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干旱地区大气光学特性对激光传输的影响分析

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摘　要:分析干旱地区近地面 8.0 m 高度处的温度、湿度、折射率结构常数、大气压强和能见度等参数的每月日变化情况,获取大气消光系数与大气湍流的可能变化特征,在此基础上,讨论波长为 1.06 μm 的激光在大气环境条件下传输距离为 1 000 m 和 3 000 m 的可能传输效果.结果表明:消光系数日变化起伏不大,各月的消光系数以冬季 1 月为最大,夏季 7 月最小,二者相差可达 2 倍,1 000 m 的平均透过率约是 3 000 m 的 1.16 倍;冬季 1 月是湍流强度最弱的月份,春季 4 月和秋季 10 月是湍流较强的月份,3 000 m 收到的湍流平均影响程度约是 1 000 m 的 1.95 倍;从传输总体效果上来看夏季 7 月的 21 时左右传输效果最佳,不同传输距离的能量分布特性也不同.

关键词:大气湍流;光传输;光吸收;光散射;激光应用;激光传输
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Research on Possible Effects of Atmospheric Optical Characteristics on Laser Propagation in Arid Area

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Abstract: By analyzing the diurnal variations in monthly variation on temperature, humidity, refactive index structure parameter, pressure and visibility at the hight of 8.0 m above ground in surface layer in arid area, the probabilistic characteristics of atmospheric extinction and atmospheric turbulence were obtained. Based on the analyzed data, the possible effecs on a special case of laser propagation in arid area are discussed under the condition that the laser wavelength is 1.06 μm and the propagation length are 1 000 m and 3 000 m respectively. The results show that the extinction coefficient of diurnal variation change little ups and downs. The extinction coefficient of each month in January during winter is the largest, the extinction coefficient in July during summer is the smallest, and the difference of the two is about twice. The average transmittance of 1 000 m is about 1.16 times that of 3 000 m. The turbulence

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strength in January is the weakest month, and April in spring and October in autumn have stronger turbulence strength. The average turbulent influence of 3 000 m is about 1.95 times that of 1 000 m. The best propagation effect is the best at 21 : 00 in July of summer. The mean intensity distribution of different propagation distance have different probability density.

Key words: Atmospheric turbulence; Light propagation; Light absorption; Light scattering; Laser applications; Laser propagation

OCIS Codes: 140.3460; 010.1290; 280.7060; 290.1310; 350.4600

0 Introduction

The atmosphere is a special fluid composed of particles and gases whose physical properties can be highly dependent upon time and local conditions. Furthermore, as an important propagation medium, the atmosphere has various effects on laser propagation especially in electro-optical systems[1], which have far reaching consequences in assessment or in the design certain types system, such as those for tracking, detection, ranging, communication, measurement, and other applications[2], which operate in surface layer. It is essential to understand the possible changes of atmospheric optical parameters describing atmospheric characteristics, followed with space and time changes, for researching the effects of atmosphere on laser propagation.

As one of special types of light propagaton, some basic theories of light propagation can also be used on laser propagaton such as light absorption and scattering. Accordingly, the theories can be used to analyze effects of lased propagation. The three main atmospheric factors that affect laser propagation are absorption, scattering and optical turbulence. Absorption and scattering by the constituent gases and particulates in the atmosphere are wavelength dependent and cause primarily attenuation of an optical wave. Atmospheric optical turbulence give rise to irradiance fluctuations, beam spreading, and loss of spatial coherence of the optical wave[3-7]. Numerical simulation and measurement are two methods in common use to research the effect of turbulence on laser propagation in various laser applications[8-13].

There are different types laser propagations which need laser propagate long distance in atmosphere. Under the premise that only considering the linear effect, only one of infrared laser systems which propagation in suface layer is considered for simplifying discussion. It is assumed that the wavelength(λ) of laser is 1.06 μm, line width $\Delta l=1$ nm, transmitter diameter $D=0.3$ m, transmitted power $P_0=0.5$ W, light-beam quality $\beta=1$, the horizontal propagation distance $L=1\ 000$ m and 3 000 m respectively, and the propagation height $h=8$ m above ground.

