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# Modeling of Laser Transmission in The Atmosphere For Virtual Test

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Abstract. *During the transmission in the atmosphere, the laser is affected by several atmospheric factors, and thereby, the laser devices vary greatly in the performance under different weather conditions. Currently, the virtual tests are more likely adopted to test the laser device's performances under various weather conditions. The laser transmission model in the atmosphere is a crucial factor in establishing these virtual testing systems. This article aims to construct the laser transmission model for satisfying the requirements in virtual tests. Specifically, in order to cover all weather types, the transmission media were classified into two types?the low- and intermediate-scattering media and the high-scattering media, respectively. The corresponding models, the first-scattering-based transmission model and the Gaussian-distribution-based transmission model were proposed, respectively. By comparing the results using the proposed model with the results using the classical MC model, the proposed model is comparable with the MC model in terms of accuracy but is preferable in terms of calculation efficiency, i.e., the proposed model is more applicable to the real-time calculations in virtual tests.*

**Keywords:** Laser transmission modeling, Atmosphere, first-scattering-based transmission model, Gaussian-distribution-based transmission model, Virtual test.

1. **Introduction.** Laser is a special type of light and exhibits a series of advantages such as favorable directionality, monochromaticity and coherence as well as long operating range. All of these strengths have made laser attract much attention from the researchers, and also acquire extensive applications in the fields of distance measurement, guidance and communication [1 3]. During the transmission in the atmosphere, the laser's energy and phase will be influenced by different weather conditions and many atmospheric environmental factors, and thereby, the capability of laser system or device will exhibit significant variations as the atmospheric environment changes. With the enhancement of computer technology and simulation modeling technology, the researchers are often more apt to use many virtual testing methods to examine the capabilities of these laser systems or devices under different weather conditions. In these virtual tests, the modeling of the laser's transmission effect in the atmosphere is quite crucial. The laser's transmission model should have quite high accuracy and computational efficiency as it determines the whole virtual testing system's credibility and perform ability. At present, some full-fledged commercial softwares have successfully simulated the transmission of laser in the atmosphere. In 1970s, the U.S. AirForce Geophysics Laboratory issued a computer simulation

program, LOWTRAN, and another two programs, MOSTRAN and FASCODE, which were developed based on LOWTRAN. Compared with LOWTRAN, MODTRAN is more efficient in simulating the attenuation coefficients of the atmospheric molecules and aerosol particles [4]. After several decades of development, LOWTRAN and MODTRAN have been gradually maturing and become two authoritative and classical simulation programs in this field. Currently, LOWTRAN and MODTRAN can be applied on different light waves and in various atmospheric environments [5]. In spite of high fidelity and accuracy, these commercial softwares are poor in computational efficiency. Therefore, they can only be applicable to the pre-simulations but are not intended for the real-time calculations in virtual tests.

Besides, many scholars have investigated the transmission models of the lasers at different wavelengths under various weather conditions. Regarding the laser transmission, different types of weather represent different types of transmission media. According to different particle sizes and concentrations, the transmission media can be divided into three types: low-scattering media, intermediate-scattering media and high-scattering media. The laser's transmission through the low-scattering media will not cause serious damages on the phase coherence of the optical field but give rise to the light intensity attenuation. Taking a typical low-scattering medium–rainfall–as the example, the rainfall is a major atmospheric medium leading to the laser attenuation [6-8], and the researchers have conducted a great deal of research on the laser transmission model through the rainfall. Using the rainfall's sheltering effect, Anura *et al.,* investigated the laser's attenuation [9]. J. Swartling *et al.,* studied the ultraviolet (UV) light's attenuation model through the rain [10]. V. P. Kandidov *et al.,* conducted an in-depth study on the laser's optical field distribution in the target plane [11]. Jia *et al.,* came up with a transmission-in-the-rain model based on the split-step Fourier transform [12]. For the intermediate-scattering media, when the laser travels through them, the phase coherence of the optical field will be heavily damaged; however, the field's optical intensity will be less affected by the high-order scattering. Accordingly, the high-order scattering can be neglected during the laser's transmission process and the light field can be accurately established based on the first-order scattering results. Various types of clouds are the typical representatives of these kinds of media. For the implementation of laser communication, Prupacher *et al.,* constructed the relation model between the effective communication range and rainfall intensity [13]. With the use of transport theory, Liou *et al.,* proposed a successive scattering model for describing the transmission through the cloud and solved the differential equation using the numerical approach, which could effectively make the model more real-time [14]. Based on the successive-order-of-scattering method, Jia *et al.,* constructed a model of describing the laser's transmission through the cloud and the related detection model [15]. Finally, we consider the laser's transmission through the high-scattering media. In these cases, considering only the first-order scattering cannot meet the requirement in simulation accuracy, and the energies of all-order scattering should be taken into full account. The typical representative of this kind of media is fog. Monte Carlo (MC) model is now most widely applied and most authoritative in dealing with the transmission in high-scattering media [16]. P. Bruscaglionl *et al.,* simulated the laser's transmission through the thick fog using the MC model, and verified the correctness of MC method [17]. Debbie Kedar *et al.,* adopted the MC method to analyze the transmission distribution condition of the photons in the fog [18]. Using MC method, the researchers can acquire high-accuracy simulation results; however, the calculations are generally time-consuming. Q Fang *et al.,* accelerated the MC calculations by means of the hardware acceleration method [19]. As described above, to meet the requirement of the laser transmission calculations in the virtual tests, the transmission model should have the ability of calculating the energy losses of the laser during the transmission through various types of media and different distances, be of fairly high computational efficiency and can satisfy the real-time calculation requirements in the virtual tests. In this article, the transmission media were classified into two types, namely, the low- and intermediate-scattering media, corresponding to clouds and rain, and the high-scattering media, corresponding to fogs. Then two different laser transmission models through these two different media were proposed, and the corresponding laser transmission calculation software was developed.

