Influence of thick atmospheric turbulence on the propagation of quantum states of light using spatial mode encoding

Brandon Rodenburg,[1] Mehul Malik,[1] Malcolm O'Sullivan,[1] Mohammad Mirhosseini,[1] Nicholas K. Steinhoff,[2] Glenn A. Tyler,[2] and Robert W. Boyd[1,3]

[1] *The Institute of Optics, University of Rochester, Rochester, NY 14627 USA*
[2] *The Optical Sciences Company, 1341 South Sunkist Street, Anaheim, California 92806*
[3] *Department of Physics, University of Ottawa, Ottawa ON K1N 6N5 Canada*
Brandon.Rodenburg@gmail.com

Abstract: The effects of thick turbulence on transverse modes of light carrying orbital angular momentum are studied theoretically and experimentally. These results have potentially important implications for free-space quantum communications systems.

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There has been a great deal of interest in exploring the possibility of a quantum communication channel in which information is impressed on the spatial degrees of freedom of a single photon light field [1, 2] for a variety of applications in communications and in particular for quantu mkey distribution (QKD) [3]. As the spatial modes of light of a free-space channel form an infinite-dimensional Hilbert space, the amount of information that a single photon can carry is in principle infinite, allowing for a clear pathway to scale the transmission rates. Orbital angular momentum (OAM) states are of particular interest for a spatial encoding scheme [4] as they are readily made in the laboratory, have well-understood quantum optical properties, and can be efficiently sorted [5].

As spatial mode encoding is usually transmitted over a free-space communication channel, effects due to atmospheric turbulence become a real concern in the design of such a system. The effects of weak turbulence, where the turbulence is fully represented by a single random phase screen in the entrance pupil of the receiver, is well known and has been studied in the context of OAM quantum communication systems in recent years [6, 7]. However these models are only appropriate for weak turbulence and this is not always applicable in real world systems. Thus there is a need to understand the effects of propagation through thick turbulence for such systems.

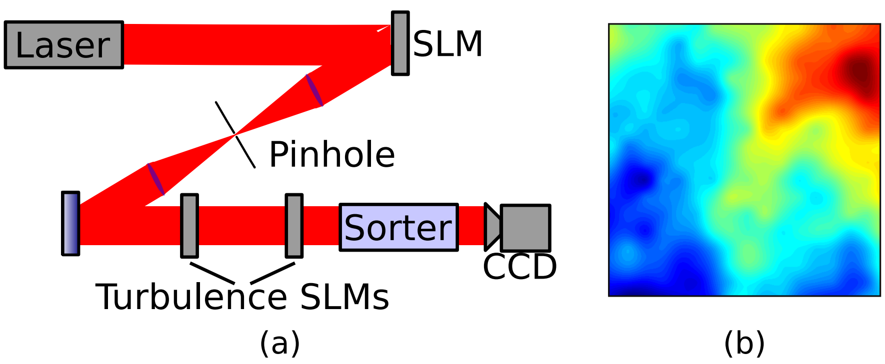
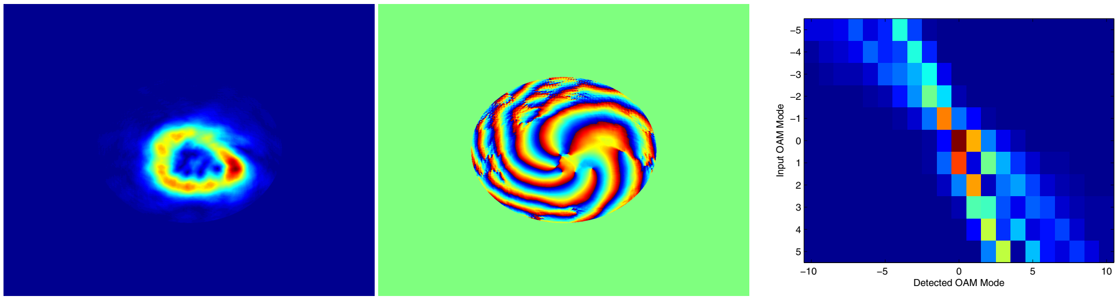


Fig. 1: (a) Schematic of our experimental setup representing the initial mode preparation, turbulence path propagation, and detection. (b) A typical realization of a random Kolmogorov phase screen used for simulating turbulence on the SLMs.

In order to experimentally study the effects of an OAM mode propagating through thick turbulence, our system was built as shown in the schematic in Fig. 1 (a). Full spatial phase and amplitude modulation of the input field is achieved



(a) (b) (c)

Fig. 2: Sample simulation of a communication system containing a turbulent free-space link. Graphed are the field (a) amplitude and (b) phase plots of a photon prepared in a Laguerre-Gaussian mode of OAM index $l = -5$. (c) Plot of the detected output probabilities of photons prepared in specific OAM modes.

with a phase-only spatial light modulator (SLM) and 4f system as described in Ref. [8]. Thick turbulence was simulated with two phase screens each with a randomly generated phase obeying Kolmogorov turbulence correlations as shown in a sample image in Fig. 1 (b). These correlations are fully characterized by a correlation length scale, r_0, known as Fried's parameter [9]. The location of each of these phase screens, as well as the r_0 values used, were chosen by numerical methods such that the resultant fields mimicked the statistical properties found in a real communication systems. The OAM modes are separated and detected as described by the device in Ref. [5].

The results of numerical simulations for a sample experiment are shown in Fig. 2. The simulated communication system has a Fresnel number of $N_f = 5$, with propagation along a 2-mile long turbulent free-space communication path. The results were averaged over 100 turbulent phase realizations and a sample output field amplitude and phase profile of a distorted Laguerre-Gaussian mode of OAM index -5 is plotted in Fig. 2 (a) and (b) respectively. Fig. 2 (c) graphically represents the spread in detected mode due to the presence of turbulence in the communication channel.

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