The atmospheric attenuation consists of molecule absorption, molecule scattering, aerosol absorption, aerosol scattering. The domain absorption molecule at 1.06 μm in the atmosphere is water. Molecule scattering is determined by molecule density. The absorption and scattering of aerosol are determined by types and concentration. The intensity of atmospheric turbulence can be described by refractive index structure parameter C_n^2. Accordingly, the atmospheric optical parameters such as temperature, relative humidity, pressure, visibility, and refactive index structure parameter are choosed to describe the possible characteristics of atmosphere.

1 Measurements

The data used in the above mentioned the atmospheric optical parameters comes from measurement results in a Gobi site of northwest arid area. Table 1 gives the general situation of the measuring instruments and measuring.

Table 1 Survey of the measuring instruments and measuring

Parameter	Instrument name	Measurement period/s	Height/m	Start-stop time
$C_n^2/\mathrm{m}^{-2/3}$	Micro-thermometer	15	8	2003.09～2005.10
Temperature/K	Integrated transmitter	15	8	2003.09～2005.10
Relative Humidity/%	Integrated transmitter	15	8	2003.09～2005.10
Pressure/Pa	Integrated transmitter	15	8	2003.09～2005.10
Visibility/km	Visibility meter	15	8	2003.10～2008.10

Fig. 1 shows the basic relations of the measured parameters and transmission effect, namely on the basis of the analysis results on atmospheric turbulence and atmospheric transmittance of measurement parameters, the effects of the atmosphere on laser paopagation are discussed.

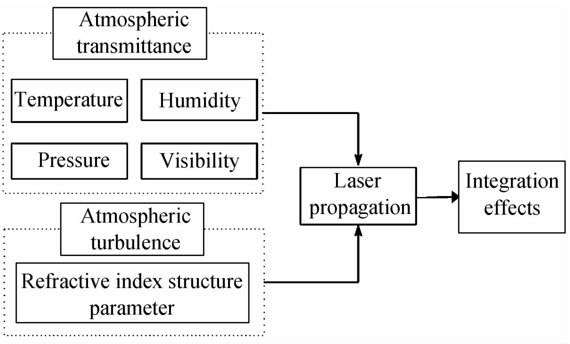
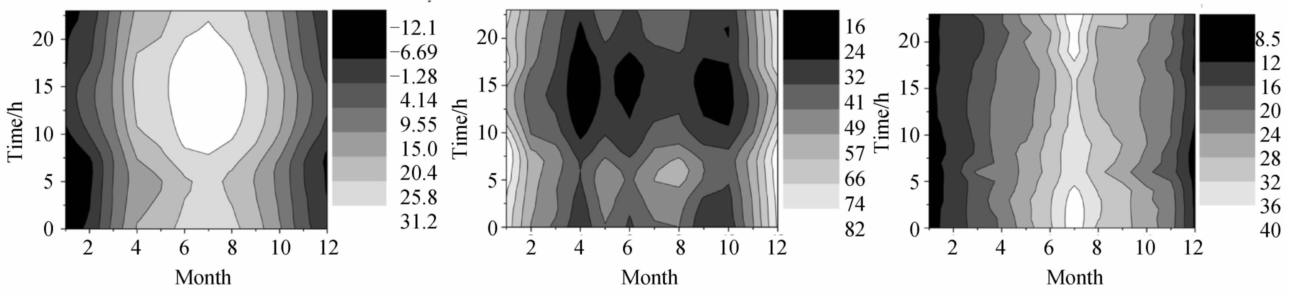


