



HAL
open science

EPLO : Free-space optics emulator for satellite ground link

Marie-Bertille Mosnier, Fabien Destic, Angélique Rissons, Rémi Douvenot,
Hélène Galiègue

► **To cite this version:**

Marie-Bertille Mosnier, Fabien Destic, Angélique Rissons, Rémi Douvenot, Hélène Galiègue. EPLO : Free-space optics emulator for satellite ground link. COAT2023, Mar 2023, Durham, United Kingdom. hal-04605048

HAL Id: hal-04605048

<https://hal.science/hal-04605048>

Submitted on 7 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

EPLO : Free-space optics emulator for satellite ground link

Marie-Bertille Mosnier^{a,b}, Fabien Destic^a, Angélique Rissons^a, Rémi Douvenot^b, Hélène Galiègue^b

^a ISAE-Supaero 10 avenue Edouard Belin, Toulouse , France

^b ENAC, TELECOM-EMA, Université de Toulouse, F-31055 Toulouse, France.

ABSTRACT

This paper presents the EPLO project (Emulateur Propagation Libre Optique), dedicated to modelling and emulating the atmospheric effects on a laser link used for ground-satellite communication. To test different modulation wave forms and their robustness to the atmospheric turbulence, an experimental bench to reproduce the front phase deformation and the effect of beam spreading is in development. This emulator generates various scenarios of turbulence. Due to the utilization of holographic methods, it also includes a beam wander effect. The turbulence patterns driving the bench are calculated through the development of Zernike polynomials, to reproduce the effect of weak or strong turbulences in terms of scintillation indexes, beam wandering, beam spreading, phase variation and the dynamic of the temporal evolution. This enables the simulation and the study of the wave front deformations when the laser passes through the atmosphere.

Keywords : Telecommunication, emulation, phase-distortion, scintillation, beam wander

1. INTRODUCTION

For years, ground-satellite communications have been performed by radio frequency signals, however this method of transmission is limited by its bandwidth. Moreover, the channels have become saturated. By using laser-links based signal communication, this issue could be overcome. However, there are two obstacles to this method - the attenuation of the signal by clouds, and the atmospheric turbulence which causes deflection and deformation of the beam wavefront. In order to correct the latter, adaptive optics systems can be implemented, which consists of analyzing the deformation of the beam to compensate it with a deformable mirror. However, this method proves to be too slow for its intended use [1]. The objective of this paper is to model atmospheric effects and to integrate them to an experimental bench, using Digital Micro-mirrors Devices. The fundamental effects concerning the optical/IR wave propagation at 1550nm [2] in a random medium are diffraction, atmospheric attenuation, atmospheric turbulence, and thermal blooming. Here we focus on atmospheric effects : beam spreading, beam scintillation, phase distortion and beam wander [3].

The bench uses a DMD (digital micro-mirror device) for its speed. The pattern can be changed every 210 μ s which is fast compared to the adjustment time of adaptive optics [1]. This allows a comparison with the same time series, the dynamics of wavefront demultiplexer, adaptive optics or other technologies. The models used to create time series will be upgraded during the PhD.

The experimental set-up to reproduce these effects is detailed in the second section. The implementation of scintillation effects is detailed in Section 3. A conclusion opens to future developments.

2. THE BENCH AND ITS COMPONENTS

Figure 1 presents the bench conceived for this experience. The different items are detailed in the following parts of this section.

