Study on attenuation characteristics of NLOS ultraviolet communication system in haze

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Abstract: In order to study the characteristics of UV communication system under the environment of haze, the physical and spectral distribution characteristics of haze particles were studied, the scattering characteristics of haze particles were analyzed in blind ultraviolet by using the theory of scattering. And by using the classical Luettgen single scattering model, the path loss characteristics of non-line-of-sight (NLOS) solar blind UV transmission were studied in the haze environment. By analyzing simulation results of the relationship between path loss and communication distance, visibility and system angle, the theoretical characteristics of haze attenuation in NLOS UV transmission system were obtained: When the communication distance is short, the path loss of the system will be greatly affected by the weather condition (visibility). When the visibility is good, the influence of communication distance on the path loss will be prominent. In practice, it should be as far as possible to select the visibility of more than 2 km weather conditions. The work of this paper provides a theoretical reference for the design of the UV-light communication system and the optimization of the system performance in the haze environment. In addition, it also has certain guiding significance for the system engineering realization.

Key words: ultraviolet communication; non-line-of-sight(NLOS); haze particles; visibility; Luettgen single scattering

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非视距紫外光通信系统中霾衰减特性研究

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摘 要: 为了研究霾环境下应用紫外光通信的系统特性,研究了霾粒子的物理特性及谱分布特性,利用散射理论分析了霾粒子在日盲紫外光波段的散射特性;并利用经典 Luettgen 单散射信道模型,研究了霾环境下非视距日盲紫外光传输的路径损耗特性。通过分析路径损耗与通信距离、能见度以及系统角度之间的关系仿真结果,得到了非视距紫外光传输系统中霾衰减的理论特性:在较短通信距离时,系统的路径损耗受天气状况(能见度)影响较大;能见度较好时,通信距离对路径损耗的影响将会突出,实际中应尽量选取能见度大于 2 km 的天气条件。文中的工作对设计霾天环境下紫外光通信系统及优化系统性能提供了一定的理论参考,同时对系统工程化实现也具有一定的指导意义。

关键词: 紫外光通信; 非视距; 霾粒子; 能见度; Luettgen 单次散射

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0 Introduction

Communication technologies used on the battlefield include wired and wireless technologies that use fixed and mobile terminal facilities for information delivery. Wired communication has the following problems, the need for pre-line, easy to be damaged, difficult to maintain, and cannot be quickly maneuver. Although wireless microwave communication has the characteristics of flexibility, it is easy to be eavesdropped, disturbed and exposed maneuvering position and so on. Atmospheric point-to-point laser communication has the characteristics of high transmission rate and good confidentiality. However, due to the narrow beam characteristics of laser, it is very difficult to achieve the aim of ATP (acquisition, tracking and pointing) between communication terminals, especially for high-acceleration mobile platforms. In addition, it is also strictly limited by communication distance; and due to high speed and high maneuverability of the tactical operation, it is difficult to realize point-to-point direct laser communication. In recent years, developed non-line-of-sight (NLOS) UV communication technology can overcome the above shortcomings. It uses the scattering effect of particles, airgel, dust and other particles of the atmosphere on the UV light (240-280 nm. Ozone has a strong absorption of it, and there is no solar radiation background of the corresponding band near the ground) for information transmission[1-2]. Because this communication technology has the special atmospheric scattering transmission characteristics, the light beam of the communication transmitter is not transmitted directly to the terminal, but the closed loop is formed by the communication terminal form receiving the scattering signal from the atmosphere. So it is a optical communication method that can realize the non-line-of-sight working mode. And for military communication, UV communication has the characteristics of low eavesdropping rate, low resolution, strong anti-interference, omni-directional, non-direct-vision, all-weather working mode and so on, which can effectively compensate for the shortcomings of wired and wireless com-munications. Because of its special and excellent performance, UV communication has wide application prospects, such as local secret communication in military field, communication during radio silence, landing on auxiliary carrier, landing of auxiliary aircraft in civil field, small sensing system, logistic emergency support communication and small-scale wireless optical LAN and so on. In particular, the NLOS secure communication characteristic is more important, so that the UV communication has more considerable application prospects for in the military field, and can be used as a special local military communication means, or as a complement to other means of communication in a certain condition. It is widely used in land, sea and air armed forces, and has a special use value and practical significance in future war and the modernization of national defense[3-5].

