International Journal of Innovative Computing, Information and Control
Volume **10**, Number **4**, August **2014**

ICIC International ©2014 ISSN 1349-4198
pp. 1447–1455

BER CHARACTERISTICS ANALYSIS OF ATMOSPHERE LASER PROPAGATION IN A VARIETY OF WEATHER FACTORS

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Received March 2013; revised December 2013

Abstract. *Complex weather conditions are the common factors affecting the laser propagation in atmosphere. The communication performance of the satellite-to-ground laser propagation can be assessed by analyzing the BER characteristics. First, the calculation method of BER of laser signal transmission in a variety of weather factors is brought forward to, based on the laser transmission model in atmospheric channel, and a combination of atmospheric attenuation model of different weather factors and the modified formula of BER; then the impact of the transmission distance, transmitted power and zenith angle on BER is analyzed further. Simulation results show that in haze days the BER renders linear change with the visibility, and the dry snow has the greatest impact on the BER; in haze days the BER is sensitive to the zenith angle, in moderate rainy days the BER has an approximate linear correlation with the zenith angle, and the impact of heavy fog and moderate snow on zenith angle is very small. The numerical results and simulation conclusions can provide reference for the design of the laser communication system.*

Keywords: Atmosphere propagation, Satellite-to-ground laser link, BER, Weather factor, Zenith angle

1. **Introduction.** Optical signal transmission will face the complex and volatile weather factors such as clouds, fog, rain, snow, haze included in atmospheric random channel in satellite-to-ground laser communications. So, it is necessary to further simulate and calculate the BER of the optical signal transmission in a variety of weather conditions during the analysis of the performance of the satellite-to-ground laser communications system. Also, because of the beam divergence angle of the laser communication in the order of micro-radians, to build satellite-to-ground laser communications network, it must design constellation system. The larger satellite-to-ground laser communication link maximum zenith angle is, the greater single satellite covering ground area is and the less number of satellites is required. However, with the increase of communication zenith angle, the communication path of the laser beam through the atmosphere becomes longer, and the influence by the atmospheric turbulence, absorption, scattering becomes more strongly, and thereby the size of communication zenith angle is constrained. On the other hand, volume, mass, power and other aspects of the satellite laser communication terminal limit the magnitude of the downlink laser power. Therefore, it is necessary to analyze the downlink communication zenith angle, to find the features of it in the condition of the bit error rate less than 10^{-7}.

Literature [1,2] established the link transmission model and atmospheric attenuation model affected by the weather, but did not establish contact between the two, so lack of simulation analysis and numerical calculation results was a direct result. Literature [3] simulated from the aspect of link, but only analyzed the transmission characteristics without in-depth study of communication indicators such as power, BER. Literature [4] used the laser link equation of rainy day to establish the BER calculation model, and carried out the numerical simulation, and drew the conclusion that BER first increases and then decreases with increasing of rainfall rate, but the corollary of the single weather model does not apply to complex weather conditions. Literature [5] mainly solved the problem of "last mile", that is to give the program of wireless broadband to the home; demonstrated results showed that atmospheric laser communication can be achieved under normal weather conditions, but the problem is lack of analysis in complex atmospheric environment of satellite-to-ground link and comprehensive interference of a variety of factors. Literature [6,7] compared the relationship between BER and transmit power also the relationship between BER and transmission distance under the impact of the clouds, fog, rain, etc. through simulation, but there is the same problem that single weather model is not suitable for other weather, and the model can be only used for horizontal communication link. Literature [8] briefly stated the impact of zenith angle on BER, and simulation results showed a nonlinear relationship between the two, but the results may be different in different weather conditions. Currently, there is lack of systematic research for BER characteristics of satellite-to-ground laser link, such as the comprehensive analysis of the impact of weather factors, transmission distance, transmit power, zenith angle on BER.

In this paper, the optical BER calculation method of satellite-to-ground link is proposed, by using the atmospheric laser transmission model, combining the attenuation coefficient calculation model of several typical weather, with the impact of some factors such as the free space loss, atmospheric attenuation, weather. Thus the simulation result of change of BER characteristic under weather conditions such as sunny, haze, fog, rain, snow and other inclement weather conditions is achieved, and the simulation result is discussed.