## 2. Laser transmission model in the low- and intermediate-scattering media.

The system-level virtual tests set the following requirements on the laser transmission model: it should focus on the analysis of the laser intensity's attenuation characteristics and attach little importance to the light field's phase coherence characteristics. Accordingly, for the low- and intermediate-scattering media in which the high-order scattering can be neglected, we can select the radius of the medium particle as the influencing factor to construct the transmission model. The low- and intermediate-scattering media are primarily the rainfall and various types of clouds, which are manifested as the medium particle's different radii and densities. The constructed model can simulate various weather conditions by setting different parameters (such as particle radius and particle density).

### 2.1. Mie scattering.

Assuming that the low- and intermediate-scattering media in this study are a category of homogeneous media, the size distribution function of the medium is denoted as *f(d, h)*, and the medium particle is spherical. The exact expression of the electromagnetic field scattered by the spherical particles can be obtained using the classical Mie scattering model. Assuming that the origin of the coordinate axis is located at the center of the spherical particle, the relative complex refractive index of the spherical particle is denoted as m, the incident wave is propagated along the $z$ axis, the incident plane wave can be expressed as:

$$E = e^{ikz} \tag{1}$$

where E is the energy of incident wave. After being scattering by the spherical particles, the scattering field of the plane wave at the point $(r, \theta, \phi)$ can be written as [20]:

$$\begin{cases} E_\phi^s = -\frac{ie^{ikr}}{kr} S_1(\theta)\sin\phi \\ E_\theta^s = -\frac{ie^{ikr}}{kr} S_2(\theta)\cos\phi \end{cases} \tag{2}$$

According to Eq. (2), the relation between the amplitudes of the scattering field and the incident field along the vertical and horizontal directions can be written as:

$$\begin{bmatrix} E_{\parallel s} \\ E_{\perp s} \end{bmatrix} = \frac{e^{ik(r-z)}}{-ikr} \begin{bmatrix} S_2(\theta) & 0 \\ 0 & S_1(\theta) \end{bmatrix} \begin{bmatrix} E_{\parallel i} \\ E_{\perp i} \end{bmatrix} \tag{3}$$

in which $S_1$ and $S_2$ denote the scattering amplitudes along the vertical and horizontal directions, respectively. Both $S_1$ and $S_2$ are the functions of the scattering angle $\theta$, and can be written as:

$$\begin{cases} S_1(\theta) = \sum\limits_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n\pi_n(\cos\theta) + b_n\tau_n(\cos\theta)\right] \\ S_2(\theta) = \sum\limits_{n=1}^{\infty} \frac{2n+1}{n(n+1)}_n \left[a_n\tau_n(\cos\theta) + b_n\pi_n(\cos\theta)\right] \end{cases} \tag{4}$$

Accordingly, by combining Eq. (2) and Eq. (3), the scattered light intensity can be written as:

$$I(\theta) = \frac{I_0}{k^2r^2}[\left|\vec{S}_1(\theta)\right|^2 + \left|\vec{S}_2(\theta)\right|^2] \tag{5}$$

in which $a_n, b_n, \pi_n$ and $\tau_n$ are the coefficients of Mie scattering.

2.2. **Transmission model based on the first-order scattering.** The transmission of a laser through the low- and intermediate-scattering medium consists of two processes: 1) the irradiation of the laser beam on the target through the medium, i.e., the laser is absorbed and scattered by the medium, and then, the forward scattered light reaches the target plane while the back scattered light is received by the detector; 2) the arrival of laser beam on the target plane, i.e., after being reflected by the target plane, the laser beam is radiated to the total space and parts of the laser energy through space radiation is reflected by the detector. The whole process can be calculated in the following three steps.

**1) Forward transmission through the medium**

The low- and intermediate-media in this article refers to rainfall and cloud, with the mainly scattering medium of water drop particles. If the scattering by the particles is not taken into account, the laser beam only undergoes the attenuation by the particles when passing through the medium, and the laser power after attenuation can be written as:

$$P^{(0)}_{forward} = P_0 \exp[-(\beta_{air} + \beta_{aer} + k_v \rho + \beta_{cld})L] \tag{6}$$

in which $P_0$ denotes the power of the laser emitted by the laser source; $\beta_{aer}$ denotes the aerosol's extinction coefficient; $k_v$ denotes the aqueous vapor's absorption coefficient; denotes the aqueous vapor's density; $\beta_{air}$ denotes the scattering coefficient of the atmospheric molecules; L denotes the laser's transmission distance to the target in the medium and $\beta_{cld}$ denotes the extinction coefficient of the medium particle. According to the size distribution profile, the extinction coefficient can be written as:

$$\beta_{cld}(Z) = \int_{r1}^{r2} \pi r^2 (Q_s(D) + Q_a(D)) N(D, Z) dD \tag{7}$$

in which $N(D, Z)$ denotes the of liquid droplets at different heights; $Q_s(D)$ and $Q_a(D)$ are the functions of $D$.

