Influence Analysis of Underwater Laser Pulse Arrival Delay

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Abstract. In order to explore the influence of pulse arrival delay in underwater laser timing technology, a fused channel model based on Monte Carlo method and phase screen method is adopted, and the influence of ocean turbulence environment on photon transmission is added in the simulation process. On this basis, the received waveform and pulse arrival delay distribution characteristics of laser pulses in two waters and different turbulent environments are analyzed. The results show that with the turbidity of waters, the enhancement of ocean turbulence and the increase of transmission distance, the received pulses waveform gradually show a positive skewed distribution, and the pulse broadening and arrival delay are continuously increasing.

Keywords: ocean optics; Monte Carlo method; photon statistics; pulse delay.

1. Introduction

At present, underwater communication mostly adopts acoustic wave communication, but the shortcomings of acoustic wave communication, such as high delay and slow speed, have a great impact on the accuracy of underwater timing technology. However, the advantages of underwater laser communication, such as long transmission distance, speed close to the speed of light, and small transmission delay, are more suitable for underwater timing technology[1].

In the current research on underwater wireless optical communication, most scholars use the Monte Carlo method to explore the effect of seawater scattering and absorption on photons[2], or the phase screen simulation method based on power inversion to study the effect of ocean turbulence on light beams. Influence[3,4]. Only Wang Yang combined the optical characteristics of seawater and the turbulent environment to analyze the performance of underwater optical communication in the channel analysis[5], but his channel model uses hypergeometric functions, which is complex and not conducive to statistics.

In order to analyze the influence of different seawater factors on the underwater laser timing pulse, based on the literature[6], this paper improves the calculation formula and simulation process, and establishes a multi-factor fusion underwater laser timing channel model. The model is used to simulate and analyze the received pulse waveform and arrival delay in different environments, which provides a theoretical reference for underwater laser timing technology.

2. Channel Model

2.1 Volume scattering function

The volume scattering function is a function model in the Monte Carlo method to describe the azimuth calculation after photons are scattered underwater, so the selection of the volume scattering function is very important. The current commonly used volume scattering function distribution is shown in Figure 1. From the figure, it can be see that the fit between the SS (Sahu-Shanmugam) volume scattering function and the Petzold volume scattering function is better than other scattering functions, so the SS volume scattering function is used in this paper.

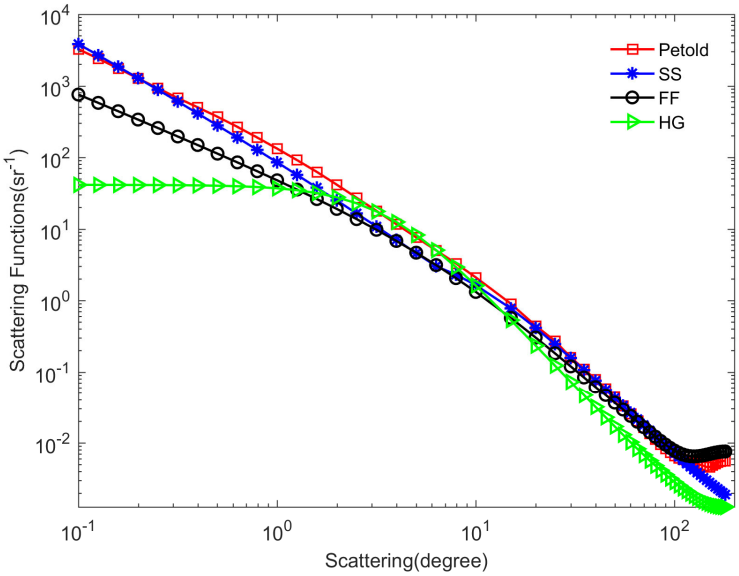


Fig. 1 Scattering function log distribution diagram

2.2 Random Phase Screen Model

Underwater turbulence is mainly caused by random fluctuations in the refractive index of water caused by changes in salinity and temperature. The phase screen method is to treat the turbulence within a certain spatial range as a barrier that randomly disturbs the optical phase, and calculate the distribution function based on the power spectrum inversion method. The calculation formula of the distribution function of the random phase screen is as follows[7]:

$$\varphi(x,y)=\mathrm{C}\sum_{k_x}\sum_{k_y}h\left(k_x,k_y\right)\sqrt{F_\varphi\left(k_x,k_y\right)}\exp\left[\mathrm{i}\left(k_x x,k_y y\right)\right] \tag{1}$$