2. **Calculation Model of BER.**

2.1. **Atmospheric laser transmission model.**

The classic model of laser transmission through slant path in atmosphere is [9]:

$$\tau(\lambda) = \exp\left[-\sec\phi \int_0^L \mu\left(\lambda, l\right) dl\right] \tag{1}$$

where, $\tau(\lambda)$ is the atmospheric transmittance for the laser of wavelength λ; ϕ is the zenith angle (rad); l is the vertical transmission distance of the laser (km); μ is the total atmospheric attenuation coefficient (km^{-1}), which is the function of λ and l.

2.2. **Transmission model of laser in free-space.**

The transmission model of laser in free-space is as follows:

$$L_{FS} \approx \left(\frac{\lambda}{4\pi z}\right)^2 \tag{2}$$

where, L_{FS} is the attenuation coefficient in free-space (km^{-1}), z is the transmission distance. In the calculation and simulation, the transmission model is used to analyze the attenuation of the pure atmospheric conditions.

2.3. **Attenuation model of different weather factors.** The atmospheric attenuation models of several weather factors such as haze, clouds, fog, rain, snow are as follows [10,11]:

(1) Haze

The atmospheric attenuation model under the influence of haze is:

$$\mu_h = \frac{3.912}{V_b}\left(\frac{0.55}{\lambda}\right)^{\alpha} \tag{3}$$

where, α is the correction factor for the wavelength, and it is related to atmospheric visibility, with different values under different visibility [8].

(2) Fog

The atmospheric attenuation model under the influence of fog is:

$$\mu_f = \frac{A}{V_b} \tag{4}$$

where, different values of A correspond to different wavelengths λ.

(3) Rain

The atmospheric attenuation model under the influence of rain is:

$$\mu_r = 0.29 + \frac{v}{2.53} - \left(\frac{v}{20.3}\right)^2 \tag{5}$$

where, v is the rate of rainfall (mm/h).

(4) Snow

The atmospheric attenuation model under the influence of snow is:

$$\mu_s = aR^b \tag{6}$$

where, R is the speed of snowfall (mm/h), while the value of a and b is related to the type of snow.

(5) Clouds

The attenuation coefficient of several typical clouds is given by experience, such as cirrus, stratocumulus, cumulonimbus, stratus, altocumulus, altostratus, nimbostratus [12].

In the above models, μ_h, μ_f, μ_r and μ_s are the attenuation coefficients of haze, fog, rain, snow respectively, with unit of km^{-1}.

2.4. **Calculation model of BER.**

(1) Calculation model of received signal power

The signal power received by the detector is:

$$P_S = P_t G_T G_R T_F L_{FS} \tau(\lambda) \tag{7}$$

In Equation (7), T_F, which is the transmittance of optical filter is brought to correct calculation model in reference [13]. P_t is the peak power of transmitter (mW), G_T and G_R are the lens gain of transmitter and receiver (dB), L_{FS} is the loss of free space (km^{-1}), $\tau(\lambda)$ is the atmospheric transmittance of the laser.

(2) Calculation model of noise

The noise power of detector is:

$$P_{\det} = \sqrt{B_{\det}} \cdot NEP_{\det} \tag{8}$$

where, $B_{\det}$ is bandwidth of the detector (GHz), $NEP_{\det}$ is noise equivalent power (pW/ $\text{Hz}^{1/2}$).

The background noise power is:

$$P_{BG} = H_{BG}\Delta\lambda A_r \theta_{\det}\eta \tag{9}$$

where, H_{BG} is the background radiation rate ($\text{Wm}^{-2}\text{nm}^{-1}\text{sr}^{-1}$), $\Delta\lambda$ is the optical bandwidth of the filter (nm), A_r is the reception area of the receiver (cm^2), $\theta_{\det}$ is the receiver's field angle of view (μrad), η is the optical efficiency of the receiver.

