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The H2020 VERTIGO project : a major milestone towards optical feeder links

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ABSTRACT

Optical feeder links are considered as a promising alternative to surpass classical RF technology for future very high capacity systems. Nevertheless, the potential of this technology shall not conceal the remaining challenges to be overcome to make it relevant for operational missions: clouds, turbulence, power generation and handling and high efficiency modulations.

VERTIGO (Very High Throughput Satellite Ground Optical Link) is a H2020 project funded by the European commission and completed early 2023 focusing on the optical link itself regardless of site diversity aspect and demonstrating in ground demonstrations required technologies to implement very high capacity optical feeder links. This paper presents an overview of the demonstrations carried out and the main achievements of the project.

Keywords: optical feeder links, modulation formats, atmospheric turbulence, mitigation techniques, high optical power amplifiers, coherent beam combining, free-space demonstrations

1. INTRODUCTION

Over past decade, free-space optical communications have increasingly caught interest in space applications, first in the field of space-space links, becoming today a key element of some satellite systems such as data relay or satellite constellations through optical inter-satellite links [1 – 3].

The next major step will be the deployment of operational space-ground optical links including optical feeder links. Indeed, the latter brings new transmission bands, increased data rate capabilities compared to conventional RF solutions, but on the other hand raises specific challenges, related to atmospheric propagation as well as optical power generation and management compatible of telecom transmissions. These topics have been partially or separately addressed for several years already [1, 4, 5, 8] but not combined in a fully representative configuration.

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VERTIGO (Very High Throughput Satellite Ground Optical Link) is a H2020 project funded by the European Union focusing on the optical feeder link itself regardless of any site availability consideration (Figure 1), and built on 3 pillars each addressing a key issue for the implementation of these links [6]: 1) Throughput increase through the use of advanced modulation/detection schemes 2) High optical power generation and management 3) Opto-mechanical and digital processing techniques for the mitigation of atmospheric propagation impairments.

This paper highlights the main achievements of this project started mid-2019 and completed early 2023.

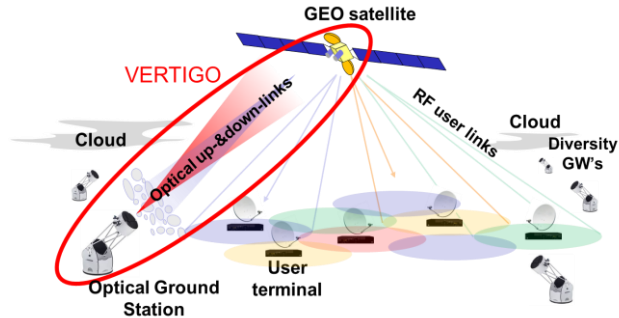


Figure 1. Illustration of a Very High Throughput Satellite system based on optical feeder link and scope of the VERTIGO project.

2. METHODOLOGY

In order to combine the different technologies in a relevant and safe manner, several demonstrations were defined in the frame of VERTIGO project, each addressing a specific subset of topics. While outdoor demonstrations were of primary interest to test high data rate transmissions and through a real atmospheric channel, the short distances compared to real GEO-ground link and associated link budgets as well as safety reasons prevented to use high optical power levels. On the other hand, a laboratory demonstration in a safe and controlled environment was the ideal place to investigate the impact of transmission at high and very high optical power, as well as of the associated dispositive used to reach such high power levels, on the integrity of telecom signals. These considerations led to 3 free-space optical links (through the atmosphere) and 1 indoor (laboratory environment) demonstrations :

- A 53 km downlink between the High Altitude Research Station of Jungfrauoch (HFSJG) at 3700 m altitude in the Swiss Alps, hosting a space terminal emulator (STE), and the Zimmerwald Observatory at 900 m altitude in Bern neighborhood, hosting a single aperture optical ground station including adaptive optics (SA-OGS), primarily addressing high data rate transmissions and atmospheric impairments mitigation through adaptive optics (Figure 2 and section 3).
- A 18 km up- and down-link between the Thun Castle at around 600 m altitude, hosting a space terminal emulator (STE), and the Zimmerwald Observatory, hosting a multi-aperture optical ground station with tip/tilt correction (MA-OGS), primarily addressing high data rate transmissions and atmospheric impairments mitigation through aperture diversity (Figure 2 and section 4).
- A 400 m downlink through a round-trip between two buildings in Fraunhofer HHI facilities, in Berlin, based on the multi-aperture ground station with tip/tilt correction and a space terminal emulator STE, addressing the coherent beam recombination in reception (section 4.2).
- An indoor link in Thales Research and Technology facilities in Palaiseau (France), addressing telecom signal transmissions at high and very high optical power (section 5).

3. JUNGFRAUJOCH – ZIMMERWALD OUTDOOR DEMONSTRATION

3.1 Demonstration setup

The demonstration setup between Jungfrauoch and Zimmerwald aimed at assessing different optical modulation formats under propagation conditions encompassing real GEO-Ground propagation conditions, in both uplink and downlink. Initially supposed to be implemented using the FEELINGS OGS developed by ONERA [7], difficulties encountered (imputable to Covid-19 pandemic) delayed its development and readiness for VERTIGO project. As a result, ONERA used another optical system, the ground terminal breadboard FEEDELIO, developed in the frame of an ESA contract [8]. A major consequence of this change was the impossibility to implement the uplink as the FEEDELIO setup was designed to operate in L-band on this link while setups of other partners were limited operate in C-band. The resulting final demonstration scheme is presented in Figure 3.

