Influence of wind speed on free space optical communication performance for Gaussian beam propagation through non-Kolmogorov strong turbulence

Peng Deng, Xiuhua Yuan, Yanan Zeng, Ming Zhao, and Hanjun Luo

Wuhan National Laboratory for Optoelectronics, Huazhong University of Science & Technology, 1037 Luoyu Road, Wuhan, Hubei, P.R.China

*Email: yuanxh@mail.hust.edu.cn

Abstract. In free-space optical communication links, atmospheric turbulence causes fluctuations in both the intensity and the phase of the received signal, affecting link performance. Most theoretical treatments have been described by Kolmogorov’s power spectral density model through weak turbulence with constant wind speed. However, several experiments showed that Kolmogorov theory is sometimes incomplete to describe atmospheric turbulence properly, especially through the strong turbulence with variable wind speed, which is known to contribute significantly to the turbulence in the atmosphere. We present an optical turbulence model that incorporates into variable wind speed instead of constant value, a non-Kolmogorov power spectrum that uses a generalized exponent instead of constant standard exponent value 11/3, and a generalized amplitude factor instead of constant value 0.033. The free space optical communication performance for a Gaussian beam wave of scintillation index, mean signal-to-noise ratio $<\text{SNR}>$, and mean bit error rate $<\text{BER}>$, have been derived by extended Rytov theory in non-Kolmogorov strong turbulence. And then the influence of wind speed variations on free space optical communication performance has been analyzed under different atmospheric turbulence intensities. The results suggest that the effects of wind speed variation through non-Kolmogorov turbulence on communication performance are more severe in many situations and need to be taken into account in free space optical communication. It is anticipated that this work is helpful to the investigations of free space optical communication performance considering wind speed under severe weather condition in the strong atmospheric turbulence.

1. Introduction

As a technology providing high bandwidth wireless communication links over a distance of several kilometers using unlicensed optical wavelengths, free space optical (FSO) communication has increasingly attracted much attention in the past decade for a variety of applications, such as used for satellite-to-satellite cross-links, up-and-down links between space platforms and aircraft, ships, and other ground platforms, and among mobile or stationary terminals to solve the last mile problem through the atmosphere\textsuperscript{[1]}. However, random spatial and temporal fluctuations in the refractive index of the atmosphere- referred to as atmospheric turbulence – give rise to random variations in the signal carrying laser beam intensity known as atmospheric scintillation\textsuperscript{[2-4]}. Related turbulence induced

\textsuperscript{1} Email: yuanxh@mail.hust.edu.cn.
effects including beam spreading and beam wander can result in power loss and increased bit error rates due to signal fading in communication channels that severely degrade the link performance \[5-6\].

Atmospheric turbulence occurs when turbulent winds in the atmosphere mix the always-present vertical moisture and temperature gradients caused by the Sun’s heating of the Earth’s surface. A quantitative measure of the intensity of atmospheric turbulence is the refractive index structure parameter, \(C_n^2\), where averaged \(C_n^2\) should be determined as a function of local differences in temperature, moisture, and wind speed at discrete points. Several atmospheric turbulence profile theoretical models for \(C_n^2\) have been developed from experimental measurements made at a variety of locations \[7-10\]. One of the most popular models is the Hufnagel–Valley (HV) model \[11\] developed for inland sites and daytime viewing conditions. However, they are inadequate to represent the microphysical influences \[12\] on refractive index structure under severe environment conditions because they do not account for specific processes such as variations of near ground wind speed for local atmospheric turbulence strength. When the refractive index structure parameter \(C_n^2\) increases due to the increasing fluctuation of wind speed and temperature, intensity of atmospheric turbulence would become stronger based on the Rytov variances \(\sigma_R^2=1.23C_n^2k^2L^{1/6}\). This situation of strong turbulence would be very normal in the application of long-distance free space optical communication for ground-ground links along horizontal path or ground-satellite links along slant path under severe weather condition \[6\] \[13\]. Thus, it is necessary to develop a scintillation theory model that is valid from weak fluctuations through strong fluctuations, including the deep saturation regime.