(3) Calculation model of BER

The detector current is divided into signal photocurrent and the current which is caused by noise. The latter includes photon noise current, thermal noise current and the noise current which is caused by atmosphere turbulence. The two are directly related to BER of the system, so the model of BER is established based on that. The sensitivity of receiver is introduced and the photocurrents caused by the signal P_s, background and noise power of detector respectively are [13,14]:

$$i_{sig} = \delta P_s, \quad i_{bg} = \delta P_{BG}, \quad i_{\det} = \delta P_{\det} \tag{10}$$

$$\delta = \frac{\eta q \lambda}{hc} M \tag{11}$$

where, q is electron charge (C), λ is the wavelength (nm), h is the Planck Constant ($\text{J}\cdot\text{s}$), c is the speed of light (m/s), M is the gain of receiver (dB).

The noise current variance of detector output is:

$$\sigma_n^2 = \sigma_{sig}^2 + \sigma_{bg}^2 + \sigma_{\det}^2 + \sigma_t^2 \tag{12}$$

where, σ_{sig}^2, σ_{bg}^2, $\sigma_{\det}^2$, σ_t^2 respectively are the current variance caused by signal light, bias light, thermal noise of detector and atmosphere turbulence.

Moreover:

$$\sigma_{sig}^2 = 2ei_{sig}B_{\det} \tag{13}$$

$$\sigma_{bg}^2 = 2ei_{bg}B_{\det} \tag{14}$$

$$\sigma_{\det}^2 = 4kTB_{\det}/R \tag{15}$$

$$\sigma_t^2 = i_{sig}2\sigma_I^2 \tag{16}$$

where, k is Boltzmann constant (1.38×10^{-23}J/K), T is thermodynamic temperature, R is detector equivalent resistance, σ_I^2 is fluctuation variance of atmosphere turbulence.

Suppose that σ_1^2 and σ_0^2 respectively are the mean square noise current when sending signal "1" and "0".

$$\sigma_1^2 = \sigma_{sig}^2 + \sigma_{bg}^2 + \sigma_{\det}^2 + \sigma_t^2 \tag{17}$$

$$\sigma_0^2 = \sigma_{bg}^2 + \sigma_{\det}^2 + \sigma_t^2 \tag{18}$$

When system noises are all stationary Gaussian white noise, then total BER of the system is:

$$BER = \frac{1}{2}\left[P(0/1) + P(1/0)\right] = \frac{1}{4}\left[erfc\left(\frac{i_{sig} - i_D}{\sqrt{2}\sigma_1}\right) + erfc\left(\frac{i_D}{\sqrt{2}\sigma_0}\right)\right] \tag{19}$$

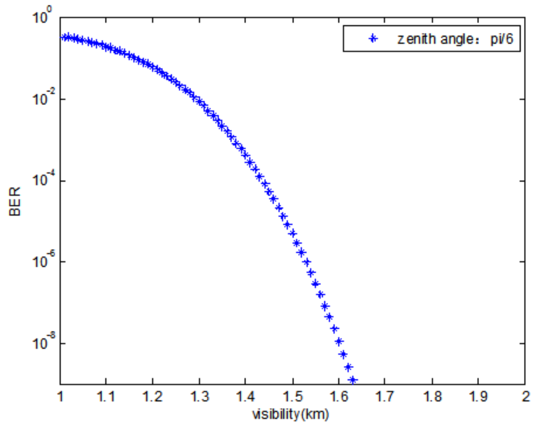
where, $P(0/1)$ is the probability that signal "1" sent by a transmitter is wrong judged into signal "0" by a receiver. $P(1/0)$ is the probability that signal "0" sent by a transmitter is wrong judged into signal "1" by a receiver. The best judgment threshold i_D can be found to make BER minimum under certain conditions.

3. **Numerical Simulation and Analysis.** This section will utilize above corrected calculation model of BER and weather attenuation model to numerically simulate BER changes under the weather conditions such us fine day, haze, fog, rain and snow. Set up the simulation parameters in communication system as follows [15]:

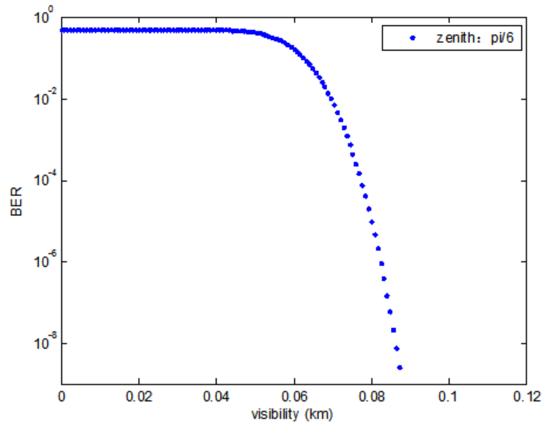
- Distance of transmission in free space $z = 610$km.
- Wavelength of laser $\lambda = 488$nm, zenith angle $\phi = 0°$.
- Power of transmitter $P_t = 13.8$mW (11.4dBm), radius $R_t = 10$cm, divergence angle $\theta = 20\mu$rad, gain of transmitter is 109.1dB.
- Sensitivity of receiver is –58dBm, radius $R_r = 75$cm, FOV (field of view) $\theta_{\text{det}} = 200\mu$rad, gain of receiver is 135dB, optical efficiency $\eta = 0.8$, bandwidth of receiver $B_{\text{det}} = 3$GHz; transmittance of optical filter $T_F = 70\%$, optical bandwidth of the filter $\Delta\lambda = 20$nm.
- Take the Noise equivalent power as $0.19\text{pW/Hz}^{1/2}$, the background radiation rate as $0.2\text{Wm}^{-2}\text{nm}^{-1}\text{sr}^{-1}$.
- Fluctuation variance of atmosphere turbulence $\sigma_I^2 = 0.008$.

3.1. **The impact of weather change on BER.** When the laser is propagated in pure atmosphere, the BER of system increased slowly with the increase of transmission distance. However, BER will be affected badly under different weather conditions. Figure 1 gives the change of BER in several typical weather conditions.

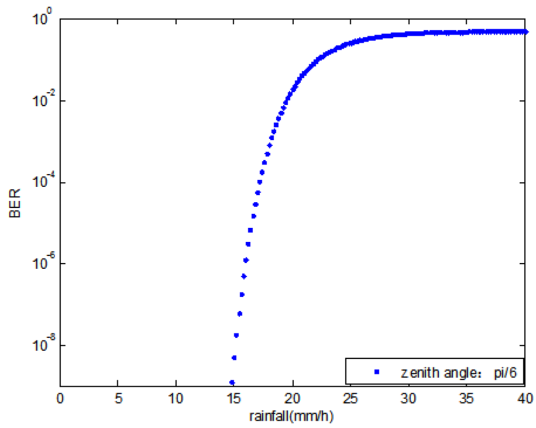
It can be seen from Figures 1(a) and 1(b), the impact of haze and fog on BER is great difference. Although the physical characteristics are similar, the absolute thickness of fog is much smaller and attenuation of the same distance is much larger than the haze



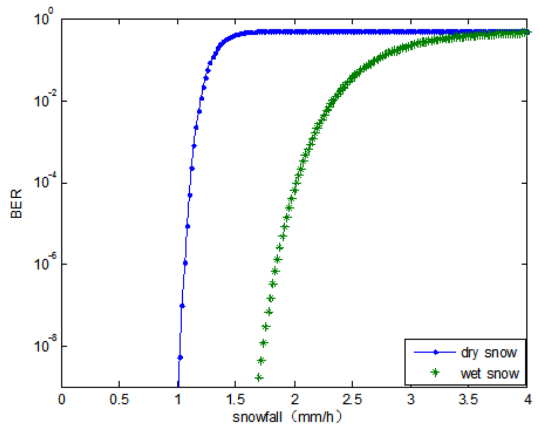
(a) BER change with visibility in haze



(b) BER change with visibility in fog



(c) BER change with rainfall speed



(d) BER change with the speed of snow

FIGURE 1. BER in typical weather conditions

from the view of vertical link. So it is presented that the BER under the haze changes along with visibility approaching linear. The BER of the fog does not change significantly in the high visibility, but it is the sharp deterioration when the visibility is down to 80 meters. Comparing Figure 1(c) and Figure 1(d), it can be seen, snow has higher effect than rainfall on the BER, but the trend is similar, which is related to their similar water molecules constitution. Along with the accelerated rate of rainfall or snowfall, BER value increases rapidly. When the rainfall exceeds 16mm/h, or the dry snowfall rate exceeds 1.1mm/h, or the wet snowfall rate exceeds 1.8mm/h, it is difficult to ensure BER is less than 10^{-7}.

