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A variable aperture method to simultaneously estimate atmospheric extinction coefficient and refractive index structure constant

Dagang Jiang [a,*], Yuanjie Yang [a], Jian Huang [a], Zhoushi Yao [b], Bin Zhu [a], Kaiyu Qin [a]

[a] School of Astronautics and Aeronautic, University of Electronic Science and Technology of China, Chengdu 611731, Sichuan, China
[b] Research & Development Center, China Academy of Space technology (Xi'an Branch), Xi'an 710036, Shanxi, China

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ABSTRACT

Both atmospheric extinction coefficient and refractive index structure constant (C_n^2) are important parameters to describe laser beam propagation in the atmosphere. The typical measurement methods for these two parameters are separated. Recently an integrated measurement method has been developed with the aperture constraint condition. In this study, a variable aperture method is proposed to simultaneously evaluate the atmospheric extinction coefficient and C_n^2 needless to consider the aperture constraint condition. The projection optics with CCD is employed to partially receive atmosphere modulated laser speckle images. Because the extinction coefficient and C_n^2 are implicit in the far-field receiving power at a certain aperture, they can be estimated through at least twice measurements of long term speckle at different equivalent aperture on the CCD image. The uncertainty analysis is also carried out. The theoretical and experimental results demonstrate that this technique is feasible, which provides an effective and economical way to understand the complicated behavior of laser beam propagation in the atmosphere.

1. Introduction

Atmospheric extinction coefficient and refractive index structure constant (C_n^2) describe transmittance (attenuation) effects and turbulence effects, respectively. Both of them are important parameters to represent laser beam propagation in atmosphere, and have been studied extensively, including in the application of free space optical communications (FSO) [1], laser radar [2], remote sensing [3] and so on.

The extinction coefficient is generally measured by lidar [4,5], visibility sensor [6] or digital photography [7,8]. The methods to measure C_n^2 can be mainly divided into two categories: one is from testing a certain turbulence effect, such as measuring the beam wander effect [9–12], the scintillation effect [13,14], and the angel-of-arrival fluctuation effect [15,16], and another is by using a specific sensor on the local test point, such as using a thermometer [17] or a sonic anemometer [18].

Those measurement methods for the extinction coefficient and C_n^2 have not been integrated into a system yet. In fact, simultaneously measurement of extinction coefficient and C_n^2 will be conducive to comprehensive understanding the behavior of laser beam propagation in the atmosphere. Especially for the application of FSO, atmospheric extinction coefficient and C_n^2 are significant channel parameters, which respectively influence the availability and bit error-rate (BER) [19,20].

In order to address this issue, a synchronous measurement technique has been developed [21], which employs large aperture projection optics to receive atmosphere modulated speckle. The extinction coefficient is evaluated through speckle irradiance and C_n^2 is estimated through beam wander effect. The receiving aperture constrain condition is necessary to ensure the speckle can be received under the long term beam wander effect even in the strong fluctuation. However, the receiving aperture will increase to the level of half meter with several kilometers propagation distance. Although Fresnel lens is a low-cost solution for larger aperture receiving, the device volume, weight and manufacture cost will inevitably increase with distance.

In this paper, we present a variable aperture method to simultaneously estimate extinction coefficient and C_n^2 without receiving aperture constraint condition, which employs projection optics and CCD to partially receive atmosphere modulated laser speckle images and estimation of extinction coefficient and C_n^2 is carried out through irradiance measurement at different equivalent aperture on the CCD image. The paper is organized in the following way. Section 2 presents the variable aperture measurement principle and uncertainty analysis. In Section 3, the experiment demonstration for this technique is carried out. Measurement device and experiment results are described. Section 4 discusses the measurement achieved and the feature of two kinds of simultaneous measurement methods. Section 5 makes a conclusion for this method.

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[*] Corresponding author.
E-mail addresses: jiangdagang@uestc.edu.cn, jiangdagang@tom.com (D. Jiang).

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2. Measurement principles

The ideal Gaussian beam is modulated by atmosphere and turns into speckle at the receiving plane. If the observing time is large than the time intervals of beam wander, the speckle irradiance can be approximately treated as a Gaussian function with an effective long term beam wander radius [22] p. 237. The order of beam wander time intervals is $\Delta t = d/v$, where d is transmitter aperture and v is transverse flow velocity of the turbulent eddies [23].

The projector optics with CCD imaging device is used to collect short term speckle irradiance at receiving aperture. And then the long term speckle irradiance distribution can be drawn through the average irradiance of short term speckles images accumulation (see Fig. 1).

Because the extinction coefficient and C_n^2 are implicit in the far-field receiving power at a certain aperture, they can be estimated through at least measurements of twice long term speckle at different receiving aperture. For example in Fig. 1, one measurement is concerned with the long term speckle irradiance at receiving aperture and the other measurement is concerned with the long term speckle irradiance at variable aperture which is obtained by CCD image processing. The receiving power can be evaluated by the linear relationship between the CCD pixel gray value and the incident irradiance. The variable aperture can be equivalently acquired through CCD image processing by using geometric mapping relationship of the size on the receiving aperture and the size at CCD plane.

2.1. The variable aperture measurement method

The mean profile of far-field irradiance at radial distance r from the optical axis in the weak to strong turbulence fluctuation can be approximately expressed as a Gaussian function with a long-term beam wander radius (W_{LT}) [22, p. 237] and [24]:

$$\langle I(r,L)\rangle \cong \frac{W_0^2}{W_{LT}^2}\exp(-\alpha L)\exp\left(-\frac{2r^2}{W_{LT}^2}\right), \qquad (1)$$

where W_0 is beam radius at transmitting plane, W_{LT} is the radius of long-term beam wander at far field and α is the atmospheric extinction coefficient.

