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Influence of angle-of-arrival fluctuations on ground-to-satellite laser uplink communication system

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Abstract: A theoretical model was established to describe the influence of the angle of arrival (AOA) fluctuations on the bit error rate (BER) performance of ground-to-satellite laser communication under the Kolmogorov turbulence. A closed form expression of BER of ground-to-satellite laser communication system was then derived based on this model. Then, considering the combined effect of scintillation, beam wander and AOA fluctuations, the probability density function of the received intensity and closed form expressions of BER for an uplink were derived. Coherent detection of circle polarization shift keying modulation was employed, which was suitable for ground-to-satellite laser communication. For an uplink, the BER performance was analyzed and compared to the conditions without taking AOA fluctuations into account under the weak, medium and strong turbulence. Variations in BER as a function of AOA fluctuations were also analyzed. Finally, the influence of intensity scintillation, beam wander and AOA fluctuations on system performance was analyzed based on laser transmission power restrictions. The results show that in addition to the intensity scintillation and beam wander, AOA fluctuations is also a non-negligible factor in the study of communication performance.

Key words: ground-to-satellite laser communication; Kolmogorov turbulence; angle of arrival (AOA) fluctuations; BER

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到达角起伏对上行星地激光通信系统性能的影响

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摘　要： 在 Kolmogorov 湍流模型下，建立了到达角起伏对星地激光通信误码性能影响的理论模型。基于该模型，推导了星地激光通信系统误码率的闭合表达式。综合考虑光强闪烁、光束漂移和到达角起伏，推导

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出三者共同作用下,星地系统上行链路的接收光强概率密度解析式以及误码率的闭合表达式。文中采用的调试方式是适合星地激光通信的相干探测圆偏振调制。针对上行链路,仿真分析了弱、中、强湍流下,三者共同作用时,星地激光通信系统的误码率,并与不考虑到达角起伏条件下进行了比较。还分析了到达角起伏与误码率的变化关系,以及在考虑发射功率受限的条件下,三者共同作用对系统性能的影响。研究结果表明,除了光强闪烁和光束漂移以外,到达角起伏也是通信性能中不可或缺的因素。

关键词: 星地激光通信; Kolmogorov 湍流; 到达角起伏; 误码率

0 Introduction

Compared with traditional microwave communication, satellite laser communication meets the demands for a large communication capacity, high data transmission rates, strong anti−interference ability, and high information security[1]. Therefore ground−to−satellite laser communication has been the attention in many countries and regions and has been extensively investigated. For ground −to −satellite laser communication, the atmosphere is part of the communication channel, in formidable weather conditions (clouds, aerosols, thunderstorm), atmospheric turbulence is the main factor influencing optical signal transmission, and random fluctuations in the atmospheric refractive index can destroy the coherence of the beam and cause different phenomenon including intensity scintillation, beam wander and angle of arrival (AOA) fluctuations, which seriously interfere with building and maintaining the laser communication link[2]. Therefore, it is necessary to study the effects of atmospheric turbulence. A ground −to −satellite laser communication can be divided into an uplink and downlink[3]. For the uplink, the intensity scintillation, beam wander and AOA fluctuations are the most important factors, while the effect of beam wander is not considered for the downlink[3]. The effects of atmospheric turbulence are more complex in the uplink, so only the uplink is considered here. In 2005, Alejandro proposed the expressions of the probability density function of the log−amplitude fluctuation and time statistic based on beam wander [4]. In 2007, Andrews studied the received intensity probability distribution model with the combined effect of intensity scintillation and beam wander based on extended Rytov theory [5]. In 2010, Sinan Zhao analyzed the combined effect of intensity scintillation and beam wander on ground−to−satellite laser communication system and proposed optimum transmitter radius for the system based on extended Rytov theory and Gamma–Gamma distribution model [6]. In 2010, Hong Guo studied the influence of beam wander on the uplink of ground −to −satellite laser communication, using an effective pointing error method, based on the lognormal distribution [7]. In 2010, Yijun Jiang investigated and compared the performance of three modulation schemes OOK, PPM and DPIM on the ground−to−satellite laser link based on an optimal threshold detection method [8]. In 2011, the Greek researcher Sandalidis studied the bit error rate (BER) of differential phase shift keying, Mary phase shift keying, and Mary quadrature amplitude modulation in an uplink based on the Gamma−Gamma distribution, with the presence of beam wander [9]. In 2013, Jiachen Ding analyzed the BER of MSK and compared it with OOK in an uplink under the influence of atmospheric turbulence consisting of weak fluctuation and beam wander[10].

