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Free-space optics emulator for coherent detection of satellite-ground link

Marie-Bertille Mosnier^{*1,3}, Sophonie Pech^{1,3}, Fabien Destic^{1,3}, Rémi Douvenot^{2,3},
Hélène Galiègue^{2,3}, Arnaud Dion^{1,3}, Angélique Rissons^{1,3}

¹ISAE-SUPAERO, Université de Toulouse, 10 avenue Marc Pégélin, 31400 Toulouse, France

²ENAC, Université de Toulouse, 7 avenue Edouard Belin, 31400 Toulouse, France

³Fédération ENAC ISAE-SUPAERO ONERA, Université de Toulouse, Toulouse, France

ABSTRACT

This paper presents a test bench for the emulation of a satellite-ground laser link, from the atmospheric propagation to its coherent detection. The scheme involves two projects. The EPLO project (Free-space Optical Propagation Emulator) aims at modeling and mitigating atmospheric impairments. The wave front deformation is emulated by time series with a DMD (Digital Micro-mirror Device), using Lee holographic methods and the Rytov approximation in the Kolmogorov theory. The signal then undergoes a correction in the TILBA-ATMO device, based on Cailabs' Multi-Plane Light Conversion (MPLC). Alongside this approach, the CALICO project (Compensation of Atmospheric losses on a laser Link by COherent detection) proposes a reception chain built on an Optical Phase-Locked Loop (OPLL) for homodyne demodulation and tracking of high Doppler rates due to low-Earth orbits. The end-to-end communication chain is here completed by implementing the OPLL-based receiver after the TILBA.

Previous studies have explored the constraints of speed and stability requirements of an OPLL for the desired application, with theoretical and simulation results. Combining EPLO and CALICO will however make it possible to physically assess on a single test bench the robustness of phase-shift keying modulation schemes, both addressing atmospheric disturbances and data recovery.

To achieve this coupling, both EPLO and CALICO parts need to be digitally simulated. The TILBA component is to be modeled and added to both simulations. The first results assessing the performance of the simulated OPLL are also expected, with a view to an FPGA implementation. This article presents the status of the modeling.

Keywords: Telecommunications, atmospheric turbulence, emulation, free-space optical communications, hybrid phase-locked loop.

1. INTRODUCTION

With increasingly saturated radio frequency wavebands, free-space optical (FSO) communications have become a major field of interest. Optical ground stations are being developed to demonstrate satellite-ground laser links, for example in France the CNES-led FrOGS [1] and ONERA's FEELINGS [2]. A successful bidirectional communication between FEELINGS and the newly launched Airbus GEO satellite TELEO was announced in July 2024 [3]. Laser links offer much greater bandwidths, as well as good compatibility with terrestrial optical fiber at a wavelength of 1550 nm (193.5 THz). Nevertheless, the transmission is confronted with atmospheric phenomena, including beam spreading, beam scintillation, phase distortion and beam wandering [4]. In addition, when considering links emitted from low-Earth orbits (LEO), the Doppler shift amounts to several GHz [5]. Coherent detection shows better spectral and energy efficiency than direct detection, especially for higher orders of modulation [6]. Yet, phase-shift keying (PSK) schemes need carrier recovery for homodyne demodulation. Both the atmospheric impairments and the Doppler effect on the signal therefore need to be addressed to achieve the communication.

*marie-bertille.mosnier2@isae-supaero.fr; phone +33 5 63 61 33 83 51; <https://www.isae-supaero.fr/fr/>

In the EPLO bench (Free-space Optical Propagation Emulator), the wavefront deformation due to the atmospheric effects is emulated with a Digital Micro-mirror device. The beam correction is then carried out by the wavefront demultiplexer TILBA-ATMO, a component assessed as an alternative to adaptive optics [7]. Simultaneously, to circumvent the additional disturbance caused by the Doppler shift, a coherent receiver based on a hybrid optical-digital phase-locked (ODPLL) is envisioned in the CALICO proposal (Compensation of Atmospheric losses on a laser Link by COherent detection). This paper presents findings obtained from both combined approaches with a view to achieve the end-to-end modeling of the downlink (Figure 1).