The setup of the demonstration in Jungfrauoch includes (Figure 4):

1. Tx optical communication setups for 10G and 25G OOK/ 25G DPSK/ Analog modulation formats
2. Tx optical communication setups for coherent modulation formats up to 1 Tbps
3. A High Power Optical Amplifier delivering up to 27 dBm optical power
4. A Space Terminal Emulator based on a 42 mm subaperture out of a 200 mm aperture

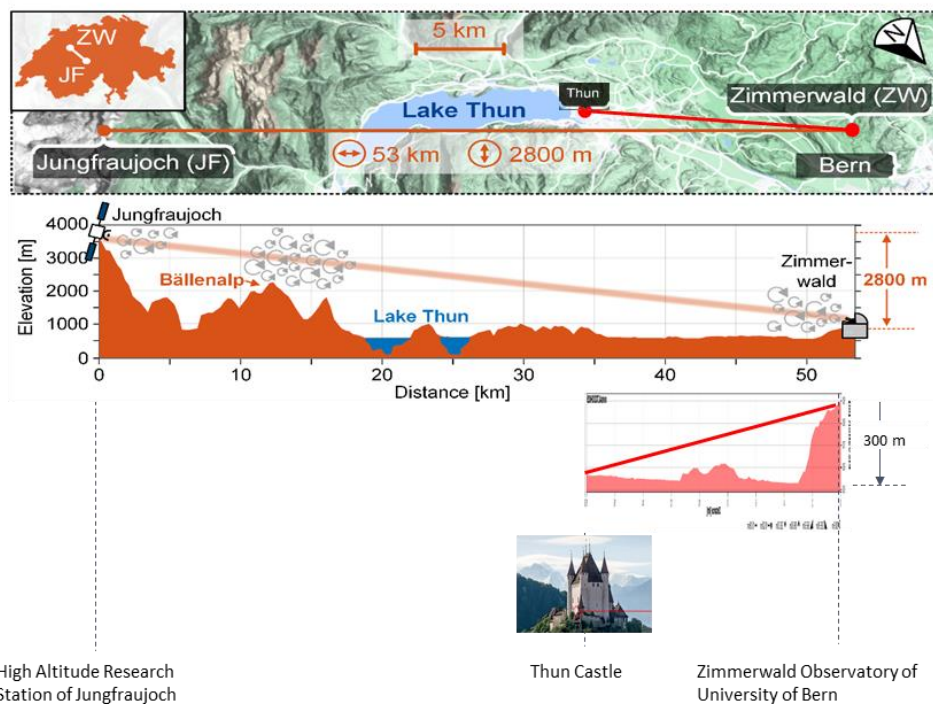


Figure 2. Sites locations and topographical profiles of the outdoor demonstrations line of sights in Switzerland (Copyright Swisstopo, Wikipedia, Google maps).

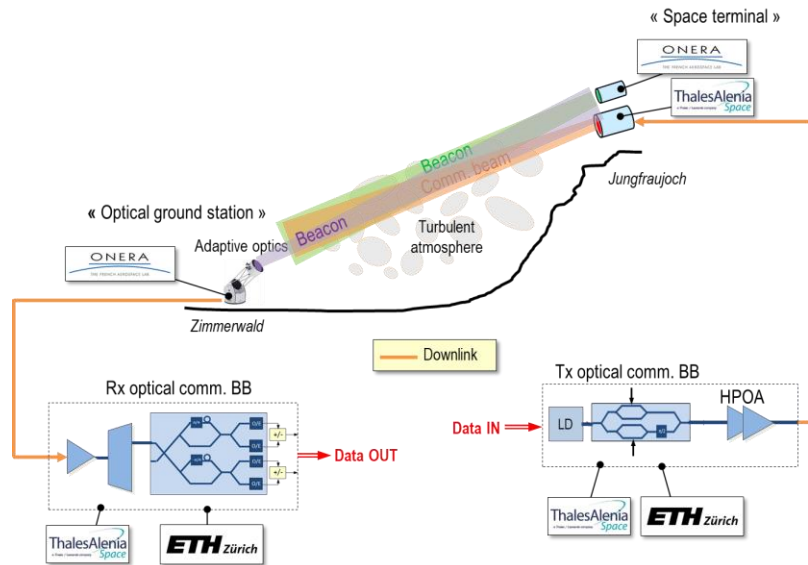


Figure 3. Illustration of the Jungfrauoch – Zimmerwald demonstration.

