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RESEARCH ARTICLE

Effects of light propagation in middle intensity atmospheric turbulence

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Abstract The purpose of this report is to present an experimental study of the effects of light propagation through atmospheric turbulence. Free space optical communication is a line-of-sight technology that transmits a modulated beam of visible light through the atmosphere for broadband communication. The fundamental limitations of free space optical communications arise from the environment through which it propagates. However these systems are vulnerable to atmospheric turbulence, such as attenuation and scintillation. Scintillation is due to the air index variation under the temperature effects. These factors cause an attenuated receiver signal and lead to higher bit error rate (BER). An experiment of laser propagation was carried out to characterize the light intensity through turbulent air in the laboratory environment. The experimental results agree with the calculation based on Rytov for the case of weak to intermediate turbulence. Also, we show the characteristics of irradiance scintillation, intensity distribution and atmospheric turbulence strength. By means of laboratory simulated turbulence, the turbulence box is constructed with the following measurements: 0.5 m wide, 2 m long and 0.5 m high. The simulation box consists of three electric heaters and is well described for understanding the experimental set up. The fans and heaters are used to increase the homogeneity of turbulence and to create different scintillation indices. The received intensity scintillation and atmosphere turbulence strength were obtained and the variation of refractive index, with its corresponding structure parameter, is calculated from the experimental results.

Keywords free space optical communication, atmospheric turbulence, scintillation

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1 Introduction

A free space optical transmission is a wireless form of connection designed for the interconnection of two points which have a direct line of sight. The system is operated by taking a standard data or telecommunications signal, converting it into a digital format and transmitting it through free space. The carrier used for the transmission of the signal is infrared and is generated by either high power light emitting diode (LED) or laser diode. Free space optics (FSO) already plays a key role in cellular networks providing cost-effective and quickly deployable connections between base stations and the nearest network switching node. The reliability and low cost of the technology has made it a popular option with global system for mobile communications (GSM) operators worldwide. With the growth of general packet radio service (GPRS) and the debut of the 3rd generation (3G) data service, a new wave of backhaul deployment is under way. As base station densities increase, more cost-effective and flexible systems are required to solve shorter site-to-site distances as well as supporting the evolution to 3G mobile technology. Backhaul networks must also provide additional capacity to meet the increased traffic demands resulting from new consent-rich mobile data services. Also, operators need equipment that can be installed rapidly to meet market demand. Atmospheric turbulence can cause fluctuation in the received signal level, which increase the bit errors in a digital communication link. Some air cells or air pockets heat up more than others. This causes changes in the index of refraction, which changes the path that the light takes while it propagates through air. The change of index of refraction appears to follow a random motion.

The paper is organized as follows: In Sect. 2, we describe the simulated turbulence. In Sect. 3, we describe the turbulence theory overview. Section 4 shows analysis and experimental results. Finally, the conclusion appears in Sect. 5.

2 Simulated turbulence

To create a laboratory-simulated turbulence, we use a turbulence box consisting of four small fans and two electrical heating elements. Figure 1(a) shows the experimental set up which is used to simulate turbulence on a laser beam. We created a laboratory simulated turbulence box (0.5 m wide, 2 m long, and 0.5 m high) and a laser source with 632.8 nm, 7.0 mW power. An optical detector connected with an optical power meter is used. The heating elements are used to produce warm air inside the turbulence box, and four small fans are used to produce wind inside the turbulence box and to increase the homogeneity of turbulence inside the box. Figure 1(b) shows the physical dimensions of the turbulence box. To characterize and analyze atmospheric turbulence on the laser beam, Helium-Neon is used along with a simulated turbulence box and a detector connected with a power meter. Our experiment is divided into two parts with respect to activities performed: in part 1, we observed the light beam through the turbulence box without switching on the fans; and in part 2, we observed the light beam through the turbulence when we put on the fans. The turbulence induces intense random fluctuation in the beam known as scintillation; in both parts we were able to create scintillation. This is an effect of many random changes in the index of refraction along the path of the beam propagation due to turbulence, and we saw beam deformation occur, because of small scale dynamic changes in the index refraction of the atmosphere. When the fans are switched on the artificial wind blowing inside the turbulence box creates different scintillation indices in regimes.

