Optik 125 (2014) 727–731

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Water mist attenuates guided laser based on Monte Carlo method☆

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ARTICLE INFO

Article history:
Received 11 March 2013
Accepted 6 July 2013

Keywords:
Water mists
Laser guide
Stealth
Monte-Carlo method
User defined function fitting

ABSTRACT

The round-trip attenuating process of lasers used for guiding in artificial water mists is studied with the Monte-Carlo method. A new way for confirming the scattering directions of photons is established based on calculating Mie cumulative probability distribution function of the polydisperse mist and user defined function fitting by Matlab. Two Monte-Carlo methods for photons tracking are mentioned and their efficiencies are discussed and balanced in this paper. A conclusion is come to that the Wight method is evidently more efficiency than the Event method, and the former is adopted in this paper. The radiuses of frequently-used water mists are usually in the range of 10^1–10^2 μm which are found to be suited to attenuate the 10.6 μm laser and can be used for laser stealth. But the effect is worse for 1.06 μm laser.

1. Introduction

The missiles as well as the bombs guided by laser have been increasingly used in battle. Because of the high accuracy and high anti-jamming ability, they pose a great threat to the modern ships, tanks, and large land targets. As effective countermeasures to laser guiding mode, the smoke has already been put into application [1,2]. But there are some difficulties in fight use, mainly because of the dispersion time needed as finding the incoming missiles. In addition, the smoke is easily driven away by the wind and it may pollute the environment. For reasons as have been mentioned, the fine water spray system which is a high effective way of anti-guided has been studied and used in the infrared stealth field [3,4]. However, there lack of research findings about water mist countermining laser guided weapons.

The scholars coming from every field have done a mount of work on the laser attenuating characteristics in other kinds of discrete media, such as smoke, dust storm, atmospheric aerosol and so on. Wu [5,6] and his partners studied the laser attenuating characteristics in the dust storm; Yong [7] and Ke [8] paid their attention to the atmosphere and rains for laser attenuating; Ge [1] studied the mechanism of smoke concealment interfering air-raid of laser-guided weapon; Wang [2] did a research on the red phosphorus smoke usage characteristics and optimal extinction diameter to emissions of infrared laser. But in a word, it needs to deeply study on the application of artificial water mist to countermine the infrared laser guiding mode.

In this paper, the study objects are 1.06 and 10.6 μm laser. The Monte-Carlo method is adopted as a calculation way, and a new method for confirming the direction of scattered photons is established. The apparent reflectivity is defined as a parameter to scale the distribution of laser echo intensity. The two wavelengths lasers of 1.06 and 10.6 μm are calculated about the echo distribution under the mist shielding as well as the changes of apparent reflectivity as a function of sprays volume fraction, depth, and spray drops radius parameters.

2. Principle of laser attenuating in water mist

As a kind of stimulated radiation, laser will be scattered and absorbed when propagating in the water mist by the spray drops. If the drops radiuses r are much smaller than the laser wavelength λ, and the absolute value of the complex refractive index m is not too large, which means the size parameter $\chi = 2\pi r/\lambda < 0.1$ and $|\chi m| << 1$, the scatter will be named as Rayleigh mode. When $\chi > 1$, it will be named as Mie mode. For the drops radiuses are usually in the range of 10^1–10^2 μm, and the most-used laser wavelengths are 1.06 and 10.6 μm, the principle of laser attenuating in water mist, see Fig. 1, is Mie scattering and absorption. When a beam of lasers incidents upon a single drop, the distribution of laser energy scattered along the zenith angle as follows:

$$\alpha_\lambda(\theta) = \frac{\lambda^2}{8\pi^2}[\left|S_1(\theta)\right|^2 + \left|S_2(\theta)\right|^2] \quad (1)$$

where α_λ is angle scattering cross section; S_1 and S_2 are vertical and parallel components of the complex amplitude function, and

☆ National defence pre-researching fund 1010502020202.
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http://dx.doi.org/10.1016/j.ijleo.2013.08.001

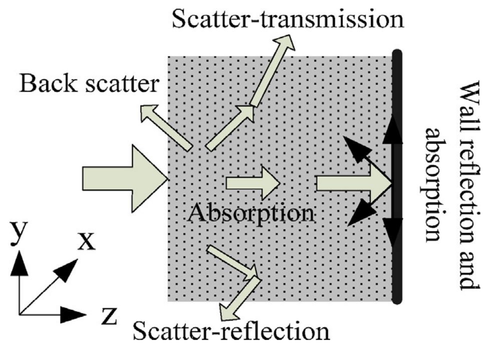

Fig. 1. Diagram for the laser attenuating in water mist.

