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Experimental verification of the turbulent effects on laser beam propagation in space

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RESUMEN

En este trabajo se modificó un diseño experimental preexistente para clasificar íntegramente los efectos térmicos de un rayo láser que se propaga en el aire. Las mejoras incorporadas al diseño previo incluyeron un láser más potente, un sistema de formación de turbulencias de alta precisión, un sensor de presión integrado, y una plataforma para ajustar la altura entre el rayo láser y el modelo de turbulencia. Este diseño no sólo puede reproducir resultados previos con exactitud, sino que además permitió la medición exitosa de nuevos datos sobre la intensidad de la turbulencia C_n^2, la varianza de Rytov (cintilación) y el diámetro de coherencia (parámetro de Fried). Los interferogramas resultantes se analizaron utilizando transformadas rápidas de Fourier. Los resultados confirman, dentro del régimen de Kolmogorov, que las fluctuaciones en fase e intensidad se incrementan en relación con la temperatura. La región turbulenta mostró perturbaciones muy intensas, en el rango de 1.1×10^{-12} m$^{-2/3}$ a 2.7×10^{-12} m$^{-2/3}$. A pesar de la intensidad de la turbulencia, con relación a la cintilación se demostró algo diferente, ya que la condición para un entorno de turbulencia débil se determinó en el laboratorio y se esperaba un bajo índice de cintilación. Esto es resultado de las distancias de propagación relativamente cortas obtenidas en el laboratorio. En la atmósfera abierta las trayectorias cubren grandes distancias y, para determinar los efectos de la turbulencia, el modelo debe generar turbulencias de mayor intensidad. De esta manera, el modelo demostró su capacidad para cuantificar y determinar plenamente los efectos térmicos de la turbulencia en un rayo láser en propagación.

ABSTRACT

In this work, we have modified an existing experimental setup to fully classify the thermal effects on a laser beam propagating in air. Improvements made to the setup include a new, more powerful laser, a precision designed turbulence delivery system, an imbedded pressure sensor, and a platform for height adjustability between the laser beam and the turbulence model. The setup was not only able to reproduce previous results exactly but also allowed new data for the turbulence strength C_n^2, the Rytov variance (scintillation) and the coherence diameter (Fried's parameter) to be successfully measured. Analysis of the produced interferograms has been discussed using fast Fourier transforms. The results confirm, within the Kolmogorov regime, that phase and intensity fluctuations increase relative to temperature. The turbulent region exhibited very strong disturbances, in the range of 1.1×10^{-12} m$^{-2/3}$ to 2.7×10^{-12} m$^{-2/3}$. In spite of the strong turbulence strength, scintillation proved otherwise, since the condition for a weak turbulence environment was determined in the laboratory and a low scintillation index was to be expected. This is as a result of the relatively short propagation distances achieved in the laboratory. In the open atmosphere, path lengths extend over vast distances and in order for turbulent effects to be realized, the turbulence model must generate stronger turbulence. The model was, therefore, able to demonstrate its ability to fully quantify and determine the thermal turbulence effects on a propagating laser beam.

Keywords: Rytov variance, thermal turbulence, Fried´s parameter, scintillation index, laser beam propagation, turbulence strength.

1. Introduction

Theories relating to atmospheric turbulence have been studied over many decades in order to better understand the impact of turbulence on the propagation of a laser beam through the atmosphere (Tatarskii, 1961). Turbulence can be described as the random mixing of air particles in the atmosphere due to either rapid or small-scale spatial and temporal refractive index fluctuations in temperature (Ishimaru, 1981; Shaik, 1988). Although slight variations in temperature can cause changes in the refractive index of air (of the order 0.1-1.0 K), the accumulative effect of such inhomogeneities expanding over vast distances poses significant challenges for laser beam propagation (Baak, 1969; Prod'homme, 1969). Research has shown that refractive index fluctuations of the atmosphere are significant near the surface of the earth and negligible at higher altitudes (Andrews and Phillips, 1988). These refractive index fluctuations cause random phase perturbations of the laser beam that can lead to beam distortion (Chatterjee and Fathi, 2014). In addition, laser propagation through turbulent media can result in scintillation (Federico *et al.*, 2004), beam wander (Berman *et al.*, 2007) and beam spreading (Weichel, 1990). The extent to which these factors affect the beam depend largely on the varying nature of the turbulent eddies that exist at several altitudes. Knowledge of these effects, attained over the years, has been used notably in the domains of military (Titterton, 2005), radar (Mead, 1990), remote sensing (Shin, 1989), satellite communications (Ojo *et al.*, 2008) and medical diagnostics (Ibrahim, 2007; Lonappen, 2007). This paper presents new modifications to a model used by Ndlovu (2013), as it has proven to be robust, cost efficient and stable in detecting and fully quantifying the effects of thermal turbulence on laser beam propagation in air. The previous method used a cigarette lighter as a turbulence source but this led to non-uniform heat distribution over a very small area (Ndlovu, 2013). In this work we have thus employed an automated heating plate for the turbulence re-creation. The design of the turbulence generator incorporates an aluminum panel with multiple high-powered resistors arranged on the underside to provide consistent heating above. In addition, a pressure sensor was positioned within the turbulent region to determine any phase fluctuations resulting from a change in pressure. The high sensitivity of the device allowed only slight variations in pressure change to be detected between the turbulent and non-turbulent regions. The primary light source used in this work was a green continuous wave He-Ne 532 nm laser. To determine the effect of thermal turbulence on laser beam propagation, a complete analysis of the produced interferograms at various temperatures has been discussed using image analysis software. Furthermore, the turbulence strength C_n^2, the Rytov variance (scintillation) and the coherence diameter (Fried's parameter) have been determined in the laboratory and shown to coincide well with published values.

2. Theory

Random fluctuations in the refractive index of the atmosphere alter the propagation pathway of light beams, which in turn effects their initial phase fronts. Once light propagates through a turbulent atmosphere, the phase fronts become distorted and experience random changes in the beam direction (beam wander) as well as random intensity fluctuations (scintillation) (Berman *et al.*, 2007). Scintillation can be classified as the fluctuations experienced in the received irradiance when light beams propagate through a turbulent atmosphere (Churnside and Lataitis, 1990). Measuring certain observations in the laboratory allows the scintillation to be calculated from (Andrews and Phillips, 1988)

$$\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}} \tag{1}$$

where C_n^2 is the refractive index structure coefficient, k is the wavenumber and L is the propagation path length. The wavelength and path length are measured in the laboratory and C_n^2 is thereafter inferred.

Propagation of the beam through turbulent conditions has shown that it undergoes a loss of coherence, focus and beam spread (Chernov, 1967; Esposito, 1967). The extent to which scintillation and beam wander occur depends largely on the combination of temperature, wind velocity and convection factors (Titterton, 1973). The key to obtaining information about the way in which beams are affected by turbulence is to determine the refractive index structure coefficient C_n^2 given by (Andrews and Phillips, 1988)

$$C_n^2 = 79.0 \times 10^{-6} \left(\frac{p}{T^2}\right) C_T^2 \tag{2}$$