In summary, about the impact of weather conditions on BER, the overall trend is consistent with each other. That is, the BER value increases rapidly as the weather conditions deteriorate. The above simulation not only clearly presents the trends of BER changing with specific weather parameters, but also visually compares the impacts of different weather conditions on BER. More importantly, the simulation results can easily estimate the communication conditions of the entire link in complex weather conditions.

3.2. **The analysis of BER on different transmission distance and transmitted power.** The BER of the channel for satellite-to-ground laser propagation is different as laser goes through different transmission distance in different weather conditions, so transmitted power is required to be changed in order to ensure the link connectivity. Using the above model, it can be judged whether the link is connectivity in a specific weather condition and also provides a basis for predicting the consumption of the transmitted power in different weather conditions by the analysis of changing relationship of transmission distance and transmitted power.

BER change is simulated by selecting several representative types of weather in the principle of ensuring the link connectivity. The representative weather conditions are moderate haze (visibility is 2km), moderate rain (rainfall speed is 6mm/h), light snow (the speed of wet snow is 2mm/h) and heavy fog (visibility is 500m).

Figure 2 is a typical weather condition; BER changes with transmission distance, which concludes the limit of transmission distance in a specific weather condition and the given BER. For example, to make the BER is not less than 10^{-7} in light snow weather, the limit distance of system communication is 900m.

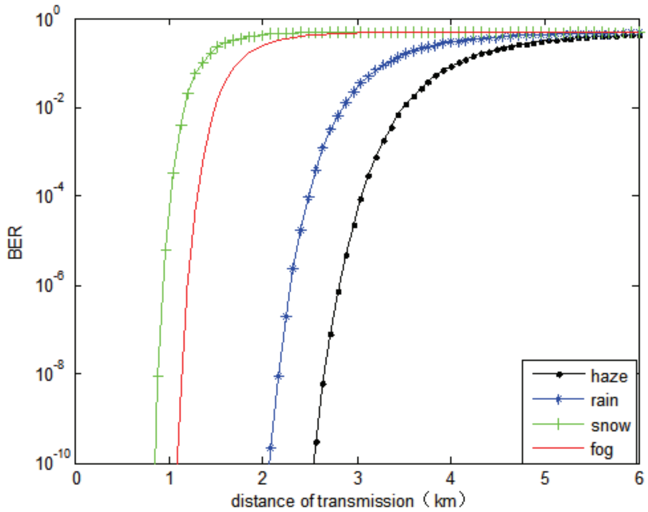


FIGURE 2. BER change with distance

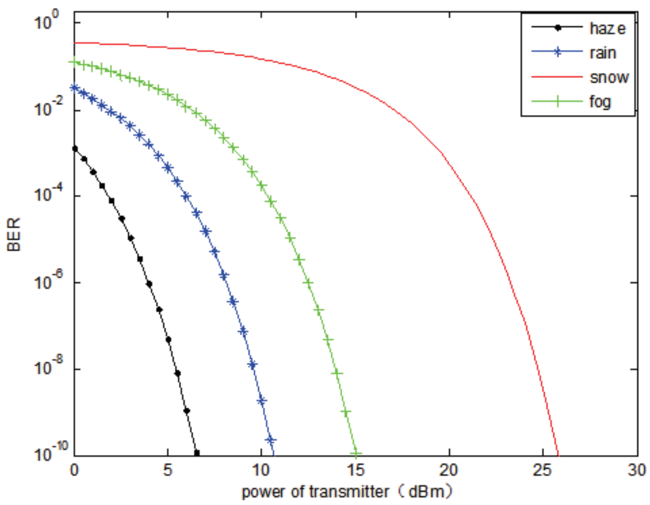


FIGURE 3. BER change with power

It can be seen from Figure 3, BER changes with transmitted power, which concludes the minimum transmitted power value what laser propagating a certain distance required in a specific weather condition and the given BER. For example, the minimum transmitted power value required by laser propagating 2km in a heavy foggy day (visibility is 500m) is 13.2dBm. If further calculating the remainder power after link loss and comparing it with the sensitivity of receiver, it can be concluded whether it can implement satellite-to-ground laser communications in this weather condition.

