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# Coupling of atmospheric perturbed optical beams with guided modes of propagation

Luca Rinaldi<sup>a</sup>, Vincent Michau<sup>a</sup>, and Mathieu Boutillier<sup>b</sup>

<sup>a</sup>DOTA, ONERA, Université Paris Saclay, 92320 Châtillon, France

<sup>b</sup>CNES, 18 Avenue Edouard Belin, 31400 Toulouse, France

## ABSTRACT

Optical satellite-to-ground communications are disrupted by the effects of atmospheric turbulence which causes scintillation and phase distortion.<sup>1,2</sup> By correcting the wave phase perturbations, adaptive optics allows the beam to be coupled into a single-mode optical fiber at reception with minimal fading. When the satellite is close to zenith, the scintillation rate is a few percent: conventional adaptive optics techniques are well suited. On the other hand, when the satellite elevation is low, the scintillation is high and conventional wavefront measurement techniques are no longer usable. We propose here a new approach to couple an incoming beam disturbed by turbulence with a set of propagation modes representative of a spatial multiplexer, including in the case of strong scintillation. We illustrate our approach by considering the case of the Laguerre-Gauss modes.

**Keywords:** Adaptive optics, laguerre-gaussian modes, free-space optical communications, atmospheric turbulence

## 1. INTRODUCTION

Optical communications in free space are of great interest because of the throughput they allow, especially for satellite-to-ground links. In addition to the high data rate, optical wavelengths allow slightly divergent beams, thus reducing the SWAP of the devices associated with this technology. Conversely, optical beams are sensitive to atmospheric turbulence. The optical turbulence causes amplitude and phase distortions that lead to fading of the signal coupled into a single-mode optical fibre (SMF). The coupling of such an optical beam into an SMF has already been described,<sup>3</sup> including in the presence of adaptive optics (AO) compensation.

Our objective here is to characterize the coupling of waves perturbed by atmospheric turbulence in a Multi Mode fiber (MMF), or in a spatial multiplexer such as a multi-plane light conversion (MPLC)<sup>4</sup> or a photonic lantern.<sup>5</sup> In all these cases, the coupling may be described by the decomposition of the wave into a set of propagation modes such as Hermite-Gaussian (HG) or Laguerre-Gaussian (LG) modes. In the following, we have chosen the LG modes which does not restrict the generality of our study since any mode of the first family may be expressed as a linear combination of the elements of the other family.<sup>6,7</sup> Used in various applications focused on their orbital angular momentum,<sup>8,9</sup> such as quantum mechanics or classical telecommunications,<sup>10</sup> Laguerre-Gaussian modes are also the most popular choice for modal decomposition.

We consider a set of  $N^2$  LG modes characterized by their radial and azimuthal degrees,  $p$  and  $l$  such that  $0 \leq p \leq N - 1$  and  $0 \leq l \leq N - 1$ .<sup>11</sup> Their complex amplitudes can be written in the paraxial assumption, in circular-cylindrical coordinates  $(r, \phi, z)$  as:

$$LG_{p,l}(r, \phi, z) \propto \frac{1}{w(z)} \left[ \frac{r\sqrt{2}}{w(z)} \right]^{|l|} L_{p,l} \left( \frac{2r^2}{w(z)^2} \right) \times \exp \left( - \frac{r^2}{w(z)^2} \right) \exp(il\phi) \quad (1)$$

where  $L_{p,l}$  represents the generalized Laguerre polynomial of order  $p$  and degree  $l$ . Fig.1 presents the transverse spatial profile of the 16 first Laguerre-Gaussian modes, at waist ( $z = 0$ ), for four different values of radial and azimuthal degrees. In the following, the modes are denoted as  $LG_i$ , where  $i$  is equal to  $i = l + Np$ .