However, in these studies, the performance of a communication system is usually influenced by only one or two types of atmospheric turbulent effects. The AOA fluctuation caused by atmospheric turbulence is an important parameter. In ground −to −satellite communication channel, the equiphase surface will not be evenly distributed after the beam propagating through atmospheric layer, the shape of equiphase surface will change randomly, which will cause AOA fluctuations at the receiver, leading to the possibility of miscalculation and further increase in the BER. Therefore, AOA fluctuation is an important parameter that can affect the quality of communication.

In this paper, a theoretical model is established to describe the influence of AOA fluctuations on the performance of BER, which is based on the Kolmogorov turbulent model. A closed form expression of BER is then derived based on this model. The combined effect of scintillation, beam wander and AOA fluctuations are then considered to derive a probability density function (PDF) of the received intensity and the closed form expressions of BER for the uplink. The BER performance is analyzed and compared to conditions without taking AOA fluctuations into account. In comparison to previous analyses which considered only the effect of scintillation, or the two effects of scintillation and beam wander combined, this research is more closely aligned to the actual influence of atmospheric turbulence on communication performance.

1 Kolmogorov turbulence model

Optical signals are susceptible to atmospheric turbulence during ground-to-satellite laser communications, including intensity scintillation, beam wander, AOA fluctuations and beam distortion, which can destroy the coherence of the beam and have a seriously detrimental influence on building and maintaining the laser communication link. The turbulent effects considered in this paper are intensity scintillation, beam wander and AOA fluctuations.

According to the Markov approximation and geometrical optics approximation for laser propagation in atmospheric turbulence, the probability density of the AOA θ meets the Rayleigh distribution [11], and the probability density function is:

$$f_\theta(\theta)=\frac{\theta}{\sigma_\theta^2}\exp\left(-\frac{\theta^2}{2\sigma_\theta^2}\right) \tag{1}$$

where σ_θ^2 is the AOA fluctuations variance of the Gaussian beam due to Kolmogorov turbulence, which is given by[12]:

$$\sigma_\theta^2=0.033\pi^2\int_0^{H_0} C_n^2(h)\times(\sqrt{0.006\ 2}\times\kappa_0)^{1/3}\times U\left(2;\frac{7}{6};6.2\times10^{-3}\times0.058\ 4D^2\kappa_0^2\right)dh \tag{2}$$

where $U(a;b;x)$ is a confluent hypergeometric function of the second kind, D is the diameter of the receiving aperture, $\kappa_0=2\pi/L_0$ and L_0 is the outer scale of the Kolmogorov turbulence. $C_n^2(h)$ is the refractive index structure constant of Kolmogorov turbulence in the stratosphere, the most widely used Hufnagel-Valley model is chosen as[13]:

$$C_n^2(h)=0.005\ 94(v/27)^2(10^{-5}h)^{10}\exp(-h/1\ 000)+2.7\times10^{-16}\exp(-h/1\ 500)+C_n^2(0)\exp(-h/100) \tag{3}$$

where v is the wind velocity transverse to the link and $C_n^2(0)$ is the refractive index structure parameter near the ground.

Based on extended Rytov theory and the intensity scintillation and beam wander model, Andrew has given a probability distribution model for intensity fluctuation for all types of atmospheric turbulence, the Gamma-Gamma distribution model and the PDF can be written as[5]:

$$f(I)=\frac{2}{\Gamma(\alpha)\Gamma(\beta)I}\left(\frac{\alpha\beta I}{<I>}\right)^{(\alpha+\beta)/2}K_{\alpha-\beta}\left(2\sqrt{\frac{\alpha\beta I}{<I>}}\right)I<0 \tag{4}$$

where K_m (·) is the modified Bessel function of the second kind of order m, and the parameters α and β denote the large scale and small scale intensity scintillation of an optical wave, respectively, which are given by the following expressions[5]:

$$\alpha=\left[34.29[\Lambda L/(kr_0^2)]^{5/6}(\sigma_{p_e}/W)^2+\exp\left(\frac{0.49\sigma_{Bu}^2}{[1+0.59(1+\Theta)\sigma_{Bu}^{12/5}]^{7/6}}\right)-1\right]^{-1} \tag{5}$$