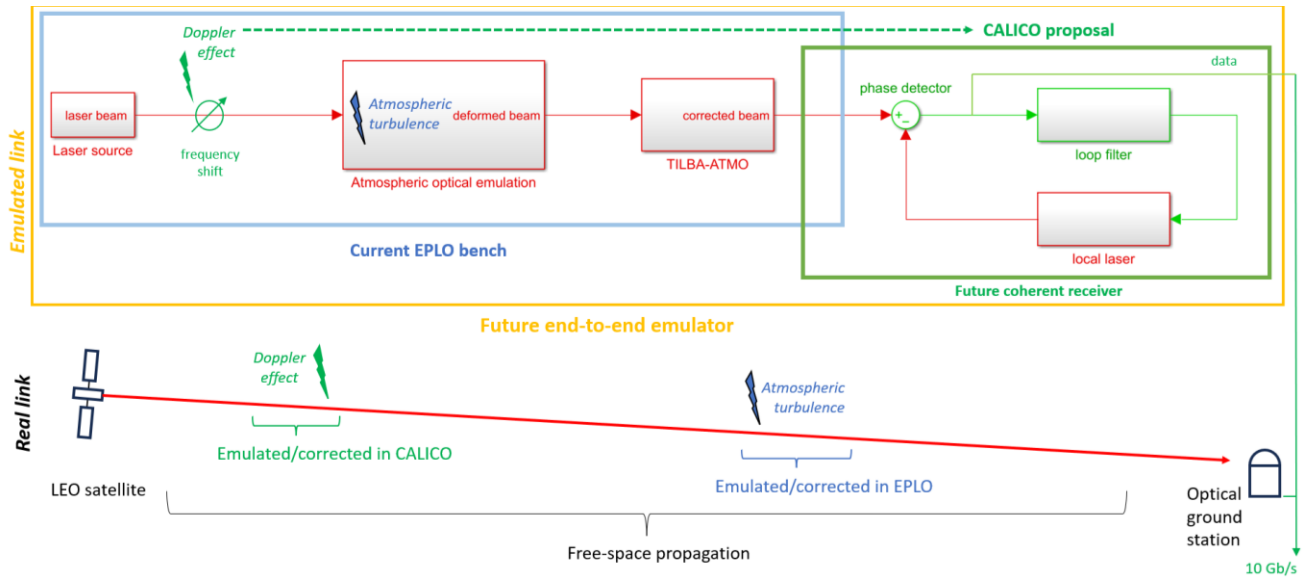


Figure 1: The envisioned end-to-end downlink emulator, and the respective scopes of the EPLO and CALICO proposals with respect to the real FSO link. The coherent receiver is detailed in Figure 4.

2. THE EFFECTS OF THE ATMOSPHERE AND SATELLITE MOTION ON THE OPTICAL SPACE TO EARTH LINK

One of the challenges is the presence of the atmosphere in which the beam spreads, which has a major impact on the link. The main causes are absorption (clouds), diffusion and fluctuations in local refractive indices (or atmospheric turbulence) [4]. The latter are caused by local changes in pressure, temperature, and humidity [4].

Atmospheric turbulence is responsible for fast spatio-temporal phenomena. In the context of this project, we are interested in four of them:

- The most known because visible to the naked eye on stars is scintillation [8]. Scintillation is due to the local variation of amplitude on the receiver. It is related to the optical path difference between distinct parts of the beam interfering with it on the observed pixel. It varies rapidly and is characterized by a normal log variance called the scintillation index.
- Phase deformation, which is also associated with the difference in optical paths traversed by the beam. It evolves more slowly than scintillation.
- The beam wandering is the fluctuation of the ray path direction due to the refraction phenomena on the larger size turbulences. It causes a variation in the received intensity on the receiver, or even a total loss of the signal if the turbulence is too strong.
- Lastly, the variation of the beam size, which does not vary directly with time, but with the thickness of the atmospheric layer and therefore the elevation of the satellite.