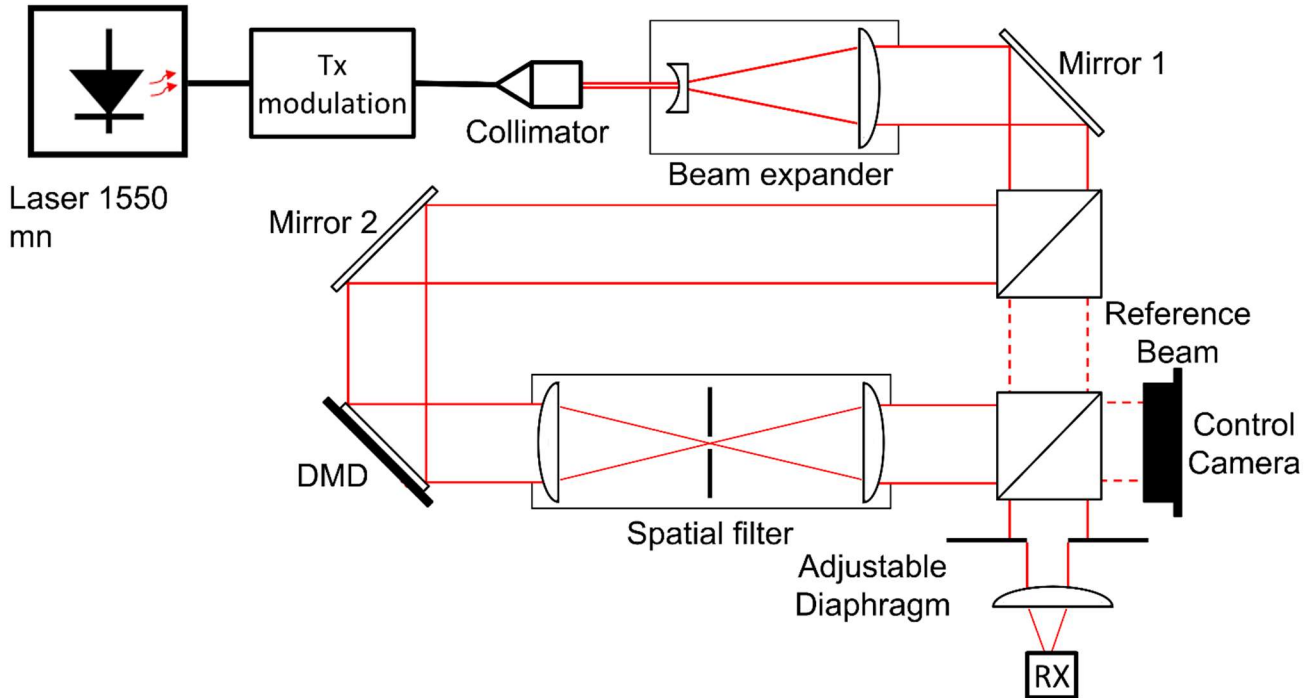


Figure 1 : EPLO Bench (DEOS, ISAE-Supaéro). The black lines represent the optical fiber, the red lines represent the propagation of the network, and the dotted lines represent the reference beams during the test phases.

2.1 The Tx modulation [4]

The transmitter is an external modulated laser system (Mach Zender modulators and laser) . Previous works [4] [5] proposed different waveform for data transmission such as OOK and QPSK modulation. Modulation has been tested on a fiber end-to-end link and validated by simulations on VPI photonics simulation tools. The EPLO bench includes this transmitter.

2.2 The Beam Expander

The beam expander is designed to give a ~ 10 mm diameter beam using a divergent lens and a convergent one. After this, the beam fits to the 11 mm DMD size. Figure 2 shows the beam after this component.

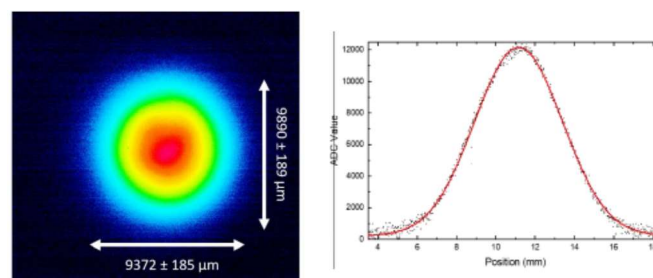


Figure 2 : Spot after the Beam expander

2.3 DMD

The DMD behaves as a blazed grating as shown in Figure 3 with a blazed angle θ_B determined by the tilt angle of the micromirrors with respect to the quiescent state, and several modes diffracted from a beam with an incident angle θ_i . The reflection angle θ_m of each mode is determined so that the amount of energy is maximized.

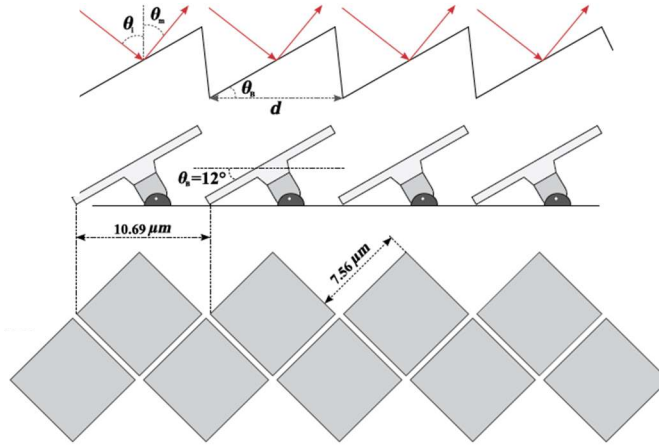


Figure 3: DMD representation

Thus, the angle of the reflected beam follows the equation

$$\theta_m = \arcsin\left(\sin(\theta_i + \theta_s) - \frac{m\lambda}{Td}\right) - \theta_s \quad (1)$$

with m the diffraction order (in our case, $m = 1$), λ the wavelength, T the spatial period of the DMD diffraction pattern, and d the spacing between two micro mirrors.