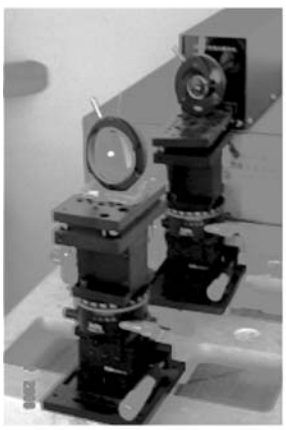
3 Turbulence theory overview

The atmosphere is not an ideal communication channel. Atmospheric turbulence can cause fluctuation in the received signal level, which increases the bit errors in a digital communication link. In order to quantify the performance limitation, a better understanding of the effect of the intensity fluctuations on the received signal, all turbulence level is needed. When a laser beam propagates through the atmosphere, turbulence causes a number of effects including scintillation. Scintillation can be described as the destructive and constructive interference of optical waves caused by the fluctuations in the index of refraction along the optical path.

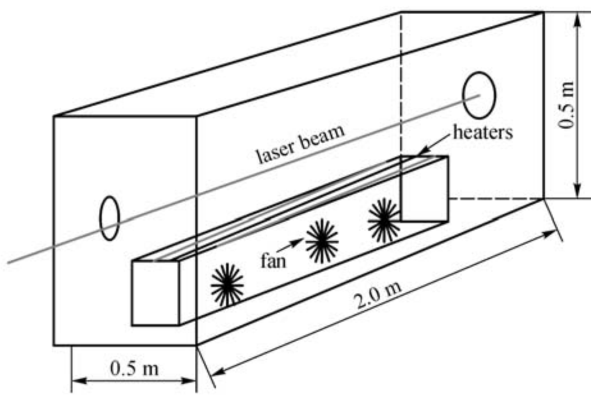
Refractive index structure function is the parameter which describes the magnitude of turbulence effects in the atmosphere for the optical range. This turbulence is an effect of turbulent air motion and fluctuations where the source of energy for this motion are gradients or changes in heating and cooling of the atmosphere and the earth's surface caused mostly by sunlight. The physical meaning of the refractive index structure function (c_{n}^2) is a measurement of strength of the fluctuations in the refractive index in the atmosphere. This parameter can be classified into two different regimes: weak turbulence and strong turbulence. Typically, value for the weak turbulence regime is $10^{-17}\,\mathrm{m}^{-2/3}$ or less and for the strong turbulence $10^{-13}\,\mathrm{m}^{-2/3}$ or more. The $\mathrm{m}^{-2/3}$ unit is derived from dimensional analysis. The Rytov method provides a solution for the variance of the log intensity fluctuations seen by a point detector. The scintillation index is defined by

$$\sigma_{\mathrm{i}}^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1, \tag{1}$$

where I is the intensity and $\langle \cdots \rangle$ denotes an ensemble average. The scintillation index is an easy variable to measure in the function of space and time and that allow a direct relationship with the c_{n}^2 parameter. Applying the optical wave model of an infinite plane wave, it can be characterized by the Rytov variance which represents scintillation index or normalized irradiance variance. By



(a)



(b)

Fig. 1 Experimental set up. (a) Laser beam set up; (b) turbulence box set up the Rytov approximation [1], then there is

$$\sigma_{\mathrm{Rytov}} = \sigma_{\mathrm{i}}^2 = 1.23 c_{\mathrm{n}}^2 K^{7/6} L^{11/6}, \tag{2}$$

where $K = 2\pi/\lambda$ is the optical wave number, λ is the wave length, and L is propagation path length.