To establish highly reliable optical communications links, quantitative estimates of various statistical quantities that are associated with atmospheric turbulence-induced scintillations are necessary. To date, all calculations relating to optical wave propagation in the atmosphere are based on the Kolmogorov model of the refractive index fluctuation spectrum. However, the significant deviations from the Kolmogorov model have been obtained in optical wave propagation through certain portions of the atmosphere, which is supported by numerous experimental evidences \[14-15\] and some results of theoretical investigation \[16-19\]. This has prompted the investigation of optical wave propagation through the atmospheric turbulence exhibiting non-Kolmogorov statistics. A. Zilberman suggested a model of turbulence spectra (Kolmogorov and non-Kolmogorov) changing with altitude on the basis of obtained experimental and theoretical data for turbulence profile in the troposphere and lower stratosphere \[20\]. Stribling et al defined the turbulence as non-Kolmogorov turbulence and presented an analysis of optical propagation in non-Kolmogorov atmospheric turbulence \[21\]. Gurvich and Belen’kii introduced a model for the power spectrum of stratospheric non-Kolmogorov turbulence and investigated the stratospheric turbulence on the scintillation and the degradation of star image \[22\].

Recently, Tosellia \[23\] et al presented a non-Kolmogorov theoretical power spectrum model and estimated free space optical system performance for laser beam propagating horizontally through non-Kolmogorov weak atmospheric turbulence. So far all of theoretical investigations for optical propagation in non-Kolmogorov atmospheric turbulence have focused on the unbounded plane or spherical wave models under the weak turbulence conditions. However, in many applications such as inter-satellite laser communication links \[6,24-25\], the plane and spherical-wave approximations do not suffice to describe the propagation properties of optical wave, and the optical performance suffers from the strong atmospheric turbulence \[19,26\]. Therefore, it is very necessary to extend the investigation of the plane and spherical-wave propagation in non-Kolmogorov weak atmospheric turbulence to Gaussian-beam wave propagation in non-Kolmogorov strong atmospheric turbulence.

In this paper, a non-Kolmogorov theoretical power spectrum is considered, which has a generalized power law that takes all the values ranging from 3 to 4. As the power law \(\alpha\) is set to the standard Kolmogorov value 11/3, the spectrum reduces to the conventional Kolmogorov one. Based on this spectrum and the refractive index structure parameter \(C_n^2\) model \[12\] within the surface boundary layer, taking account into the fluctuations of wind speed, free space optical communication performance for a Gaussian beam wave of scintillation index, mean signal-to-noise ratio \(<\text{SNR}>\), and mean bit error rate \(<\text{BER}>\), have been derived by extended Rytov theory in non-Kolmogorov strong turbulence. Then the influence of wind speed on free space optical communication performance has been analyzed.
2. Non-Kolmogorov Spectrum

The theoretical power spectrum model that describes non-Kolmogorov optical turbulence \cite{23, 27} is considered, which obeys a more general power law and in which the power-law exponents can take all the values ranging from 3 to 4,

\[
\Phi_n(\kappa, \alpha) = A(\alpha) \tilde{C}_n^2 \kappa^{-\alpha}, \quad 2\pi/\ell_0 \leq \kappa \leq 2\pi/\ell_0, \quad 3 < \alpha < 4
\]  

where \( \kappa \) is the magnitude of three dimensional wave number vector (in units of rad/m), \( \alpha \) is the spectral power-law exponent, \( \tilde{C}_n^2 = \beta C_n^2(v) \) is a generalized refractive-index structure parameter that describes the strength of the turbulence along the path, \( \ell_0 \) and \( L_0 \) denote the inner and outer scales of turbulence, respectively, and \( A(\alpha) \) is a function defined by

\[
A(\alpha) = \frac{1}{4\pi^2} \Gamma(\alpha - 1) \cos\left(\frac{\pi\alpha}{2}\right)
\]  

where the symbol \( \Gamma(x) \) represents the gamma function. When the power law \( \alpha \) is equal to 11/3, \( A(11/3) = 0.033 \), and the spectrum reduces to the conventional Kolmogorov spectrum

\[
\Phi_n(\kappa, v) = 0.33 C_n^2(v) \kappa^{-11/3}
\]  

where \( C_n^2(v) \) represents the refractive-index structure parameter as function of wind speed \( v \).