Lee's holography method is implemented to reproduce Zernike's polynomial. Every amplitude and phase screen can be reproduced [5], as illustrated in Figure 4 with a Laguerre-Gaussian mode.

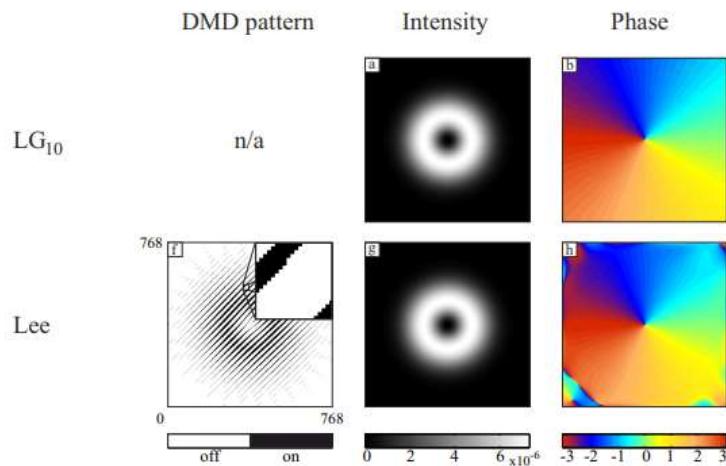


Figure 2 : Results of Lee holographic method to reproduce Laguerre-Gaussian 10 mode with perfect spatial filter [5]

2.4 The spatial filter

The spatial filter uses two 400 mm focal length lenses assembled in a 4f configuration: the spatial filter is in the focal plane of each lens. This arrangement allows the selection of only the first order of diffraction to apply Lee holographic method

2.5 The adjustable Diaphragm

The adjustable Diaphragm models the aperture diameter of the telescope. This allows the modification of the Fried parameter: $\frac{d}{r_0}$ with d the aperture diameter of the telescope, and r_0 the beam diameter. This ratio has a significant impact on the quality of the communication [1].

2.6 The Rx

In the Rx part, there are two parts, the adaptive one and the photodetection one that follows. In the configuration, which is still in settings process, the adaptive part is composed by a Tip-tilt and a wavefront demultiplexer (Tilba ATMO) as it is shown in Figure 6. And the Photodetection parts include the reception parts used in previous studies [4] [5].

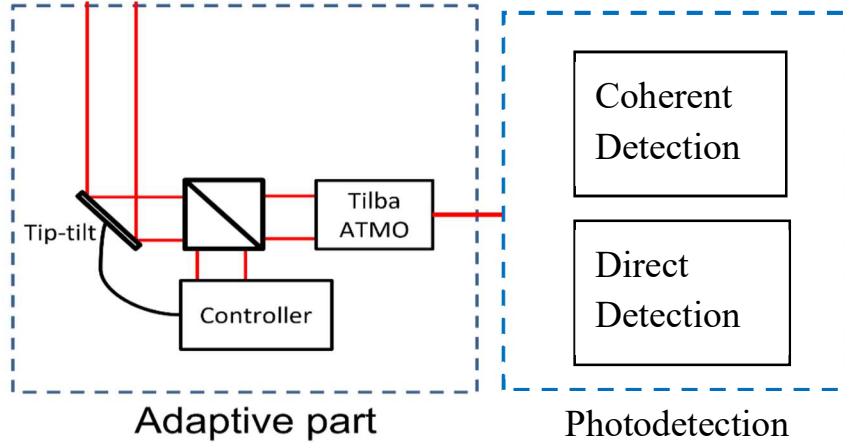


Figure 3: example Adaptive part composed by Tip-tilt and Tilba ATMO

In the next section we present how to reproduce the effects of turbulence thanks to this bench.