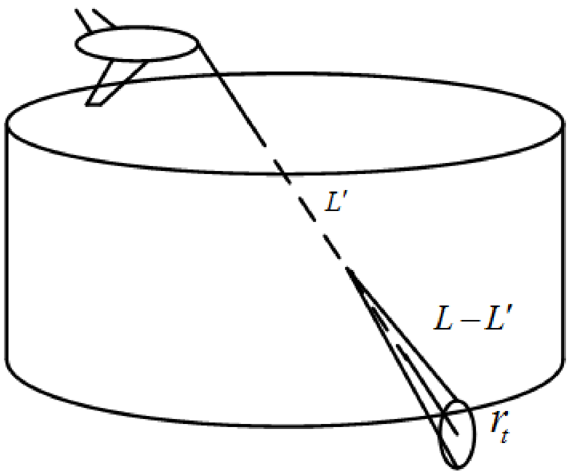



FIGURE 1. Illustration of a laser's forward transmission

Fig. 1 illustrates the laser's forward transmission. Based on the multi-order scattering model and the spatial positions of the target and laser emitter, the original first-order scattering function can be written as:

$$P^{(1)}(L', \Omega') = F_0 \exp[-\beta_{aer} L' - \beta_{cld} L'] \tag{8}$$

In Fig.1, L' denotes the distance between the laser emitter and the scattering point, and L-L' denotes the distance between the scattering point and the target. rt denotes the equivalent radius of the target. Based on the fundamental formula of multi-order scattering, the original power accumulation function induced by the first-order scattering in the receiving plane can be expressed as:

$$J^{(1)}(L', \Omega) = \frac{\tilde{\omega}}{2} F^{(0)}(L', \Omega) \int_0^{\Psi_1} P(\Theta) \sin \Theta d\Theta \tag{9}$$

in which, $PD(\theta)$ denotes the phase function of the liquid droplets with the radius of D,

$$\Psi_1 = \tan^{-1}\left(\frac{r_t}{L - L'}\right) \tag{10}$$

where $r_t$ denotes the equivalent radius of the target. The laser power induced by the first-order scattering received by the target plane can be written as:

$$P^{(1)}_{forward} = \int_0^L J^{(1)}(L', \Omega) \exp(-\beta_{ear}(L - L') - \beta_{cld}(L - L')) * (\beta_{ear} + \beta_{cld}) dL' \tag{11}$$

The power induced by the second-order and higher-order scattering, which corresponds to the radiation power of the receiving plane can be neglected, and therefore, the total laser power received by the target surface can be written as: $P_t = P^{(0)}_{forward} + P^{(1).}_{forward}$

2.3. **Reflection by the target surface.** The laser beam is reflected by the target surface and entered the medium space. The reflected power depends on the power of the laser reaching the target surface and the relativity of the target surface. Assuming that the target plane is characterized by an ideal uniform distribution, the reflected power of the target surface can be written as:

$$P_{ref} = \lambda P_t \tag{12}$$

in which $\lambda$ denotes the reflectivity of the target and denotes the power of the laser beam striking the target plane.

**3) Transmission of the reflected power in the medium** The transmission of the reflected power into the medium is still calculated according to the first-order scattering approximation. Since the reflected power are fully reflected in the space, only the diffuse reflected power with the aperture radius of $r_r$ can be received by the detector, and the detected direct transmission power can be written as:

$$P^{(0)}_{back} = \left(\frac{r_r}{2L}\right)^2 P_{ref} \exp[-(\beta_e + \beta_{cld})L] \tag{13}$$

The first-order scattering power of the target reflection, , can be calculated by Eq. (11). As stated above, the back scattering also exists when the laser beam irradiates the target and the back scattering power $P_{cldback}$ can also be captured by the detector. Therefore, the transmission power of this scattering can be calculated by Eq. (9). The total laser power acquired by the detector can be written as:

$$P_{total} = P^{(0)}_{back} + P^{(1)}_{back} + P_{cldback} \tag{14}$$

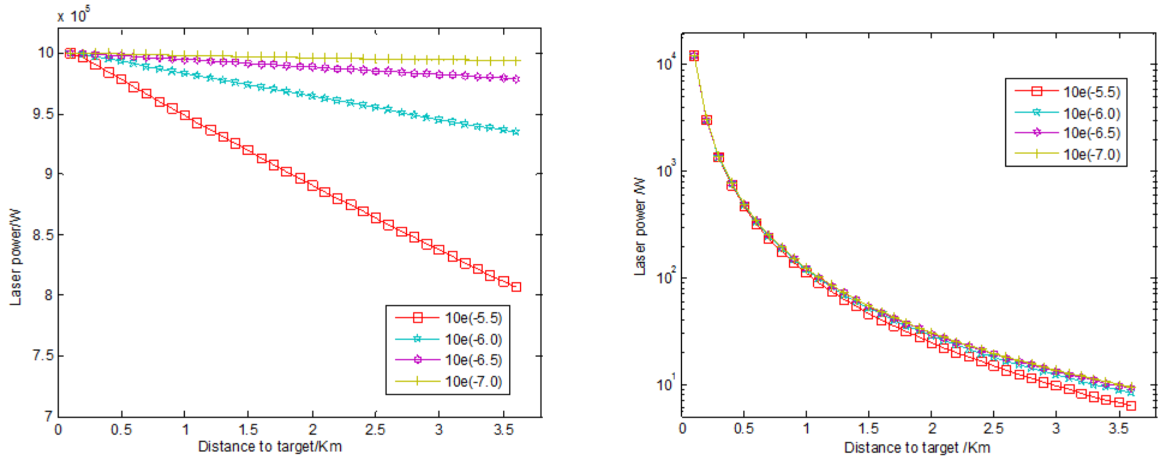
2.4. **Model verification.** In this section, by comparing the results obtained by the proposed model with the results using MC model, the validity of the above-established transmission model in the low- and intermediate-scattering media was verified. The experimental program was complied with Matlab R2011a version, and operated on the laptop computer (Thinkpad T430, Intel Core i5-2.6GHz?4GB Memory). The related parameter settings in model verification are listed in Table 1. In accordance with the test conditions, the simulations were conducted on six groups of the particles with different radii. The average radius of the particles ranges from $10^{-5.5}$ to $10^{-7.0}$, with the interval of $10^{0.5}$. Fig.

TABLE 1. Parameters in simulations

| Laser wavelength | Incident power | Target reflectivity | Equivalent radius of the target | Aperture radius of the detector | FOV of the detector |
|---|---|---|---|---|---|
| 1.06$\mu$m | $10^5$W | 50% | 2.5m | 0.1m | 5° |

2 a) displays the simulation results of the laser power received at the target. It can be concluded that, for the medium particles with the same radius, the laser power decreases as the distance between the target and laser source increases; for the medium particles with different radii, the attenuation goes stronger as the radius increases when the laser travels through the same distance.

The laser energy received by the receiver includes the energy reflected by the target and the energy generated by the laser's back scattering. Fig. 2 b) displays the laser energy received by the receiver as the transmission distance between the laser sources to the target varies. At the transmission distance increases, the laser energy received by the receiver decreases gradually; for the medium particles with different radii, the smaller the particle's radius, the smaller the velocity of attenuation. It should be noted that the