Based on local micrometeorological information derived through application of Monin–Obukhov turbulence theory\cite{9, 12}, a useful expression for the refractive index structure parameter as function of wind speed \( v \) can be given as

\[
C_n^2(v) = \frac{b K_h(v)}{\varepsilon(v)^{1/3}} \left(\frac{\partial n}{\partial h}\right)^3
\]  

where \( b \) is a constant, \( K_h(v) \) is the turbulent exchange coefficient for heat diffusion\cite{9}, \( \varepsilon(v) \) is the energy dissipation rate due to wind shear and buoyancy\cite{12}, and \( \partial n/\partial h \) is the vertical gradient of the index of refraction (\( n \)). For the hypothesis of universal equilibrium under steady-state conditions, the energy dissipation rate equals the sum of the rate of energy production due to wind shear \( M \) and buoyancy \( B \)

\[
\varepsilon = M + B = K_m \frac{\partial \bar{v}^2}{\partial h} + K_h \left(\frac{\varepsilon}{\theta^2}\right) \frac{\partial \theta}{\partial h}
\]  

where \( K_m \) is the turbulent exchange coefficient for momentum, and \( \bar{v} \) is average wind speed. Here \( g \) is acceleration due to the Earth’s gravity (9.8m/s), \( K_h \) is the turbulent exchange coefficient for heat, and \( \theta \) is mean potential temperature \( \theta = T + 0.0098h \). The flux profile relationships for the vertical gradients of average wind velocity and mean potential temperature have similar forms, and are given by

\[
\frac{\partial \bar{v}}{\partial h} = u^* \frac{1}{k_h} \Phi_m \left(\frac{h}{L}\right), \quad \frac{\partial \theta}{\partial h} = T^* \frac{k_h}{k_m} \Phi_h \left(\frac{h}{L}\right)
\]  

where \( k_h \) is von Karman’s constant taken to be 0.4, \( u^* \) is friction velocity, \( T^* \) is characteristic temperature, \( \Phi_m(h/L) \) is dimensionless wind shear, \( \Phi_h(h/L) \) is dimensionless temperature gradient, \( L \) is the Monin-Obukhov length that is fundamental in describing the onset of turbulence and the vertical structure of turbulence-induced flux profiles in the Earth’s surface boundary layer\cite{9, 12}.

With knowledge of the friction velocity \( u^* \), it is possible to estimate the turbulent exchange coefficient for heat \( K_h \) and the turbulent exchange coefficient for momentum \( K_m \).

\[
K_h = k_h u^* \Phi_h \left(\frac{h}{L}\right), \quad K_m = k_m u^* \Phi_m \left(\frac{h}{L}\right)
\]  

By ignoring small contribution to the total differential from fluctuations in atmospheric pressure, optical turbulence-induced vertical gradient of the index of refraction can be approximated by

\[
\frac{\partial n}{\partial h} \approx \frac{\partial n}{\partial \theta} \frac{\partial \theta}{\partial h} = \left(-77.6 \times 10^{-6} Pa\right) \frac{T^*}{k_h T^2} \Phi_h \left(\frac{h}{L}\right)
\]
3. Scintillation Index

The scintillation index is one of the most important parameters that is usually used to characterize laser beam propagation through atmospheric turbulence. For the propagation of Gaussian beam wave, the scintillation index is usually expressed as the sum of the radial component and the longitudinal component\(^2\),

\[
\sigma^2_r (r, L) = \sigma^2_{r, r}(r, L) + \sigma^2_{r, L}(L)
\]  

(9)

The radial component physically denotes the off-axis contribution to the scintillation index and vanishes at the beam center line \((\rho = 0)\) or as \(\Lambda = 0\) (corresponding to an infinite wave such as a plane or spherical wave), whereas the longitudinal component is constant through the beam cross section in any transverse plane. To describe the beam characteristics at the input plane and output plane of the transceivers, we use a set of non-dimensional beam parameters. The curvature parameter \(\Theta\) and the Fresnel ratio \(\Lambda\) at the output plane are defined by \(\Theta = L/R\) and \(\Lambda = \lambda L/\pi W^2\), respectively. Here, \(W\) and \(R\) denote the radius of the beam size and the radius of curvature of phase front at the receiver in the distance of \(L\) from the transmitter.