The setup of the demonstration in Zimmerwald includes (Figure 4):

5. Rx preamplified optical communication setups for 10G and 25G OOK/ 25G DPSK/ 10 MSps in C-band Analog modulation formats
6. Rx preamplified optical communication setups for coherent modulation formats up to 1 Tbps
7. A 350 mm Single Aperture OGS with adaptive optics (8x8 subapertures Shack Hartman Wavefront Sensor, Deformable mirror with 11x11 actuators, 1.5 kHz sampling frequency)

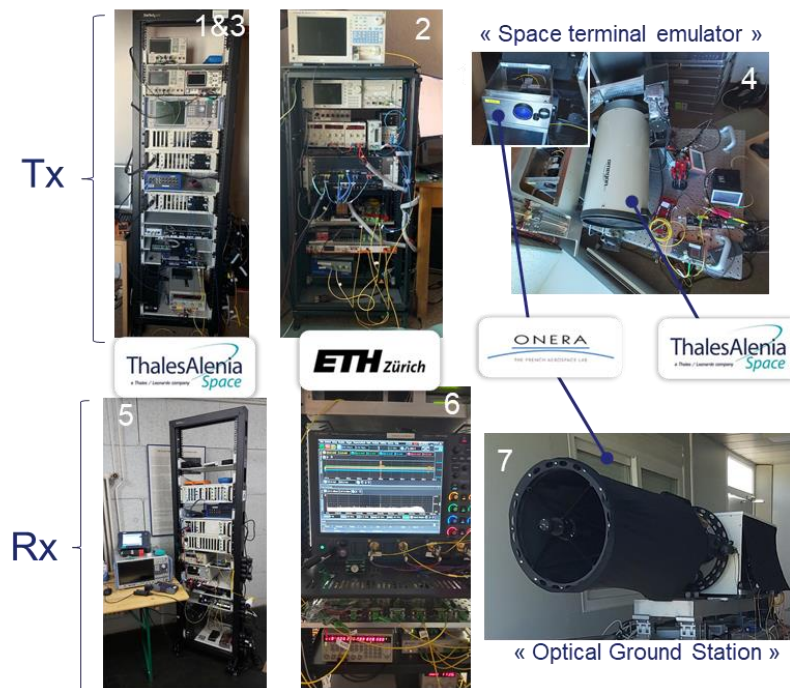


Figure 4. Setups in Jungfrauoch (top) and in Zimmerwald (bottom).

3.2 Channel characterization

The turbulence properties were estimated by ONERA from the data acquired through the adaptive optics system: Fried parameter (r_0), scintillation index (from intensity variations in Shack Hartmann subapertures), turbulence profile (Cn^2), anisoplanatic angle (θ_0). The Figure 5 hereafter presents the Fried parameter, scintillation index and isoplanatic angle variations during two time windows of the test campaign. It appears that r_0 values were between 2 and 8 cm and above 4 cm most of the time (night from 18 to 19 July shows a worst case during the test campaign), hence of same order of magnitude as for GEO-ground links and quite manageable with the FEEDELIO bench that was designed to handle a Fried parameter of a few centimeter. On the other hand scintillation index, always above 1 due to layers with strong turbulence far from OGS, exceeded the expected values on a GEO-ground link for which we estimate that scintillation index values above 1 should represent less than 1% of the occurrences. Even if not optimized (while at state-of-the-art) to handle such high level of scintillation, the Adaptive Optics bench was stable and provided a very noticeable improvement of the statistics of fiber coupled flux (see telecom performance results in section 3.3).

The derivation of the isoplanatic angle (Figure 5 –bottom) from estimated turbulence profiles (Figure 6) shows that it was always smaller than $4 \mu\text{rad}$ and even around $2 \mu\text{rad}$ most of time while it is expected to be mostly larger than $10 \mu\text{rad}$ on Ground-GEO line-of-sight. Moreover, the diffraction angle of the OGS was $4.1 \mu\text{rad}$, so that the isoplanatic angle is narrower than the diffraction angle, which is a very peculiar regime that does not correspond to the GEO case. It is clear from these evaluation that the implementation of an uplink with additional emulation of a point ahead angle was not relevant on this line of sight: it would not have been representative at all of a Ground-GEO link and it would have led to a channel too perturbed to provide relevant and usable data. Uplink pre-compensation on a relevant line of sight had been anyway previously demonstrated during the FEEDELIO experiment [8].