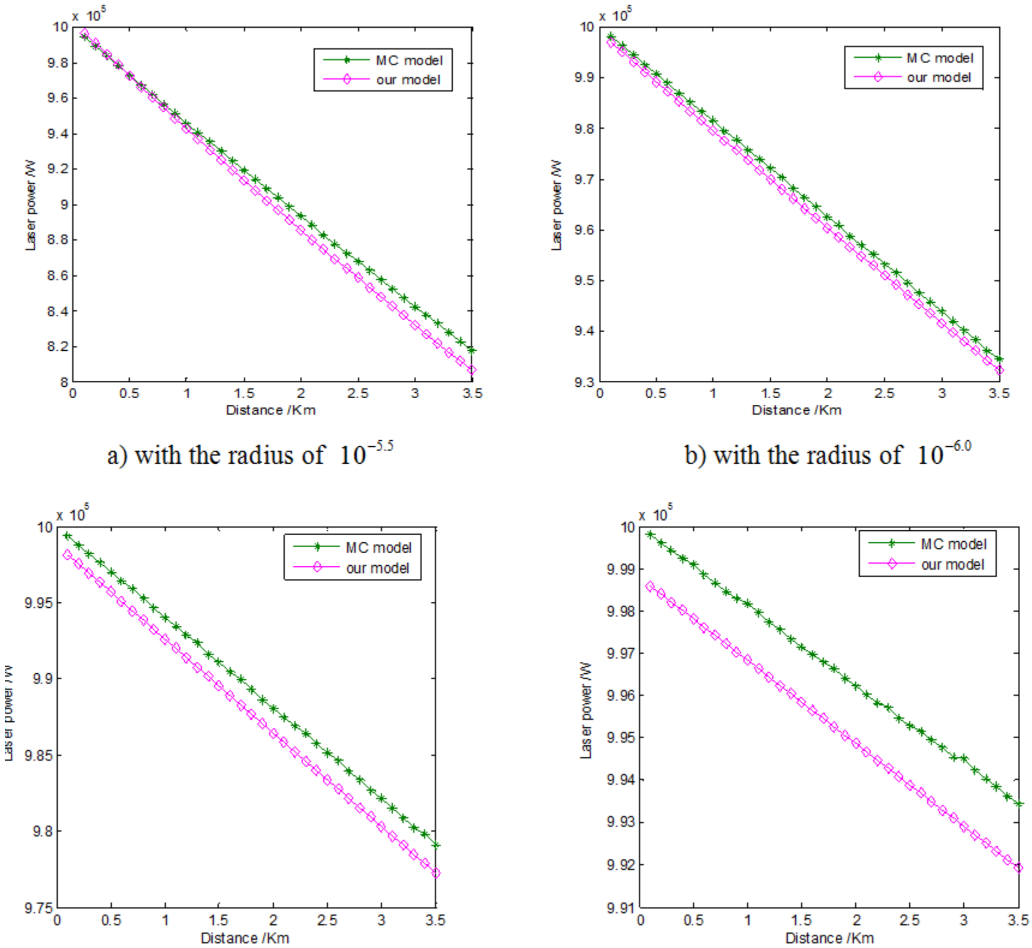

a) Laser power received by the target b) Laser power received by the receiver

FIGURE 2. Variation of the laser power with the transmission distance.

simplified medium particles were adopted in the simulations, and the real comparison model can hardly be found in the natural world. The validity of the proposed model was verified by comparing the results using this model with the results using the standard MC model, as the results presented in Fig. 3. In the model, the number of the photons was set as $10^6$, and the power of each photon was set as $1w$. One can easily observe from Fig. 3 that the results of two models are basically consistent with each other.

For a more direct comparison with the MC model in terms of accuracy, the maximum calculation errors of 4 groups of test results using two models were calculated, as the results listed in Table 2. The relative errors between the results using two models were fairly small, indicating that the results using the proposed model could satisfy the test requirements.

The efficiency of the proposed model was also calculated and compared with the results with the results using MC model and AMC model [10], and the results are presented in




a) with the radius of $10^{-5.5}$

b) with the radius of $10^{-6.0}$

c) with the radius of $10^{-6.5}$

d) with the radius of $10^{-7.0}$

FIGURE 3. Comparison of the laser's transmission power results using two models

TABLE 2. Statistics of the maximum calculation errors of the results using two models

| Serial number | The proposed model ($\times 10^5$) | The MC model ($\times 10^5$) | Relative error |
|---|---|---|---|
| 1 | 8.06 | 8.17 | 1.3% |
| 2 | 9.32 | 9.35 | 0.3% |
| 3 | 9.77 | 9.79 | 0.2% |
| 4 | 9.92 | 9.93 | 0.1% |

Fig. 4. It can be observed that, in terms of calculation efficiency, the proposed model far exceeded the MC and AMC model. Using the proposed model, the average calculation time is 16 ms, suggesting that it can meet the requirements of real-time calculations in virtual tests.

3. **Laser transmission model in the high-scattering media.** In the high-scattering media, the energy generated by the high-order scattering among the particles can hardly be neglected. To overcome the shortage of low calculation efficiency in the existing transmission models through high-scattering media, in combination with the common assumptions that the medium can be treated as the parallel plates, this article proposed a high computing-efficiency multi-scattering photon transmission model.

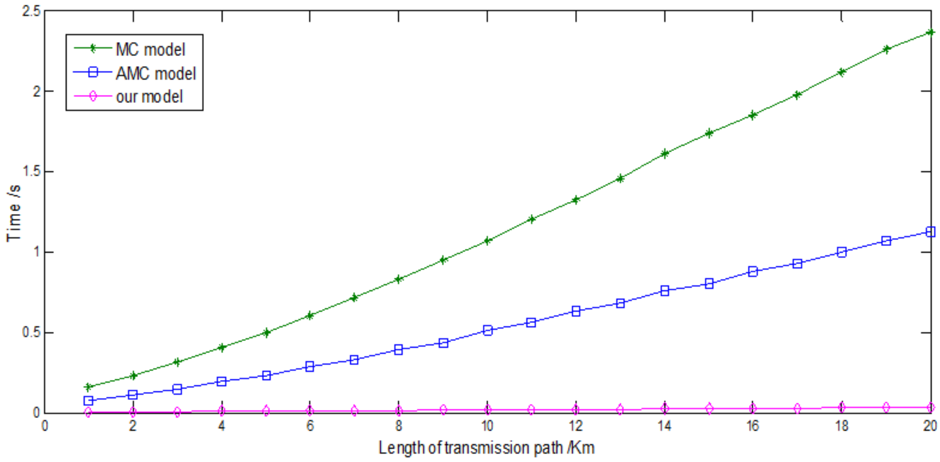



FIGURE 4. Comparison of the calculation times of the proposed model with the other models

3.1. **Laser transmission model based on Gaussian distribution.** MC model is a popular laser transmission model through high-scattering media at present. Based on the idea of statistics, this model is to conduct a large number of data statistics on the motions of photons, and finally derive the required data. Obviously, the great advantage is that no physical hypotheses are required; however, the weakness is that this model is quite time-consuming in simulation, which is thus not applicable to real-time simulations. This article proposed a photon transmission model based on Gaussian distribution. Assuming that the photons follow the Gaussian distribution along the radial direction, the number of the photons between two radii and the number of the photons within a certain radius can be written as:

$$
\begin{aligned}
&P_i = P\exp(-\tfrac{r_i}{S}) / \sum_{i=1}^{N_{up}} \exp(-\tfrac{r_i}{S}) \\
&P_{\mathrm{i}} = P\sum_{\mathrm{k=1}}^{\mathrm{i}} \exp(-\tfrac{r_k}{S}) / \sum_{i=1}^{N_{up}} \exp(-\tfrac{r_i}{S}) \\
&P = \sum_{i=1}^{N} Photon(i).weight
\end{aligned}
\tag{15}
$$