3.3. **The zenith angle change on the impact of BER in different weather conditions.** In the simulation of Section 3.2, the zenith angle is set as a fixed value $\phi = 30°$, and it does not consider the impact of the zenith angle on satellite-to-ground communications. Below, consider the influence of the zenith angle to the optical transmission error rate under different weather conditions.

It can be seen from Figure 4, the moderate haze is more sensitive to the zenith angle for the sake of its smaller attenuation coefficient. Moderate rain is not sensitive to both the smaller and the larger zenith angles, and BER along with the increase of the zenith angle in the interval $\pi/6 \sim \pi/3$ presents an approximately linear change. We can draw a conclusion that the zenith angle must be less than 45° if BER is less than 10^{-7}. Because of the larger attenuation coefficient, the impact of heavy fog on the zenith angle is not sensitive. For the attenuation coefficient of moderate snow is the greatest, the adjustment of the zenith angle on BER almost entirely does not work at the moment.

4. **Conclusions.** In this paper, by synthesizing the existing laser transmission model in atmospheric channel and the atmospheric attenuation model of different weather conditions, and based on the modified formula of BER, the calculation method of BER of laser signal transmission in a variety of weather factors is brought forward to and the impact of a variety of weather factors and zenith angle on BER of the satellite-to-ground laser propagation is simulated and analyzed. The simulations reveal the impact of weather factors on BER, and the overall trend is consistent with each other. That is, the BER value increases rapidly as the weather conditions deteriorate. However, the impact of a variety of weather factors on BER presents the following characteristics. In the haze days the BER renders linear change with the visibility. The initial change of BER in foggy days is not sensitive, but it is deteriorated sharply when the visibility is down to 80 meters. The

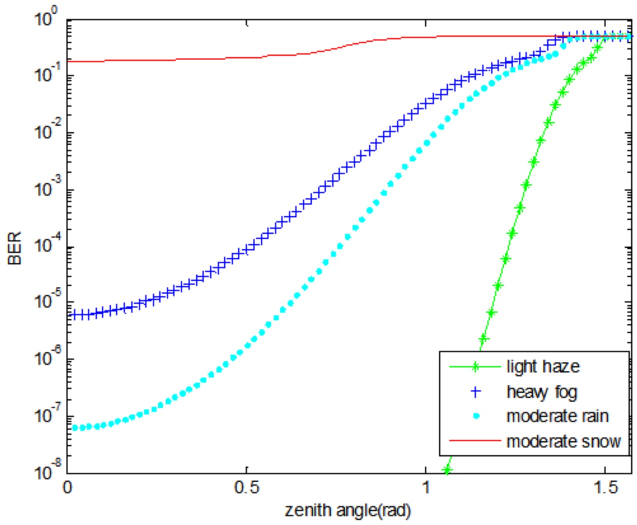


FIGURE 4. The relationship of BER and the zenith angle in different weather conditions

impact of rain and fog on BER is relatively similar, and the BER increases more than 10^{-7} when the rainfall is over 16mm/h. The impact of dry snow on BER is greater than wet snow, and the sharp deterioration degree of BER is more obvious with the increasing snowfall.

The simulation results further show that the impact of the zenith angle in a variety of weather factors on the BER of laser signal transmission is different. The BER in haze days is sensitive to the zenith angle. The BER and zenith angle in the interval $\pi/6 \sim \pi/3$ presents an approximately linear change in moderate rainy days. However, if the zenith angle is less than 45°, the BER of link can be made sure that it is less than 10^{-7}. The impact of heavy fog from the zenith angle is very small. And because the attenuation coefficient of moderate snow is too big, the adjustment of the zenith angle does not play a leading role.

The numerical results and simulation conclusions can estimate the BER of the satellite-to-ground laser propagation in typical weather conditions. It can also be used to analyze the feasibility of satellite-to-ground laser propagation and provide reference for the design of transmitted power and the choice of sensitivity of receiver. In the constellation of satellite-to-ground laser communication system design, we use the model and analysis method of this paper with considering comprehensively the reasonable values of parameters under different weather conditions. Thus we obtain as far as possible big communication zenith angle and proper transmission power, and make the performance and cost ratio of the system achieve the optimum.

Acknowledgment. This work was supported by the Scientific Research Project of Liaoning Province Educational Committee (No. L2012440).

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