In the formula, k_x and k_y is the light wave number in the x and y directions of the phase space frequency domain; C is the variance constant factor of the control phase screen; $h\left(k_x,k_y\right)$ is the Fourier transform of the Gaussian random number with the mean equal to 0 and the variance equal to 1; $F_\varphi\left(k_x,k_y\right)$ is the phase power spectrum, which is calculated as follows:

$$F_\varphi\left(k_x,k_y\right)=2\pi k^2\Delta z\Phi\left(k_x,k_y\right) \tag{2}$$

In the formula, k is the light wave number in vacuum; Δz is the distance between phase screens; $\Phi\left(k_x,k_y\right)$ is the refractive index fluctuation spectrum of seawater, which is calculated as follows:

$$\begin{aligned}\Phi\left(k_x,k_y\right)&=0.388\times10^8\varepsilon^{-1/3}\kappa^{-11/3}\times\left[1+2.35\left(\kappa\eta\right)^{2/3}\right]\\&\times\frac{\chi_\mathrm{T}}{\omega^2}\left(\omega^2e^{-A_\mathrm{T}\delta}+e^{-A_\mathrm{S}\delta}-2\omega e^{-A_\mathrm{TS}\delta}\right)\end{aligned} \tag{3}$$

In the above formula, κ is the spatial frequency; ε is the turbulent kinetic energy dissipation rate, the value range is [10-10,10-1]; η is the Kolmogorov microscale; ω is the temperature and salinity gradient ratio, the value range is [-5,0]; χ_T is the mean square temperature dissipation rate, the value range is [10-10,10-4]; Fixed parameter values:

$$\begin{cases}A_\mathrm{T}=1.863\times10^{-2}\\A_\mathrm{S}=1.9\times10^{-4}\\A_\mathrm{TS}=9.41\times10^{-3}\\\delta=8.284\times\left(\kappa\eta\right)^{4/3}+12.978\left(\kappa\eta\right)^2\end{cases} \tag{4}$$