Our analysis evolved from the extend Rytov theory\(^2\) by taking into account the role of decreasing spatial coherence of the optical wave as it propagates through strong atmospheric turbulence. Based on the extended Rytov theory, the irradiance of the field can be expressed as \(I = X.Y\), where \(X\) represents large scale (refraction properties) and \(Y\) denotes small scale (diffraction properties) fluctuations. Assumed that both of the fluctuations are statistically independent from each other, the implied scintillation index takes the following form\(^2\)

\[
\sigma^2 (\alpha) = \langle X \rangle \langle Y \rangle - 1
\]

\[
= \sigma^2_{X}(\alpha) + \sigma^2_{Y}(\alpha) + \sigma^2_{X}\sigma^2_{Y}(\alpha)
\]  

(10)

Based on the relationship between the log-amplitude variance and the scintillation index, the longitudinal component of the total scintillation index then takes the form

\[
\sigma^2_{l, j}(\alpha) = \exp(\sigma^2_{\alpha, X,j}(\alpha) + \sigma^2_{\alpha, Y,j}(\alpha)) - 1
\]  

(11)

Based on the Non-Kolmogorov spectrum model and the one-dimensional quantities \(\xi = 1 - z / L; \eta = Lk^2 / k\), the large-scale and small-scale log-irradiance variance for a Gaussian beam wave are defined by

\[
\sigma^2_{m, X,j}(L, \alpha) = 16\pi^2 k^2 L \int_0^1 \frac{\kappa \Phi_n (\kappa, \alpha) G_X (\kappa, \alpha) \sin^2 \left( \frac{Lk^2}{2k} \xi (1 - \Theta) \right)}{k^2} d\kappa d\xi
\]

\[
\times \exp(-\frac{\Lambda Lk^2 \xi^2}{k})
\]  

(12)

\[
= 8\pi^2 k^2 L \int_0^1 \frac{\kappa \Phi_n (\kappa, \alpha) G_X (\kappa, \alpha) \exp(-\frac{\Lambda Lk^2 \xi^2}{k})}{k^2}
\]

\[
\times [1 - \cos(\frac{Lk^2}{k} \xi (1 - \Theta))] d\kappa d\xi
\]  

(13)

The large-scale and small-scale filter function\(^2\) are defined, respectively, by

\[
G_X (\kappa, \alpha) = \exp(-\frac{\kappa^2}{k^2})
\]  

(14)

\[
G_Y (\kappa, \kappa') = \frac{\kappa^a}{(k^2 + \kappa^2)^{a/2}} \exp\left( -\frac{\Lambda Lk^2 (z / L)^2}{k} \right)
\]  

(15)

The quantities \(k_X\) and \(k_Y\) represent the low-pass and high-pass spatial frequency cutoffs that related to the correlation width and scattering disk of the propagating optical wave.
Therefore, using the non-Kolmogorov power spectrum in Eq.(1) and following the same procedure as discussed in Ref. [2, 23] for the standard Kolmogorov spectrum, the scintillation index for a Gaussian beam wave propagating in non-Kolmogorov strong atmospheric turbulence are analyzed.

In strong fluctuation regimes where inner scale and outer scale effects are negligible, the longitudinal component of scintillation index is derived by,

$$\sigma_{\alpha}^2(L, \alpha) = \exp\left(\frac{0.492\sigma_R^2}{(1 + f_x(\alpha, \Theta)\sigma_R^{-2})^2} + \frac{0.51\sigma_R^2}{(1 + f_y(\alpha, \Theta)\sigma_R^{-2})^2}\right) - 1, \quad 0 \leq \sigma_R^2 \leq \infty$$

(16)

where $$\sigma_R^2$$ denotes the longitudinal component of the scintillation index for Gaussian beam wave under non-Kolmogorov weak turbulence can be expressed as

$$\sigma_R^2 = \frac{1}{\alpha - 1}A(\alpha)C_n^2k^3(2 - \alpha\pi)\Gamma\left(\frac{2 - \alpha}{2}\right)\Gamma\left(\frac{2 + \alpha}{2}\right), \quad 0 < \alpha < 2$$

(17)

where $$\sigma_R$$ is a non-Kolmogorov Rytov variance for plane wave in weak turbulence defined by

$$\sigma_R^2 = R(\alpha)\sigma_{Rytov}^2(\alpha) = -6.5\pi^2A(\alpha)\Gamma(1 - \frac{\alpha}{2})\sin(\frac{\alpha\pi}{4}) \times 1.23C_n^2k^3\frac{\alpha}{L^2}$$

(18)

where

$$\sigma_{Rytov}^2(\alpha) = 1.23C_n^2k^3\frac{\alpha}{L^2}$$

(19)

$$R(\alpha) = -6.5\pi^2A(\alpha)\Gamma(1 - \frac{\alpha}{2})\sin(\frac{\alpha\pi}{4})$$

(20)

Note that for Kolmogorov case $$\alpha = 11/3$$, $$R(11/3) = 1$$.