$$\beta=\frac{1}{\exp\left(\frac{0.51\sigma_{Bu}^2}{(1+0.69\sigma_{Bu}^{12/5})^{5/6}}\right)-1} \tag{6}$$

where L is the distance of the transmission beam, and

W is the beam radius at the receiver. It is useful to introduce various parameters to describe a Gaussian beam, where W_0 and F_0 denote the beam radius and the phase front radius of curvature at the transmitter[5]

$$\Theta_0=1-\frac{L}{F_0} \qquad \Lambda_0=1-\frac{2L}{kW_0^2}$$

$$\Theta=\frac{\Theta_0}{\Theta_0^2+\Lambda_0^2} \qquad \Lambda=\frac{\Lambda_0}{\Theta_0^2+\Lambda_0^2} \tag{7}$$

For the collimation beam, $\Theta_0=1(F_0=\infty)$. $\sigma_{\mathrm{p_c}}$ is the pointing error variance in presence of beam wander defined by[5]:

$$\sigma_{\mathrm{p_c}}=\sqrt{r_c^2}\left[1-\left(\frac{\pi^2 W_0^2/r_0^2}{1+\pi^2 W_0^2/r_0^2}\right)^{1/6}\right] \tag{8}$$

where r_c^2 is the beam wander variance, it is expressed by:

$$r_c^2=0.54L^2\left(\frac{\lambda}{2W_0}\right)^2\left(\frac{2W_0}{r_0}\right)^{5/3}, \quad H>20\ \mathrm{km} \tag{9}$$

And σ_{Bu}^2 is the Rytov variance for a beam wave in the uplink[5]

$$\sigma_{\mathrm{Bu}}^2=8.70\{\mathrm{Re}\int_{h_0}^{H} C_n^2(h)[\zeta^{5/6}(\Lambda\zeta+i(1-\overline{\Theta}\zeta))^{5/6}-\Lambda^{5/6}\zeta^{5/3}]\mathrm{d}h\}\times$$
$$k^{7/6}(H-h_0)^{5/6}\sec^{11/5}(\zeta) \tag{10}$$

where $\zeta=1-(h-h_0)/(H-h_0)$ is a link parameter, r_0 is the coherence diameter under Kolmogorov turbulence, which is defined as[14]:

$$r_0=[0.423k^2\sec\zeta\int_{h_0}^{H} C_n^2(h)\mathrm{d}h]^{-3/5} \tag{11}$$

where H and h_0 are the altitudes of the satellite and the transmitter on the ground, respectively. ζ is the zenith angle. The mean irradiance $<I>$ of a Gaussian beam on the receiver plane can be modeled as[14]:

$$<I>=\begin{cases}\dfrac{\Theta^2+\Lambda^2}{[1+5.66(W_0/r_0)^{5/3}]} & \dfrac{W_0}{r_0}<1\\[2ex] \dfrac{\Theta^2+\Lambda^2}{[1+5.66(W_0/r_0)^{5/3}]^{6/5}} & \dfrac{W_0}{r_0}>1\end{cases} \tag{12}$$

2 System performance analysis

In this paper, circle polarization shift keying is employed using two types of circular polarization to denote the data states of the information. Due to the rotational symmetry of circular polarization, its performance is unaffected by relative motion between the two terminals, making it very suitable for a mobile communications terminal[15], particularly ground-to-satellite laser communication. At the receiver, coherent detection mode is adopted which can improve the receiving sensitivity and reduce the influence of atmospheric turbulence when mixed with the local oscillator signal.

The error performance is also analyzed, which is an important parameter for indicating the communication performance of the system. It can be assumed that P_r is the total power at the receiver, P_lo is the power of the local oscillator signal and R is the responsivity of the photodetector.