The UV communication uses the scattering function of atmospheric particle of the light to realize signal transmission. Atmospheric particles include clouds, fog, haze, air molecules, smoke, etc., in which the scattering effects of cloud, fog and air molecules on UV signals have been reported in detail[6-7]. In recent years, the haze phenomenon attracts most public attention and is increasingly well known especially in the city, it directly affects people′s daily life. In the research and application of UV communication technology in the city, it will inevitably encounter haze. Xie Yisong, Cai Binbin et al. have studied the aerosol optics, microphysical properties and scattering extinction characteristics of haze[8-9]. However, there is no report on the influence of the existence and distribution of haze particles of UV communication system performance. Therefore, starting from the study of physical and spectral distribution characteristics of haze particles, the scattering properties of haze particles of the UV (λ=266 nm) band are analyzed by using the scattering theory. And the path loss

characteristic of the NLOS UV transmission is studied by using the classical Luettgen single scattering channel model. And the relationship between path loss and communication distance, visibility and system angle in the simplified single-scattering channel model is simulated by using Matlab, and the theoretical characteristics of haze attenuation in NLOS UV communication system are obtained. The research of this paper provides some theoretical references for the design and optimization of NLOS UV communication system in haze environment, and also has some guiding significance of improving system communication quality in the haze environment.

1 Distribution of haze particles

Haze is caused by organic hydrocarbons, dust, nitric acid, sulfuric acid and a large number of very fine dry dust particles which float evenly in the air. Some of these dry dust particles are hygroscopic, they are affected by water vapor and atmospheric condensation nuclei to form unadsorbed moisture growth particles, which directly determine the size of haze particles, complex refractive index and structural characteristics of particles. Thereby it indirectly changes the scattering characteristics of haze particles and affects the visibility of the atmosphere, so that the visibility of clear sky weather is less than 10 km [9]. Haze particle is a kind of aerosol particle which is harmful to human health. It has the largest concentration near surface, decreases rapidly to height and can penetrate into the stratosphere. Its scale distribution range is 0.001-10 μm, average diameter is about 1-2 μm.

1.1 Distribution function of haze particles and haze attenuation

The scattering and absorption characteristics of haze particles are very important to the size and refractive index of particles. Usually, the spectral distribution function is used to characterize the distribution of particles of each scale. It is one of the important characteristics of the light scattering and attenuation study [6,10]. Deirmendjan model (also known as generalized Gamma or exponential distribution model) is the most widely used and greatest applicability scale distribution model for haze particles, and it is also one of the most widely used aerosol models for scattering problems. Its form is as follows[11]:

$$n(r)=ar^{\alpha}\exp(-br^{\beta}) \tag{1}$$

Where a is the total number of particles, b, α, β are positive constants. When β=1, the above formula is a generalized standard Gamma function distribution. Deirmendjan model is not only most suitable for marine and continental haze, but also for the distribution of stratosphere haze particles. The model parameters in different situations are shown in Tab.1.

Tab.1 Parameters of Deirmendjan for haze droplet size distribution

Environment	a	b	α	β
Continent	4.976×106	15.118 6	2	0.5
Maritime	5.333×104	8.944 3	1	0.5
Stratosphere	4.000×105	20.000	2	1

Atmospheric visibility refers to the maximum horizontal distance that people with normal vision can see and recognize objects of the sky in the weather conditions of the day. It is often used to reflect the concentration of aerosols. It is often used to reflect the concentration of aerosols, and can also be used to study the attenuation of optical signal transmission caused by haze. The empirical model formula used to predict the haze attenuation coefficient is as follows [12]:

$$\mu=\frac{3.912}{V_b}\left(\frac{0.55}{\lambda}\right)^{a_\lambda}(\mathrm{km}^{-1}) \tag{2}$$

