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Modification of atmospheric extinction coefficient of non-line-of-sight ultraviolet communication under weak turbulence

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ABSTRACT

A calculation method of scintillation attenuation (SA) for non-line-of-sight (NLOS) ultraviolet (UV) communication is proposed on the basis of weak turbulence theory. To improve the channel model under turbulent environment, the atmospheric extinction coefficient in combination with UV single-scatter approximation model is modified based on SA. The in-depth analysis and interesting conclusion of atmospheric extinction coefficient named the turbulence coefficient versus different factors, including refractive-index structure parameter at the ground with measurement data, transceiver range and transceiver apex angles, are conducted.

1. Introduction

The atmosphere, which varies with time and space, is usually recognized as the propagation medium of ultraviolet (UV) communication. When propagating through the atmosphere, UV signals are affected by the atmospheric attenuation coming from the absorption and scattering effects of molecules, aerosols and particles, and by the atmospheric turbulence deriving from the fluctuation of refractive index due to the changes of temperature and wind speed. The atmospheric turbulence is often ignored in the case of short-haul communication [1]. However, with the development of advanced ultraviolet sources and detectors, non-line-of-sight (NLOS) UV communication can be realized for the long distance of 1–2 km [2]. Meanwhile, the typical meteorological conditions from great temperature difference are also the objective cause of atmospheric turbulence that cannot be ignored. Consequently, the turbulence effect should be considered in the process of UV signal propagation.

In most of the existing literature, the turbulence effect is often quantitatively studied by irradiance fluctuation, beam spreading, beam wander and phase fluctuation. However, from the view of the power loss resulting from intensity fluctuation at the receiver, the turbulence effect can also be quantified by scintillation attenuation (SA). It was defined as two times the standard scintillation variance in [3], and an empirical expression for weak turbulence and plane wave propagation was given in the literature. It is hard to derive a precise expression for atmospheric turbulence because of its eternal change, especially in the strong turbulence. On the basis of intensity data statistics, [4] proposed a method of available power for SA and demonstrated the applicability of the expression in [3] for atmospheric refractive-index structure parameter C_n^2 less than 10^{-14}. Another empirical formula of SA appearing in [5–7] under weak turbulence was based on the variance of irradiance fluctuation, but it was shown in [8] that there was a great difference between this method and the method of available power. All the calculating methods of SA above are primarily available to the horizontal link of wireless optical communication with an assumption that C_n^2 is constant. In NLOS UV communication, the link budget and the probability density function of received optical power were investigated by [9,10] based on SA respectively. However, both of them regarded the whole slant link as two horizontal links without considering the variation of C_n^2 with altitude. Additionally, as atmospheric attenuation is primarily reflected by the atmospheric extinction coefficient in the existing UV propagation models, the SA can also be added to improve the propagation model by the modification of atmospheric extinction coefficient in our opinion.

This paper is organized as follows. Section 2 proposes a calculation method of SA for NLOS UV communication based on weak turbulence theory. In Section 3, combining with UV single-scatter approximation model, we modify the atmospheric extinction coefficient on the basis of SA. According to the experiment data of cross-sea link and offshore link of Yantai, Shandong Province, China, the turbulence coefficient versus refractive-index structure parameter at the ground, transceiver range and transceiver apex angles are analyzed in Section 4. Finally, we draw our conclusions in Section 5.

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2. SA of NLOS UV communication link

Assuming that the atmosphere is homogeneous and isotropic, the relationship between variance of optical intensity and C_n^2 based on Rytov approximation is given by [11]

$$\sigma_I^2 = K \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6} \tag{1}$$

which is true for $\sigma_I^2 < 1$. Where K is constantly 1.23 for the plane wave, and 0.5 for the spherical wave, k depicts the wave number, L depicts the distance between transmitter and receiver of the optical wireless link.

Tropospheric scintillation effects are usually studied from the log-amplitude of the observed signal, defined as the normalized variance of the intensity. The intensity and the speed of the fluctuations increase with the wave frequency. For a plane wave under weak turbulence, the scintillation variance σ_χ^2 (dB^2) can be expressed by the relation [3]

$$\sigma_\chi^2 = 23.17 \cdot k^{7/6} \cdot C_n^2 \cdot L^{11/6} \tag{2}$$

Therefor, the SA in [3] is given by

$$\alpha_{Rytov} = 2\sigma_\chi = 2 \cdot \sqrt{23.17 \cdot k^{7/6} \cdot C_n^2 \cdot L^{11/6}} \tag{3}$$

Another expression for SA under weak turbulence is given by [5] with the form

$$\alpha_{Wilfert} \approx |10 \cdot \log(1 - \sqrt{\sigma_{r,I}^2})| \tag{4}$$

where $\sigma_{r,I}^2$ is the variance of optical intensity with the same expression as that in Eq. (1).

According to the detailed mathematical analysis of the turbulence in atmospheric transmission media presented by Larry C. Andrews [11], an evoluted expression for SA based on Eq. (4) is obtained by [8]

$$\alpha_{Andrews} = 10 \cdot \log |(1 - \sqrt{\overline{\sigma}_I^2(D_{RXA})})| \tag{5}$$

where

$$\overline{\sigma}_I^2(D_{RXA}) \cong \exp\left[\frac{0.49 \cdot \beta_0^2}{(1+0.18 \cdot d^2 + 0.56\beta_0^{12/5})^{7/5}} + \frac{0.51 \cdot \beta_0^2 (1+0.69 \cdot \beta_0^{12/5})^{-5/6}}{1+0.9 \cdot d^2 + 0.62 \cdot d^2 \cdot \beta_0^{12/5}}\right] - 1 \tag{6}$$

which contains two parameters. The first one is parameter d, which is related to the wavelength λ, link distance L, and receiving optical lens diameter D_{RXA}

$$d = \sqrt{\frac{2 \cdot \pi}{4 \cdot \lambda \cdot L}} \cdot D_{RXA} \tag{7a}$$

While the second parameter β_0^2 is given by

$$\beta_0^2 = 0.5 \cdot C_n^2 \cdot k^{7/6} \cdot L^{11/6} \tag{7b}$$

Compared with the Wilfert method, the Andrews method smooths the turbulence effects virtually by introducing the factor of receiving optical lens size.

