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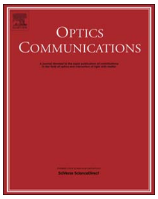

Non-line-of-sight optical scattering communication based on atmospheric inhomogeneity

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In this paper, a new non-line-of-sight (NLOS) propagation model in inhomogeneous atmosphere for long range is presented. The optical scattering communication is simulated, in which the single-scatter propagation model is used and the atmospheric inhomogeneity is also taken into account. Through the comparison with that in other atmosphere conditions, the scattering phase function is found to be a function of height. Moreover, the received energy does not decrease monotonically as the apex angle increases, and there is an optimal apex angle in which the received energy is the largest. All these results are conducive to the precise calculation of the optical scattering communication for long range.

1. Introduction

Non-line-of-sight (NLOS) scattering communication is based on the optical scattering theory. Compared with the traditional communication, it has a lot of advantages, such as the good secrecy, good anti-jamming ability as well as the ability of bypassing the barrier [1]. In 1970, Lerner [2] and Kennedy [3] analyzed the characteristics of atmospheric optical scattering channel, which brought hope to the optical scattering communication. Then in 1991, Luettgen [4] proposed a NLOS single-scatter propagation model and analyzed the impulse-response as well as the path loss and received energy for short range. Since then, researchers have begun to focus on the NLOS scattering communication [5–8]. This model can also be adopted by the laser communication for bistatic lidar.

However, so far, little attention has been paid to the scattering optical communication in the inhomogeneous atmosphere and for the long range, which may cause serious errors to the optical communication for long range. What's more, the studies may be more reasonable and more persuasive if the researchers have taken the atmospheric inhomogeneity into consideration. Therefore, further related studies are still necessary. In view of this situation, this paper aims to investigate the optical scattering communication in the inhomogeneous atmosphere and apply this model to the optical communication.

The structure of this paper is as follows: in Section 2, the single-scatter propagation model, on which the new one is based, is reviewed; in Section 3, the scattering and extinction coefficients in the inhomogeneous atmosphere as well as the phase function in isotropic scattering are presented; then the received energy and the path loss for a particular set of parameters under different types of atmosphere conditions are investigated in Section 4; and finally, a brief conclusion is provided in Section 5.

2. The single-scatter propagation model

The NLOS scattering communication is based on the single-scatter propagation model, as shown in Fig. 1, where β_t and $\Delta\theta_t$ are the apex angle and divergence angle of the transmitter, respectively; β_r and $\Delta\theta_t$ are the apex angle and half field of view of the receiver, respectively. According to the single-scatter propagation model proposed by Luettgen [4], an impulse of energy E_t emits at t=0 from the transmitter into the atmosphere and the scattered irradiance at the receiver is as follows:

$$E_R(\xi)=\frac{E_t c k_s exp(-k_e r\xi)}{2\pi\Omega_t r^2}\int_{\eta_1(\xi)}^{\eta_2(\xi)}\frac{2g(\phi(\xi,\eta)P(\ \theta_s)}{\xi^2-\eta^2}d\eta \tag{2.1}$$

c = $3\times10^8 m/s$ is the velocity of light, and r is the communication distance.

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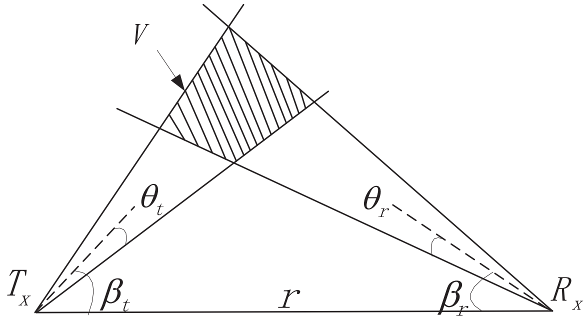

Fig. 1. Single-scatter propagation model.

$\xi = ct/r$ is the radial component, η is the angular coordinate, andΦ is the azimuthal coordinate.

k_s is the atmospheric scatter coefficient, k_a is the absorption coefficient, and k_e is the extinction coefficient, with $k_e = k_s + k_a$.

$P(\theta_s)$ is the scatter phase function, with $P(\theta_s)$=1 in the isotropic scattering.

Ω_t is the transmitter solid cone angle, and $g(\phi(\xi,\eta)$ is the optical scatter channel capacity.

Integrating over the time t results in the received energy at the receiver

$$E = \frac{\pi D^2}{4} * \int_{t_{min}}^{t_{max}} E_R\left(\frac{ct}{r}\right)dt \tag{2.2}$$

D is the diameter of the receiver.