Where V_b is the atmospheric visibility, km; a_λ is the wavelength correction factor. The value of a_λ varies according to different visibility conditions, as follows:

$$a_\lambda=\begin{cases}0.585V_b^{1/3} & V_b\leqslant 6\ \mathrm{km}\\ 1.3 & \text{Average visibility}\\ 1.6 & \text{Particularly good visibility}\end{cases} \tag{3}$$

In the case of average visibility, the value of V_b is generally 10 to 12 km, and the value of 23 km is for

particularly good visibility. During the winter of 2015, haze yellow and orange warnings are frequently issued in Xi′an. Visibility in the 2-5 km is for the moderate haze, while the visibility under severe haze is less than 2 km. For this low-visibility case, the French scholar Nabouls [13] et al. revised the value a_λ and gave the following formula:

$$a_\lambda=\begin{cases}0.16V_b+0.34 & 1\ \text{km}<V_b\leqslant 6\ \text{km}\\ V_b-0.5 & 0.5\ \text{km}<V_b\leqslant 1\ \text{km}\\ 0 & V_b\leqslant 0.5\ \text{km}\end{cases} \tag{4}$$

Therefore, the relationship between atmospheric attenuation and the change of visibility and wavelength can be predicted using the empirical model.

1.2 Scattering properties of haze particles

By using Eq.(2) is only able to obtain atmospheric attenuation changes with visibility and wavelength. In fact, the atmospheric environment, atmospheric particle size distribution, variation of refractive index caused by the change of particle composition and other factors will affect the atmospheric attenuation of light transmission. In order to calculate the transmission attenuation of haze in a more accurate way, we need to consider the above factors to study the scattering characteristics of haze particles. At present, the study of scattering characteristics of haze particles is mainly analyzed by Mie scattering theory, where it is assumed that the haze particles as a single substance and its microphysical features(such as particle size and complex refractive index) are fixed. In this way, all of the above factors can be considered in calculation based on the theory of Mie scattering[6,10].

When using Mie scattering theory to calculate the attenuation of light transmission caused by haze particles, the extinction cross section $Q_{i,j}(D)$(Total Cross-Section, TCS) of a single spherical haze particle should be calculated at first, that it is sum of the absorption and scattering coefficients:

$$Q_{i,j}(D)=\frac{2\pi}{k^2}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}(a_n+b_n) \tag{5}$$

In the formula, D is haze particle diameter, a_n and b_n are Mie scattering coefficient which are function of wavelength, radius of the particle and complex index of refraction.

$$a_n=\frac{\psi_n(\alpha)\psi_n'(\beta)-m\psi_n(\beta)\psi_n'(\alpha)}{\xi_n(\alpha)\psi_n'(\beta)-m\psi_n(\beta)\xi_n'(\alpha)} \tag{6}$$

$$b_n=\frac{m\psi_n(\alpha)\psi_n'(\beta)-\psi_n(\beta)\psi_n'(\alpha)}{m\xi_n(\alpha)\psi_n'(\beta)-\psi_n(\beta)\xi_n'(\alpha)} \tag{7}$$

In addition, k is the wave number, $\alpha=ka$, $\beta=kma$, $\psi_n(x)=xj_n(x)=\sqrt{\pi x/2}\,J_{n+\frac{1}{2}}(x)$, $\xi_n(x)=xh_n^{(1)}(x)=\sqrt{\pi x/2}\,H_{n+\frac{1}{2}}^{(1)}(x)$.

The radius of the haze particle is r=0.001−10 μm, the optical signal attenuation caused by the unit distance is as follows:

$$A=4.343\times10^3\int_0^{\infty}Q(r)n(r)\mathrm{d}r(\mathrm{dB/km}) \tag{8}$$

In the above formula, n (r) is the scale distribution function of the haze particle obtained according to Eq.(2).