2.3 Channel Model Simulation Flowchart

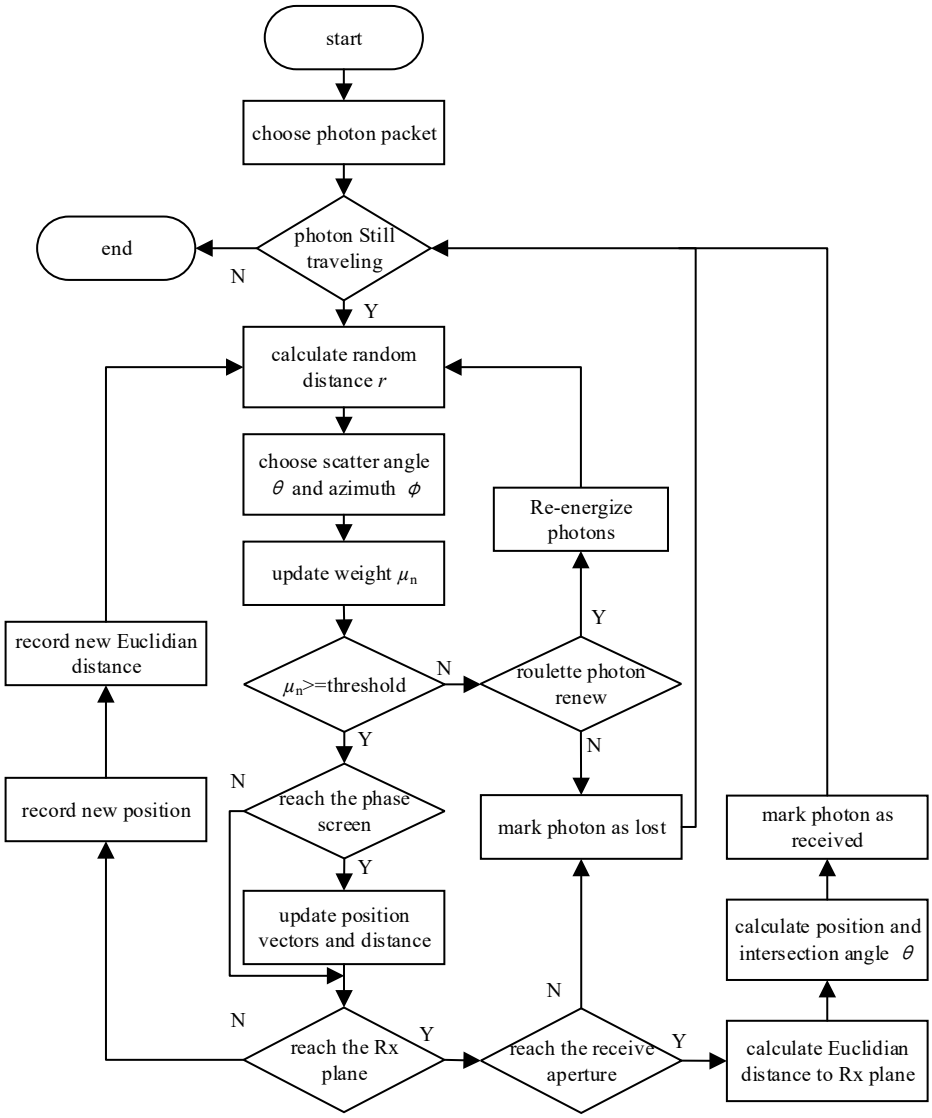


Fig. 2 Channel model simulation flowchart

The simulation flow chart of this paper is shown in Figure 2. On the basis of the traditional Monte Carlo simulation process, the judgment calculation of the phase screen is added, and the influence of the underwater turbulent environment is considered in the photon transmission process. The fused underwater laser channel model makes it more comprehensive to analyze the influence of seawater environmental factors on the pulse arrival delay.

2.4 Judgment of reaching the phase screen

First, we set the z-axis as the direction of the photon's transmission to the right, and the distance of the phase screen interval distribution on the z-axis is z_{phase}, and then determine whether the photon reaches the phase screen by formula:

$$r \cdot \cos\theta_n + z_{\text{add}} \geq z_{\text{phase}} \tag{5}$$

In the above formula, r is the random step size for scattering, z_{add} is the sum of the scattering distances in front of the photon in the beam propagation direction, θ_n is the nth scattering angle.

When the photons reach the phase screen, we regard the phase screen as a super-interface, that is, the phase-abrupt interface[8]. From the generalized refraction theorem, the formula for the angle of refraction can be deduced as follows:

$$\theta_{\mathrm{tx}} = \arcsin\left(\sin\theta_{\mathrm{ix}} + \frac{\lambda_0}{2\pi \mathrm{n}} \frac{d\Phi}{dx} \right) \tag{6}$$

Where θ_{ix} and θ_{tx} are the incident angle and refraction angle in the x-axis direction, respectively, λ_0 is the wavelength of the light beam in vacuum, n is the refractive index of light in water, and Φ is the phase function of the meta-interface. Same goes for the y-axis.

The direction vector of the updated photon after passing through the phase screen is:

$$\begin{cases} \mu_{\text{x-phase}} = \mu_x + \dfrac{\lambda_0}{2\pi \mathrm{n}} \dfrac{d\Phi}{dx} \\ \mu_{\text{y-phase}} = \mu_y + \dfrac{\lambda_0}{2\pi \mathrm{n}} \dfrac{d\Phi}{dy} \\ \mu_{\text{z-phase}} = \sqrt{1 - \mu_{\text{x-phase}}^2 - \mu_{\text{y-phase}}^2} \end{cases} \tag{7}$$

Where μ_x and μ_y are the direction vectors before arrival.

The coordinates of the updated photon on the phase screen as:

$$\begin{cases} x_{\mathrm{p}} = x_{\mathrm{m}} + \left(z_{\text{phase}} - z_{\text{add}} \right) \dfrac{\mu_x}{\mu_z} \\ y_{\mathrm{p}} = \mathrm{y}_{\mathrm{m}} + \left(z_{\text{phase}} - z_{\text{add}} \right) \dfrac{\mu_y}{\mu_z} \\ z_{\mathrm{p}} = z_{\text{phase}} \end{cases} \tag{8}$$

where x_{m} and y_{m} are the coordinates of the photon before this scattering.

The remaining step size of the photon is $r_0 = r - \left(z_{\text{phase}} - z_{\text{add}} \right) / \mu_{z-\text{phase}}$.

3. Simulation Analysis

In the underwater wireless optical communication system, since the seawater environment has a great influence on the optical phase, the IM/DD(Intensity Modulated/Direct Detected) method is mostly used. so this paper defines that the received optical pulse reaches half of its power peak value as the actual pulse receiving time. The pulse arrival delay is the difference between the actual pulse receiving time and the theoretical receiving time.