The large scale and small scale parameters $$f_x(\alpha)$$ and $$f_y(\alpha)$$ can be expressed by

$$f_x(\alpha, \Theta) = \left(\frac{V(\alpha)Z(\alpha, \Theta)}{0.98}\right)\frac{\sigma_R^2}{\sigma_B^2}$$

(21)

$$f_y(\alpha) = \left(\frac{\ln 2}{0.51}\right)^{\frac{2}{3}}$$

(22)

where

$$Z(\alpha) = \int_0^1 (1 - \Theta\xi)^{-4}(1 - \Theta\xi)^{\beta-4}\frac{d\xi}{[(1 - \Theta\xi)^{\alpha-2} - (1 - \Theta)^{\alpha-2}]^{\alpha-2}}$$

(23)

$$B(\alpha) = \frac{\pi^2}{123} \frac{4(1 - \alpha)}{(1 + \alpha/2)\Gamma(\alpha/2)}\frac{A(\alpha)}{R(\alpha)\Theta(\alpha - 1)}$$

(24)

$$V(\alpha) = \frac{8\pi^2}{123R(\alpha)(\alpha - 2)}\frac{1}{\Gamma(6 - \alpha)}\frac{R(\alpha)(\alpha - 2)}{B(\alpha)^{\alpha-6}}$$

(25)

For the radial component, our analysis results in

$$\sigma_{\alpha}^2(\mathbf{r}, L, \alpha)_{\text{untracked}} = 4.42\sigma_R^2\Lambda_e^{\alpha-4}\left(\frac{\sigma_{pe}^2}{W_{LR}^2}\right)^2 + 4.42\sigma_R^2\Lambda_e^{\alpha-4}\left(\frac{r - \sigma_{pe}^2}{W_{LT}^2}\right)^2, \quad \sigma_{pe} \leq r \leq W.$$  

(26)

where $$\sigma_{pe}$$ denotes an effective pointing error in the presence of beam wander effects. $$W_{LR}^2(\alpha)$$ is long term spot size caused by large scale induced beam wander defined by

$$W_{LR}^2(\alpha) = W^2(1 + T(\alpha)), T(\alpha) = -16A(\alpha)\frac{1}{\alpha - 1}\frac{\alpha}{2}\Lambda_e^{\alpha-4}\sigma_R^2(\alpha)$$

(27)
The long term spot size\(^2\) is characterized by the effective beam parameter \(\Lambda_e(\alpha) = 2L/kW_{LT}(\alpha)\). Therefore, the total scintillation index for Gaussian beam wave in non-Kolmogorov strong turbulence and in absence of inner scale and outer scale effects is given by

\[
\sigma_i^2(r, L, \alpha)_{\text{untracked}} = \exp\left(\frac{0.49\tilde{\sigma}_g^2}{1 + f_2(\alpha, \Theta)\tilde{\sigma}_R^{\alpha-2}} + \frac{0.51\tilde{\sigma}_g^2}{1 + f_1(\alpha)\tilde{\sigma}_R^{\alpha-2}}\right) - 1
\]

\[
+ 4.42\tilde{\sigma}_g^2\Lambda_e \left(\frac{\sigma_{pe}}{W_{LT}}\right)^2 + 4.42\tilde{\sigma}_g^2\Lambda_e \left(\frac{r - \sigma_{pe}}{W_{LT}}\right)^2, \quad 3 < \alpha < 4, 0 \leq \sigma_R^2 \leq \infty, \sigma_{pe} \leq r \leq W. \quad (28)
\]

Using scintillation index model, the comparison of scintillation index as function of wind speed for simulated model with that for the Hufnagel-Valley model\(^{[11]}\) and BKB model\(^{[7]}\) is shown in figure Figure 1, taking \(L = 1\) km; \(T=300\) K; \(\lambda=1.55\) nm; \(h=4\) m. We deduce from figure Figure 1 that for wind speed lower than 11 m/s, excluding wind speed values close to 3, there is an increase of scintillation for the simulated Gaussian wave model, but for H-V model and BKB model it is constant and reduced, respectively. For wind speed greater than 11 m/s, the scintillation indexes for several models approach to the similar values. The physical interpretation of difference is that the power spectrum contains fewer eddies of high wave numbers; therefore, scintillation effects are reduced.