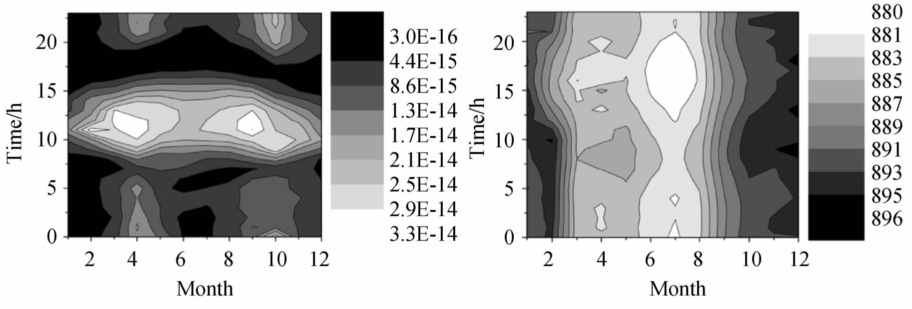
Fig. 1 Block diagram of measuring

2 Data analysis

By analyzing the diural variations in monthy variation on temperature, humidity, refactive index structure parameter, pressure and visibility at the hight of 8.0 m in suface layer, the number data in one year of the respective average of these parameters is 288. Fig. 2(a) and Fig. 2(b) shows the possible variation of temperature and humidity respectively. The average temperature of June to August is higher in the year, and the duration of daily high temperature is longer. The relative humidity in winter time is lager. Fig. 2(c) and Fig. 2(d) shows the possible variation of visibility and C_n^2 respectively. The daily variation of visibility is not obvious compared with temperature, the visibility of summer night is relatively good, and winter is the opposite. The C_n^2 of sunset time is relatively small, and the turbulence strength is weak in winter. Fig. 2(e) shows the possible variation of atmospheric pressure. The lowest atmospheric pressure occus during the summer afternoon.



(a) Temperature of monthly variation (b) Humidity of monthly variation (c) Visibility of monthly variation



(d) C_n^2 of monthly variation (e) Pressure of monthly variation

Fig. 2 Characteristics of measured parameters of monthly variation

2.1 Molecular extinction

Molecular extinction includes molecular absorption and molecular scattering

2.1.1 *Molecular absorption*

Absorption cross section α_M of the gas is definrd as

$$\alpha_M=\left(\frac{p}{P}\right)N\sigma \tag{1}$$

where p is partial pressure of the gas(in Pa), P is atmospheric pressure(in Pa), N is number density(in m^{-3}), σ is absorption cross section of the gas(in m^{-1}).

N is gotten from the following form

$$N=A_V\frac{P}{RT} \tag{2}$$

where A_V is Avogadro constant (6.022169×10^{-23} mol^{-1}), R is gas constant(8.31432 $J\cdot mol^{-1}\cdot K^{-1}$), T is temperature(K).

2.1.2 *Molecular scattering*

Molecular scattering can be calculated from Raleigh scattering theory. At 1.06 μm, molecular extinction is smaller value than aerosol extinction. Accordingly, the effect of molecular extinction can not be considered.

2.2 Aerosol extinction

Transmittance T, which express atmospheric transparence , is related to extinction coefficient k_{ex} and propogation length L. If the atmosphere is homogeneous in horizontal, the expression about transmittance T is given by

$$T=\exp(-k_{ex}L) \tag{3}$$

According to Koschmieder′s law, the relation between the meteorological range of visibility and extinction coefficient k_{ex} at 0.55 μm is expressed as

$$V=\frac{1}{k_{ex}}\ln\frac{C}{\varepsilon} \tag{4}$$

where ε is the threshold contrast of observer and C is inherent contrast of the target. In terms of $C=1$ and $\varepsilon=0.02$, meteorological range of visibility is defined as[14]

$$V_{0.02}=3.912/k_{\mathrm{ex}} \tag{5}$$

According to the definition of WMO, threshold contrast ε is 0.05. Eq. (5) is rewritten as

$$V_{0.05}=2.996/k_{\mathrm{ex}}\approx 3.0/k_{\mathrm{ex}} \tag{6}$$

Eq. (5) is used to the follows for unification. Thus, extinction coefficient at 0.55 μm can be computed from visibility. The relation between extinction coefficient at 0.55 μm and extinction coefficient at 1.06 μm is dependent on the characteristics of molecular extinction and aerosol extinction extinction at the two wavelengths. Molecular absorption is minor than molecular scattering, accordingly at 0.55 μm, molecular scattering is the dominating part of molecular extinction at 0.55 μm.