In the simulation experiment, the optical soliton beam is taken as the experimental light source. The fixed parameter settings in the experiment are shown in Table 1.

Table 1. Experimental setup parameters

Light source				Receiving end	
number of photons	Wavelength (nm)	Beam radius(mm)	Divergence half angle (mrad)	Receiving radius (m)	Receiving field of view (degree)
10^6	532	2	1.25	1	90

3.1 Analysis of Pulse Arrival Delay in Two Waters

In order to study the arrival delay of optical pulses in different waters, this section simulates and analyzes the received optical pulses in clear waters and harbor waters under different communication distances (1m-7m). These two waters represent the two states in which seawater absorbs and scatters light from weak to strong, and the absorption coefficient and attenuation coefficient are referred to [2].Set the initial transmit pulse width to 200 picoseconds.

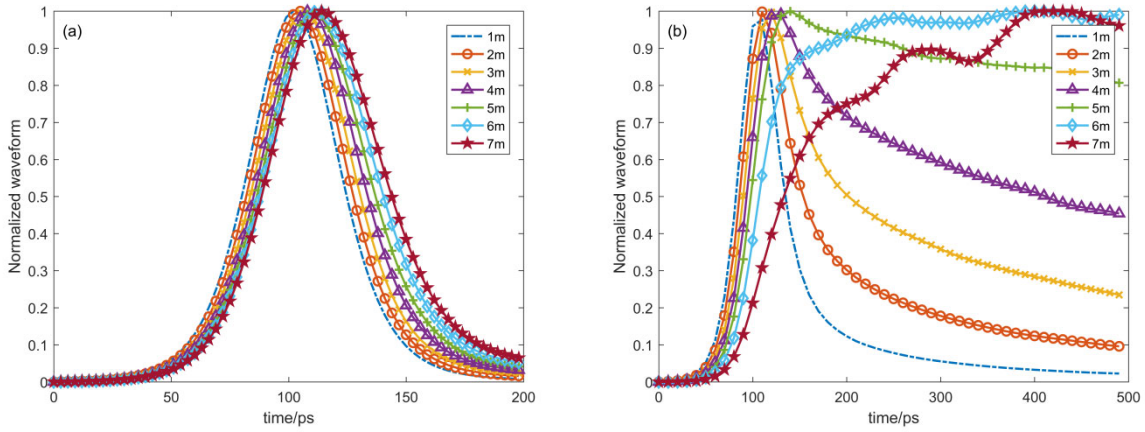


Fig. 3 Received pulse waveform distribution

In the above figure, 3(a) is the pulse reception waveform in clear water, and 3(b) is in harbor water. It can be seen from the figure that in the two waters, with the increase of the transmission distance, the longer the arrival delay of the received pulse waveform is, the more serious the pulse broadening is, the waveform gradually becomes positively skewed. It is most obvious in harbor waters, and the received pulse waveform is distorted with the increase of transmission distance. This is mainly because harbor waters have a greater impact on the beam than in clear waters. When the transmission distance increases, the number of photons that deviate from the ballistic transmission increases.

According to the received pulse waveform, the pulse arrival delays in the two waters are calculated respectively, as shown in Figure 4:

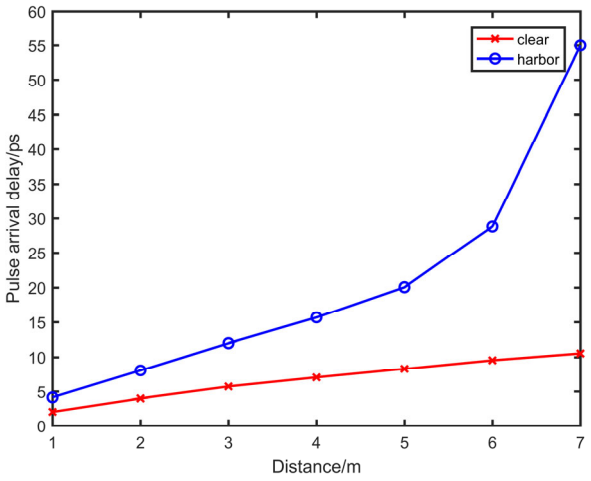


Fig. 4 Pulse arrival delay comparison

From the comparison of the data in the above figure, it can be seen that under the same transmission distance, the arrival delay of the pulse in the harbor water is high, which indicates that with the turbidity of the water, the beam scattering is serious, and the arrival delay of the optical pulse is larger. In the transmission distance of 1-7m, the delay change in clear waters does not exceed 12ps, while the delay change in harbor waters reaches 55ps, which shows that the more turbid the waters, the greater the change of delay with distance.