The mechanics of the satellite in low-Earth orbit also impairs the communication. Coherent detection imposes frequency and phase synchronization between the received and local carriers to perform homodyne demodulation. A coarse study of the satellite's motion relatively to the receiver yields the received frequency f_r as a function of the original emitted carrier frequency f_c (fixed by the chosen wavelength $\lambda = c/f$), Earth radius R_E , celerity of light c , satellite altitude h and satellite angular speed ω ($\omega = \sqrt{GM/(R_E + h)^3}$ where G is the gravitational constant, M the Earth mass):

$$f_r(t) = \left(1 + \frac{R_E(R_E+h)\omega \cos(\omega t)}{c \sqrt{R_E^2 + (R_E+h)^2 - 2(R_E+h)R_E \sin(\omega t)}} \right) f_c(t) \quad (1)$$

The maximum frequency variation is about 24 ppm at an altitude of 419 km (altitude of the International Space Station for instance). Applied to a 1550 nm optical carrier (193.5 THz), we find a $\Delta f = \pm 4.6$ GHz shift, a value consistent with previously published results [5, 6, 7, 9]. Without appropriate tracking, such an amount causes loss of phase and frequency synchronization and therefore failure of the demodulation.

3. EMULATION OF THESE EFFECTS

The bench shown in Figure 2 has been designed at ISAE-SUPAERO to produce the desired effects in thermal deformation on the beam.

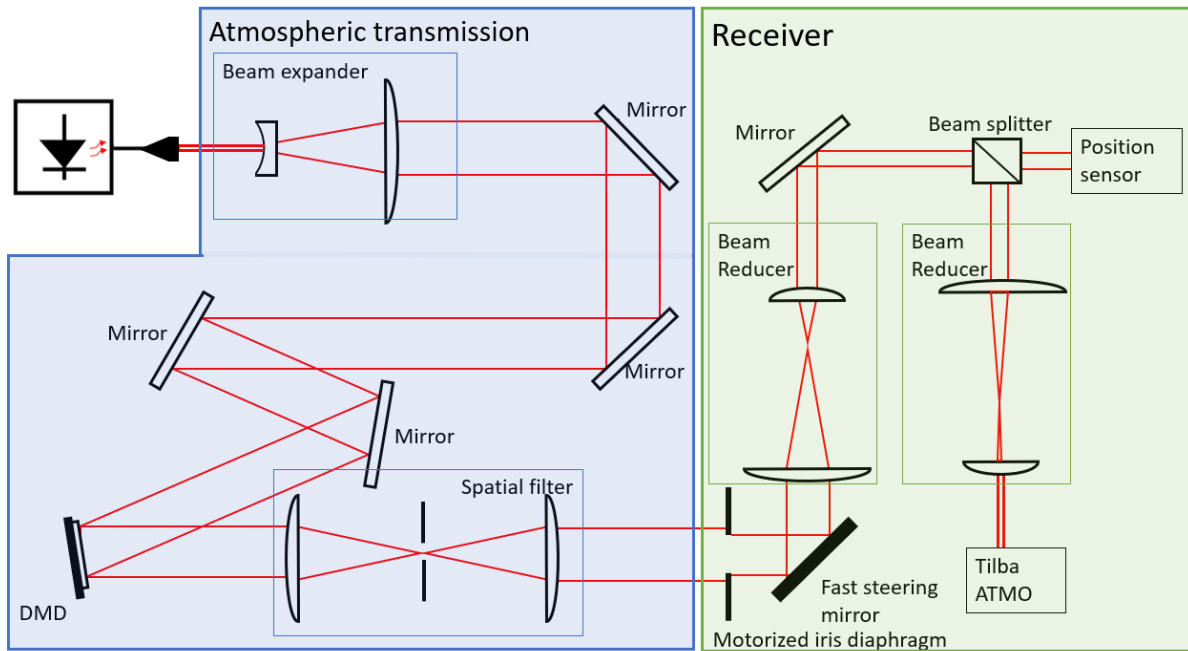


Figure 2. EPLO bench: the blue part is the atmospheric part, and the green is the reception one.

It uses four active components: the DMD, adjustable diaphragm, fast steering mirror and TILBA-ATMO from Cailabs. The first one reproduces scintillation, phase deformation and beam wandering by holographic principle [7]. Beam spreading is not directly emulated, but its effects are. The main effect of beam spreading is to change the parameter of Fried. This parameter is the ratio of the receiver size to the beam size at receiver. It is related to link quality. The fast-steering mirror and the TILBA-ATMO are in the reception chain in order to correct the deformations.