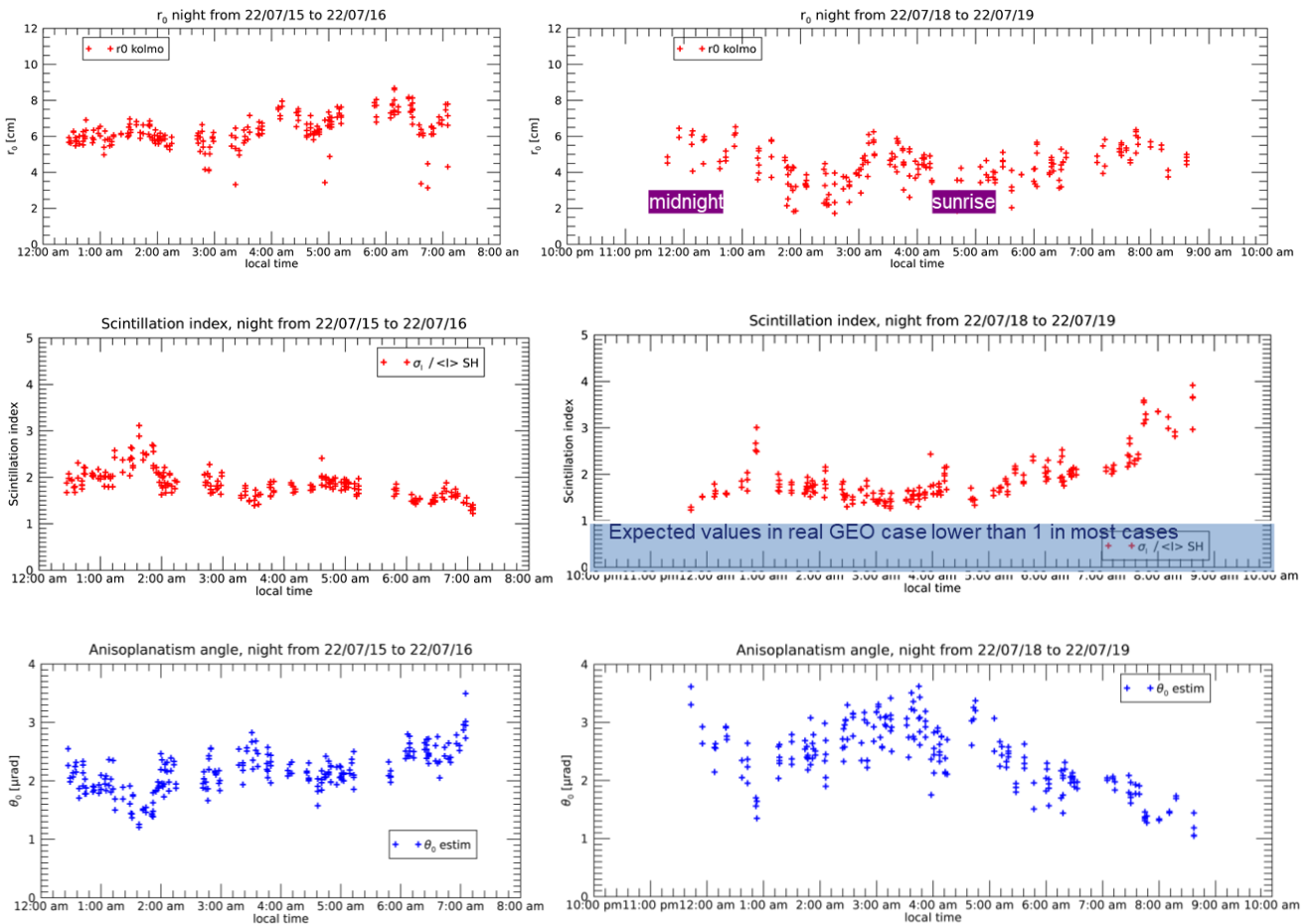


Figure 5. Fried parameter (top), scintillation index (middle) and isoplanatic angle (bottom) estimated by ONERA from experimental data recorded using the FEEDELIO adaptive optics bench.

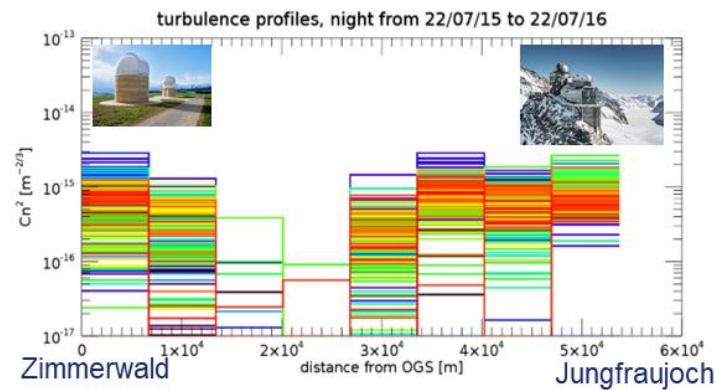


Figure 6. Turbulence profiles during one night inferred by ONERA from Adaptive Optics data. Blue tones correspond to beginning of the night, red tones to end of the night.

3.3 Telecom transmission characterization

The transmission performance of telecom signals relying on modulation formats based on Intensity Modulation/ Direct Detection and coherent were assessed through the 53-km line of sight. The received optical power together with the cumulated BER performance was measured every second for digital formats (25G OOK and DPSK) while constellation diagrams and EVM were recorded for RF-over-FSO transmission at 10 MSps (QPSK, 8-PSK, 16-APSK, 16QAM). Figure 7 presents some examples of such measurements over time. Due to an issue on Rx or Tx settings, the relative BER performance of OOK and DPSK (measured simultaneously on the same propagation channel through WDM implementation) were not in accordance with theory but demonstrated the robustness of these formats to turbulent propagation conditions. RF-over-FSO measurements highlighted large excursion range (up to 40%) of EVM values in the same second record. Additional results can be found in [9].