The effect of AOA fluctuations caused by Kolmogorov turbulence is firstly considered. The BER of the ground-to-satellite communication system can be expressed as:

$$P_{\mathrm{AOA}}=\int_{-\infty}^{\infty} f_\theta(\theta)P_{ec}(I)d\theta \tag{13}$$

where $P_{ec}(I)=\frac{1}{2}\,\mathrm{erfc}\sqrt{\frac{I^2\cos(\theta)\overline{\gamma}}{4}}$ represents the total BER for a given value of I and θ, and $\mathrm{erfc}(x)$ is the complementary error function. For ease of calculation, the equivalent signal-to-noise ratio(SNR) can be defined as $\overline{\gamma}=R^2P_\mathrm{r}P_\mathrm{lo}/(2N_0B)$, where N_0 is the side power spectral density and B is the bandwidth of the photodetector. The parameter $K_v(x)$ in Eq.(4) and $\mathrm{erfc}(x)$ can be expressed by Meijer-G functions as follows: $K_v(x)=\frac{1}{2}\times G_{0,2}^{2,0}\left[\frac{x^2}{4}\middle|\begin{matrix}-\\ v/2,-v/2\end{matrix}\right]$ and $\mathrm{erfc}(\sqrt{x})=\frac{1}{\sqrt{x}}\times G_{0,2}^{2,0}\left[x\middle|\begin{matrix}1\\ 0,1/2\end{matrix}\right]$, where $G_{0,2}^{2,0}[\cdot]$ is the Meijer−G function. Eq. (1) can be substituted into Eq. (13), using the generalization of classical Meijer′s integral from two G functions and the Gaussian−Hermite approximation, the average BER can be expressed as

$$P_{\mathrm{AOA}}=\sum_{k=1}^{m} w_k\times\frac{1}{2\sqrt{\pi}}\times G_{1,2}^{2,0}\left(\frac{I^2\cos^2(\sqrt{2}\,\sigma x_k)\bar{\gamma}}{4}\middle|\begin{matrix}1\\0,2\end{matrix}\right)\tag{14}$$

The combined effect of the three factors (intensity scintillation, beam wander and AOA fluctuations) is considered to derive the PDF of the received intensity and the closed−form error probability for the uplink. The receiving power is related to the light intensity at receiver, and the light intensity is affected by the intensity scintillation, beam drift and AOA fluctuations. The closed form expressions of PDF of the intensity considering the three factors can be derived by

$$\begin{aligned}f_w(I)=&\int_{-\infty}^{\infty}\frac{2}{\Gamma(\alpha)\Gamma(\beta)I}\left(\frac{\alpha\beta I}{<I>}\right)^{(\alpha+\beta)/2}\times K_{\alpha-\beta}\left(2\sqrt{\frac{\alpha\beta I}{<I>}}\right)\\&\frac{\theta}{\sigma_\theta^2}\exp\left(-\frac{\theta}{2\sigma_\theta^2}\right)\mathrm{d}\theta=\frac{1}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{\alpha\beta I}{<I>}\right)^{(\alpha+\beta)/2}\times\\&\sum_{k=1}^{m} w_k\times G_{0,2}^{2,0}\left(\frac{\alpha\beta I}{<I>}\middle|\begin{matrix}-\\\frac{\alpha-\beta}{2},\frac{-\alpha+\beta}{2}\end{matrix}\right)\end{aligned}\tag{15}$$

Therefore, based on the three factors, the average BER probability can be derived using circle polarization shift keying modulation with coherent detection in the uplink under Kolmogorov turbulence as:

$$P=\int_0^{\infty} f_w(I)P_{ec}(I)\mathrm{d}I\tag{16}$$

By substituting Eq. (15) into Eq. (16), and using the generalization of classical Meijer′s integral from the two G functions and the Gaussian−Hermite approximation, the closed−form error probability can be expressed as:

$$\begin{aligned}P=&\frac{2^{\alpha+\beta-2}}{\pi^{3/2}\Gamma(\alpha)\Gamma(\beta)}\times\sum_{k=1}^{m} w_k\times\\&G_{5,2}^{2,4}\left(\frac{8\bar{\gamma}\cos^2(\sqrt{2}\,\sigma_\theta x_k)<I>^2}{(\alpha\beta)^2\sigma_\theta^2}\middle|\begin{matrix}\frac{1-\alpha}{2}\ \frac{2-\alpha}{2},\frac{1-\beta}{2},\frac{2-\beta}{2},2\\1,\frac{3}{2}\end{matrix}\right)\end{aligned}\tag{17}$$

