure 8. Beam acquisition through the visible camera behind the STE telescope.

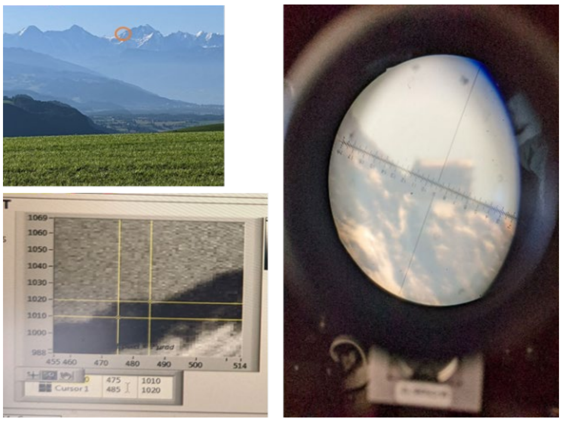

Figure 9. Beam acquisition through visible camera behind telescope of AO ground station.

For the validation of the representativeness of the channel in comparison with a GEO satellite - ground link, the channel has been characterized based on the received signal in the AO ground station.

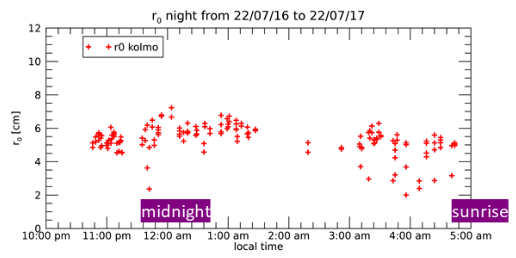

Figure 10. Fried parameter r0 inferred from AO-data.

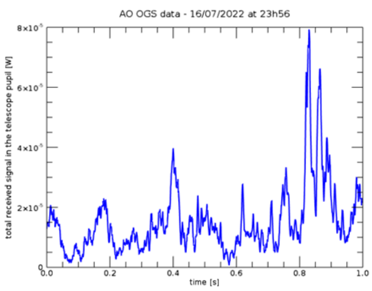

Figure 11. Power flux in the telescope pupil.

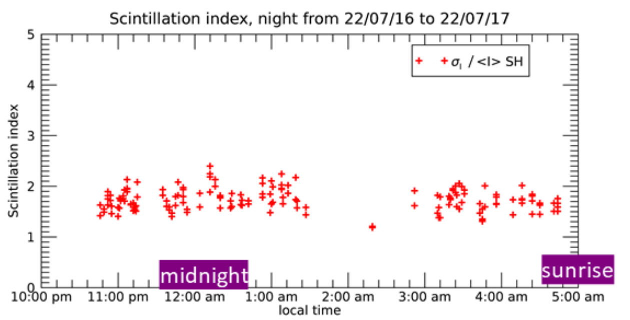

Figure 12. Variance of the log amplitude and the intensity variance in the AO sub-aperture ($\sigma^2 I$) inferred by ONERA from AO-data.

While phase perturbations were manageable, with r0 of a few centimeters (Figure 10), scintillation was always saturated and very strong (Figure 12), resulting in high power fluctuations (Figure 11). Expected values for real GEO feeder links are much milder, less than 0.3 in most cases, since distant layers are much more turbulent in the VERTIGO demo case (Figure 13) than in the GEO case for which turbulence decreases strongly with altitude.

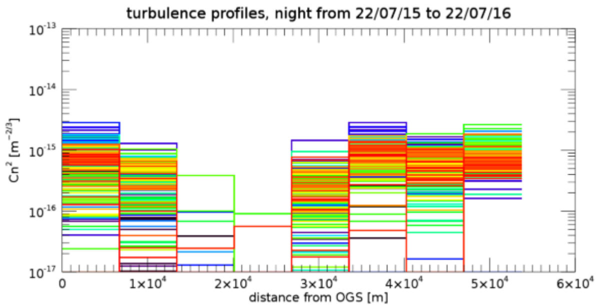

Figure 13. Turbulence profiles inferred by ONERA from AO-data. The beginning of the night is in blue tones, the end in red tones. Zimmerwald is on the left, while the Junfraujoch is on the right.