In addition, the longitude component and radial component of scintillation index are plotted as function of Rytov index in figure Figure 2. We deduce from figure 2 that, for Rytov index lower than 1 under weak turbulence, scintillation index remarkable increases with respect to Rytov index; instead for Rytov index values greater than 1 in moderate to strong turbulence, scintillation index decreases slightly with respect to the Rytov index. That is the saturation effect of the scintillation index under strong irradiance fluctuations.

**Figure 1.** The scintillation index as function of wind speeds for various turbulence models.
4. Performance analysis of FSO system in non-Kolmogorov strong atmospheric turbulence

The performance of FSO system can be seriously deteriorated by turbulence-induced scintillation resulting from beam propagation through the atmospheric turbulence. Specifically, the moderate-strong scintillation can lead to power loss at the receiver and eventually to fading of the received signal below a prescribed threshold. The reliability of a FSO system operating in such an environment can be deduced from the theoretical model for the probability density function (PDF) of the randomly fading irradiance signal. From knowledge of the PDF model, we can calculate the mean signal to noise ratio (SNR) and the bit-error-rate (BER) of FSO system in non-Kolmogorov strong turbulence.

The probability density function (PDF) used under strong irradiance fluctuations for the case of a point receiver is the Gamma-Gamma distribution model. The Gamma-Gamma PDF\(^{[2, 26]}\) is given by

\[
p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} \frac{1}{\langle I(0, L) \rangle^{(\alpha+\beta)/2}} K_{\alpha, \beta}(2\frac{\alpha\beta I}{\langle I(0, L) \rangle}), I > 0
\]  

where we are taking the general case of mean irradiance \(\langle I(0, L) \rangle \neq 1\) and \(K_{\alpha, \beta}(x)\) is a modified Bessel function. \(\alpha\) and \(\beta\) are positive parameters directly related to the large-scale and small-scale scintillation index of the Gaussian wave according to

\[
\alpha = \frac{1}{\sigma_X^2} = \frac{1}{\exp\left(\frac{0.49\sigma_B^2}{(1 + f_X(\alpha, \Theta))\sigma_B^2}\right) - 1}, \quad \beta = \frac{1}{\sigma_Y^2} = \frac{1}{\exp\left(\frac{0.51\sigma_B^2}{(1 + f_Y(\alpha, \Theta))\sigma_B^2}\right) - 1}
\]  

In the presence of atmospheric turbulence, the received signal exhibits additional power losses and random fluctuations. We examine the mean signal-to-noise ratio in the presence of atmospheric turbulence using a non-Kolmogorov power spectrum. Based on Refs.[2, 27], the mean signal-to-noise ratio \(\langle SNR \rangle\) at the output of the detector in the case of a shot-noise limited system assumes the form

\[
\langle SNR \rangle = \frac{SNR_0}{\sqrt{1 + \sigma^2(I, L, \alpha)SNR_0^2}}
\]  

where \(SNR_0\) is the signal-to-noise ratio in the absence of turbulence.

Given the PDF model for irradiance fluctuation and the mean signal-to-noise ratio through atmospheric turbulence, the probability of error is considered a conditional probability that must be

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**Figure 2.** The longitude component and radial component of scintillation index as function of Rytov scintillation index.
averaged over the PDF of random signal to determine the unconditional mean BER. In terms of a normalized signal with unit mean, this leads to the mean BER expression\cite{2,27}

\[
Pr(E) = \langle BER \rangle = \frac{1}{2} \int_0^\infty p_\gamma(u) \text{erfc} \left( \frac{\langle SNR \rangle u}{2\sqrt{2}} \right) du
\]

where \( p_\gamma(u) \) is the gamma-gamma distribution with unit mean and the threshold \( i_r = 0.5s \).