As the photons are absorbed by the medium during the transmission process, they attenuate and their distribution exhibits a step-by-step change in each medium layer. Accordingly, the core guideline is to separate the medium into several layers like the parallel plates, then the variables in each medium layer are calculated in accordance with the transmission theory in a step-wise manner, and finally, the results can be acquired using the Gaussian distribution theory. Fig. 5 displays the geometric construction of the second scattering. To analyze the transmission process of the photons, the formula for calculating the number of photons after scattering attenuation in different planes can be derived, in which $Z_n$ denotes the $n-th$ medium. According to Berr-Lambert's Law, the total number of the photons in the layer of $Z_2$ can be written as:

$$N_{0\_1} = N_0 \exp[-\beta_1\gamma_1(Z_2 - Z_1)] \tag{16}$$

in which $N_0$ denotes the initial number of photons, and $N_{0\_1}$ denotes the number of photons which were not scattered by the $Z_1$ plane. In the layer of $Z_2$, the number of the

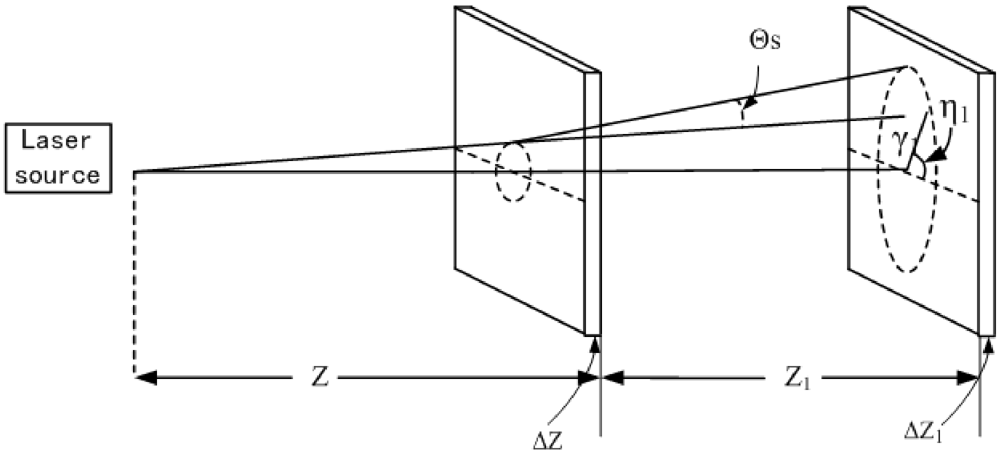



FIGURE 5. Illustration of the geometric parameters of the transmission by the photons' secondary scattering

forward scattering photons can be calculated by:

$$N_{1\_2} = N_{0\_1}\mu_2\gamma_2\alpha_2^2(Z_3 - Z_2) \tag{17}$$

where $\mu_2\gamma_2\alpha_2^2(Z_3 - Z_2)$ denotes the ratio of the number of the forward scattering photons in the layer of to the number of the photons after prior-order scattering, and $N_{1\_2}$ denotes the number of the photons after first-order forward scattering. Based on Fig. 6, the

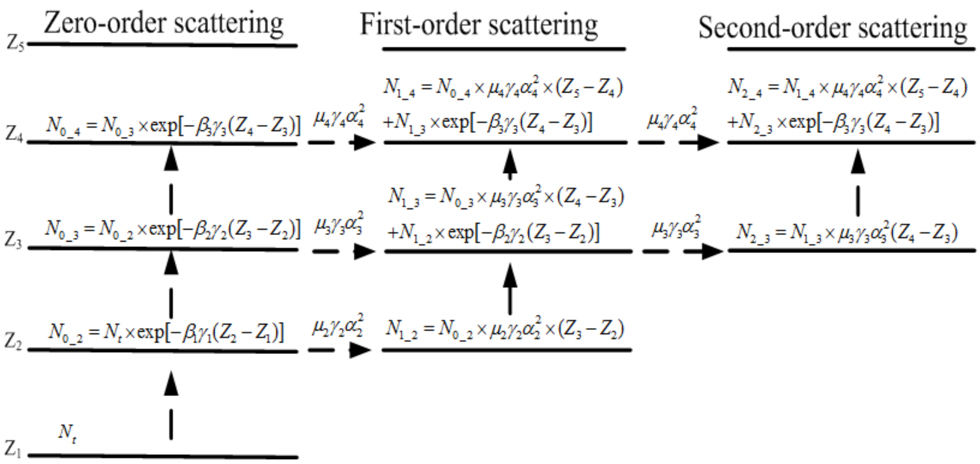



FIGURE 6. Numbers of the photons after several orders of scattering in various medium layers

calculation formulas of the number of the photons after several orders of scattering can be inferred. The number of the photons after zero-order scattering can be calculated by:

$$N_0 = N_t \prod_{n=1}^{N_{medtotal}} \exp[-\beta_n\gamma_n(Z_{n+1} - Z_n)] \tag{18}$$