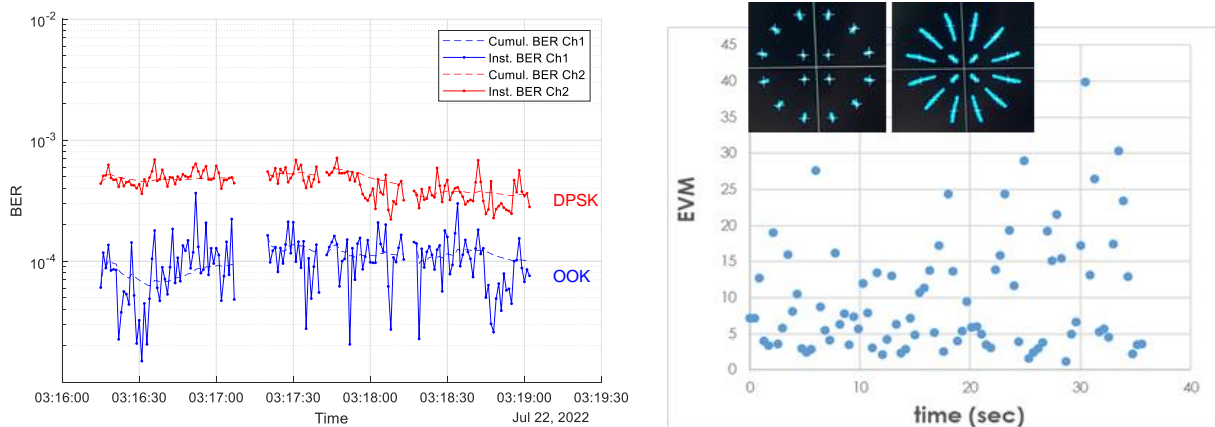


Figure 7. Examples of results: measured Bit-Error-Rate over time of 25G OOK and DPSK (left) Error Vector Magnitude over time (right).

Coherent transmissions were also assessed through digitization of received signals at 256Gsa/s over 16 μ s time slots with offline processing of the acquired data. The Figure 8 shows some examples of results achieved with DP-16QAM and DP-64QAM both transmitting around 1 Tbps line rate. The predominance of noise impairment at low received power makes 16QAM outperform 64QAM while modulator bandwidth limitation discriminates lowest order and high speed modulations. A record transmission at 1 Tbps over 53 km on a single wavelength was achieved in the frame of this test campaign. Other lower order coherent modulation formats, more compatible of short/medium term implementation in

optical feeder link systems were tested as can be seen on right side of Figure 8 presenting the electrical SNR achieved as a function of the received optical power (ROP) for a 32 GBaud DP-QPSK modulation format. It can be seen that the quality of FSO measurements (purple square) are in agreement with the ones obtained in the back-to-back measurements (black curve) in the lab. The gain provided by tip/tilt correction and more complete correction through adaptive optics can be observed in Figure 9 showing the received power distribution with or without correction. Up to 28.1 dB improvement on power distribution was achieved with adaptive optics in this test sequence. Further results on coherent transmissions are accessible in [10-12].

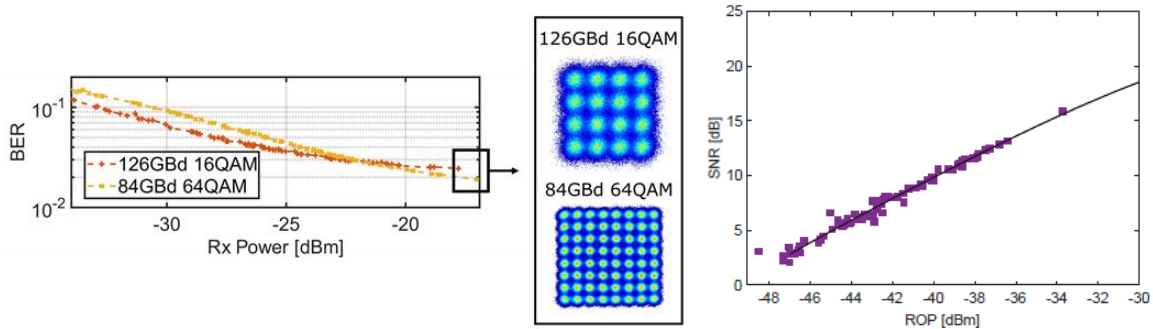


Figure 8. Examples of results: measured Bit-Error-Rate as a function of received power for 16QAM and 64QAM (left and middle) measured Electrical SNR as a function of received power of DP-QPSK (right).

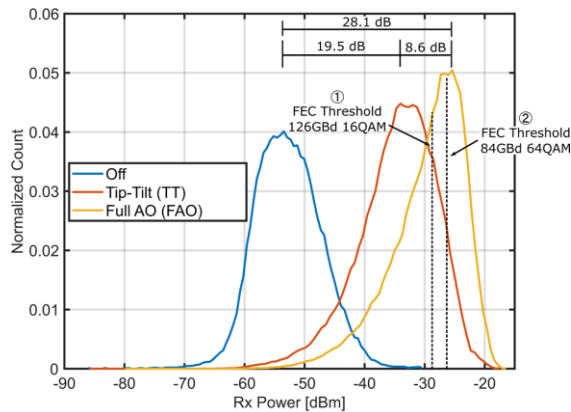


Figure 9. Reduction of atmospheric perturbations on optical signal through tip/tilt and full Adaptive Optics correction.

