OCEANIC LIDAR: THEORY AND EXPERIMENT

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ABSTRACT

Study on the upper ocean is of great significance to the global climate change and carbon cycle. Lidar can be used to effectively detect depth-resolved optical properties of the ocean. However, both theory and experiment of oceanic lidar are limited by complex multiple scattering. Several progresses by Zhejiang University will be illustrated in this paper: 1) a polarized lidar system was developed, and a Monte Carlo model and a radiative transfer model were established (Zhou, et al. *remote sensing*, 2019; Zhou, et al. *Journal of remote sensing*, 2019; Xu, et al. and Liu, et al. *Journal of remote sensing*, 2019); 2) Cross validations are demonstrated to verify the availability of the lidar system and models (Liu, et al. *IEEE TGRS*, 2019); 3) phase function effects on backscatter and attenuation are studied considering multiple scattering, respectively (Liu, et al. *Optics Express*, 2019). Oceanic lidar is proven to have great potential in marine studies.

1. INTRODUCTION

Study on the upper ocean is of great significance to the global climate change and carbon cycle. The ocean color remote sensing based on the airplane or satellite, like SeaWiFS, is able to collect the global data over a long term efficiently. Nevertheless, the limited information about the depth and the dependence on the natural light partly restrict its applications. So far, the oceanographic lidar, one of the active remote sensing methods, has been employed in detecting

fisheries, phytoplankton layers and internal waves, etc., in the upper ocean [1-3].

In general, interpretation of lidar signals is not difficult under the well-known single-scattering approximation. However, in dense media, such as clouds, seawater, etc., the preceding and following events are accompanied by strong multiple scattering [3]. A portion of photons that are lost in the scattering events could eventually contribute to the lidar signals through multiple scattering. As a result, large errors could be introduced into the single-scattering approximation. Therefore, it is important to quantify and analyze lidar signals with multiple scattering.

Several progresses by Zhejiang University will be illustrated in this paper: 1) a polarized lidar system was developed, and a Monte Carlo model and a radiative transfer model were established; 2) Cross validations are demonstrated to verify the availability of the lidar system and models; 3) phase function effects on backscatter and attenuation are studied considering multiple scattering, respectively.

2. METHODOLOGY

2.1 The lidar system

The developed shipborne oceanic lidar transmitted a laser pulse into the seawater and detected the lidar returns for the retrieval of the seawater optical properties, as shown in Fig. 1. The transmitter included a frequency-doubling Q-switched Nd:YAG pulsed laser at 532 nm, with a

single pulse energy of 5 mJ, a pulse width of 10 ns and a repetition frequency of 10 Hz.

Fig. 1. The lidar field experiment in the Yellow Sea. Lidar system mounted on the fore deck of the ship and *in situ* instruments going into the water.

2.2 Monte Carlo models

The standard MC and semianalytic MC models are employed to provide MC-simulated results. The basic principle of the MC simulation is to treat photons as classical particles [4] and simulate the trajectories of a number of photons to measure the relevant information. The standard MC algorithm refers to the method described in [4]. The semianalytic MC algorithm refers to the method illustrated in [5], where an analytical estimate is calculated for the possibility of the collection of scattered photons at certain points.

The semianalytic MC algorithm greatly improves the calculation efficiency compared with the standard MC algorithm [6].

2.3 Analytical model

The analytical model employed in this paper follows the work of Katsev [7] and Malinka [8]. Seawater has very sharp forward peaks in its phase function that make the probability of scattering into the near-forward directions much larger than that of scattering into the backward hemisphere. If the optical thickness of the media is not too large, it is assumed that the trajectories that contribute to lidar signals primarily consist of single backscattering and small-angle forward multiple scattering on the outgoing and returning legs [7], namely the QSA approximation, which forms the foundation of the analytical model [6].

3. RESULTS

3.1 Cross validation

The lidar signals calculated by the analytical model, semianalytic MC algorithm and standard MC algorithm are shown in Fig. 2. The effects of height, FOV and water type are shown in Fig. 2 (a)-(c), respectively. The semianalytic MC and standard MC algorithms are simplified as “Semi MC” and “Stan MC”, respectively, in each legend. To give a more explicit picture, the lidar signals are normalized by their maximums, and the dynamic ranges are set to 4 orders of magnitude. In Fig. 2, the results of the three algorithms agree very well at different conditions [6].

Fig. 2. Normalized lidar signals are calculated by the analytical model, semianalytic MC algorithm and standard MC algorithm at different: (a) heights; (b) FOVs; and (c) water types.

Figure 3 shows lidar signals calculated by the analytical model (orange solid lines) and measured by the lidar (blue solid lines with error bars) with a large, full FOV of 200 mrad. The average values in blue solid lines and standard deviations in blue error bars of 10 lidar-measured

signals during the *in situ* operation period are plotted. Dynamic ranges of 3-4 orders of magnitude can then be realized in most cases. As shown in Fig. 3, the analytical model can perfectly match the lidar-measured results at different stations [6, 9].

Fig. 3. (a)-(f) are the lidar signals calculated by the analytical model (orange solid lines) and measured by the lidar (blue solid lines with error bars) at Stations 1-6, respectively.

3.2 Phase function effects

The effective 180° VSF $\beta_p'^\pi$ can be obtained from the simulated signals. $\beta_m'^\pi$ is assumed to be equal to true molecular 180° VSF β_m^π because the molecular VSF is smooth in the backward direction. Figures 4(a)-4(c) show the simulation results of Cases A-C, respectively. The true 180° particulate VSFs β_p^π (dashed lines) that are the products of the scattering coefficients and phase

functions at 180° remain constant with depth. The effective 180° particulate VSFs $\beta_p'^\pi$ (solid lines) typically remain consistent with β_p^π at the water surface but deviate from β_p^π with increasing depth. The degrees of deviations are closely related to the simulation conditions and phase function [10].

Fig. 4. Phase function effects on the effective particulate 180° VSF under (a) Case A (clear ocean, FOV of 50 mrad), (b) Case B (coastal ocean, FOV of 50 mrad) and (c) Case C (coastal ocean, FOV of 200 mrad).

The lidar attenuation coefficient α can be retrieved, as shown in Fig. 5. The sum of the absorption and backscattering coefficients ($a + b_b$) (black dashed lines) is used as a reference because α should be always greater

than $(a + b_b)$ under QSA approximation [3, 11]. The term α is close to $(a + b_b)$ for all phase functions at the water surface and increases with depth because of loss during multiple scattering.

Fig. 5. Phase function effects on the lidar attenuation coefficient under (a) Case A (clear ocean, FOV of 50 mrad), (b) Case B (coastal ocean, FOV of 50 mrad) and (c) Case C (coastal ocean, FOV of 200 mrad).

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