The above methods are primarily available for the horizontal link. For NLOS UV communication, the whole link is often regarded as two slant links, one is from the transmitter (Tx) to the common scattering zone and the other is from the common scattering zone to the receiver (Rx). Fig. 1 depicts a NLOS UV communication link under the turbulent environment. We define parameters as follows. Let θ_1 and θ_2 be the Tx and Rx apex angles between each axis and the horizontal axis, ϕ_1 and ϕ_2 the Tx full beam angle and Rx FOV, and β_1 and β_2 the Tx off-axis angle and Rx off-axis angle, θ_s the scattering angle between the forward direction of incident waves and the observation, V the common scattering volume, r the Tx and Rx baseline separation, and r_1 and r_2 the distances of the common volume to the Tx and Rx, respectively. Note that from Eq. (1), C_n^2 is constant for the horizontal link, but for slant path (downlink or uplink), altitude-dependence of $C_n^2(h)$ should be taken into account [12]. One of the most widely used models for $C_n^2(h)$ is the Hunfnagel-Valley (H-V) model described by [13]

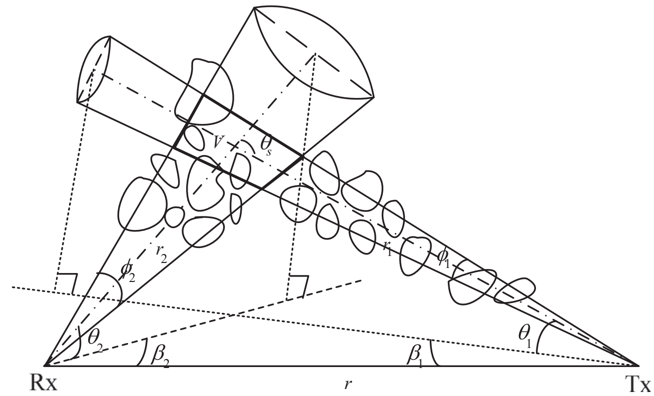

Fig. 1. NLOS UV communication link in atmospheric turbulence.

$$C_n^2(h) = 0.00594(v/27)^2(10^{-5}h)^{10}\exp(-h/1000) + 2.7\times10^{-16}\exp(-h/1500) + A\exp(-h/100) \tag{8}$$

where h is in meters (m), v is the root-mean-square windspeed in meters per second (m/s), and A is a nominal value of $C_n^2(0)$ at the ground in $m^{-2/3}$. Furthermore, the altitude-dependence of r_1 and r_2 should also be considered for uplink and downlink of NLOS UV communication in Eq. (1). From Fig. 1, it is easy to obtain the following expressions for an altitude h, $r_1 = h/\sin\theta_1 = h/\sin(\pi/2-\zeta_1) = h\sec(\zeta_1)$, $r_2 = h/\sin\theta_2 = h/\sin(\pi/2-\zeta_2) = h\sec(\zeta_2)$, where ζ_1 and ζ_2 denote the zenith angles at Tx and Rx respectively. Hence, SA based on Eq. (3) at the Tx link and the Rx link can be respectively given by

$$\alpha_{Rytov,Tx}(h) = 2 \cdot \sqrt{23.17 \cdot k^{7/6} \cdot C_n^2(h) \cdot (h\sec\zeta_1)^{11/6}} \tag{9a}$$

$$\alpha_{Rytov,Rx}(h) = 2 \cdot \sqrt{23.17 \cdot k^{7/6} \cdot C_n^2(h) \cdot (h\sec\zeta_2)^{11/6}} \tag{9b}$$

The vertical profiles of σ_I^2 according to [13] are

$$\sigma_I^2(H) = 2.25k^{7/6}(H-h_0)^{5/6}\sec^{11/6}(\zeta)\int_{h_0}^{H} C_n^2(h)\left(1-\frac{h-h_0}{H-h_0}\right)^{5/6}\left(\frac{h-h_0}{H-h_0}\right)^{5/6} dh \tag{10a}$$

for the uplink case, and

$$\sigma_I^2(H) = 2.25k^{7/6}\sec^{11/6}(\zeta)\int_{h_0}^{H} C_n^2(h)(h-h_0)^{5/6}\, dh \tag{10b}$$

for the downlink case. Where h_0 is the height above ground level of the uplink Tx and/or downlink Rx, and is assumed to zero in our paper. Eq. (10) is true for $\sigma_I^2(H) < 1$ and valid for $0 \le \zeta \le \pi/3$.

In order to quantify the SA for the whole slant link, it is necessary to average the influence of altitude on SA, which is completed by averaging the integration of Eq. (9) with similar structure of Eq. (10), except for the constant coefficient. The final expression is given by

$$\alpha_{Rytov,NLOS} = 2\left[\sqrt{\frac{1}{H}\int_0^H 23.17 \cdot k^{7/6} \cdot \sec^{11/6}(\zeta_1) \cdot C_n^2(h) \cdot \left(1-\frac{h}{H}\right)^{5/6} \cdot h^{5/6}\, dh} + \sqrt{\frac{1}{H}\int_0^H 23.17 \cdot k^{7/6} \cdot \sec^{11/6}(\zeta_2) \cdot C_n^2(h) \cdot h^{5/6}\, dh}\right] \tag{11}$$