Aerosol extinction is determined by aerosol types and concentration. The aerosol types are given as follows[15-16].

1) Continental aerosol (including continental clean, continental average, continental polluted); 2) Urban aerosol; 3) Maritime aerosol(including maritime clean, maritime polluted maritime tropical); 4) Desert aerosol; 5) Arctic aerosol; 6) Antarctic aerosol.

The differences of optical properties of aerosol , which are mainly the differences of refractive indexes and particles spectrum, are depended on aerosol types. Various aerosol types have various different components. The components are divided into the follows 1) Insoluble particles; 2) Mineral particles (including nuclei mode, accumulation mode, coarse mode, transported); 3) Water-soluble particles; 4) Soot particles; 5) Sea-salt particles (including accumulation mode, coarse mode); 6) Sulfate particles.

The mass mixing ratios of the components is under influence of humidity. Given the specific aerosol types and the invariable particles spectrum, factor of concentration proportionality can be derived from the actural extinction (visibility) at 0.55 μm and the theoretical extinction at 0.55 μm. Based on the factor, the actural extinction at 1.06 μm can be gotten.

Thus, an assumption on continental aerosol particles is used to compute extinction at 0.55 μm and extinction at 1.06 μm under different humidity condition.

From the above discussion, the relation between 0.55 μm and 1.06 μm on extinction of continental aerosol particales under the condition of different humidities can be used to estimate the actural extinction at 1.06 μm under the condition of different humidities. The relation is given by the expression

$$\frac{k_{0.55}}{k_{1.06}}=\frac{k^{*}_{0.55}}{k^{*}_{1.06}} \tag{7}$$

where $k_{0.55}$ and $k_{1.06}$ are theoretical value with software, $k^{*}_{0.55}$ is actual extinction.

From Eq. (7) $k^{*}_{1.06}$ can be computed. Nevertheless, k and k^{*} are related humidity. The actual humidities are not consistent with the theoretical humidities absolutely. If a fitting function between $k_{1.06}/k_{0.55}$ and humidities can be gotten, $k^{*}_{1.06}$ can be compulated by the function and $k^{*}_{0.55}$. Thus, the relation between $k_{1.06}/k_{0.55}$ and the theoretical humidities can be used by fit function to be expressed as follows

$$\begin{cases} y=0.39462-6.28597\times 10^{-4}x & (0\leqslant x<70\%) \\ y=0.3474+1.25988\times 10^{-11}\mathrm{e}^{x/4.45218} & (70\%\leqslant x\leqslant 100\%) \end{cases} \tag{8}$$

where x is theoretical humidity(which is continuous), y is ratio $k_{1.06}/k_{0.55}$.

From Eq. (7), Eq. (8) and the computed results of software, the actual extinction coefficient at 1.06 μm can be computed. Fig. 3 gives characteristics at 1.06 μm of total extinction coefficient. The change of total extinction coefficient is contrary to the visibility. The extinction coefficient in January during winter is the smallest, The extinction coefficient in January during winter is the largest, and the extinction coefficient in July during summer is the smallest, and the difference of the two is about twice. In contrast to the monthly variation extent of extinction coefficient, the diurnal variation extent of extinction coefficient is not distinct.

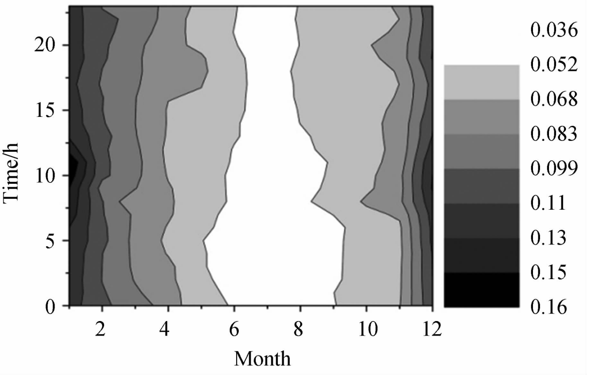


Fig. 3 Characteristics of total extinction coefficient of monthly variation at 1.06 μm

Fig. 4 and Fig. 5 shows characteristics at 1.06 μm of transmittance of 1 000 m and 3 000 m respectively. The average transmittance of 3 000 m, which is 0.80, is slightly lower than that of 1 000 m, which is 0.93.