Considering the effects of intensity scintillation and beam wander, without taking AOA fluctuations into account, the system error rate is:

$$\begin{aligned}P_0=&\int_0^{\infty} f_w(I)P_{ec}(I)\mathrm{d}I=\frac{2^{\alpha+\beta-3}}{\pi^{3/2}\Gamma(\alpha)\Gamma(\beta)}\times\\&G_{5,2}^{2,4}\left(\frac{8\bar{\gamma}<I>^2}{(\alpha\beta)^2\delta^2}\middle|\begin{matrix}\frac{1-\alpha}{2}\ \frac{2-\alpha}{2},\frac{1-\beta}{2},\frac{2-\beta}{2},1\\0,\frac{1}{2}\end{matrix}\right)\end{aligned}\tag{18}$$

3 Numerical results and discussion

In this section, the combined effect of intensity scintillation, beam wander and AOA fluctuations is considered to simulate the BER P for the uplink. The value is compared with the BER P_0 when only the intensity scintillation and beam wander are considered, as shown in Fig.1. For the simulations and analyses, the height of the synchronous satellite from the ground H=36 000 km, the altitude of the transmitter on the ground h_0=3 m, the wind velocity v=21 m/s, the refractive index structure parameter near the ground $C_n^2(0)=1.7\times10^{-14}$ m$^{-2/3}$, λ=1.55 μm, w_0=0.1 m, D=0.2 m, ζ=30° were selected. The refractive index structural parameters were selected as 7.5×10^{-17}, 3.6×10^{-15} and 1.7×10^{-13}, representing weak, moderate and strong turbulent scenarios, respectively. Accordingly, the parameters for intensity scintillation in the Gamma−Gamma atmospheric turbulent channel are there for $\{\alpha=4.05,\beta=2.74\}$, $\{\alpha=3.16,\beta=2.55\}$ and

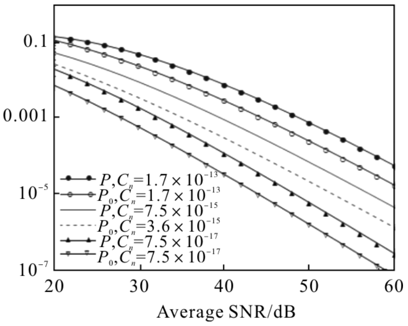


Fig.1 P and P_0 as a function of the average SNR in different turbulent channels

$\{\alpha=3.25,\beta=2.53\}$, for weak, moderate and strong turbulent respectively.

As shown in Fig.1, for the same level of turbulent intensity, both P and P_0 fall as the SNR increases, and the curve of P is always above that of P_0. Additionally, under the strong turbulence, the difference between the two curves increases as the SNR rises. Under poor SNR conditions, there is only a small difference in visibility when only the effects of intensity scintillation and beam wander are considered rather than the effects of the three factors, therefore it is acceptable to use only the effects of the two factors to analyze the BER of this system. With a large SNR, there is a large deviation between the two curves. For weak or moderate turbulence, the interval between them is large regardless of whether the SNR is small or large SNR, and the BER deviation is large when the effects of two factors are considered rather than three factors. This means that depending on the intensity scintillation and beam wander, the performance of the system will be further deteriorated by AOA fluctuations. Thus it can be seen that for ground-to-satellite laser communication systems, it is not sufficient to consider only intensity scintillation and beam wander, and the effect of AOA fluctuations should also be taken in account.

The variation of BER is shown in Fig.2 as a function of AOA fluctuations variance under different Kolmogorov turbulent intensities and SNR (50, 55, 60 dB). The results indicate that the BER increases as the AOA fluctuations variance increases for weak, moderate and strong turbulence. In Fig.2 (a), (b) and (c), when the AOA fluctuations variance is less than 7×10^{-11}, there is a leveling off in the changing trend of BER, and the AOA fluctuations has little effect on the communication system. When the AOA fluctuations variance is above 7×10^{-11}, the BER increases rapidly. This shows that the effect of the AOA fluctuations on BER is significant within a certain range. This further illustrates that AOA fluctuations caused by atmospheric turbulence can severely impact the communication quality of ground-to-satellite laser links. Inpractical applications, the AOA variance needs to be controlled to be smaller than this value.