Now, let us consider the atmospheric attenuation issue. When laser beam propagates through the air, it is exposed to attenuation depending on the weather condition. The equation of the laser transmission in air is described by Beer's law as [2]

$$\tau(z) = \frac{P_{\mathrm{Receiver}}}{P_{\mathrm{Total}}} = \mathrm{e}^{-\alpha} = F_1 = 10\log \mathrm{e}^{-\alpha}, \tag{3}$$

where τ is the transmission, F_1 is the attenuation, P_{Receiver} is the received power, P_{Total} is the transmitted power, σ is the atmosphere attenuation or total extinction coefficient, and z is the distance between transmitter and receiver. The atmosphere attenuation can be obtained by the sum of four coefficients as

$$\sigma = \alpha_{\mathrm{m}} + \alpha_{\mathrm{a}} + \beta_{\mathrm{m}} + \beta_{\mathrm{a}}, \tag{4}$$

where α_{m} is the molecular absorption coefficient, α_{a} is the aerosol absorption coefficient, β_{m} is the molecular or Rayleigh scattering coefficient, β_{a} is the aerosol or Mie scattering coefficient. The attenuation is related to wavelength by the empirical formula as

$$\sigma \approx \beta_{\mathrm{a}} = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}, \tag{5}$$

where V is the visibility in km, λ is the wavelength in nanometers, q is the size distribution of scattering particles, and there are

$$q = \begin{cases} 1.6, & \text{for high visibility} \, (V > 50 \text{ km}), \\ 1.3, & \text{for average visibility} \, (6 \text{ km} < V < 50 \text{ km}), \\ 0.585 V^{1/3}, & \text{for low visibility} \, (V < 6 \text{ km}). \end{cases}$$

Scintillation index is used to indicate the strength of the intensity function. It is defined as the normalized variance of the intensity fluctuations which can be expressed as Eq. (1); for weak fluctuations, scintillation index is equal to the Rytov variance which can be calculated as Eq. (2). Probability density function (PDF) of normalized intensity should be lognormal [3] and it can be described as

$$p_{\mathrm{w}}(I) = \frac{1}{\sqrt{2\pi\sigma_{\mathrm{i}}^2}} \frac{1}{I} \exp\left\{ -\frac{\ln I + (\sigma_{\mathrm{i}}^2/2)^2}{2\sigma_{\mathrm{i}}^2} \right\}. \tag{6}$$

According to Kolmogorov theory [3], if the atmosphere turbulence is homogenous and isotropic, for weak fluctuation, the probability distribution of received intensity should be lognormal; and for strong fluctuation far into the saturation, PDF is assumed to be governed by the negative exponential distribution [4] as

$$p_{\mathrm{s}}(I) = \frac{1}{\langle I \rangle} \exp\left(-\frac{I}{\langle I \rangle} \right). \tag{7}$$

4 Analysis and experimental results

Low visibilities will decrease the effectiveness and availability of FSO systems; we analyzed the attenuation by using Beer's law; the attenuation is related to wavelength and visibility. We saw that the atmospheric attenuation coefficient is a function of wavelength. Figure 2 shows the attenuation against visibility with our experimental wavelength of 632.8 nm. Figure 3 shows a theoretical comparison of the attenuation between the laser wavelengths 632.8 and 1550 nm by using Eqs. (3) and (5). Figures 4 and 5 show our simulation results when the laser beam passes through the simulated turbulence box when fans were switched off and on, respectively.

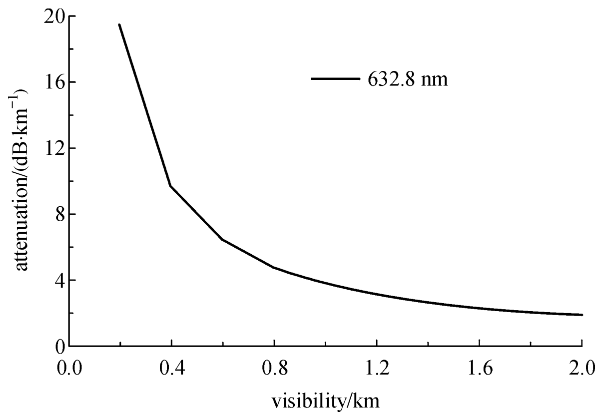


Fig. 2 Theoretical attenuation of 632.8 nm against visibility by using Eqs. (3) and (5)