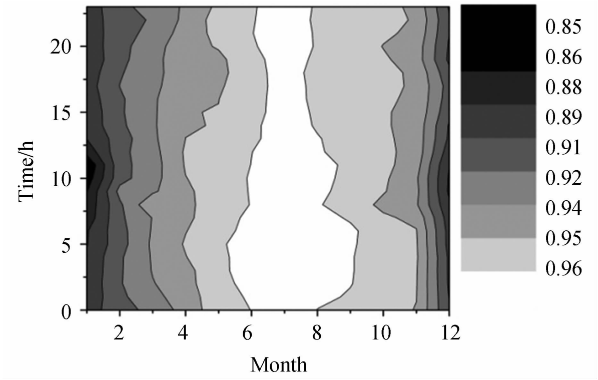


Fig. 4 Characteristics of 1000 m total transmittance of monthly variation at 1.06 μm

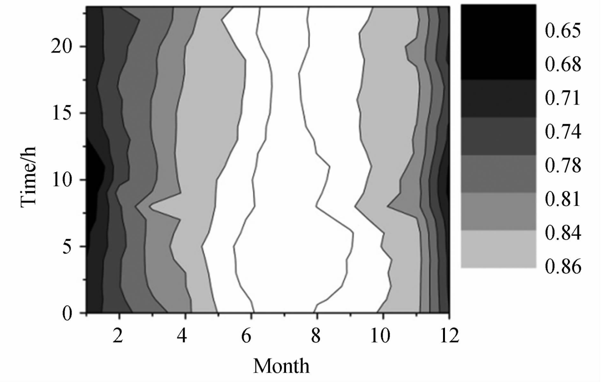


Fig. 5 Characteristics of 3000 m total transmittance of monthly variation at 1.06 μm

2.3 Turbulence

As another optical parameter to describle turbulence strength, Atmospheric coherent distance ρ_0 which represents the magnitude of the integrated optical turbulence present, is used to evaluate the effects of atmospheric turbulence on the performance of optical systems. For the convergent beam, atmospheric coherent distance ρ_0 can be connected to the refractive index structure parameter C_n^2 via the expression[17]

$$\rho_0 = \left[1.46k^2\int_0^L C_n^2(h)\left(\frac{L-h}{L}\right)^{5/3}\mathrm{d}h\right]^{-3/5} \tag{9}$$

where k is the optical wave number related to the optical wavelength λ by $k=2\pi/\lambda$, L is the propagation distance, h is the location of the turbulent layer and $C_n^2(h)$ is the the refractive index structure parameter as a function of height. Under the condition of horizontal path, Eq. (11) can be written by[18]

$$\rho_0 = \left[1.46k^2C_n^2(h)L\left(\frac{L-h}{L}\right)^{5/3}\right]^{-3/5} \tag{10}$$

In laser engineerings, the Fried parameter r_0 (atmospheric coherence length) is widely used. The relation between r_0 and ρ_0 is given by

$$r_0 = 2.1\rho_0 \tag{11}$$

Atmospheric turbulence leads to facula broadening. When transmitter diameter (D), propagation length(L), and focus(f) are given, the efficiency factor of light propagation whch is caused by facula broadening for atmospheric turbulence can be writen as