The number of the photons after first-order scattering can be calculated by:

$$N_1 = N_0 \sum_{n=2}^{N_{medtotal}} [\mu_n\gamma_n\alpha_n^2(Z_n - Z_{n-1})] \tag{19}$$

Table 3. Parameter settings in the present simulations

| Serial number | $\mu a/km$ | $\mu s/km$ | g | np | $\Theta/rad$ | $N_{medtotal}$ |
|---|---|---|---|---|---|---|
| 1 | 0.006 | 0.3 | 0.9 | 106 | 0.3 | 20 |
| 2 | 0.015 | 0.6 | 0.9 | 106 | 0.3 | 20 |

The number of the photons after second-order scattering can be calculated by:

$$N_2 = N_0 \sum_{n=2}^{N_{medtotal}} \sum_{m=n+1}^{N_{medtotal}} [\mu_n \gamma_n \alpha_n^2 (Z_{n+1} - Z_n)] \times [\mu_m \gamma_m \alpha_m^2 (Z_{m+1} - Z_m)] \quad (20)$$

In these formulas, $N_{medtotal}$ denotes the number of medium layers. The computational formulas after higher-orders scattering can be derived in a similar way.

3.2. **Model verification.** Then the validity of the above-constructed laser transmission model in the high-scattering media was verified by comparing the obtained results with the results using the standard MC model, a model with comparatively high recognition degree. The experimental program was complied with Matlab R2011a version, and operated on the laptop computer (Thinkpad T430, Intel Core i5-2.6 GHz, 4GB Memory).

To verify the correctness of the proposed model, two groups of tests were conducted for examining the model's accuracy. The parameters in tests are listed in Table 3, in which g denotes the asymmetry factor. The H-G function in Mie scattering theory was adopted as the phase function in the proposed model, which can be expressed as:

$$P(\theta) = \frac{1 - g^2}{2(1 + g^2 + 2g\cos\theta)^{\frac{3}{2}}} \quad (21)$$

The forward scattering part approximately follows the Gaussian distribution, i.e., the forward-scattered photons can be represented by the Gaussian distribution. Denote the scattering angle corresponding to 63.2% energy of the particles' scattering phase function as $\Theta$ . According to the definition of phase function, the scattering angle can be described as According to the definition of phase function, the scattering angle can be described as $\int_0^{\Theta} P(\theta)\sin\theta d\theta = 0.632$. When g=0.9, $\Theta = 0.3rad$. In Table 3, $\mu_a$ denotes absorption coefficient, s denotes scattering coefficient, $g$ is asymmetry factor, $np$ denotes total number of photons, $\mu_s$ denotes the scattering angle corresponding to 63.2 % energy, and $N_{medtotal}$ is number of medium layers.

According to the statistics using the standard MC methods, the average value of the length of photon movement can be obtained, i.e.,$\bar{l} = \langle -\ln(\xi) / \mu_{\text{ext}} \rangle$. When the photons arrive at the objective plane, the average scattering order is $N = \frac{L}{2\bar{l}}$. The parameters in the present simulation model were then selected in accordance with this average order. If the scattering order exceeds the average value N, the resolution of the path is smaller than the average value $\bar{l}$. Fig. 7 displays the simulation results using two models, from which we can observe that the total number of the photons arriving at the receiving plane calculated using the proposed model fit well with the results using the standard MC model. Moreover, the number of photons decreases and the attenuation increases with the increase of distance. The parameters $\mu a$ and $\mu s$ in experiment 2 are greater than those in experiment 1, so more photons are absorbed by media in experiment 2. To make a more accurate comparison between the proposed model and the standard MC model in terms of the degree of accuracy, the maximum calculation errors of these two groups of tests using the proposed model and the standard MC model were calculated, as the results presented in Table 4. One can easily observe that the relative errors between the results using the proposed model and the results using the MC model are fairly small, which can