4. THUN – ZIMMERWALD AND BERLIN OUTDOOR DEMONSTRATIONS

4.1 Thun- Zimmerwald demonstration

The multi-aperture is another technique to mitigate atmospheric impairments addressed in the frame of VERTIGO by Fraunhofer HHI. While initial plan was to experiment both approaches, Single Aperture OGS with adaptive optics and Multi-Aperture OGS with tip/tilt correction on the same line of sight (Jungfrauoch – Zimmerwald), the link budget for this link range was too tight with the available multi-aperture setup. As a result, an alternative line of sight was selected between the Zimmerwald and the castle of Thun 18 km apart (see Figure 2). The high-level scheme and pictures of the setup are shown in Figure 10 and Figure 11 respectively. It includes (a detailed description of the setup is available in [13]) :

- In Zimmerwald: 4 x 20 mm diameter apertures, each associated with Rx and Tx optical amplifiers, 10 Gb/s SFP+ transceivers and FPGAs. The optical Tx power was 4 x 20 dBm.

- In Thun: 1 single 20 mm aperture with Rx and Tx optical amplifiers, 10 Gb/s SFP+ transceivers and FPGAs. The optical Tx power was 10 dBm.

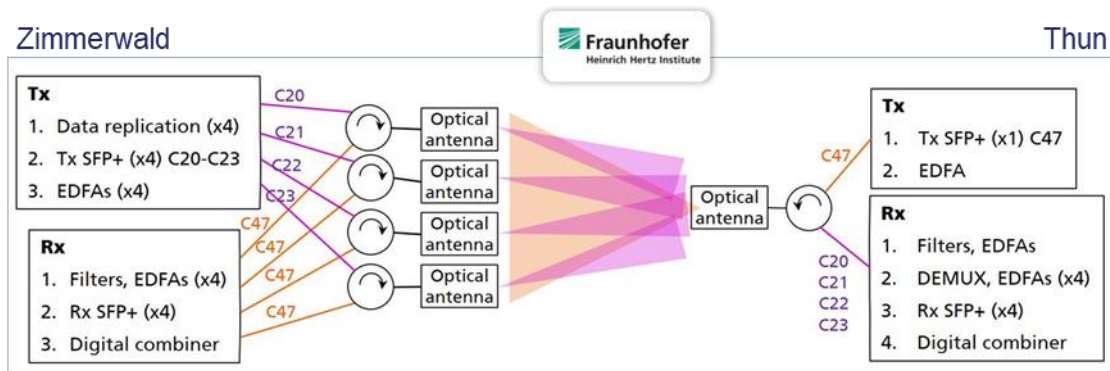


Figure 10. Scheme of the Thun – Zimmerwald test setup.

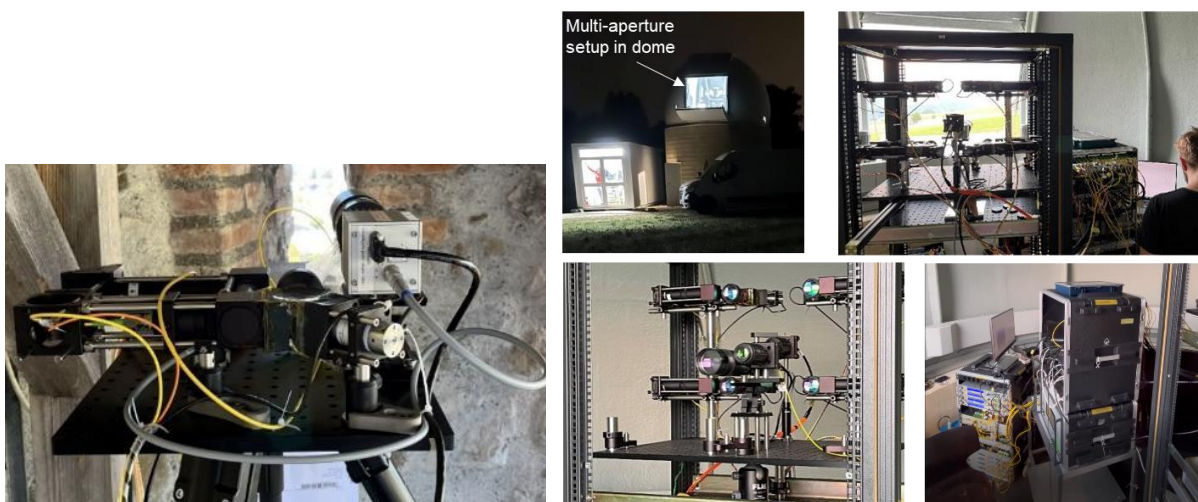
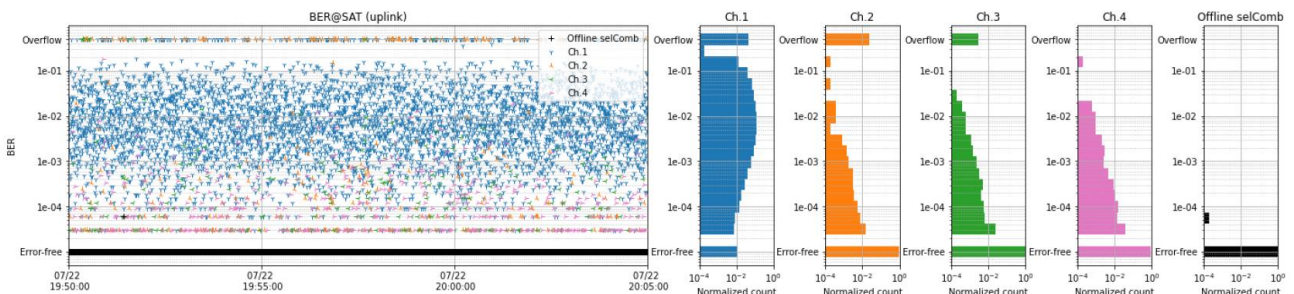


Figure 11. Pictures of the single aperture terminal at Thun Castle (left) 4-aperture OGS in dome at Zimmerwald (middle and right).

