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A synchronous measurement technique for the evaluation of atmospheric extinction coefficient and refractive index structure constant

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ABSTRACT

Atmospheric extinction coefficient and refractive index structure constant (C_n^2) are important parameters to represent laser beam propagation in the atmosphere. However, to best of our knowledge, the typical measurement methods for these two parameters have not been integrated into a system. Therefore, a synchronous measurement technique for the evaluation of atmospheric extinction coefficient and C_n^2 is proposed, which is applicable from weak to strong fluctuation. This technique employs projector image optics with larger aperture Fresnel lens to receive atmosphere modulated speckle. The extinction coefficient is evaluated by speckle irradiance and C_n^2 is evaluated by speckle wander effect. The receiving aperture constrain condition is also discussed to ensure the speckle can be received in the long term beam wander effect under the strong fluctuation. The theory and experiment demonstration indicate that this technique provides a feasible way to simultaneously measurement extinction coefficient and C_n^2.

1. Introduction

Atmospheric extinction coefficient and refractive index structure constant (C_n^2) are important parameters to represent laser beam propagation in the atmosphere. The extinction coefficient describes transmittance (attenuation) effects and the C_n^2 describes turbulence effects, which are commonly researched in the application areas of free space optical communications (FSO) [1], laser radar [2], remote sensing [3] and so on.

The extinction coefficient is typically measured by lidar or visibility sensor. The lidar is basing on the backscatter measurement with the assumption that the atmospheric extinction to backscatter ratio is certain and then the extinction can be indirectly retrieved by inversion algorithms [4,5]. However, the extinction to backscatter ratio is highly variable [6]. The visibility sensor is basing on the laser transmission measurement with the condition that the distance between transmitter and receiver is short (about half meter) and then the beam propagation effects (diffraction and beam wander) can be ignored [7]. The visibility sensor measurement result is then inferred to be homogeneous within a several mile radius around the sensor [8,9]. It only performs accurately when the climatic conditions are relatively stable.

Another approach to assess the atmospheric visibility is using digital photography [10,11]. The CCD camera is calibrated as an irradiance meter and measures the extinction coefficient through transmission characteristics of target and background irradiance, which is validated by the contrast experiment with lidar [11].

The C_n^2 measurement methods are varied. The measurement techniques include two main categories. One is to measure the C_n^2 by testing a certain turbulence effect, such as measuring the beam wander effect to evaluate C_n^2 [12–15], measuring the scintillation effect to evaluate C_n^2 [16,17], and measuring the angel-of-arrival fluctuation effect to evaluate C_n^2 [18,19]. Those methods depend on a basic assumption that the laser beam approximately horizontally propagates thought a quasi uniform landscape (whole terrestrial surface or water surface). The other technique is to measure the C_n^2 by a specific sensor on the local test point, such as using a thermometer [20] or a sonic anemometer [21].

Beam wander represents the movement of the beam center, which is initially received and measured by a large homogenous reflectance board [12,13]. However, the receiving irradiance decreases greatly by the reflect board. Some improved measurement methods come out, such as measured with large aperture receiving optics [14] and measured with three photo-detectors in a triangle-shaped array placed on the receiver plane [15]. It is worth noting that those C_n^2 evaluation methods are based on the relationship of C_n^2 and beam wander in the weak fluctuations, which is a simple analytic form with some estimation error in the strong fluctuations. Furthermore, the appropriate receiving aperture

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for the beam wander measurement has not been investigated in those researches.

Scintillation represents the received irradiance fluctuations, which is described by a fourth-order statistic named scintillation index. The behavior of irradiance fluctuations is actually a combination of atmospherically induced scintillation and that caused by appreciable beam wander [22,23] p. 274. For the purpose of measurement simplification, the typical measurement of C_n^2 from scintillation usually neglects beam wander influence. Angle-of-arrival fluctuations represent the average wave-front fluctuations, which is associated with beam phase distortion in the atmosphere. The thermometer or a sonic anemometer is easily influenced by the heat source or wind field on the local test point.

In sum, to best of our knowledge, the typical measurement methods for the extinction coefficient and C_n^2 have not been integrated into a system. 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 important channel parameters, which respectively influence the availability and bit error-rate (BER) [24,25].

In this paper, inspired by the Fresnel lenses rear projection displays [26], we present a synchronous measurement technique with receiving aperture constraint condition, which employs large aperture projection optics to receive atmosphere modulated laser speckle images and evaluate extinction coefficient and C_n^2 from speckle images. The paper is organized in the following way. Section 2 presents the synchronous measurement principle and discusses the constraint condition of the receiving aperture. 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 sketches some future suggestions. Section 5 makes a conclusion for this measurement technique.