3.2 Influence of Seawater Turbulence on Pulse Arrival Delay

The underwater turbulent environment will disturb the light intensity and phase of wireless optical transmission, so it is necessary to explore the influence of the ocean turbulent environment on underwater laser timing. However, there are many ocean turbulence control parameters, and it is not practical to use a single parameter to explore the pulse arrival delay. Therefore, in this section, based

on the research results of the literature[9], the values of strong and weak turbulence parameters are set as shown in Table 2.

Table 2. Strong and weak turbulence parameters

	ε / $m^2 \cdot s^{-3}$	χ_T / $K^2 \cdot s^{-1}$	η / m	ω
Strong	10^{-5}	10^{-7}	10^{-3}	-2.5
Weak	10^{-7}	10^{-5}	10^{-3}	-0.5

The experimental conditions choose to simulate and analyze the received pulse waveform and arrival delay in the strong and weak turbulent environment in the clear water, because the clear water has the least effect on the photon scattering and the best observation effect. Other simulation conditions remain unchanged, the turbulent phase screen interval is set to 0.4m,the transmission distance is 10m. The received pulse waveform and arrival delay are shown in Figure 5

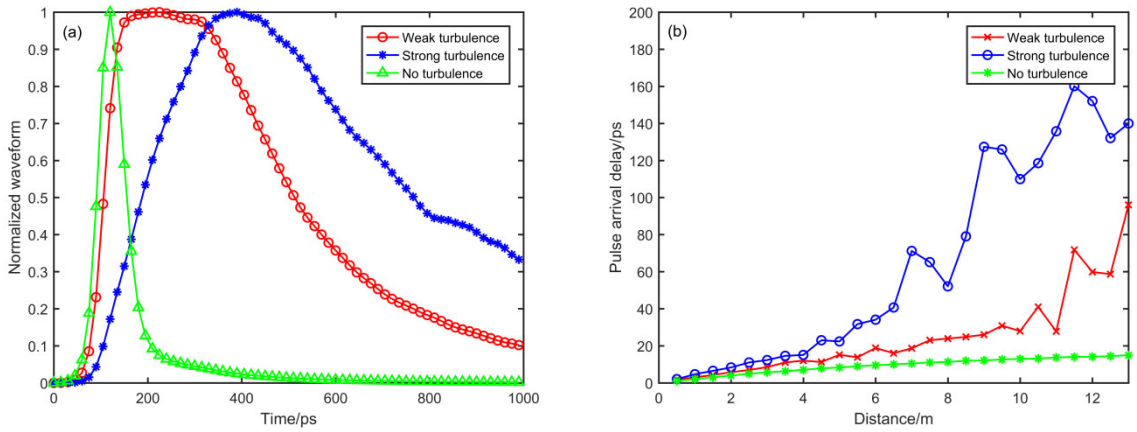


Fig. 5 Received pulse waveform and delay distribution

As shown in Figure 5(a), since the beam is affected by the turbulent environment, the pulse broadening and arrival delay of the received pulse waveform become larger, and increase with the intensity of the turbulent environment.

It can be seen from Figure 5(b) that due to the influence of unstable turbulence, the pulse arrival delay fluctuates up with the increase of transmission distance, and the stronger the turbulence, the greater the fluctuation. During short-range communication within 4m of clear water, ocean turbulence has little effect on the arrival delay of laser pulses. This is because the receiving spot radius is small during short-range communication, and most of the beam energy is still transmitted in the ballistic path in the turbulent environment. When communicating at transmission distances greater than 4m, as the turbulence intensity increases, the number of photons that deviate from the ballistic path increases, resulting in an increase in the fluctuation of the received pulse delay.

4. Summary

In this paper, based on the Monte Carlo method, combined with the phase screen method for simulating ocean turbulence, the underwater optical timing channel model is improved. The model is used to simulate and analyze the arrival delay of pulses in two waters and different turbulent environments. The results show that the pulse broadening and arrival delay gradually increase with the increase of distance and the turbidity of waters, and the waveform distribution is positively skewed with long trailing tail. At the same distance, the stronger the turbulent environment is, the wider the received pulse waveform is, and the pulse arrival delay shows an increasing trend of fluctuation.

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