1.3 Simulation and analysis of haze attenuation

For Xi′an and other mainland, the main haze particles components of troposphere aerosols are dust particles(70%), water-soluble particles(29%) and soot etc. The operating wavelength of the ultraviolet communication system is selected as 266 nm, and the complex refractive indices of dust and water-soluble haze particles are n=1.74+0.47i and 1.53+0.008i, the typical size of haze particles in the Mie calculation is r=0.001−10 μm. Empirical model Eq.(2) and Eq.(4) are used to obtain the relationship between the haze attenuation coefficient and the visibility. And then in the case of considering atmospheric environment and atmospheric haze particles with different refractive index (ignoring soot particles) and particle size distribution, using Mie theory Eq.(5) and haze particle spectral distribution function Eq.(1), and according to Eq.(8) and the relationship between attenuation coefficient and visibility[14], the relationship between visibility and attenuation of UV light signal which is caused by haze is given by simulation, as shown in Fig.1.

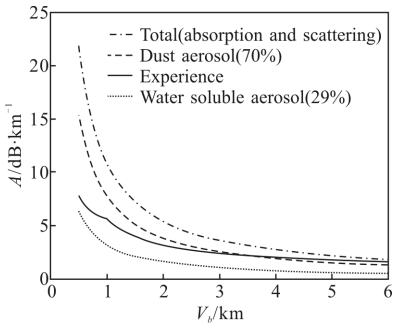

Fig.1 Attenuation due to haze as a function of V_b at 0.266 μm

It can be seen from the simulation results from Fig.1 that the attenuation coefficient decreases with the increase of visibility. In the case of low visibility, the attenuation of dust caused by dust particles is larger. When the visibility is less than 3.6 km, the contribution of only dust particles to 0.266 μm UV light is larger than that calculated by empirical formula. The attenuation coefficient caused by water-soluble particles is less than the predicted result. When the visibility is greater than 5 km, the Mie theoretical calculation results are basically the same as the predicted results; the attenuation coeffi-cient tends to balance. That is mainly because in this case, the atmospheric particle size and UV band can be basically comparable. When the visibility is good, the ultraviolet light can use the atmospheric particles to achieve scattering transmission.

2 Single scattering channel model of UV

At present, the most commonly used NLOS blind UV communication single scattering channel model is based on the long spherical surface of the coordinate system, that is proposed by Mark R. Luettgen and others based on single scattering channel model of David M. Reilly[15]. While in this paper, the single-scattering channel model is simplified by Xu Zhengyuan[16] based on the Luettgen single scattering channel model, which is assumed that, the photon that emitted from the transmitter only occurs once scattering in the process of reaching the receiver, other multiple scattering is negligible.

The non-line-of-sight UV communication link is shown in Fig.2. Defined parameters are as follows: E_t is the emission pulse energy, λ is the wavelength, Ω_1 is the transmitter radiation cone solid angle. V is the effective scattering volume of the transmitter (T_x) and the receiver (R_x), R is the distance between T_x and R_x, and R_1 and R_2 are the distances between effective scattering volumes T_x and R_x respectively. θ_T and θ_R are defined as the elevation angle and the elevation angle, β_T and β_R are the emis-sion field half-angle and the receiving field half-angle respectively. Let k_e as the extinction coefficient of the atmosphere, that is the sum of scattering and absorption coefficient according to Eq.(8), $k_e=k_s+k_a$; meanwhile $\theta_s=\theta_T+\theta_R$, A_r is the aperture of the receiving area, $P(u)$ is the scattering phase function, $u=\cos\theta_s$, c is the speed of light.

