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Lens ghost imaging in a non-Kolmogorov slant turbulence atmosphere

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ABSTRACT

Based on the method of *computation* reference channel and the extended Huygens–Fresnel integral, the model of lens ghost imaging with fully spatially incoherent linear polarization light through a slant turbulent channel has derived. The model shows that the resolution ratio of ghost imaging decreases as the power-law exponent of non-Kolmogorov turbulence increasing or the object location departing from the source. The zenith angle of channel has little influence to the quality of the ghost imaging. The minimum distinguishable centre-separation of double slit decreases as the power-law exponent of non-Kolmogorov turbulence increasing.

1. Introduction

Ghost imaging was first implemented with position-momentum entangled photons [1]. The possibility of using classic light for ghost imaging was first pointed out in Ref. [2] and later several efforts have been made in order to compare quantum and classic ghost imaging [3–5]. In Refs. [6–9], ghost imaging with thermal and pseudo-thermal light are revealed. Recently, the ghost imaging with thermal light in Kolmogorov atmospheric turbulence and horizontal channel were studied based on the extended Huygens–Fresnel integral [10,11]. Cheng et al. [10] demonstrated that ghost imaging can provide imaging performance superior to direct imaging through the atmosphere. On the experimental side, ghost imaging with and without lenses through thin layers of turbulence have been carried out [12,13]. Zhang et al. [14] based on the computational ghost imaging arrangement with "virtual detector" and the extended Huygens–Fresnel integral, lensless ghost imaging with fully spatially incoherent light radiation through a slant *non-Kolmogorov turbulence*-channel has been studied. Cheng et al. [15] studied lensless ghost imaging with Gaussian Schell-mode pulse beam through a slant non-Kolmogorov turbulencet atmosphere-channel, based on the optical coherent theory, the extended Huygens–Fresnel integral and the approximation of the form of spatial-temporal coherence function of the laser field in the product of the spatial and temporal coherence function. In recent quantum ghost imaging experiment [13] and theoretical analysis [16], it was found that the effect of the thin layer turbulence can nevertheless be mitigated under certain conditions. It also has been found that in the case with lenses the effect of the turbulence is strongly dependent on the location of the turbulent layer, with the effect becoming more prominent as the turbulence is moved closer to the lens [16]. However, to the best of our knowledge, the properties of the lens ghost imaging of slant path non-Kolmogorov turbulence have not been taken into account.

In this paper, we theoretically analyse computational lens ghost imaging with fully spatially incoherent light radiation and in non-Kolmogorov atmospheric turbulence. In Section 2, the model of lens ghost imaging in non-Kolmogorov slant turbulence-channel is given and the calculation results are given in Section 3. We conclude our findings in Section 4.

2. Lens ghost imaging in the slant non-Kolmogorov turbulence atmosphere

Let us consider the computational ghost imaging scheme [17] shown in Fig. 1. In this lens ghost imaging scheme, the test channel is a slant turbulence-channel and the reference channel is a computation simulation channel. In the test channel, a fully spatially incoherent source E_s propagates through atmospheric turbulence channels. There is an unknown object $O(\xi)$ located in this channel, and the bucket detector D_t is used in the channel. The distance between the source and the detector, the source and the object, the object and the lens, the lens and the detector are d_0 (d_1+d_2), d_1, and d_3 ($d_3=f$) respectively. In the reference channel, the model of computational field is constituted by a reference imaging system in which the source field E_s is same as test channel and is imaged by a lens and turbulence free system. The propagation distance from the source to the reference imaging lens is $d_0=d_1+d_2$ and

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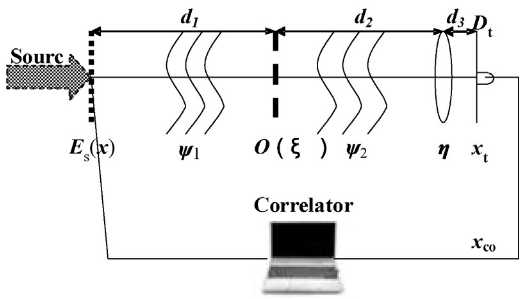

Fig. 1. Lens ghost-imaging in a slant atmospheric turbulence system.

the focal length of reference imaging lens also is f. The object image is obtained by correlating the intensity measured by the D_t bucket detector at plane x_t with the calculated field for filed propagation from source plane to spatial resolving "virtual" detector D_{co} at x_{co} plane.

According to the extended Huygens–Fresnel integral [16], the field $E(\xi)$ of linear polarization source field $E_s(x)$ propagation from source to object plane can be represented as

$$E(\xi)=\frac{1}{\sqrt{i\lambda d_1}}\int dx_1E_s(x_1)\exp\left[\frac{ik}{2d_1}(x_1-\xi)^2+\psi_1(x_1,\xi)\right] \quad (1)$$

where $\psi_1(x,\xi)$ is the random part of a spherical wave propagating through the atmosphere from the source plane to the object plane.

The output field of $E(\xi)$ propagates through object is given by

$$E'(\xi)=\frac{O(\xi)}{\sqrt{i\lambda d_1}}\int dx_1E_s(x_1)\exp\left[\frac{ik}{2d_1}(x_1-\xi)^2+\psi_1(x_1,\xi)\right] \quad (2)$$

where $O(\xi)$ denotes the transmission function of the object.

