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Semi-analytic Monte Carlo radiative transfer model of laser propagation in inhomogeneous sea water within subsurface plankton layer

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HIGHLIGHTS

- A semi-analytic Monte Carlo radiative transfer model for inhomogeneous water is developed.
- The input optical vertical profile can vary with a resolution as high as 0.11 m.
- The influences of water optical properties, boundary and lidar systems were studied.
- The simulation curve was quite similar to that of the lidar measurements.

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ABSTRACT

Current Monte Carlo simulation methods of laser propagation in sea water are mostly based on the assumption of homogeneous water. In this study, a semi-analytic Monte Carlo radiative transfer model is developed to study laser propagation in inhomogeneous sea water within subsurface plankton layer. It is based on analytical estimate of the probability of collection by a remote receiver of scattered or emitted photons; in particular, the water optical input parameter of vertical profile is no longer simply set as a constant. In the new transfer model, the input optical vertical profile can vary with a resolution as high as 0.11 m. Using this model, we study the influences of water optical properties, multiple scattering, wind-driven sea surface condition, and lidar incident angle. The effective lidar attenuation coefficient is found to depend on the field of view of the lidar system: it approaches attenuation coefficient with a narrow field of view, and approaches absorption coefficient with a wide-enough field of view. We also find the lidar transmittance through the air-sea interface decreases significantly as the wind speed increases to greater than 7 m/s, and the transmittance can even be reduced by half when the wind speed reaches 18 m/s. Finally, we compare the simulations by our new model with airborne lidar measurements. We find that the simulation curve is quite similar to that of the lidar measurements. The absolute error of normalized simulation signals compared with the measurements is within 0.05, suggesting the effectiveness and applicability of our approach for inhomogeneous water.

1. Introduction

Monte Carlo simulation is a fundamental and versatile approach toward modeling light transport in sea water [1]. Its main advantage over the commonly used radiative transfer equation is that it requires fewer simplified approximations, which can be extended to more complex media with relative ease [2]. In recent years, Monte Carlo simulation techniques have been widely used to study laser radiative transfer in the ocean. Gordon [3] investigated the effects of multiple scattering on the interpretation of laser pulses from the ocean, and found the effective lidar attenuation coefficient strongly depends the field of view of the lidar system. Poole et al. [4] described a semi-analytic Monte Carlo radiative transfer model (SALMON) based on calculating analytically at each collision the probability that the photon would return directly to the receiver without further interactions. Ramella-Roman et al. [5,6] simulated polarized light transport by propagating the Stokes Vector state of a photon. There are many other Monte Carlo studies of radiative transfer in scattering media [7–11]. However, in almost all of these studies, the Monte Carlo simulation methods are based on the assumption of optically homogeneous water, and the vertical profile of water optical input parameter is often assumed to be a constant. There is a need to study light propagation in inhomogeneous sea water, for instance, to simulate laser propagation through subsurface chlorophyll maximum layer.

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The goal of this study is to develop a new semi-analytic Monte Carlo radiative transfer model of laser propagation in inhomogeneous sea water within subsurface plankton layer. The newly developed model presented in this study is based on analytical estimate of the probability of collection by a remote receiver of scattered or emitted photons, and the vertical profile of water optical input parameters is no longer a constant. In particular, the input optical vertical profile can vary with a resolution as high as 0.11 m. We also study the influences of water optical properties, multiple scattering, wind-driven sea surface condition, and lidar incident angle using this model. Finally, we compare the simulations by our new model with airborne lidar measurements.

2. Theory and modeling

Monte Carlo simulation of light propagation in sea water requires random selection of photon step size, scattering angle and reflection or transmission at boundaries [1]. In this study, the water column was divided into many layers with various optical properties to describe inhomogeneous water. First, a series of photon step sizes s were generated as follows:

$$s = \frac{-\ln(RND)}{\mu_t(z)} \tag{1}$$

where RND is a series of random numbers, which follow uniform distribution between [0,1]; $\mu_t(z)$ is the total attenuation coefficient at depth $z = \mu_a(z) + \mu_s(z)$, where $\mu_a(z)$ and $\mu_s(z)$ are absorption coefficient and scattering coefficient at depth z, respectively. The existing Monte Carlo simulation methods mostly assume sea water be optically homogeneous; in fact, sea water is often optically inhomogeneous. To simulate the real optical condition of sea water, we allow $\mu_t(z)$, $\mu_a(z)$ and $\mu_s(z)$ vary with depth z in this study. Therefore, the photon weight ***w(i)*** (initial value being 1) decreases as the total step size increases.

At each photon collision, the photon was scattered into a new trajectory according to the Henyey-Greenstein (H-G) function; meanwhile, the current photon weight ***w(i)*** was multiplied by the absorption coefficient. When a photon's weight dropped below the threshold of 10^{-4}, the roulette procedure was employed.