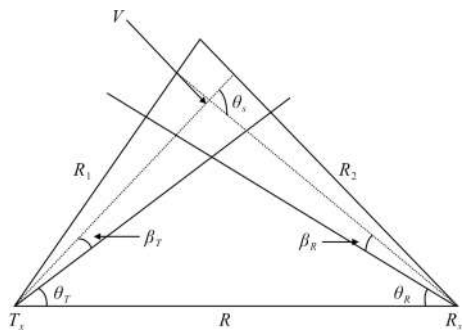

Fig.2 NLOS UV communication link

As can be seen from reference[17], it is supposed that the volume element d_V can be regarded as the secondary radiation source, its radiation energy to the space is:

$$dE_r=\frac{E_t k_s P(u) A_r \cos(\zeta)\exp[-k_e(R_1+R_2)]}{4\pi\Omega_T(R_1R_2)^2} \tag{9}$$

Where ζ is angle between the axis of receiver and the vector of receiver to effective scatter volume. The total energies received at the receiver are obtained by calculating the integral dE_r numerically on the effective scattering volume using a long spherical coordinate system. In order to obtain an easily processed analysis result, it is assumed that the effective scattering volume is small, $\zeta=0$ approximately. Where $\Omega_1=2\pi(1-\cos\beta_T)$, $R_1=R\sin\theta_R/\sin\theta_s$,

$R_2 = R\sin\theta_t/\sin\theta_s$, $\theta_s = \theta_T + \theta_R$, then the final energy received by the receiver is:

$$E_r = \frac{E_t k_s P(u) A_r V \sin^4\theta_s \exp[-k_e(R_1+R_2)]}{8\pi^2 R^4 (1-\cos\beta_T)\sin^2\beta_T \sin\beta_R} \tag{10}$$

In addition, when the effective scattering volume V is small, V can be approximated by the difference between the two cone volumes[16], that is:

$$V = \frac{1}{3}\pi(D_1^2 h_1 - D_2^2 h_2) \tag{11}$$

Wherein, D_1, h_1, D_2, h_2 are the radius and heights of the cone respectively, they can be expressed as:

$$h_1 = R_1 + R_2\beta_R,\ D_1 = h_1\beta_T \tag{12}$$

$$h_2 = R_1 - R_2\beta_R,\ D_2 = h_2\beta_T \tag{13}$$

Substituting Eq.(12) and (13) into Eq.(11) yields:

$$V = \frac{\pi R^3 \beta_T^2 \beta_R \sin\theta_T (6\sin^2\theta_R + 2\beta_R^2 \sin^2\theta_T)}{3\sin^3\theta_s} \tag{14}$$

The path loss is defined as:

$$L = 10\lg\frac{E_t}{E_r} \tag{15}$$

By substituting Eq.(10) and Eq.(14) into Eq.(15), the path loss is as follow:

$$L = 10\lg\frac{12\pi R(1-\cos\beta_T)\sin\theta_T \sin^2\theta_R}{k_s P(\cos\theta_s) A_r \beta_T^2 \beta_R \sin\theta_s (3\sin^2\theta_R + \beta_R^2 \sin^2\theta_T)} \times \exp\left[\frac{k_e R}{\sin\theta_s}(\sin\theta_T + \sin\theta_R)\right] \tag{16}$$

3 Analysis of simulation result

In the simulation of path loss of the ultraviolet communication link with haze environment, the working wavelength is 266 nm and aperture area of receiver is 1 cm^2. The following figures show relationships between path loss of ultraviolet communication link and various parameters.

Figure 3(a) is the relationship between path loss of UV communication link and half-angle of transmitting and receiving FOVs. Wherein, transmitting and receiving elevation angles are 30°, the visibility is 2 km, the communication distance is 1 km. From Fig.3(a), it can be seen that the larger the half-angle of receiving field is, the smaller the path loss is, and the less the change is. Fig.3 (b) shows the variation of the path loss with transmitting and receiving elevation angles.

