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Behavior of the laser beam wandering variance with the turbulent path length

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Abstract

We experimentally study the variance of the transverse displacement, or wandering, of a laser beam after it has traveled through indoor artificially convective turbulence. In a previous paper (Opt. Commun., vol. 242, p. 57, November 2004) we have modeled the atmospheric turbulent refractive index as a fractional Brownian motion. As a consequence, a different behavior is predicted for the wandering variance: it grows with L, the path length, as L^{2+2H}, where H is the Hurst exponent associated to the fractional Brownian motion. The traditional cubic dependence is only recovered when $H = 1/2$—the ordinary Brownian motion. This is the case of strong turbulence or long path length. Otherwise, for weak turbulence and short path length deviations from the usual expression should be found. In this work we experimentally confirm the previous assertion.

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1. Introduction

As a result of the fluctuating nature of the refractive index in a turbulent medium any laser beam that propagates through it experiments deflections. This phenomenon is commonly known as *laser beam wandering* because of the dancing the beam performs over a screen. These displacements are perpendicular to the initial unperturbed direction of propagation, and arise from the beam phase fluctuations. Obviously, it is very sensitive to turbulence; therefore, characteristic scales and parameters associated to the turbulence can be derived from it, such as: the inner scale l_0 [1–4], the outer scale L_0 [5], the refractive index structure constant C_n^2 [1,3], and the Fried coherence length [6]. It should be stressed that for a thin beam, i.e., a beam whose lateral dimension is smaller than the inner scale [7], the deflections are due to all the scales of the turbulence. Because of its random nature, laser beam wandering is usually characterized in terms of its variance. Several authors have experimentally and theoretically attended this problem, or the equivalent problem of angular beam wandering

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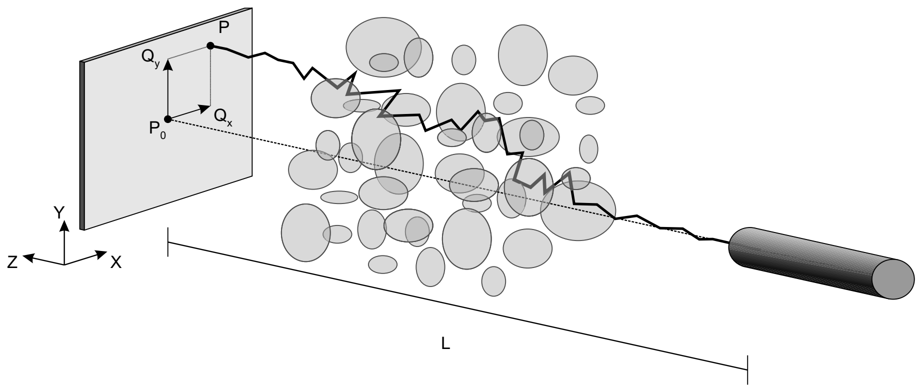

Fig. 1. Illustration of the laser beam wandering. P and P_0 are the points where the beam crosses the screen in the presence and in the absence of turbulence, respectively.

variance.[1] Beckmann [8] and Consortini and O'Donnell [9] treated this problem by using the Geometric Optics approximation.[2] They found that for weak turbulence, long turbulent path length ($L \gg L_0$) and independently of the model used for the refractive index fluctuations (Kolmogorov, Tatarskiĭ, modified von Karman [11]), the displacements variance grows like the third-power of the turbulent path length:

$$\mathrm{Var}(Q_x) = \mathrm{Var}(Q_y) \propto L^3, \tag{1}$$

with Q_x and Q_y the displacements on a normal plane to the initial direction of the laser beam—z is the propagation direction, see Fig. 1 for more details. Consortini et al. [7] have also confirmed experimentally this dependence in the case of strong indoor turbulence. It should be noted that the variances for each axis are likely to differ in the case of anisotropic turbulence and their ratio gives information about this anisotropy. Otherwise, originated from the Russian School, other authors [12–15] have obtained the cubic dependence but assuming a Markovian approximation for the turbulent refractive index fluctuation.[3] Nevertheless, Pérez et al. [17] have recently proved the equivalence between this approach and the Geometric Optics approximations. In the latter the Markovian property is indirectly applied. Moreover, experiments on laser beam wandering for short path length [18,19] have shown the presence of memory effects invalidating the use of the *memoryless* Markovian approach for all spatial scales. To overcome this limitations, in the aforementioned paper [17], the fractional Brownian motion (fBm) is introduced as a new model for the turbulent refractive index—further details about the fBm stochastic process can be found at Refs. [20–22]. This extends the Markovian approximation introducing memory effects or long-correlation. Now, within this fractal stochastic model, a new expression is derived for the displacements variance:

$$\mathrm{Var}(Q_x) = \mathrm{Var}(Q_y) \propto L^{2+2H}, \tag{2}$$

where H is the Hurst exponent, the characteristic parameter of a fBm. Note that for Markov processes $H = 1/2$, and the cubic dependence is recovered. This is the case of long turbulent path lengths or strong turbulence at any path length. But for propagation through short paths with weak turbulence memory effects, $H \neq 1/2$, should be observed. In this paper we confirm experimentally possible deviations from the traditional (memoryless) cubic dependence.

2. Experimental setup

The experimental measurements were performed in the laboratory, where convective turbulence was generated over the paths by two electric heaters in parallel. Each one of these is 70 cm long and has 700 W of power. In order to have different turbulent path lengths, several mirrors and a tube were employed. The different experimental setups are presented schematically in Fig. 2. Measurements were made over 10 turbulent path lengths varying from 0.5 m to 5 m in increments of 0.5 m. Note that the tables protected the laser and mirrors from the thermal convection. Also, the distance between the turbulent region and the mirrors allowed us to avoid possible enhancement effects.[4] The same eddies are not crossed by the incident and reflected beams. It should be stressed that we have not taken into account the *lever effect* that suffers the laser beam when it crosses the interface between the turbulent and non-turbulent regions—see [23] for further details about this effect. This configuration defect can be overcome by considering a straight propagation path.

[1] Remember that displacement and angular beam wandering variances are proportional with factor L^2, with L the length of the turbulent path.

[2] Within this approximation $l_0 \gg (\lambda L)^{1/2}$, where λ is the wavelength. See Ref. [10], p. 120.

[3] A process X_t is markovian or posesses the Markov property if the future behavior of it given what has happened up to time t is the same as the behavior obtained when starting the process at X_t [16].

[4] It was shown theoretically and experimentally [23] that the propagation of a thin beam backwards and forwards in the same turbulent layer introduces a multiplicative coefficient (enhancement) in the wandering variance result.