In this paper, an improved semi-analytic approach is used for the estimated value $E(i)$of the fraction of photons collected by the remote receiver upon a scattering event at collision point i based on Poole's method [4]:

$$E(i) = \frac{p(\theta)}{4\pi}\Delta\Omega \exp\left(\sum_{1}^{i} -u_t(i)d_i'\right)w(i)$$
$$= \frac{p(\theta)}{4\pi}\frac{A}{(H+d)^2}\exp\left(\sum_{1}^{i} -u_t(i)d_i'\right)w(i) \tag{2}$$

where $p(\theta)$ is the scattering phase function, $\Delta\Omega$is the small solid angle of photon received by the detector, A is the detector aperture, H is the flight height, d' is the distance between point i and air-sea interface, and d_i' is the depth of each layer. The vertical resolution can reach 0.11 m in this study. Above 500 layers has been simulated here, and an improved H-G function was used to shorten the elapsed time substantially [12]. The signal level due to solar radiation is defined as a Gaussian white noise with a mean of zero and a standard deviation equal to 1. The solar radiance reflected from the water column is set 0.025 $\mathrm{w\,m^{-2}\,sr^{-1}\,nm^{-1}}$ [13]. The lidar geometric model of scattering event is shown in Fig. 1.

As the photon moves toward the sea surface, the determination of total transmission $t_t$for specific viewing and sea wave conditions in rough sea surface [14,15] is given by:

$$t_t = t_p \times t_r \tag{3}$$

where t_p is the transmission at calm sea surface, which can be calculated by the Fresnel theorem, and t_r is the transmission in the wind-roughened surface as a function of wind speed u:

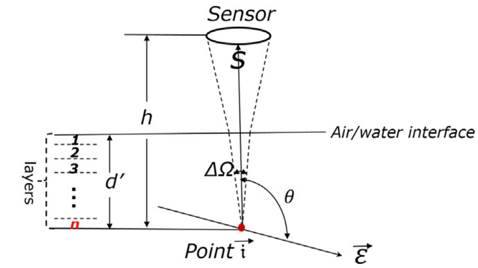

Fig. 1. Lidar geometric model of scattering event at collision point i.

$$\begin{cases} t_r = 1{-}1.2\times10^{-5}\times u^{3.3}, & u \leqslant 9\ m/s \\ t_r = 1{-}1.2\times10^{-5}\times u^{3.3}\times(0.225u{-}0.99), & u > 9\ m/s \end{cases} \tag{4}$$

3. Results

3.1. Influence of water optical property on lidar echo signal

Influences of water optical properties on simulation results were analyzed. Simulations were conducted by using 10,000,000 photons for a given detector height of H = 100 m, field of view of FOV = 6 mrad, detector aperture of A = 0.06 $\mathrm{m^2}$, sea bottom depth of d = 40 m, and sea bottom albedo of ρ_b = 0.03. The run time of the simulation was about 293 s. The normalized received signals varies with water attenuation coefficient $\mu_t$and water single albedo ω_0. Fig. 2 shows that the normalized received signal decreases as μ_t increases, while it increases as ω_0 increases. In addition, the decay speed of echo signal slows down and the curve of echo signal becomes rougher as ω_0 increases. It

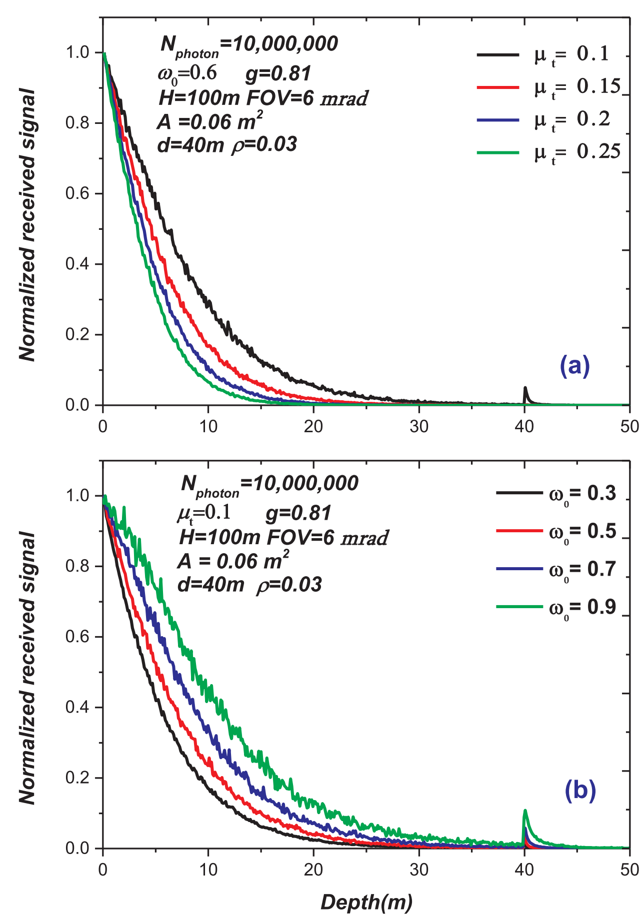

Fig. 2. Influences of water optical properties on simulation results: (a) influence of water attenuation coefficient and (b) influence of water single albedo.