Due to scintillation that was even stronger than foreseen [3], communication chain experiments were mainly performed during nights and early mornings to obtain good performance in relatively representative turbulence conditions.

Mean received power varies continuously due to turbulence condition, visibility and pointing accuracy. The estimated link budget for midnight (16.7) is given in Table 1. Link loss has been measured to be around -55.5 dB averaged over the turbulence induced losses at this time instant.

Table 1. Link Budget.

Optical launch power	**27.00**	**dBm**
STE TX net antenna gain	**80.00**	**dB**
Transmission losses	**-240.00**	**dB**
Mean turbulence induced losses	-7	dB
AO OGS RX net antenna gain (to fiber)	**112.70**	**dB**
Losses in fiber	**-1.20**	**dB**
Mean received power at LNA input	**-28.50**	**dBm**
Mean link loss	**-55.50**	**dB**

2 sets of equipment (TAS-F and ETHZ) has been used for the communication chain experiments. TAS-F performed experiments with OOK, DPSK modulation and radio-over-fiber communication.

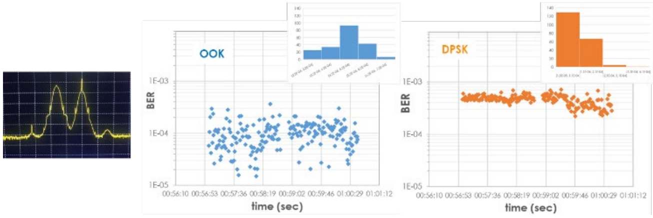

Figure 14. BER over time for OOK and DPSK modulation at 25G.

OOK 10 & 25G and DPSK 25G signals were successfully transmitted, with up to 4 wavelength division multiplexing (WDM) channels resulting in a total throughput of 100 Gbps. During several minutes, raw bit error rate (BER) before forward error correction (FEC) around 10^{-4} and down to 10^{-6} were reached.

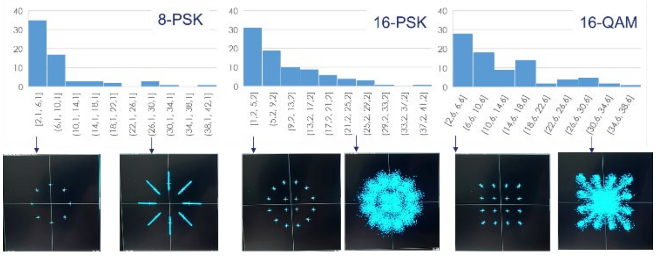

Figure 15. EVM histograms for 8-APSK, 16-APSK, 16-QAM modulations.

RF analog signals with DVB-S2 like signals were successful with low (2-3%) error vector magnitude (EVM). More details on setup and results can be found in [4].

ETHZ tested successfully different coherent modulation formats. The results in Figure 16 summarize the best results from the demonstration.

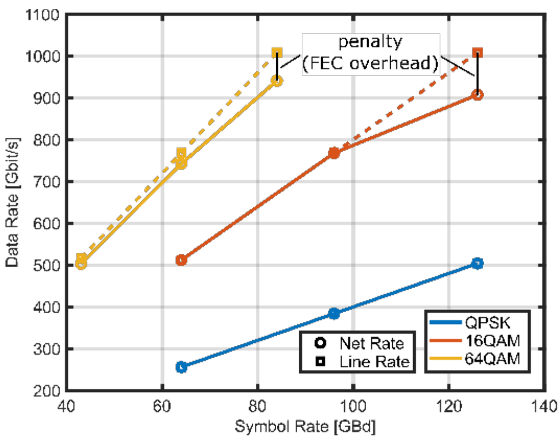

Figure 16. Line rate (dashed) and net-rate (solid) as a function of symbol rate and modulation format.

The best results have been obtained with high received powers. The 64QAM signal outperforms the 16QAM signal because the latter is limited at high-speed by the 38 GHz IQ-modulator. Unlike in fiber transmission, where high powers are penalized by the nonlinear Shannon limit, the FSO link can accommodate high power.

More details on the coherent communication setup and results can be found in [5]. Additionally, more results based on acquired data will be presented in future conferences and publications.

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Internet data bases

https://www.space-vertigo.eu

Collaborating partners / networks

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