3. IMPLEMENTATION OF TURBULENCES EFFECTS

The development of a bi-dimensional dynamic time series generator is one of the main topics of this PhD work. Technical settings of the bench are led using static images : the spatial distortion of the phase and amplitudes are based on Rytov approximation models [3] and strong turbulences extensions (we stay on one deformation there is no time evolution of it). For this article we assume that we have two dimensional time series for scintillation, a time series of Zernike's polynomial for the phase distortion, a time series of beam Wander angles, and another one of beam spreading.

3.1 Phase distortion

To reproduce the phase distortion, which is given by a combination of Zernike polynomials, we configure the DMD by the Lee holographic method [6]. This method uses interferograms designed by computer which are implemented in the DMD matrix. Considering the binary state of each pixel (On or Off), the beam is modulated in phase and amplitude by the diffraction of the interferogram.

To obtain an electronic field as

$$A(x, y)e^{i\varphi(x, y)} \quad (2)$$

a binary interferogram $h(x, y)$ composed by rectangular fringes can be used. The phase and the amplitude are coded by the width and the position of each fringe [7]. The interferogram must have the form :

$$h(x, y) = \text{sign} \left\{ \cos \left(2\pi \frac{x}{T} + 2\pi\delta(x, y) \right) - \cos(\pi q(x, y)) \right\} \quad (3)$$

where $\delta(x, y)$ and $q(x, y)$ control the position and the width of each fringe following :

$$\delta(x, y) = \frac{\varphi(x, y)}{2\pi} \quad (4)$$

$$q(x, y) = \frac{\arcsin\{A(x, y)\}}{\pi} \quad (5)$$

The parameter T corresponds to the spatial periodicity of the fringes then qT represents the width of the fringe. The interferogram can be expressed as a Fourier spatial series like follows :

$$h(x, y) = \sum_m U_m = \sum_m \frac{\sin\{\pi m q(x, y)\}}{\pi m} \exp \left(j 2\pi m \left(\frac{x}{T} + \frac{\varphi(x, y)}{2\pi} \right) \right) \quad (6)$$

To maximize the efficiency of the first order of diffraction, we attribute a constant value to the parametric function $q(x, y)$. Then when $q(x, y) = \frac{1}{2}$ and $x = T$ the diffraction of the first order contains the phase information $\varphi(x, y)$. Finally, using the equations (2) and (6), it is possible to generate a binary interferogram. The DMD is then parametrized by this interferogram to emulate the atmospheric effect on the phase [8].

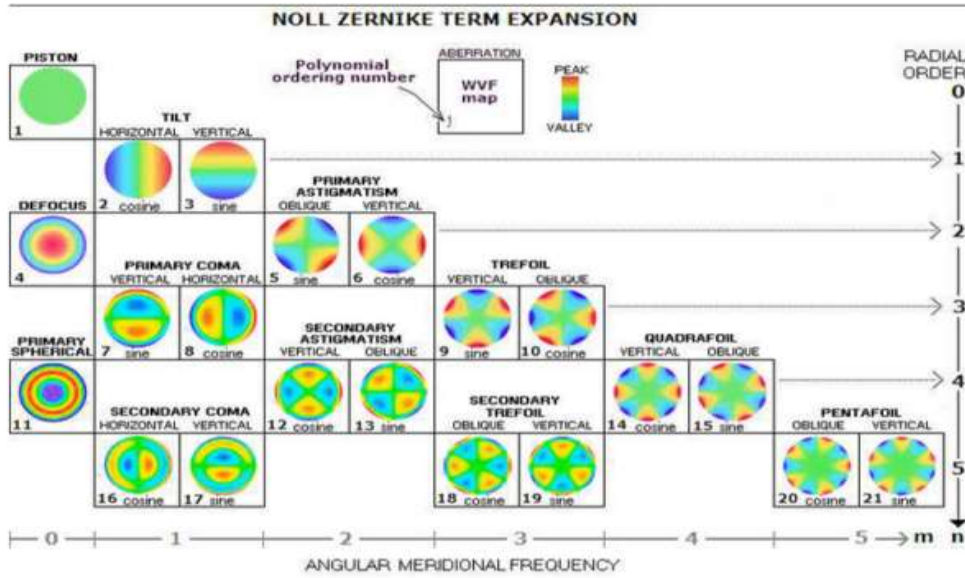


Figure 4: First order of Zernike polynomials [9]

With a good spatial filter, the beam has the local chosen phase, under the limit of the pixelization, obviously the number of micro-mirrors used gives the maximum resolution achievable.