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e-mail: luca.rinaldi@onera.fr

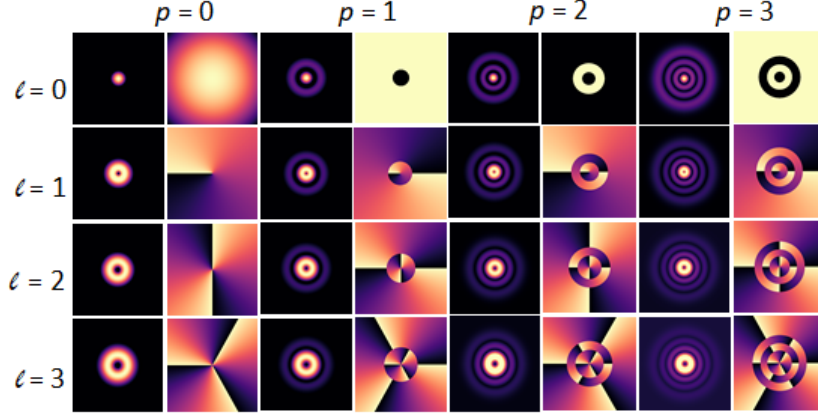


Figure 1. Spatial profile (intensity: left, phase: right) of the 16 first Laguerre-Gaussian modes.

Finally, the complex amplitude in the pupil plane may be written as :

$$P_0\Psi_{turb} = \sum_{i=0}^{N^2-1} a_i LG_i + \Psi_{res}, \quad (2)$$

where  $\Psi_{turb}$  is the complex amplitude of the incident beam, and  $P_0$  the characteristics function associated to the telescope pupil.

## 2. SATELLITE-GROUND OPTICAL LINK: COUPLING EFFICIENCY

Coupling efficiency is defined as the ratio of the average power coupled into a fiber to the average power in the receiver aperture plane. The coupling between the turbulent field and a mode  $LG_i$  propagating in the spatial multiplexer is given by the normalized overlap integral:<sup>3</sup>

$$S = \frac{\langle P_0\Psi_{turb}|LG_i \rangle}{(\langle P_0\Psi_{turb}|P_0\Psi_{turb} \rangle \langle LG_i|LG_i \rangle)^{1/2}} \quad (3)$$

where  $\langle | \rangle$  denotes the inner product. The fields are assumed normalized in the pupil plane:

$$S = \langle P_0\Psi_{turb}|LG_i \rangle = a_i.$$

The coupling efficiency,  $\eta$ , between a turbulent field and a MMF, characterized by  $N^2$  LG modes, writes:

$$\eta = \sum_{i=0}^{N^2-1} |a_i|^2 \quad (4)$$

Section 2.1 is dedicated to the coupling efficiency in absence of atmospheric turbulence for different sets of Laguerre-Gaussian modes is presented. The effects of turbulence on the perturbed optical beam are illustrated in section 2.2. Conclusion are drawn in section 3.

### 2.1 Coupling in case of a plane wave

The coupling efficiency  $\eta$  has been estimated by numerical simulation in case of a plane wave and for sets of growing numbers of  $LG_i$  modes such that  $1 \leq N^2 \leq 49$ . Fig.2 presents  $\eta$  as function of the ratio  $D/2w$ ,  $D$  being the pupil diameter and  $w$  the waist size of the considered set of modes. As expected (Fig. 2 (a)), the coupling efficiency  $\eta$  is equal to 0.82 for  $N^2 = 1$  (Gaussian profile). Increasing the number of LG modes increases the coupling efficiency: the maximum value of 0.95, reached with the set of 49 modes, is obtained for  $D/2w \approx 3, 6$ .