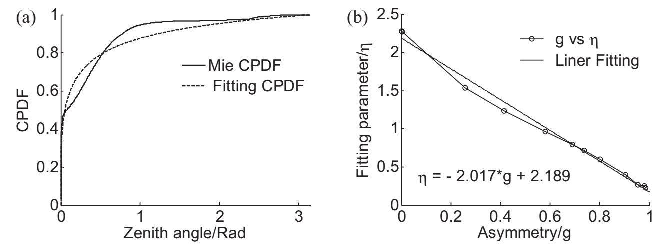

Fig. 2. Fitting CPDF with user defined function: (a) Comparison between Mie and Fitting CPDF and (b) Relationship between unknown parameter η and asymmetry g.

they are the function of m and χ, and are usually calculated by the Mie theory. But the water mist is a kind of aerosol which consists of fine and thick drops, and the laser attenuating in them accords with the Lambert–Beer's law:

$$I_\lambda = I_{0\lambda}\exp(-\kappa_{ext}L) \tag{2}$$

where $\kappa_{ext,\lambda}$ is volume attenuation coefficient, which consists of the volume absorption coefficient $\kappa_{abs,\lambda}$ and volume scattering coefficient $\kappa_{sca,\lambda}$:

$$\kappa_{ext,\lambda} = \kappa_{abs,\lambda} + \kappa_{sca,\lambda} \tag{3}$$

$$\kappa_{abs,\lambda} = N_d\int_0^\infty \pi r^2 n(r) Q_{abs} dr \tag{4}$$

$$\kappa_{sca,\lambda} = N_d\int_0^\infty \pi r^2 n(r) Q_{sca} dr \tag{5}$$

where N_d is the number density of drops, and can be expressed with mist volume fraction f_v:

$$N_d = \frac{f_v}{\int_0^\infty 4/3\pi r^3 n(r)dr} \tag{6}$$

where $n(r)$ is the probability density function of the drops radiuses expressed as:

$$n(r) = \frac{1}{\sqrt{2\pi}r\ln\sigma}\exp\left(-\frac{(\ln r-\ln r_0)^2}{2(\ln\sigma)^2}\right) \tag{7}$$

where r_0 is geometry average radius; σ is geometry standard deviation, and $\ln\sigma$ is logarithm of standard deviation.

However, the Lambert–Beer's law is based on the single scattering, and it needs to consider the multiple scattering for the fine mists [9,10]. Taking the multiple scattering into account, the Mont-Carlo method is adopted.

3. Monte-Carlo method

Monte-Carlo method translates the process of laser transportation into a probability model which abstracts a large number of independent photons from laser. The trajectories of the photons are tracked with a series of pseudo-random numbers ξ, and through which the disturbing of laser by water mist is described.

3.1. Photon tracking model

The random step is expressed as $l = -(1-\xi_1)/k_{ext}$ [11,12], and the scattering direction is confirmed by zenith angle θ and azimuth φ. As a result of the isotropic scattering for the azimuth, the random azimuth is expressed as $\varphi = 2\pi\xi_2$. The scattering for the zenith angle is anisotropic. Set the cumulative probability distribution function of the scattering photons in the zenith angle direction equal to a pseudo-random number: $\xi_3 = F(\theta) = 0.5\int_0^\theta P(\theta)\sin(\theta)d\theta$, in which $P(\theta)$ is scattering phase function. However, the difficulty is that $P(\theta)$ or $F(\theta)$ cannot be written as explicit formulations, except for some approximate formulas, such as H-G phase function and linear phase function. In view of the similarity of the CPDF and logarithmic Function, the solution to the difficulty in this paper is to make user defined function fitting of $F(\theta)$ based on the least square method. Define the objective function as:

$$F(X) = [lg(X)]^\eta \tag{8}$$

where $X \in (1,10)$, so $F(X) \in (0,1)$, and it satisfies the demand of range of CPDF. There is a linear relationship between X and zenith angle range $\theta \in (0,\pi)$:

$$X = \frac{9}{\pi}\theta + 1 \tag{9}$$

From formulas (8) and (9), $F(\theta)$ can be deduced:

$$F(\theta) = [lg(\frac{9}{\pi}\theta + 1)]^\eta \tag{10}$$

Make $F(\theta)$ equal to ξ_3, the corresponding zenith angle can be obtained, see Fig. 2a:

$$\theta = F^{-1}(\xi_3) = \frac{\pi}{9}(10^{\xi_3 1/\eta} - 1) \tag{11}$$

For the unknown parameter η, it is obtained by Matlab fitting with the function (10). A linear relationship between η and g is found through large number of fittings, see Fig. 2b.

Translate the direction (θ_s, φ_s) of the transitional coordinate system into the standard coordinate system:

$$\theta' = \cos^{-1}\left[\cos(\theta_s)\cos(\theta) + \sin(\theta_s)\sin(\theta)\cos(\varphi_s)\right] \tag{12}$$

$$\varphi' = \begin{cases} \varphi + \tan^{-1}\left(\dfrac{\sin\theta_s\sin\varphi_s}{\varepsilon}\right), & \varepsilon > 0 \\ \varphi + \tan^{-1}\left(\dfrac{\sin\theta_s\sin\varphi_s}{\varepsilon}\right) + \pi, & \varepsilon < 0 \end{cases} \tag{13}$$

$$\varepsilon = \cos(\theta_s)\sin(\theta) - \sin(\theta_s)\cos(\varphi_s)\cos(\theta) \tag{14}$$

In formulas (10)–(12), θ" and φ' mean the zenith angle and azimuth of the standard coordinate system.

When the photons move to the position $n+1$ from position n, the new position is expressed as:

$$\begin{cases} x_{n+1} = x_n + L\sin(\theta')\cos(\varphi') \\ y_{n+1} = y_n + L\sin(\theta')\sin(\varphi') \\ z_{n+1} = z_n + L\cos(\theta') \end{cases} \tag{15}$$