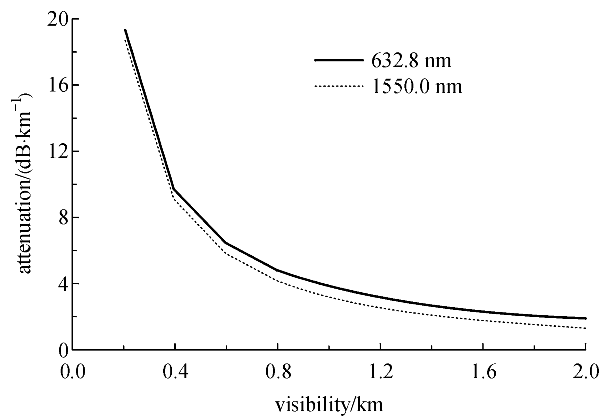


Fig. 3 Comparison of attenuation between laser wavelengths 632.8 and 1550 nm

In the FSO link, the scintillations of the received beam cause signal degradation. Also, the receiver will collect all

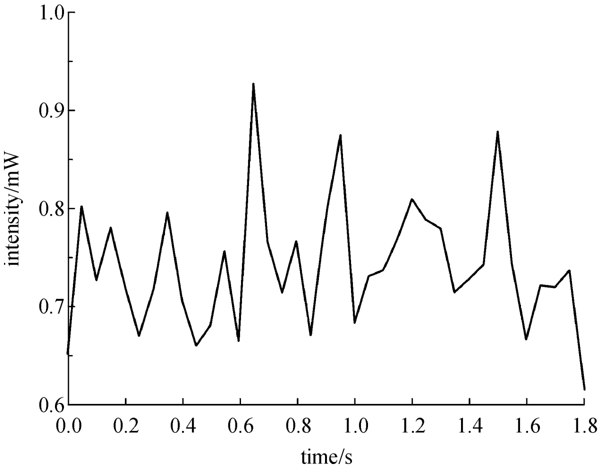


Fig. 4 Behavior of light beam when passes through turbulence box while fans are switched off

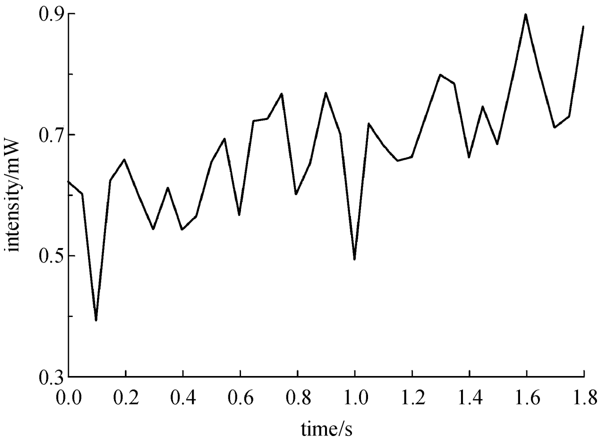


Fig. 5 Behavior of light beam when passes through turbulence box while fans are switched on

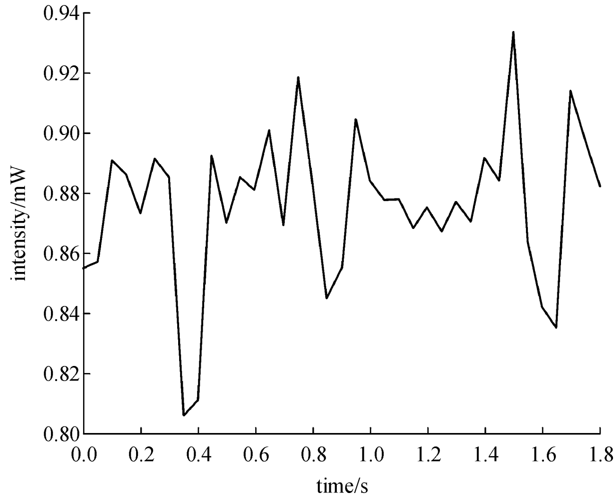


Fig. 6 Behavior of light beam when passes through turbulence box while fans are switched on (second trial)