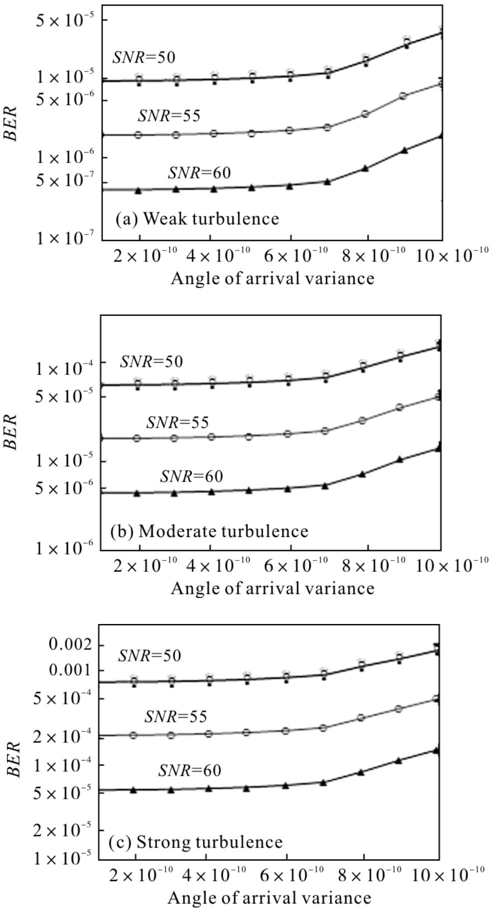
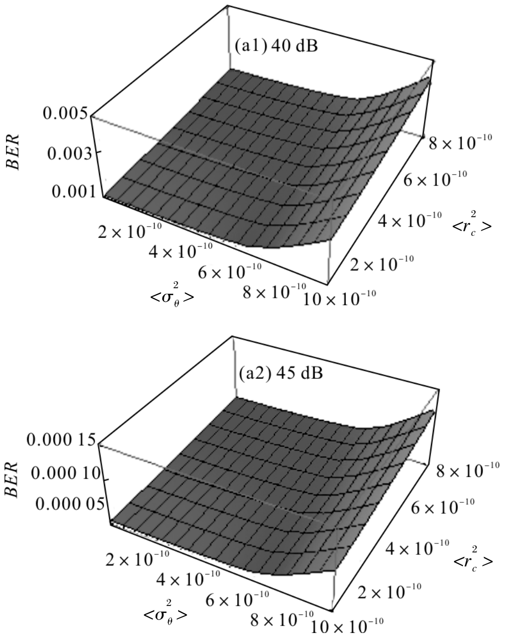


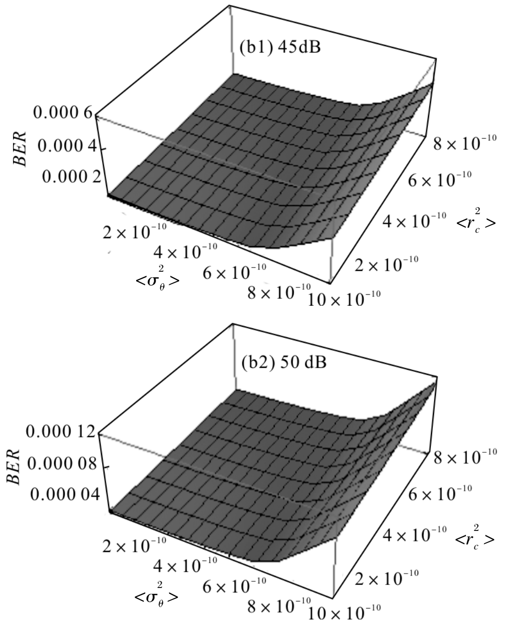
Fig.2 BER as a function of AOA fluctuations variance in different turbulent channels and SNR

In order to improve the quality of star to laser communication links, methods to increase the SNR are generally adopted, but these methods are limited by the laser transmission power. From the perspective of laser transmission power restriction, the influence of intensity scintillation, beam wander and AOA fluctuations on BER in uplink is analyzed, as shown in Fig.3.

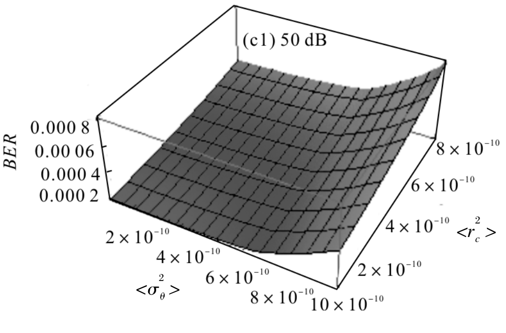
According to the experimental results for atmospheric turbulence[16-17], under Kolmogorov turbulence, the AOA fluctuations variance is mainly within the range from 1×10^{-10} to 10×10^{-10}, and the beam wander variance is mainly within the range from 1×10^{-5} to 8×10^{-5}. Therefore, the simulation analysis is within this range.