Using SFP+ transceivers and FPGAs, the BERs of the individual aperture channels were calculated in real time. In both directions, the BERs of the four aperture channels were combined offline with an ideal selection combining (best BER selected). Examples of resulting BER measurements from each channel and after best channel selection are provided in Figure 12 hereafter [13]:



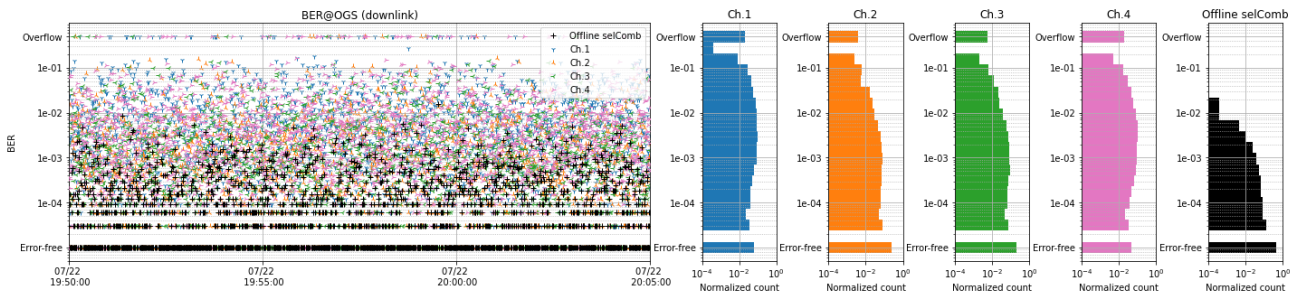


Figure 12. BER performance from individual channels and after (offline) best channel selection. Uplink (top) has lower BER than downlink (bottom) because it has more Tx power.

4.2 Rx beam combining demonstration

As another way to implement aperture diversity in reception, coherent beam combining was implemented in Fraunhofer HHI facilities in Berlin using a PIC (Photonic Integrated Circuit) combiner developed and operated by Thales Research & Technology [15-16]. Based on terminals from HHI similar to the ones previously depicted, a unidirectional link from the single-aperture terminal to the multi-aperture receiver was established with a round trip of ~400 m between two buildings (Rx and Tx being collocated in a building and the other building being equipped with a mirror). The signals received from the four apertures were coherently recombined in the optical domain on the PIC. The Figure 13 presents the block diagram as well as an example of the BER evolution (measured over sequences of ~5000 bits after amplification, detection and offline processing) achieved by performing such a combining with up to 4 apertures.

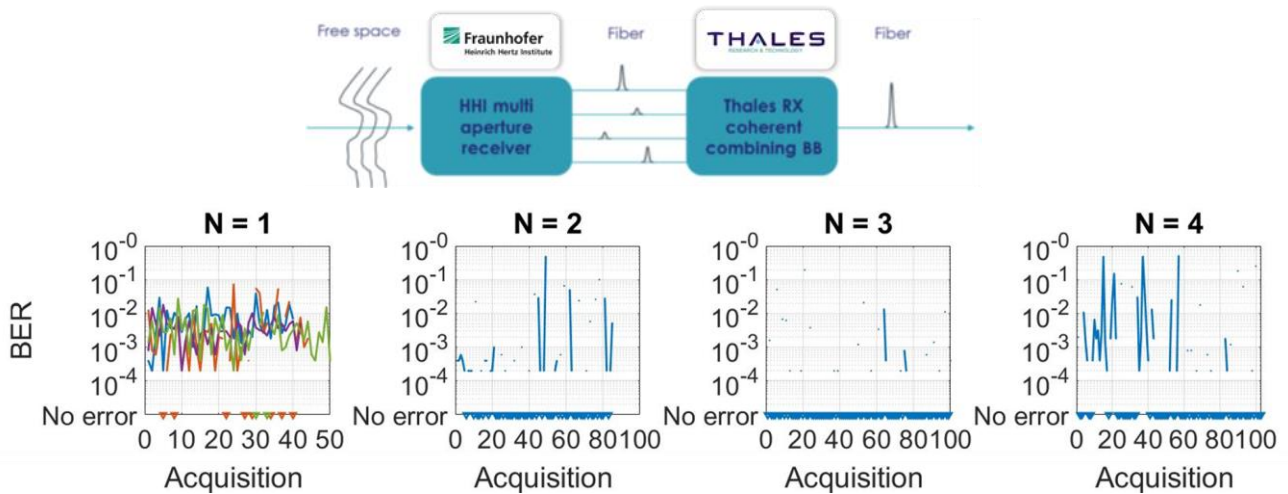


Figure 13. Rx coherent beam combining block diagram (top) and BER of 10G OOK with N=1 to N=4 apertures (bottom).