And W_{LT} is defined as

$$W_{LT} = W\sqrt{1+1.63\sigma_R^{12/5}\Lambda}, \qquad (2)$$

where L is the propagation distance and W is beam radius at distance L. On the assumption that beam is collimated to the diffraction limit, the far field beam radius is $W = W_0(1+\Lambda_0^2)^{1/2}$ and $\Lambda_0 = 2L/kW_0^2$. The actual beam divergence is very difficult to achieve approximately diffraction limit, therefore, the far field beam radius in this research is considered as $W \cong 0.5(d+\theta_{div}L)$, where d is transmitting aperture and θ_{div} is beam divergence. σ_R^2 is Rytov variance and $\sigma_R^2 = 1.23C_n^2k^{7/6}L^{11/6}$. C_n^2 is atmospheric refractive index structure constant and k is wave number and $\Lambda = 2L/kW^2$.

Therefore, the receiving power $P(D,L)$ on the circular aperture D can be expressed as

$$P(D,L) = 2\pi\int_0^{\frac{D}{2}}\langle I(r,L)\rangle r\,dr \approx P_0\exp(-\alpha L)\left[1-\exp\left(-\frac{D^2}{2W_{LT}^2}\right)\right], \qquad (3)$$

where P_0 is transmitting power.

The relationship of single pixel gray value $h(x,y)$ and incident irradiance $I(x,y)$ can be expressed as the following [25,26]:

$$h(x,y) = A_{pix}R_{CCD}t_{int}GI(x,y) = KI(x,y), \qquad (4)$$

where A_{pix} is the area of pixel, R_{CCD} is the CCD response and t_{int} is the integration time. G is the circuit gain, which represents the amplification factor from CCD analog signal to digital gray value. K is a constant and $K = A_{pix}R_{CCD}t_{int}G$, which should be calibrated with optics system.

Ignoring the background light, the optical power on the receiving aperture can be estimated through the sum of CCD pixel gray value:

$$P(D,L) = \iint_{A_D} I(x,y) = \frac{1}{K}\iint_{A_D} h(x,y) = \frac{H(D)}{K}, \qquad (5)$$

where $H(D)$ is the sum of laser illuminated gray value with equivalent diameter D. A_D is circle area with equivalent diameter D on the CCD plane and $4(x^2+y^2) \le D^2$.

Combing Eqs. (3)–(5), the measurement equations can be written as

$$f_i(x_0,x_1) = H(D_i) - KP_0x_0[1-\exp(D_i^2x_1)] = 0, \quad i = 1,2,3\ldots n, \qquad (6)$$

where $x_0 = \exp(-\alpha L)$ and $x_1 = -1/2W_{LT}^2$, i represents the number of measurements. When $i = 2$, α and C_n^2 can be estimated from the two solutions of the Eq. (6). When $i > 2$, the overdetermind nonlinear Eq. (6) can be solved by the Newton method basing on the least squares principle [27]. Then, the extinction coefficient can

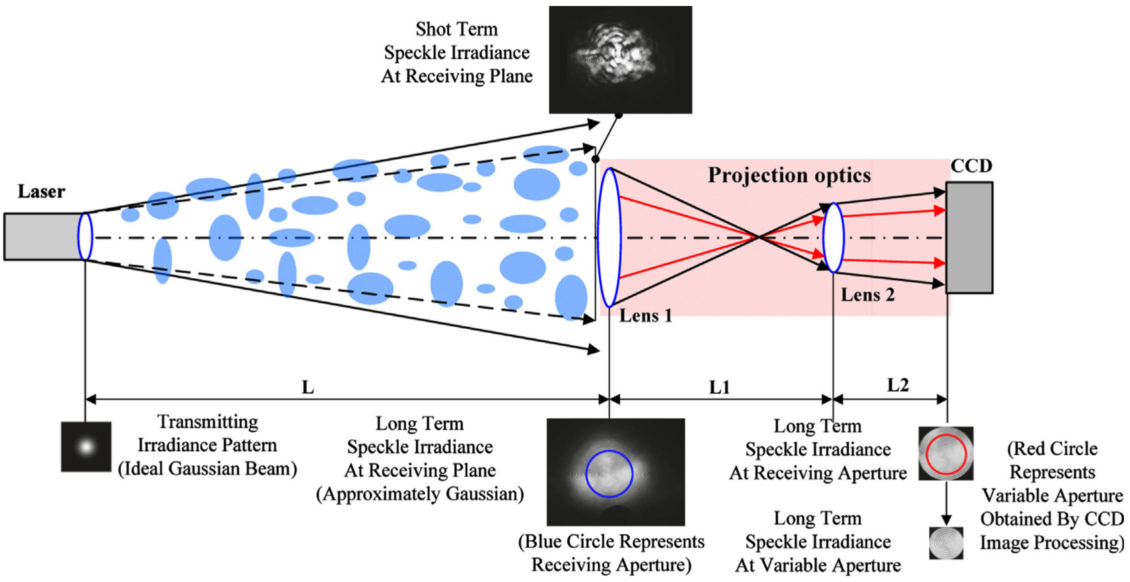

Fig. 1. Illustration of variable aperture processing method using projection optics.