2. Measurement principles

When a collimated laser propagates in atmosphere, it is modulated by atmospheric molecules. The ideal Gaussian beam from the transmitter turns into speckle at the receiving aperture (see Fig. 1). The projector optics images the small size of speckle irradiance on the CCD. According to the geometric mapping relationship, the variance of the random displacement of the beam center at the receiving aperture can be obtained by series CCD images. Therefore, the C_n^2 can be measured through beam wander effect. Meanwhile, based on the linear relationship between the CCD pixel gray value and the incident irradiance, the receiving speckle power can be evaluated by the sum of CCD image gray value. Combined with the transmitting power and the propagation distance, the extinction coefficient is available.

Furthermore, the receiving aperture should be large enough to ensure the speckle can be received under the long term beam wander effect. Otherwise, the partial speckle receiving will increase measured C_n^2 and extinction coefficient.

2.1. Projection optics design

The projection optics is composed by two lenses. The focal length of lens 1 is F_1 and the focal length of lens 2 is F_2. The distance between lens 1 and lens 2 is L_1 and the distance between lens 2 and CCD is L_2. When $L_1 = F_1 + F_2$ and $L_2 = L_1 F_2 / F_1$, the ABCD matrix is:

$$\begin{pmatrix} -F_2/F_1 & 0 \\ 0 & -F_1/F_2 \end{pmatrix} \tag{1}$$

The beam radius W' at receiving aperture becomes $W' F_2/F_1$ at CCD plane. The phase front radius of curvature F' at receiving aperture becomes $F' F_2^2 / F_1^2$ at CCD plane.

2.2. Measurement C_n^2 from speckle images

The C_n^2 can be treated as a constant in a horizontal path that traverses a uniform topography. Using the extended Huygens–Fresnel principle, under the assumption of the Kolmogorov power law spectrum and an infinite outer scale, the relationship of variance of beam wander and C_n^2 for a collimated beam can be expressed as following [23] p. 250:

$$\langle r_C^2 \rangle = 7.25 C_n^2 L^3 W_0^{-1/3} \int_0^1 \xi^2 \left[1 + 1.63 \sigma_R^{12/5} \Lambda_0 (1-\xi)^{16/5}\right]^{-1/6} d\xi \tag{2}$$

where W_0 is the beam radius at the transmitter and $\Lambda_0 = 2L/kW_0^2$. L is the propagation distance. σ_R^2 is Rytov variance and $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$. $< r_C^2 >$ is the variance of the random radial displacement of the beam center at the receiving aperture and $r_C^2 = x_C^2 + y_C^2$. The random axial displacement x_c and y_c can be obtained as following:

$$x_C = \beta \sum_{x=1}^{M} \sum_{y=1}^{N} x h(x,y) \Big/ \sum_{x=1}^{M} \sum_{y=1}^{N} h(x,y)$$
$$y_C = \beta \sum_{x=1}^{M} \sum_{y=1}^{N} y h(x,y) \Big/ \sum_{x=1}^{M} \sum_{y=1}^{N} h(x,y) \tag{3}$$

where x_c and y_c are the speckle centroid at receiving aperture. M and N are axial pixel number of CCD. $h(x,y)$ is the gray value in position (x,y) on CCD plane. $\beta = F_1/F_2$ is the geometric amplification

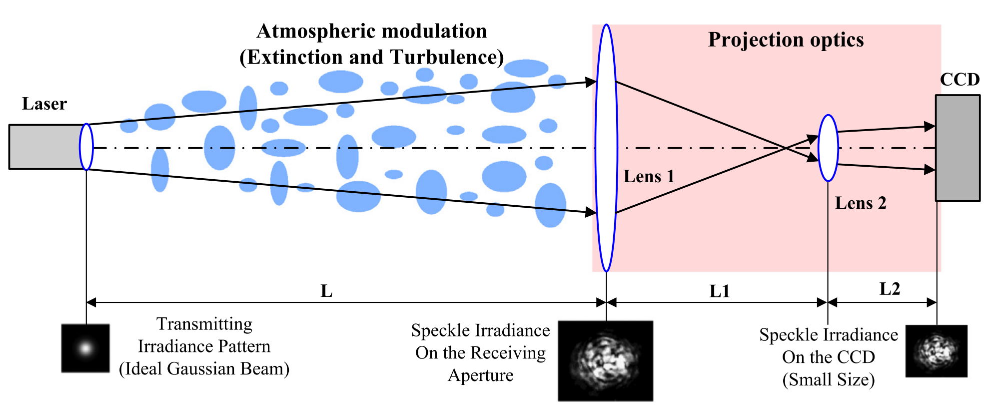

Fig. 1. Illustration of laser propagation from laser source to CCD plane.