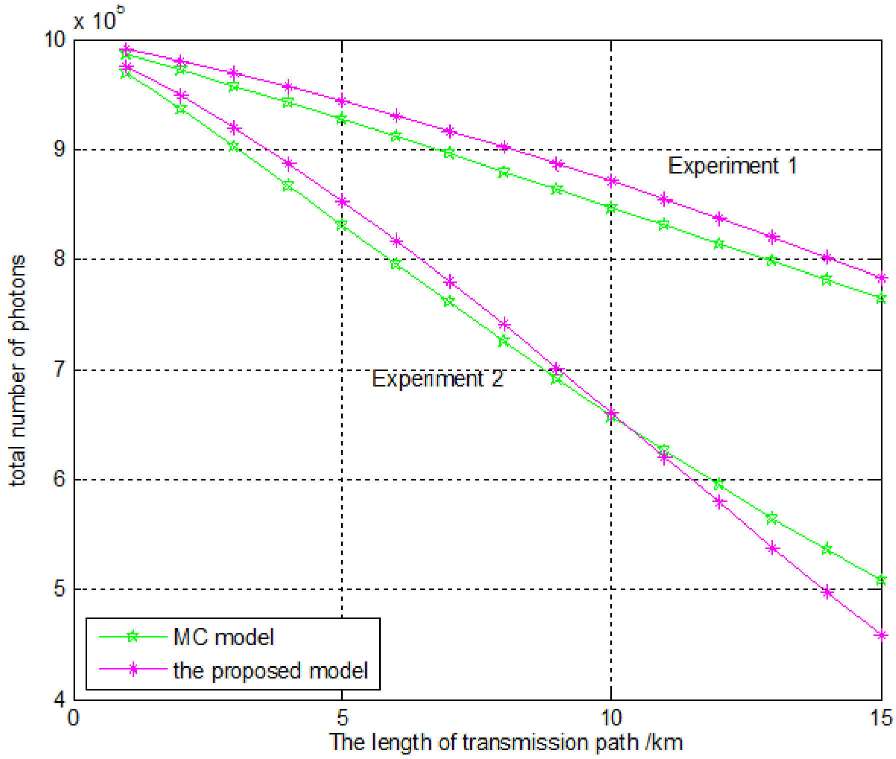



FIGURE 7. Comparison of the calculated total number of photons using the proposed model and the standard MC model

TABLE 4. My caption

| Serial number | The proposed model ($\times 10^5$) | MC model ($\times 10^5$) | Relative error |
|---|---|---|---|
| 1 | 8.58 | 8.36 | 2.6% |
| 2 | 4.62 | 5.08 | 9.1% |

meet the test requirements. Subsequently, the calculation efficiency of the proposed model was assessed by comparing with the results using the MC model and the AMC model as described in Ref. [10]. Fig.8 presents the comparison results, from which we can observe that the calculation time of our proposed model far less than the MC model and the AMC model. The calculation time of MC model and AMC model will increase with the length of transmission path, however our model's calculation time remains unchanged and is not influenced by transmission distance, which is because that the calculation complexity of our model is only determined by medium's resolution and the stop scattering order. The average simulation time using the proposed model is 32 ms, suggesting that it can meet the real-time requirements in virtual tests.

4. **Conclusion.** In virtual tests related to laser transmission, the calculation of energy attenuation is required to be efficient and real-time, to meet these requirements a laser transmission model in the atmosphere was proposed in this article. According to the weather conditions, the atmospheric transmission media can be classified two types, namely, the low- and intermediate-scattering media and the high-scattering media. The laser transmission models through these two types of media were constructed, respectively. The laser transmission model through the intermediate- and low-scattering media is based on the first-order scattering, i.e., only the first-order scattering is taken into account and the

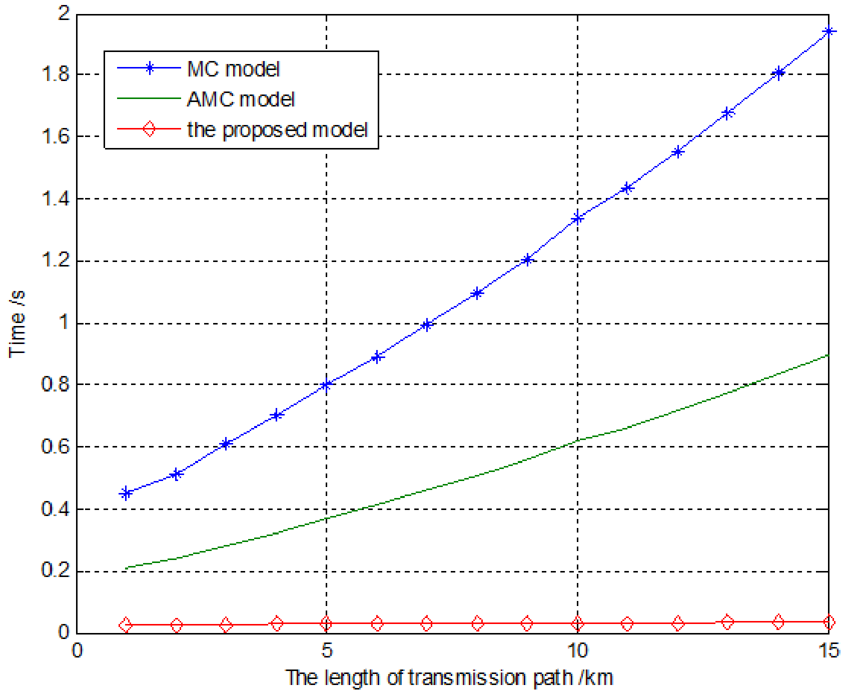



Figure 8. Comparison of calculation times between the proposed model and the other models

laser powers at the target and the detector can be acquired by calculating the laser's forward transmission energy, back transition energy and the reflected energy by the target; while the laser transmission model through the high-scattering media uses the assumption that the medium can be regarded as multiple parallel plates, and the final laser energy can be obtained by calculating the number of photons after several orders of scattering by different medium layer. Besides, the contrast tests between the proposed models and the standard MC model were conducted, and the results show that the proposed models are comparable with the MC model in accuracy but are superior to the MC model in terms of calculation efficiency. Therefore, the proposed model can meet the real-time requirements in virtual tests.

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