3.2 The Scintillation

To reproduce the local amplitude deformations, the number of micromirrors in ON positions is modified, without changing their spatial distribution [8]. Figure 8 shows an example of this modulation.

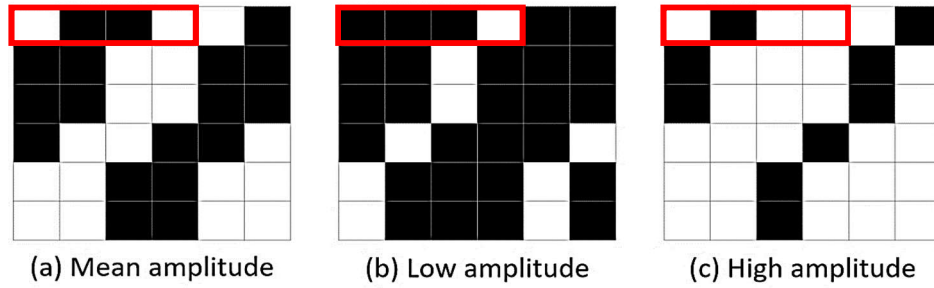


Figure 5 : Modification of the amplitude while keeping the same phase for a spatial period of 4 micro-mirrors. The black pixels are the OFF micro-mirrors, and the white pixels are the ON micro-mirrors

3.2 The Beam Spreading

Beam Spreading is a variation of the Beam radius. The implication of this is a variation of the Fried parameter. Here the Beam Expander is fixed therefore the beam radius is constant. Then we use the Adjustable Diaphragm to modify the Fried parameter.

3.2 The Beam Wander

The Beam Wander is modeled by changing the spatial frequency of the diffraction grating on the DMD. Only the first order is selected, which changes the position of the center of the beam on the Adjustable Diaphragm. Because we only change the spatial frequency, it is only a mono-dimensional modulation.

4. Conclusion

Experimental settings are still in progress. First test results show interferences between the reference beam and the modulated beam on the camera, but we are still adjusting the spatial filter. A study of the impact of the size of the spatial frequency on the interferogram shows that the higher the frequency, the better spatial discretization of the effect but also the less we can emulate the wandering effect and the less precision on the phase we can have. We also want to investigate the limitations on different scenarios of turbulence and satellite azimuth. When optimal conditions will be reached, we will implement the first temporal series of Zernike polynomials to drive the DMD and evaluate the effect on scintillation index. In a second step, we will study the impact of the Fried parameter with the adjustable diaphragm.

A Wavefront demultiplexer (Cailabs TILBA ATMO) and a tip-tilt will be integrated on the receiving chain (Rx). For this a controlled polar is required, we are working on it and on the injection parts, to characterize if the DMD polar deformation.

Références

- [1] Camboulives A.-R. «Compensation des effets de la turbulence atmosphérique sur un lien optique montant sol-satellite géostationnaire : impact sur l'architecture sol» PhD thesis, Université Paris Sud, (2017).
- [2] Hemmati H. «Near-Earth Laser Communications, Second Edition (2nd ed.) » *CRC Press*, (2020).
- [3] Andrews L. C. and Phillips R. L. «Laser Beam Propagation Through Random Media: Second Edition» *Scopus Export 2000s*, (2005).
- [4] Panasiewicz J. «Photonics technologies for satellite payload and communication links : microwave photonic vector generation and coherent optical reception architecture» PhD thesis, ISAE-Supaero, (2022).
- [5] Goorden S. A., Bertolotti J. and Mosk A. P., « Superpixel-based spatial amplitude and phase modulation using a digital micromirror device» *OPTICS EXPRESS*, (2014).
- [6] Noll R. J., «Zernike polynomials and atmospheric turbulence». *Journal of the Optical Society of America*, (1976).
- [7] Lee W.-H., «Binary computer-generated holograms» *Appl Opt*, (1979).
- [8] Anzuola E, Belmonte A. «Generation of atmospheric wavefronts using binary micromirror arrays» *Appl Opt*, (2016).
- [9] Sacek V., «Zernike expansion schemes,» [En ligne]. Available (03/2023): https://www.telescope-optics.net/zernike_expansion_schemes.htm.
- [10] Elayoubi K. «Étude des chaînes de communication pour liaisons optiques à travers l'atmosphère» PhD Thesis, ISAE-Supaero , (2019).