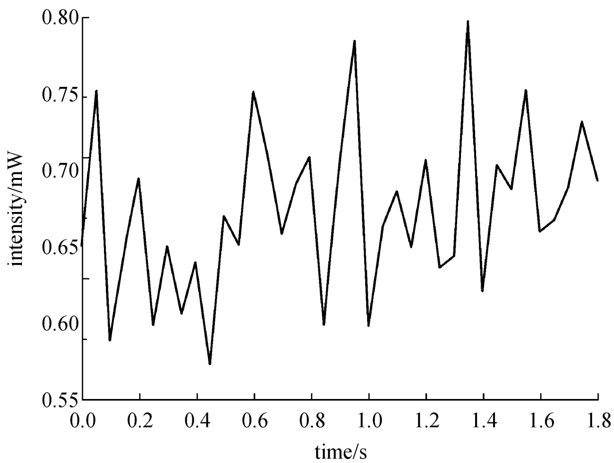


Fig. 7 Behavior of light beam when passes through turbulence box while fans are switched off (second trial)

transmitted data or intensity; in our case we observed the reading of the optical detector by using an optical power meter. The statistical method was used in the data analysis in the paper. The following figures show the graphs of intensity against time from both events. Figures 6 and 7 show the same behavior while the second trial was performed.

The performance of FSO link depends on different factors. These factors are considered as follows. Turbulence in the form of scintillation causes fading. This means bit errors may occur. The turbulence causes signal-to-noise ratio (SNR) losses by phase distortion mainly for systems using coherent laser. The attenuation and scattering in aerosols and gases will cause worse SNR and losses in the link budget [5].

Table 1 shows the calculation of refractive index structure parameter from experimental results.

Weak turbulence results: by using Rytov approximation from Eq. (2), there is

Table 1 Calculation of refractive index structure parameter from experimental results

event	scintillation index	refractive index structure parameter / $m^{-2/3}$
no turbulence	0.3029	4.55×10^{-11}
turbulence	1.1339	1.70×10^{-12}
no turbulence	0.1420	2.13×10^{-11}
turbulence	0.0070	1.15×10^{-10}

$$c_{\mathrm{n}}^2=\frac{\sigma_{\mathrm{i}}^2}{1.23\ K^{7/6}L^{11/6}},$$

where c_{n}^2 represents the turbulence intensity.

The experimental results give a point detector variance of 0.3 or less which is considered to be weak turbulence and their corresponding c_n^2 values can be calculated using the Rytov variance equation.

Intermediate turbulence results: the variance of $\sigma_i^2 = 0.45$. Such a variance is above the limit of 0.3 for the Rytov approximation in weak turbulence; it can be considered as low intermediate turbulence.

c_n^2 is often determined as a function of local differences in temperature, moisture, and wind velocity at discrete points. This expression suggests that larger wavelengths would experience a small variance. The energy cascades from larger to smaller scales (turbulent eddies) "break down" into smaller and smaller structure. However, in turbulence theory the outer scale L_o is considered as a parameter that defines the greatest size of eddies. This is valid only in the so called inertial range $l_o < r < L_o$, where l_o is the inner scale that represents roughly the smallest eddy size.

The irregularity of the beam intensity is shown below when it passed through the turbulence box. The irregularity of the beam intensity is shown in Figs. 8 and 9. The pictures were taken at different times of each event. In one event turbulence was not introduced to the turbulence box and the second picture was taken when turbulence was introduced in the turbulence box.

The changing of light intensities in time and space at a plane of the receiver that is detecting a signal from a transmitter, located at a distance is defined as the atmospheric scintillation. Figures 8 and 9 show the strength of the intensity fluctuation.

We have seen the break up of the laser beam into multiple patches and this causes the beam to lose its lateral coherence. Figure 10 shows the spatial intensity distribution in a laser beam that has passed through 1 km of atmosphere with weak turbulence [6].

5 Conclusion

In this paper, the experimental results agree with the theory that scintillation is directly related to the difference in air and ground temperature, and temperature turbulence can be observed. However, for modeling of temperature turbulence in a laboratory, several heaters can be used and the propagating beam moves above these heaters from the transmitter to the receiver. No weather condition like rainfall, snowfall, and fog are included. The optical path was 2 m and the data analysis was mainly based on a turbulence theory. Both events were successfully achieved by producing results which are consistent with respect to activities performed. We have shown figures in this paper for easy analysis and comparison with other research findings. Our results lie in the intermediate turbulence region fitted between weak and intermediate turbulence. Theory shows excellent agreement with the expected