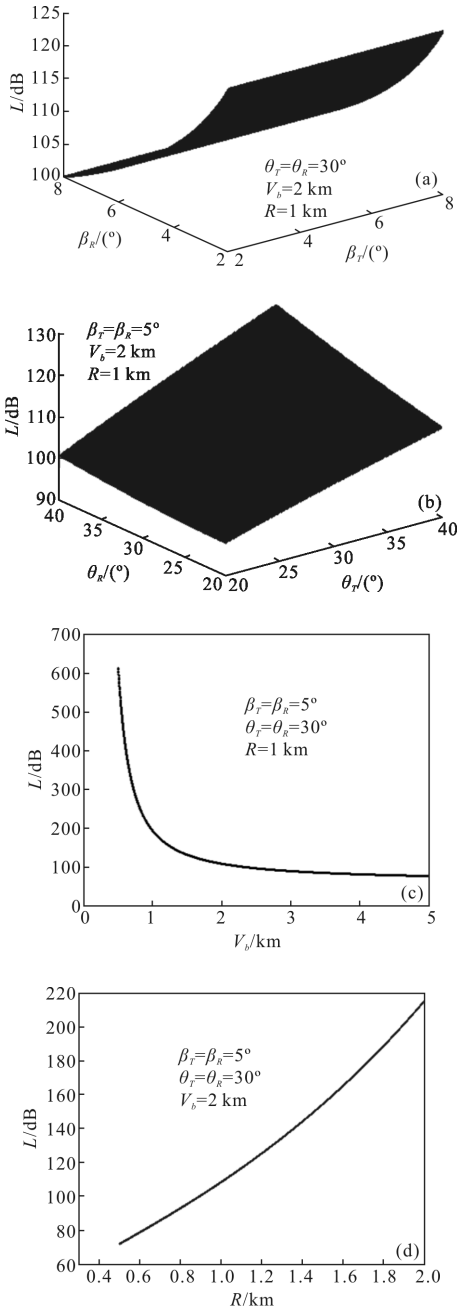

Fig.3 Relationship between path loss and various parameters in haze environment

Wherein, the transmit and receive half-angles are both 5°, and the visibility is 2 km and the communication distance is 1 km. It shows that the path loss increases with the increase of transmitting and receiving elevation angles, but the amplitudes are different. The amplitude increases more sharply with the transmitting elevation angle than receiving elevation angle. Fig.3(c) shows the relationship between path loss and visibility when

the transmitting and receiving half-angles are 5° respectively, the transmitting and receiving elevation angles are 30° and the communication distance is 1 km. The simulation results show that the path loss drastically decreases with the increase of visibility when the visibility is 0.5-2 km, and the decrease rates become slow when visibility is more than 2 km. Fig.3(d) shows the relationship between path loss and communication distance when the transmitting and receiving angles are both 5°, the transmitting and receiving elevation angles are 30° and the visibility is 2 km. The simulation results show that the path loss increases with the communication distance.

By analyzing the above figures and data, it can be seen that the shorter the communication distance is, the smaller the path loss is. However, the communication system is affected by the weather condition (visibility), and the path loss does not appear the lowest point in the selected maximum range of visibility. But when the visibility is greater than 2 km, the loss is slowed down. Therefore, we should try to select the weather condition of visibility that more than 2 km in experiment. In addition, the influence of communication distance on path loss begins to be prominent with the increase of visibility in haze environment. Therefore, a shorter communication distance can achieve better communication quality in good weather condition (visibility greater than 2 km). Furthermore, according to the simulation results of Fig.3(a), (b), we can guide the design of UV communication system through a reasonable choice of system angle.

4 Conclusion

Based on the research demand that the haze attenuation characteristics are needed to be determined, we apply ultraviolet light communication system in city. Firstly, the physical properties and spectral distribution of haze particles are studied. The scattering properties of haze particles in the ultraviolet region are analyzed by using scattering theory. Also the empiric formula and the attenuation theory of scattering theory are analyzed and compared under haze environment. Then, based on the classical Luettgen single scattering channel model, the path loss characteristics of NLOS blind UV transmission in haze environment are studied, the relationships between path loss and communication distance, visibility and system angle are analyzed using Matlab. Final conclusion: the path loss of NLOS blind UV communication system is greatly affected by weather condition (visibility) in short communication distance. When the visibility is good, the influence of communication distance on the path loss will be prominent. Therefore, we should try to select the weather condition of visibility of more than 2 km in application. The work in this paper provides a theoretical reference for the design and optimization of NLOS solar blind UV communication system in haze environment, and also provides some theoretical support for the performance evaluation of UV communication system.