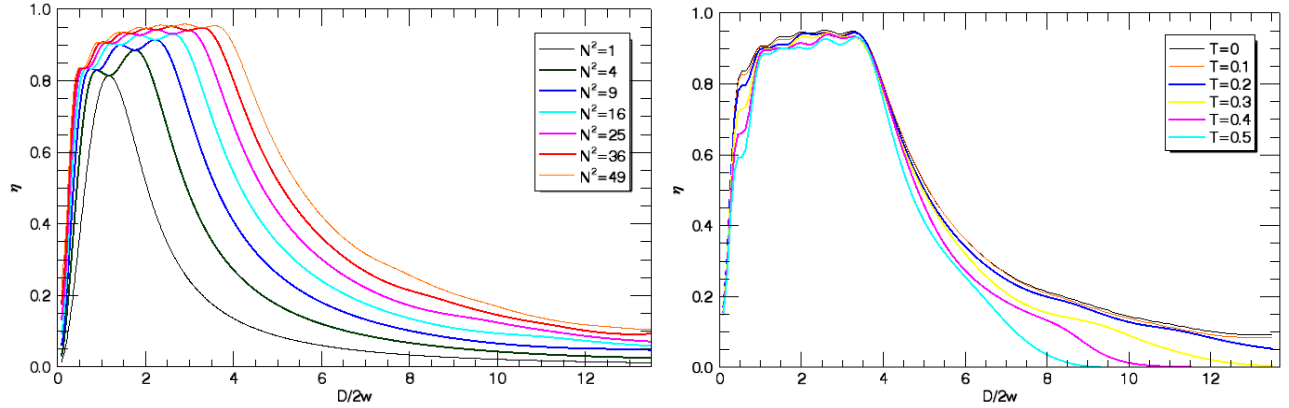


Figure 2. Coupling efficiency as function of the pupil diameter normalized by the waist, considering (a) a finite set of LG modes of growing number, (b) a set of 36 LG modes with a central occultation  $T$  from 0 to 50% of the pupil diameter  $D$ .

Furthermore, in Fig. 2 (b)  $\eta$  is presented for a set of  $N^2 = 36$  Laguerre-Gaussian modes, function of a pupil with a central occultation here noticed by  $T$ , from 0 to 50% of the total pupil diameter  $D$ . As shown in the figure above, with a set of 36 LG mode the effect of central occultation on the coupling efficiency is not significant as long as the occultation rate is less than 40%.

## 2.2 Coupling in case of atmospheric turbulence

Assuming the atmospheric turbulence described by Kolmogorov's law, its effects on wave propagation can be characterized by the Fried parameter,  $r_o$ . We have simulated the wave propagation between a satellite and the ground with a wave optics code developed in our laboratory.<sup>12</sup> The propagation is representative of a geostationary (GEO) - ground link at  $30^\circ$  of elevation. The main parameters characterizing the propagation are:  $r_0 = 6.9 \text{ cm}$  and  $\sigma_\chi^2 = 0.086$  at  $\lambda = 1550 \text{ nm}$ . The diameter of the receiver pupil is equal to  $D = 25 \text{ cm}$ . The complex amplitudes in receiver pupil plane are decomposed on  $N^2 = 49$  Laguerre-Gaussian modes. We have estimated the covariance matrix of coefficients  $a_i$  from 40 complex amplitudes obtained with our propagation code. Fig. 3 presents the cumulative term of the eigenvalues of the covariance matrix: it represents the coupling efficiency as function of the number of eigenmodes used for the coupling. A coupling rate of 54% is obtained with a dozen degree of freedom.

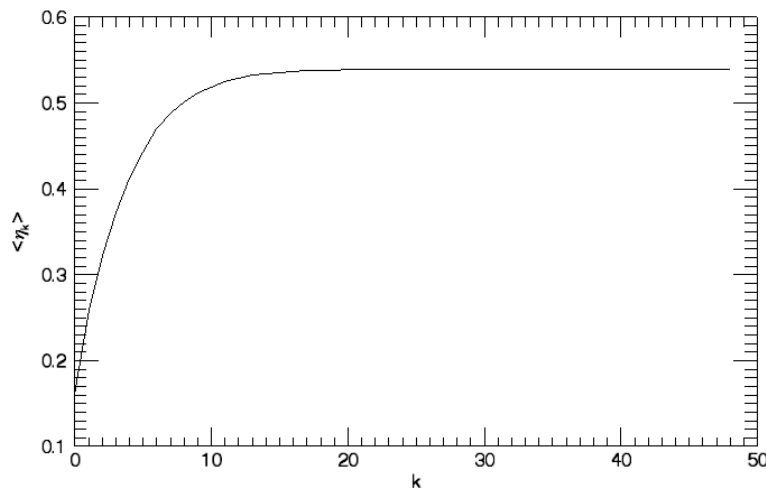


Figure 3. Average of the coupling rate function of the eigenvalues  $k$  with a combination of  $N^2 = 49$  LG modes

### 3. CONCLUSION

The coupling efficiency  $\eta$  between an incoming disturbed beam and a set of Laguerre-Gaussian modes was characterized here function of the pupil diameter  $D$  normalized by the waist size, also in presence of a central occultation  $T$ . A value of  $\eta$  equal to 0.95 is obtained with a combination of 49 LG modes and a circular pupil, while the effect of a central occultation is not significant increasing the number of LG modes. Furthermore, we evaluate the covariance matrix  $\langle a_i a_j \rangle$ . The average of the coupling efficiency was evaluated function of the number of eigenmodes used for the coupling, obtaining  $\eta = 0.54$  with a set of 49 LG modes in which the incoming beam is decomposed.

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