$$F=(L\lambda/\pi D)^2/\langle\rho_L^2\rangle \tag{12}$$

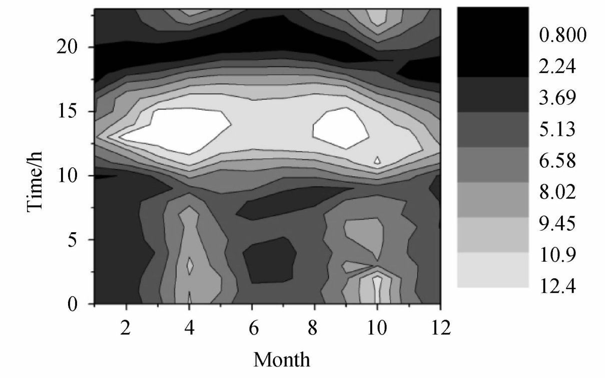
where ρ_L is the equivalent radius of facula. If $f=L$, ρ_L is given by the expression

$$\langle\rho_L^2\rangle=(L\lambda/\pi D)^2+(L\lambda/\pi r_0)^2 \tag{13}$$

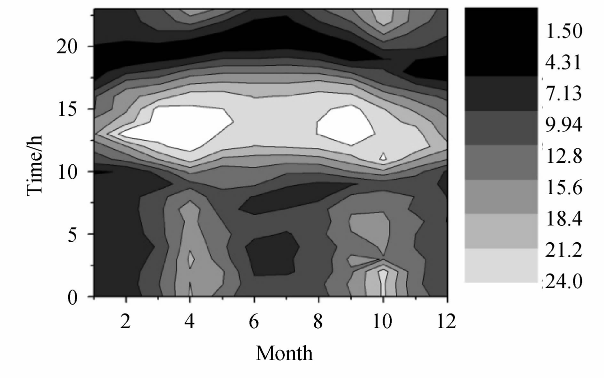
substituting Eq. (15) in Eq. (14), Eq. (14) is rewriten by

$$F=[1+(D/r_0)^2]^{-1} \tag{14}$$

From the above discuss, D/r_0 can be used to define turbulence effects. Fig. 6 (a) and Fig. 6 (b) shows characteristics of D/r_0 for a convergent beam wave at 1.06 μm of 1 000 m and 3 000 m separately. As are shown in the figures, the strength of turbulence in Spring and Autumn are stronger than the strength of turbulence in Summer and Winter. The turbulence strength in January is the weakest in all twelve months. The turbulence strength in April and October are stronger than that of other months . The strongest strength of turbulence in the whole day appears at. the time of 1 to 2 hours after noon. The weakest strength of turbulence in the whole day appears at the time of 1 to 2 hours before sunset. . The overall average of D/r_0 at 1.06 μm of 3 000 m is nearly twice that of 1 000 m.



(a) L=1000m



(b) L=3000m

Fig. 6 Characteristics of D/r_0 for a convergent beam wave at 1.06 μm of different distances

3 Integration effects

A simplified expression for calculating the mean peak intensity without considering the atmospheric propagation effects is shown bellow

$$I_0=P_0\pi(D/2)^2/(\lambda L)^2 \tag{15}$$

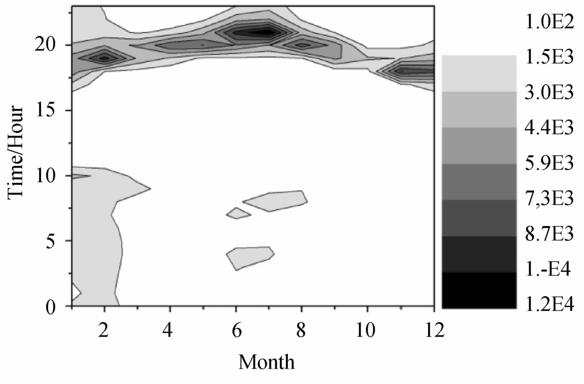
For convenience, the distribution of light intensity is assumed Gaussian distribution. Thus, the mean intensity, which is in the area contained $1-e^{-1}$ (63.2%) total power, is written by