References:

[1] Zhang Hailiang. Study on the characteristics of propagation of ultraviolet communication system [D]. Changsha: National University of Defense Technology, 2012. (in Chinese)

[2] Lan Tian, Ni Guoqiang. Simulation research on ultraviolet atmospheric transmission in UV communication [J]. ***Transactions of Beijing Institute of Technology***, 2003, 23 (4): 419-423. (in Chinese)

[3] Jeffery J Puschell, Robert Bayse. High data rate ultraviolet communication systems for the tactical battlefield[C]//Proc of the Tactical Communication Conference, 1990: 253-267.

[4] Ni Guoqiang, Zhong Shengdong, Liu Liudi, et al. Study on ultraviolet communication through disengaged atmosphere [J]. ***Optical Technique***, 2000, 26(4): 297-303. (in Chinese)

[5] Li Jiye, Qiu Keni. Military application of UV communication [J]. ***Optics & Optoelectronic Technology***, 2005, 3(4): 19-21. (in Chinese)

[6] Yang Ruike, Ma Chunlin, Han Xiang′e, et al. Study of the attenuation characteristics of laser propagation in the

atmosphere [J]. ***Infrared and Laser Engineering***, 2007, 36 (S): 415-418. (in Chinese)

[7] Bai Lu, Tang Shuangqin, Wu Zhensen, et al. Study of random sample scattering phase functions of polydisperse atmospheric aerosol in ultraviolet band [J]. ***Acta Physica Sinica***, 2010, 59(3): 1749-1755. (in Chinese)

[8] Xie Yisong, Li Donghui, Li Kaitao, et al. Aerosol optical and microphysical properties in haze days based on ground ased remote sensing measurements [J]. ***Journal of Remote Sensing***, 2013, 17(4): 970-980. (in Chinese)

[9] Cai Binbin. Analysis of scattering extinction characteristics and influence of aerosols in the city haze weather [D]. Tianjin: Nankai University, 2007. (in Chinese)

[10] Ma Chunlin. Study of influences of atmospheric transmission characteristics on per-formances for laser detection [D]. Xi′an: Xidian University, 2008. (in Chinese)

[11] Mccontney E J. Atmospheric Optics [M]. Pan Naixian, Mao Jietai, Wang Yongsheng, translated. Beijing: China Science Publishing & Media Ltd., 1998. (in Chinese)

[12] Gan Xinji, Guo Jin, Wang bin, et al. Attenuation prediction for 1.06 μm laser propagation in the troposphere [J]. ***Journal of Changchun University of Science and Technology***, 2006, 29(2): 8-13. (in Chinese)

[13] Aher Nabouls. Fog attenuation prediction for optical and infrared waves[J]. ***Opt Eng***, 2004, 43(2): 319-329.

[14] Ansari A J, Evans B G. Micro wave propagation in sand and dust storms[J]. ***IEE Prodeedings F-Communications, Radar and Signal Processing***, 1982, 129(5): 317-322.

[15] He Hua, Ke Xizheng, Zhao Taifei. Research of ultraviolet non-line-of-sight single scattering link model [J]. ***Acta Optica Sinica***, 2011, 30(11): 3148-3152. (in Chinese)

[16] Xu Zhengyuan, Ding Haipeng, Brian M Sadler, et al. Analytical performance study of solar blind non-line-of-sight ultra violet short-range communication links [J]. ***Optics Letters***, 2008, 33(16): 1860-1862.

[17] Hou Qian, Li Xiaoyi, He Pan, et al. Study on non-line-of-sight single scattering model [J]. ***Modern Electronics Technique***, 2010, 30: 58-61. (in Chinese)