The field at the lens plane η can be obtained as

$$E(\eta)=\frac{-i}{\lambda\sqrt{d_1d_2}}\iint dx_1d\xi E_s(x_1)\exp\left[\frac{ik}{2d_1}(x_1-\xi)^2+\psi_1(x_1,\xi)\right]\times O(\xi)\exp\left[\frac{ik}{2d_2}(\xi-\eta)^2+\psi_2(\xi,\eta)\right] \quad (3)$$

where $\psi_1(\xi,\eta)$ is the random part of a spherical wave propagating through the atmosphere from the object plane to the lens plane.

Appling the Fourier-transform of lens, the field $E(x_t)$ in the bucket detector D_t can be written as

$$E(x_t)=\frac{1}{i\lambda\sqrt{i\lambda d_1d_2f}}\iiint dx_1d\xi d\eta E_s(x_1)\times\exp\left[\frac{ik}{2d_1}(x_1-\xi)^2+\psi_1(x_1,\xi)\right]\times O(\xi)\times\exp\left[\frac{ik}{2d_2}(\xi-\eta)^2-i\frac{kx_t\eta}{f}+\psi_2(\xi,\eta)\right] \quad (4)$$

Following the Huygens–Fresnel integral, the calculated field of reference channel, which is connected to the source field and propagating in turbulent free channel, is given by

$$E(x_{co})=\frac{1}{\sqrt{i\lambda f}}\int dx_2E_s(x_2)\exp\left(-\frac{ikx_2x_{co}}{f}\right) \quad (5)$$

Based on the optical coherent theory, in the one dimensional case, the second-order degree of coherence containing the imaging of the object is given by [17]

$$G(x_t,x_{co})=\langle I(x_t)I(x_{co})\rangle-\langle I(x_t)\rangle\langle I(x_{co})\rangle \quad (6)$$

where $I(x_t)$ and $I(x_{co})$ denote the intensities in the test channel and reference channel, respectively. The brackets denote an average over all realizations of the field.

Assuming the turbulence fluctuations in the channel d_1 and d_2 are statistical independence, the intensity correlation can be represented as

$$\left\langle I(x_t)I(x_{co})\right\rangle=\frac{1}{\lambda^4d_1d_2f^2}\iint\iint\iint\iint O(v)O^*(v')dx_1dx_1'dx_2dx_2'd\xi d\xi'd\eta d\eta'\langle\exp[\psi_1(x_1,\xi)+\psi_1^*(x_1',\xi')]\rangle\langle E_s(x_1)E_s^*(x_1')E_s(x_2)E_s^*(x_2')\rangle \exp\left\{\frac{ik}{2d_1}[(\xi-x_1)^2-(\xi'-x_1')^2]\right\}\langle\exp[\psi_2(\xi,\eta)+\psi_2^*(\xi',\eta')]\rangle\exp\left\{\frac{ik}{2d_2}[(\xi-\eta)^2-(\xi'-\eta')^2]-i\frac{kx_t}{f}[\eta-\eta']\right\}\exp\left[-\frac{ikx_{co}}{f}(x_2-x')\right] \quad (7)$$

The last term in Eq. (6) can be expressed as

$$\langle I(x_t)\rangle\langle I(x_{co})\rangle=\frac{1}{\lambda^4d_1d_2f^2}\iint\iint\iint\iint O(v)O^*(v')dx_1dx_1'dx_2dx_2'd\xi d\xi'd\eta d\eta'\langle\exp[\psi_1(x_1,\xi)+\psi_1^*(x_1',\xi')]\rangle\langle\exp[\psi_2(\xi,\eta)+\psi_2^*(\xi',\eta')]\rangle\langle E_s(x_1)E_s^*(x_1')\rangle\langle E_s(x_2)E_s^*(x_2')\rangle\exp\left\{\frac{ik}{2d_1}[(\xi-x_1)^2-(\xi'-x_1')^2]\right\} \exp\left[-\frac{ikx_{co}}{f}(x_2-x_2')\right]\exp\left\{\frac{ik}{2d_2}[(\xi-\eta)^2-(\xi'-\eta')^2]-i\frac{kx_t}{f}[\eta-\eta']\right\} \quad (8)$$

The statistical average $\langle\exp[\psi_1(x,\xi)+\psi_1{}^*(x',\xi')]\rangle$ coursed by the turbulence fluctuations can be described approximately by [18]

$$\langle\exp[\psi_1(x,\xi)+\psi_1{}^*(x',\xi')]\rangle=\exp\left[-\frac{1}{2}D_\psi(x-x',\xi-\xi';z)\right] \quad (9)$$

where $D_\psi(x-x',\xi-\xi';z)$ is the structure function of the turbulent fluctuations.

We assume the source obeys the Gaussian statistics with a zero-average mean and can be represented as

$$\langle E_s(x_1)E_s^*(x_1')E_s(x_2)E_s^*(x_2')\rangle=\langle E_s(x_1)E_s^*(x_1')\rangle\langle E_s(x_2)E_s^*(x_2')\rangle+\langle E_s(x_1)E_s^*(x_2')\rangle\langle E_s(x_2)E_s^*(x_1')\rangle \quad (10)$$

The two-point correlation functions $\langle E_s(v)E_s^*(x_2')\rangle$ of fully spatially incoherent beams can be expressed

$$\langle E_s(x_1)E_s^*(x_2')\rangle=I_0\delta(x_1-x_2') \quad (11)$$

where I_0 is a constant, and $\delta(x_1-x_2')$ is Dirac delta function.