$$\langle I_0\rangle=[P_0\pi(D/2)^2/(\lambda L)^2](1-e^{-1}) \tag{16}$$

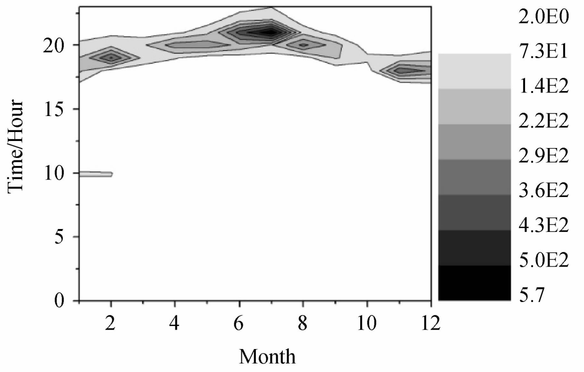
Accounting for the linear atmospheric propagation effects, Eq. (18) can be written by

$$\langle I\rangle=\langle I_0\rangle T[1+(D/r_0)^2]^{-1} \tag{17}$$

Based on the laser system parameters and atmospheric parameters, at 1.06 μm of the propagation length of 1 000 m and 3 000 m the mean intensity, which is in the area contained $1-e^{-1}$ (63.2%) total power, are shown in Fig. 7 (a) and Fig. 7 (b) respectively. From the above discussion, there are great difference on propagation effects in different time. The propagation effect in winter is the best than the propagation effect in other seasons because it has longer time in which the mean intensity are larger. Nevertheless, the propagation effect in dusk is the best in the whole day during summer, especially at 21 : 00 in July. At the same time, the propagation effect of 1000 m distance is about 37.5 times as much as that of 3 000 m.



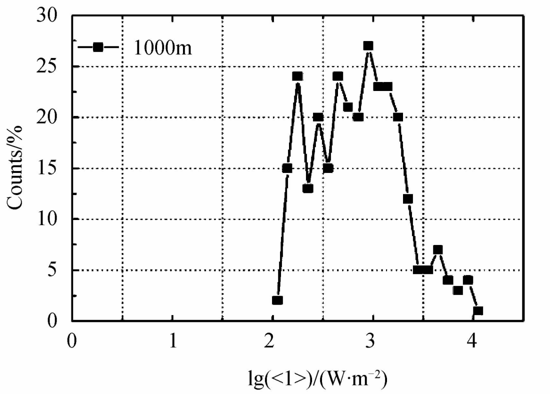
(a) *L*=1000m



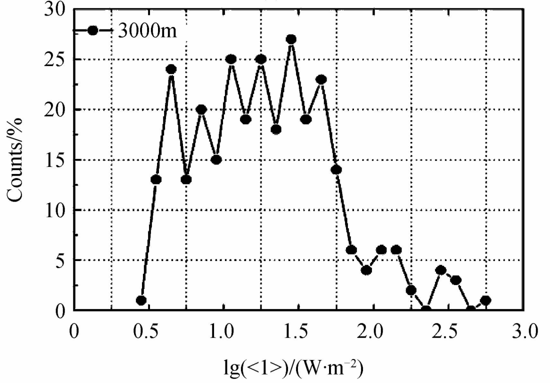
(b) *L*=3000m

Fig. 7 Characters of the mean intensity of laser at different distances

The probability density of mean intensity are shown in Fig. 8 (a) and Fig. 8 (b) respectively. The probability density distribution of mean intensity of 1 000 m and 3000 m are different.



(a) *L*=1000m



(b) *L*=3000m

Fig. 8 Probability density of mean intensity of laser at different distances

4 Conclusion

Given the laser system parameters, possible effects of atmospheric optical characteristics on laser paopagation in arid area are gotten by using actual atmospheric optical parameters. From the above discussion, the complexity of atmosphere on laser propagation can be explained. Under the condition of different area and different time, the effects of molecular absorption, and aerosol extinction, and turbulence are different. The results in arid area are different from the results in the paper[4] obviously. Thus, in the various laser propagation which include feasibility on laser engineerings, efficiency evaluation of laser engineerings and so on should realized the atmospheric optical characterstics of area in which laser engineerings are used. The comprehensive anysis on possible changes of atmosphere also should be taken.

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