5. LABORATORY DEMONSTRATION

5.1 Indoor demonstration setup

The main objective of the laboratory (indoor) demonstration, held in Thales Research and Technology lab, in Palaiseau in Paris area, was to assess the impact of high optical power transmission on telecom signals integrity and related performance. The setup included the IM/DD optical communication chain presented in paragraph 3.1 as well as a fibered channel emulator (composed of variable optical attenuators) from Thales Alenia Space France, two 50W and one 10W optical amplifiers as well as a high power wavelength multiplexer from G&H [14], a coherent beam combiner developed by Thales Research & Technology and FPGA coding/decoding boards developed by Creonic. Spatial coherent combination is here used to overcome the limits of conventional high power optical amplifiers (HPOAs) operating at very high power (degraded spatial beam quality coming from the large heat load and/or photodarkening effects, HPOAs that becomes very sensitive to Stimulated Brillouin Scattering) to minimize the impact of the optical amplification on the telecom signals.

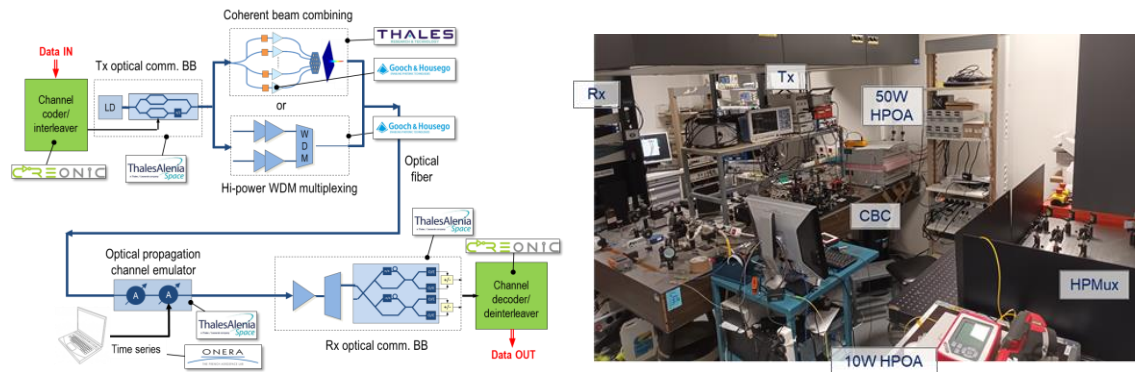


Figure 14. Scheme of the indoor demonstration (left) and picture of the setup in TRT laboratory (right).

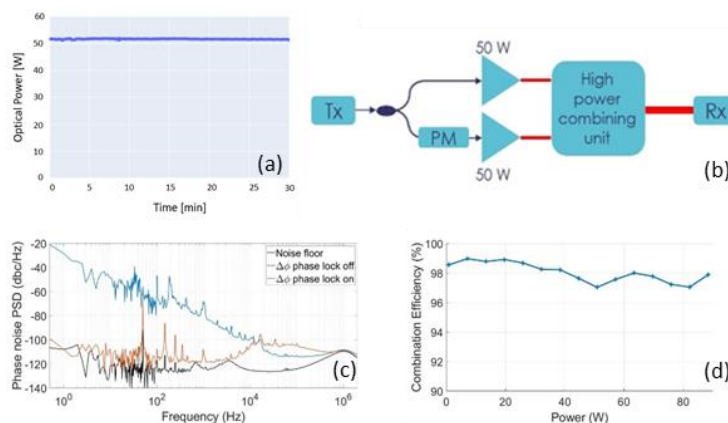


Figure 15. High and very high optical power generation : (a) single 50W amplifier output power stability over time (b) coherent combining scheme of the two 50W amplifier outputs (c) phase noise performance of the coherent combiner in closed loop (d) combining efficiency of two amplifiers.

During the test campaign telecom data transmission based on 10G OOK, 25G OOK and DPSK were achieved at high power using a single 50W amplifier and up to 97W on a single wavelength based on the coherent combination of the output of two 50W amplifiers with 97 % of combining efficiency with limited impact on the communication signal at the reception. Compatibility with wavelength division multiplexing was also demonstrated with optical carriers going through the same CBC unit.

6. CONCLUSION

The VERTIGO project completed early 2023 combined major technologies required for the implementation of future optical feeder links through 4 demonstrations addressing advanced modulation format for capacity increase, atmospheric perturbations mitigation techniques as well as the generation and handling of high and very high optical power for the transmission of telecom signals. In spite of difficulties encountered during the execution of the project largely due to Covid-19 pandemic, several major results were achieved and two records were established: a transmission speed in free-space of up to 1 Tbit/s on a single wavelength over 53 km and the transmission of optical communication signals carrying data at 25 Gbps at a record breaking optical power of 97 W opening the way to 100W-class transmissions.

While further tests to capitalize on the results of VERTIGO, the next step will be to target a full-scale coherent laser link between a geostationary satellite and a ground station.

7. ACKNOWLEDGEMENTS

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Finally, the consortium also thanks James Osborn (Centre for Advanced Instrumentation, Durham University) for kindly providing turbulence profile database [17] used in the frame of VERTIGO for the characterization of the GEO-ground link.

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