This bench needs to be resistant to the variation of frequency, as it induces a change in the wavelength. In our bench a modification of the wavelength will impact the direction of the beam and then the alignment after the DMD. A deviation of $\Delta f = \pm 4.6$ GHz will make a wavelength of 1550 ± 0.04 nm. The variation of the angle after the DMD is less than 2×10^{-6} rad which is negligible in comparison to the size of the optical bench.

Then, one problem created in the bench is the signal cut-off related to the DMD. On the bench, the DMD is the main active element. It allows us to produce phase distortion, scintillation, and beam wander [4]. We created diffraction gathering using a holographic method [13]. The DMD is a matrix of 1600 x 2560 square micro-mirror separated by 7.5 μm . Those micro-mirrors can have 3 different orientations along the diagonal: On (+12°), Off (-12°) and stand-by (0°). Changing the diffraction gathering means changing the position of each micro-mirror. This creates signal cut-off for the link. These signal cut-offs are controlled and last at least 105 μs , while the refresh time of the loop is only 0.01 μs . Then this can be seen as signal losses. It is modelled with diffraction as shown in Figure 3.

This duration of signal cut-off can be compared to the loss of the signal due to fading with adaptive optics (AO). The shorter the fading, the harder for AO to correct it [14]. With a LEO link, the probability for a fading to be longer than 105 μs is between 74% (high performance AO) and 93% (low performance AO) [14]. Obviously, the temporal dynamics of inter-fading differs from the exposure time of the diffraction gathering. For the DMD, the duration of a diffraction gathering is between 200 μs and 2 ms depending on the turbulence scenario used. These exposure durations correspond to 70% of the cases of inter-fading for a low performance AO and of 18% of the cases for high performance AO [14]. Then they are comparable to a low performance AO. In addition, we can remove the measurements associated to these cut-offs when processing the data.

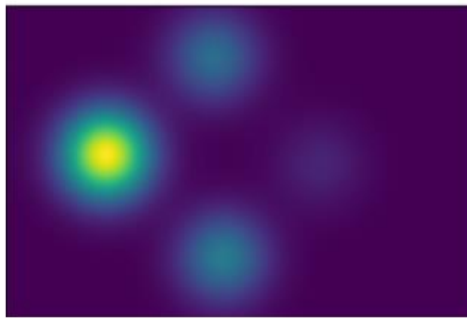


Figure 3: Result of the modelling of the optical field on a screen placed 10 cm from the DMD. The 10 cm is the actual distance between the DMD and the spatial filter. All micro-mirrors are in the On position.

In the future, the Doppler effect will also be emulated in the optical bench by electrically piloting the frequency of the laser source.

4. CORRECTION OF THE OPTICAL LINK

To correct the atmospheric effect, the adaptive part is composed of a fast steering mirror, a wavefront demultiplexer (TILBA-ATMO) and two beam reducers to fit the size in the TILBA-ATMO, as shown in Figure 2. The first results have been presented at ICSOS 2023 [10].

Regarding the compensation of the Doppler shift, a common technique for carrier recovery is the phase-locked loop (PLL). However, there is little literature dealing with its practical design for space optical communications. To tend towards an FPGA and/or DSP-based implementation, a hybrid model is built, assuming a quaternary phase-shift keying (QPSK) modulation. In the selected architecture (Figure 4), the phase detection block comprises the optoelectrical demodulation of the data (90° optical hybrid, balanced detection); 4th power of the demodulated electric signal to recover the residual carrier due to the phase error remaining in locked state; an averaging filter to mitigate transient disturbances; and the phase discrimination itself [11].