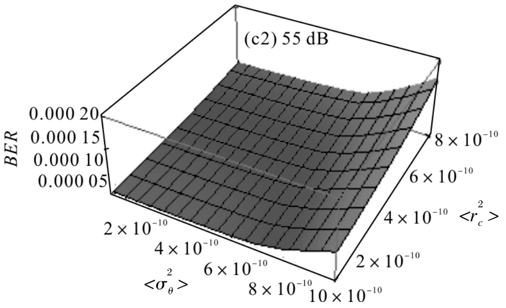


(a) Weak turbulence



(b) Moderate turbulence





(c) Strong turbulence

Fig.3 BER as a function of beam wander variance and AOA fluctuations variance with different turbulent intensities

To meet the requirements of basic ground-to-satellite laser communication, the BER value should reach at least 10^{-5}. The BER is 10^{-4} orders of magnitude in Fig.3(a1), (b1), (c1), and the BER is 10^{-5} orders of magnitude in Fig.3(a2), (b2), (c2). It can be seen in Fig.3 that BER increases as the AOA fluctuations variance and beam wander variance increase. Additionally, where there is a laser emission power restriction, SNR needs to reach at least 45 dB under weak turbulence, at least 50 dB under moderate turbulence, and at least 55 dB under strong turbulence to meet basic communication requirements. The research provides a more realistic theoretical basis for choosing a transmitter in a ground-to-satellite laser uplink communication system.

Additionally, meeting the requirements of basic communication, Fig.3(a2), (b2), (c2) shows that under different turbulent intensities, the combined effect of AOA fluctuations and beam wander on BER is different. Under weak turbulence (Fig.3 (a2)), when the AOA fluctuations variance is less than 7×10^{-10} and the beam wander variance is less than 6×10^{-5}, the changing trend of BER levels off, so the AOA fluctuations and beam wander have little effect on the communication system. Beyond this range, the BER increases rapidly. Under moderate turbulence (Fig.3(b2)), the changing trend of BER is similar to Fig.3 (a2). When the AOA fluctuations variance is less than 7×10^{-10} and the beam wander variance is less than 5×10^{-5}, the changing trend of BER is flat. The AOA fluctuations variance is less than 6.5×10^{-10} and the beam wander variance is less than 4.5×10^{-5} under strong turbulence.

This indicates that under different turbulent intensities, by controlling the AOA fluctuations and the beam wander within a certain range, there will be a smaller change in BER. This can simplify the structure and enhance the real-time property of the system without additional technologies (such as LDPC coding, interlace) or equipment (such as an electronic amplifier or an adaptive equalizer) to improve the system performance.

4 Conclusion

A closed form expression of BER on the effect of AOA fluctuations has been derived under the Kolmogorov turbulence. In the uplink, the combined effect of intensity scintillation, beam wander and AOA fluctuations have been considered and the BER performance has been simulated and analyzed and compared with the results when AOA fluctuations has not been taken into account. The results show that there is only a small deviation in BER performance under poor SNR conditions and strong turbulence. However, there is a large deviation under the weak or moderate turbulence or when there is a large SNR and strong turbulence.

The variation of BER as a function of AOA fluctuations has also been researched. It can be concluded that under different turbulent intensities, when the AOA fluctuations variance is more than 7×10^{-11}, the changing trend of BER is flat. Beyond this range, the BER increases rapidly.

Finally, the influence of intensity scintillation, beam wander and AOA fluctuations on BER in an uplink has been analyzed based on laser transmission power restrictions. The results indicate that to meet the requirements of basic ground-to-satellite laser communication, the SNR needs to reach at least 45 dB under weak turbulence, at least 50 dB under moderate turbulence and at least 55 dB under strong turbulence. In addition, under different turbulent intensities, the combined effect of AOA fluctuations and beam wander on BER is different. Under different turbulent intensities, when the AOA fluctuations and beam wander is controlled to be within a certain range, the change of BER is flat and the effects on the ground-to-satellite laser communication system is smaller. In comparison with previous analysis that is only based on scintillation or the two effects of scintillation and beam wander, this research provides a theoretical basis for performance analysis that is closer to real-life conditions for a ground-to-satellite laser communication link.

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