Fig. 8 Irregularity of beam intensity distribution in laser beam that has passed through 2 m of non-simulated atmospheric turbulence (pictures are taken with a time interval of 2 min)

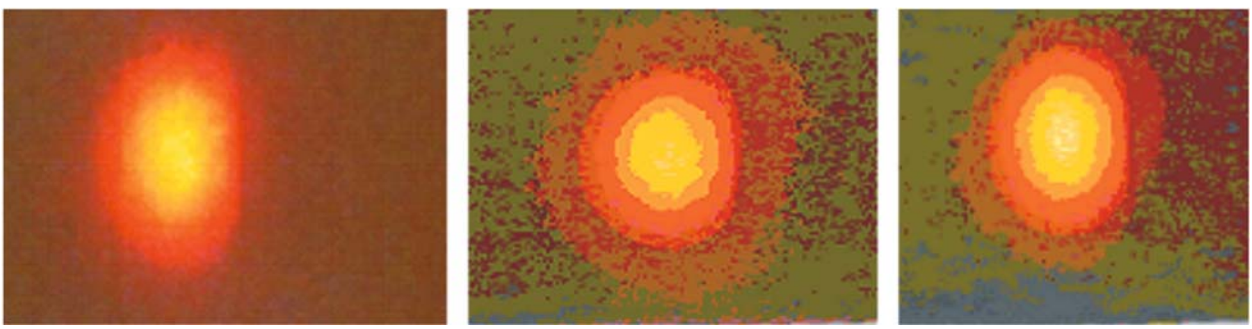


Fig. 9 Irregularity of beam intensity distribution in laser beam that has passed through 2 m of simulated atmospheric turbulence (pictures are taken with a time interval of 2 min)

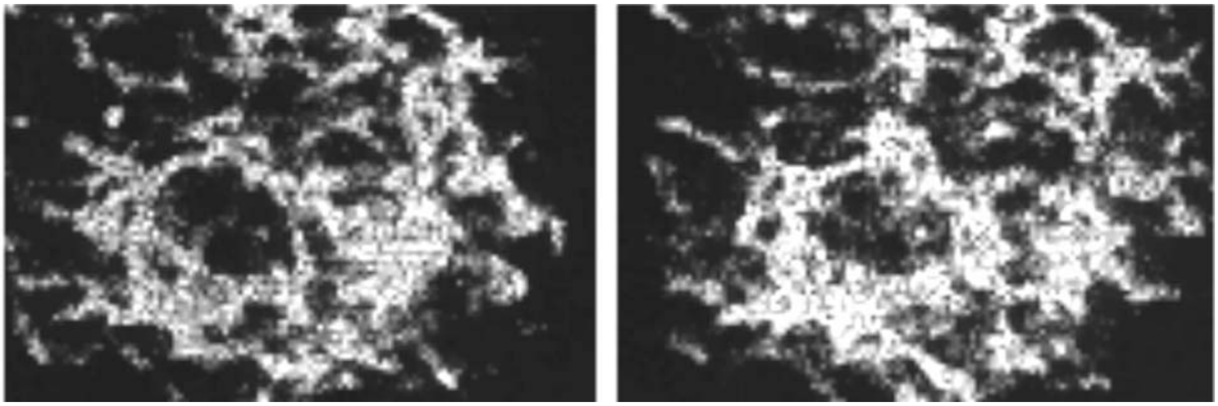


Fig. 10 Spatial intensity distribution in laser beam that has passed through 1 km of atmosphere with weak turbulence (pictures are taken with a time interval of 2 ms)

behavior; also, we have seen the laser beam experiencing fluctuation of beam (size, beam position) and intensity distribution within the beam. As we have argued, the atmosphere is a homogenous medium with changing parameters, like temperature and pressure. This is what causes some of its optical effects. From our point of view, the atmospheric turbulence channel is regarded as statistical process whose statistical properties are tuned depending on the features of the surrounding environment. Finally, it is worth saying that one characteristic of turbulent air motion is that it is unpredictable, which made this more of a general study of optics through a random media. We have learned that there are several limitations and uncertainties such as temperature gradients and moisture and these factors can make the results different in dealing with this random media. More effort is required to evaluate and define the unpredictable physical atmospheric behavior.

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