3. The inhomogeneous atmosphere

In the traditional NLOS scattering communication, the atmospheric scattering and extinction coefficients are considered as fixed values. Nevertheless, the atmosphere is not homogeneous [9,10] and the atmospheric parameters, like the atmospheric density, pressure and aerosol concentration, are the function of height.

3.1. The atmospheric scatter and extinction coefficient

Scattering and absorption play an essential role in the optical communication. k_s is the atmospheric total scattering coefficient, and $k_s = k_s{}^{Mie} + k_s{}^{Ray}$, where $k_s{}^{Ray}$ refers to the Rayleigh scattering coefficient, and $k_s{}^{Mie}$ represents the Mie scattering coefficient.

For the Rayleigh scattering [11],

$$k_s{}^{Ray}(\lambda) = \frac{8\pi^3\left(m^2-1\right)^2}{3N_m\lambda^4} \tag{3.1}$$

where N_m is the molecular number density, m is the refractive index of atmosphere, and λ is the wavelength of incident light.

N_m and m are all functions [12–14] of the atmospheric molecular mass density ρ:

$$m(z)-1=\left[m(0)-1\right]\frac{\rho(z)}{\rho(0)} \tag{3.2}$$

$$N_m(z) = N_m(0)\frac{\rho(z)}{\rho(0)} \tag{3.3}$$

Under standard atmosphere [15],

$$\left[m(0)-1\right] \times 10^6=64.\,328+\frac{29498.\,1}{146-\lambda^{-2}} + \frac{255.\,4}{41-\lambda^{-2}} \tag{3.4}$$

where $m(0)$, $\rho(0)$ and $N_m(0)$ are the atmospheric parameters on the ground, while $m(z)$, $\rho(z)$ and $N_m(z)$ are the atmospheric parameters at the height of z. With regard to the mass density ρ, a function of height, the US standard atmosphere in 1976 can be taken as a reference [16].

For the Mie scattering [17],

$$k_s{}^{Mie}(\lambda) = \pi \int_{r_{min}^a}^{r_{max}^a} r^2 n(r) Q_{sc}(\alpha, m_a)dr \tag{3.5}$$

$$k_a{}^{Mie}(\lambda) = \pi \int_{r_{min}^a}^{r_{max}^a} r^2 n(r) Q_{sc}(\mathrm{\alpha},\mathrm{m_a}) Q_{sc}(\alpha, m_a)dr \tag{3.6}$$

where r_{min}^a and r_{max}^a are the lower and upper limits of the particle sizes. $Q_{sc}(\alpha,m_a)$ and $Q_{sc}(\alpha,m_a)$ are the scattering and extinction efficiency, respectively, referring to the MATLAB Functions for Mie Scattering and Absorption [18]. Moreover, α is the size parameter, with $\alpha = 2\pi r/\lambda$, and m_a is the complex refractive index, which refers to the software package OPAC (Optical Properties of Aerosols and Clouds) [19]. $n(r)$ is the radial distribution function.

As the size distributions of aerosol particles follow the log-normal distributions [20]:

$$n(r) = \frac{dN_a}{dlnr} = \frac{N_a}{\sqrt{2\pi}\ln\sigma} exp\left[-\frac{\left(lnr - lnr_{mod}\right)^2}{2\left(ln\sigma\right)^2}\right] \tag{3.7}$$

In which N_a denotes the total particle number density, σ means the width of the distribution, and r_{mod} is the particle mode radius.

The distribution of aerosol particles drops exponentially [21] with height,

$$N_a(z) = N_a(0)e^{-\frac{z}{H}} \tag{3.8}$$

where H is the scale height; z is the altitude above ground, while $N_a(0)$ and $N_a(z)$ are the total particle number density at the height of zero and z, respectively.

In the vast territory of the world, aerosol varies with locations greatly. Meanwhile, the size distribution and composition of aerosols also show large differences.

The detection examples in other researches are also given below. The size and distribution of particles [22] are displayed in Table 1.

The parameters of the standard atmosphere on the ground [22] are provided in Table 2.

In Fig. 2(a), the atmospheric molecular mass density profile is illustrated, which refers to the US standard atmosphere in 1976, and the number density of molecule and aerosol is presented in

Table 1
The size distribution of aerosols.

r (μm)	n	Points (μm)	Percentage (%)	Cumulative percent (%)
0~4	104	0.026	10.4	10.4
4~6	160	0.080	16	26.4
6~8	161	0.0805	16.1	42.5
8~9	75	0.075	7.5	50.0
9~10	67	0.067	6.7	56.7
10~14	186	0.0465	18.6	75.3
14~16	61	0.0305	6.1	81.4
16~20	79	0.0197	7.9	89.3
20~35	103	0.0034	10.3	99.6
35~50	4	0.0001	0.4	100.0
>50	0	0.0	0.0	100.0
总计	1000		100.0	