Using the scintillation index for the Gaussian beam wave model, the probability density function under strong atmospheric turbulence are plotted as function of log intensity for several wind speeds in figure Figure 3, taking \( L = 1 \text{ km}; T = 300 \text{ K}; \lambda = 1.55 \text{ nm}; h = 4 \text{ m} \). It is clear now that wind speed variation has a serious impact on the probability density function for Gaussian wave; in particular, for log intensity lower than zero, the probability density function increases with an increase in log intensity; while for log intensity greater than zero, it decreases rapidly with the increase of log intensity. Also for this diagram, there is a maximum point where the curves change their slope, because the scintillation begins to decrease to zero. With the increase in wind speed, the slope of the curves becomes steeper.

The mean signal-to-noise ratio <\text{SNR}> is plotted in decibel units as a function of signal-to-noise ratio without turbulence \( \text{SNR}_0 \) for several wind speed values in figure 8, using the Gaussian wave model for strong scintillation. We take the following parameters: \( L = 1 \text{ km}; T = 300 \text{ K}; \lambda = 1.55 \text{ nm}; h = 4 \text{ m}; \alpha = 3.3 \) for non-Kolmogorov spectrum, compared with Kolmogorov spectrum \( \alpha = 11/3, v = 11 \text{ m/s} \).

As shown in figure Figure 4, illustrates the impact of the wind speed variation on the <\text{SNR}> performance. With the increase in wind speed values from 3 m/s to 20 m/s, excluding the values close to 3, there is a translation of the curves toward greater values, or, in other words, there is a gain on the system performance. That because the refractive index parameters reach to very low values with an increase in wind speed and consequently the scintillation reported before approaches smaller values.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{The probability density functions under strong atmospheric turbulence as function of log intensity for several wind speeds.}
\end{figure}
Figure 4. Mean Signal to Noise Ratio as a function of Signal to Noise Ratio without turbulence for several wind speeds, using Gaussian beam wave model for strong scintillation index.

Figure 5. Bit error rate as function of SNR for various wind speeds, using the Gaussian beam wave model through non-Kolmogorov strong turbulence

The mean bit error rate as a function of <SNR> for several wind speed values using the Gaussian beam wave model for strong scintillation in figure Figure . We take the same parameters, L = 1 km; T=300 K; λ= 1.55 nm; h= 4 m; α=3.3 for non-Kolmogorov spectrum, compared with Kolmogorov spectrum α=11/3, v=11 m/s. The plot in figure Figure shows the impact of the wind speed variation on <BER> performance. Also in this analysis, when wind speed increases from 3 m/s to 20 m/s, excluding alpha values close to 3, there is a translation of the curves toward smaller values. In other words, there is an improvement on the system performance. It results from that the refractive index parameters reach to very low values with an increase in wind speed and consequently the scintillation reported before approaches smaller values. To the best of our knowledge, the physical mechanism of transition function of the turbulence spectral exponent α form between wind speeds v in turbulent atmospheric layers need be investigated.
5. Conclusion
The influence of wind speed on free space optical communication performance for a Gaussian beam wave of scintillation index, mean signal-to-noise ratio $<\text{SNR}>$, and mean bit error rate $<\text{BER}>$, have been analyzed by extended Rytov theory in non-Kolmogorov strong turbulence. It has been shown in strong turbulence, for a horizontal link, the scintillation index as variations depending on wind speed lead to results somewhat different than obtained with the standard value of Kolmogorov with constant wind speed. For wind speed lower than 11 m/s, excluding wind speed values close to 3, there is an increase of scintillation for the simulated Gaussian wave model. For wind speed greater than 11 m/s, the scintillation indexes for several models approach to the smaller values. With the increase in wind speed values from 3 m/s to 20 m/s, excluding the values close to 3, there is an improvement on the system performance. Specifically, the low wind speed gets more impact from a power law spectrum variation and it leads the most contribution on the scintillation index variation. Although our final expressions for the scintillation have been obtained by extended Rytov theory, which is necessary to adopt in strong turbulence conditions, they reduce to the proper results also in weak turbulence.

Acknowledgments
This research was financially supported by National High Technology Research and Development Program of China (No. 2008AA01Z207). The authors are grateful for a grant from National High Technology Research and Development Program of China.

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