Theoretical PLLs are described using well-known continuous-time (CT) transfer functions (TFs). However, a direct conversion to the Z-domain would not account for the non-linearities of the phase detector, nor the delays introduced by the components. A behavioral approach (the useful data for the loop are the phase information at the input/output) is needed to validate a Z-transform TF directly originating from the classical CT model [12]. Additionally, considering realistic latencies for computations in the FPGA, a number n of delay samples should be added to this TF. This results in a closed-loop TF of the form:

$$H(z) = z^{-n} \frac{a - bz^{-1}}{1 - 2z^{-1} + z^{-2} + az^{-n} - bz^{-n-1}} \quad (11)$$

where a, b are functions of the gains of the loop components. When this transfer function has a denominator of degree $n > 4$, the roots can no longer be analytically computed. Then an analytical study of the stability cannot be conducted. An appropriate setting of the gains must still be found to obtain a stable ODPLL, and to meet the speed requirements in respect to the Doppler dynamics and targeted bitrate (10 Gb/s).

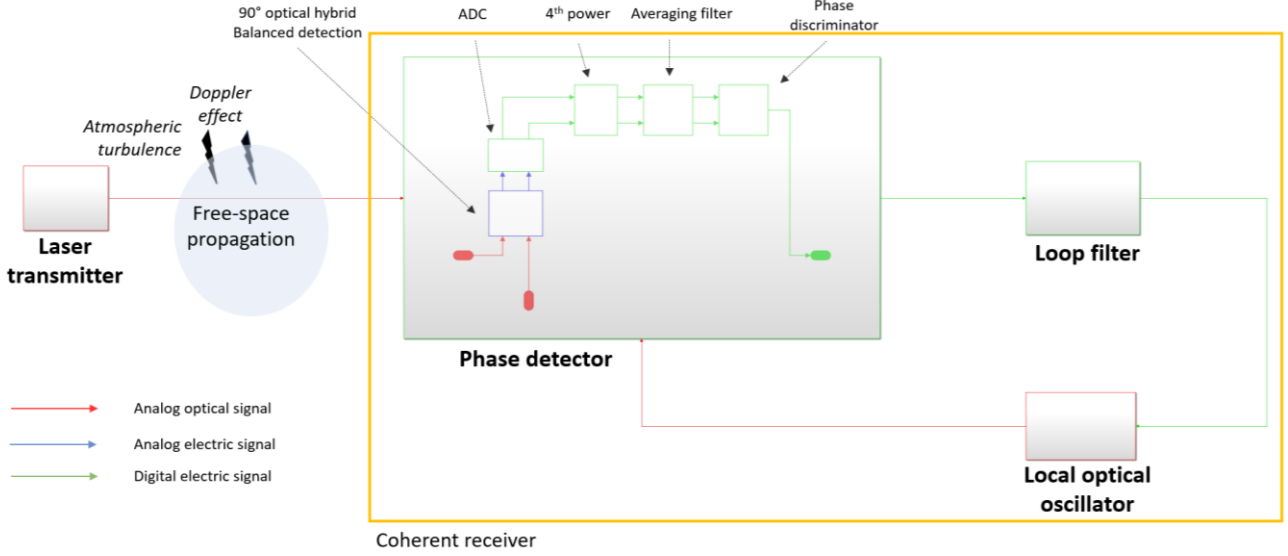


Figure 4. General architecture of the hybrid optical-digital phase-locked loop (ODPLL).

5. CONCLUSION AND PROSPECTS

Experimental settings are still in progress. Concerning the atmospheric effects, we are working on the development of the modeling to take into account high frequency variations. We also work on reception parts to analyze the effect of the TILBA-ATMO on phase deformation. As regards the Doppler effect, the coherent receiver must comply with stringent stability and speed requirements to ensure the link bitrate under high values of frequency shift adding up to the atmospheric phase deformation. Finding suitable values of gains for the ODPLL will allow the validation of the Z-domain behavioral description of the system. Using these gains, a component-based model on VPI Photonics simulator will be developed. The digital parts of the loop are also to be coded in VHDL, simulated with Vivado software tools, and tested on an FPGA board to assess the real latency. This study will help us refine the loop theoretical model in an iterative way and deduce practical specifications for the components needed. Ultimately, the ODPLL-based coherent receiver will be hardware implemented and integrated in the EPLO bench. Both the correction of atmospheric effects and Doppler tracking in an overall coherent detection scheme will then be addressed in the obtained bench, thereby completing the end-to-end emulation of the communication chain.

6. ACKNOWLEDGEMENTS

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