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Polarized ocean Scheimpflug lidar for polarization features measurement of suspended particles in water bodies

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Abstract: Polarized multi-wavelength ocean lidar offers an efficient means of characterizing the size, shape, and concentration of suspended particulate matter in water, thereby playing a pivotal role in comprehending the dynamics of such particles. This paper introduces an optical approach aimed at capturing information encoded in the polarization of the lidar signal, employing polarization angles of 0°, 45°, 90°, and 135°, to analyze suspended particles. A laboratory demonstration utilizing polarized ocean Scheimpflug lidar is presented herein. Experimental findings involving spherical or irregular silicon dioxide particles demonstrate the efficacy of distinguishing between them by analyzing the polarization characteristics of the backward-scattered light. The study involves the measurement of typical suspended particles with varying shapes and the subsequent comparison of their polarization characteristics in Stokes method to validate the proposed approach. The versatility of the laboratory system suggests its potential applicability as a shipborne ocean lidar or even when integrated into submersibles.

1. Introduction

With the advancement of technology, researchers have gained the capability to study large-scale horizontal patterns of phytoplankton[1], suspended particle distribution[2], and optical properties across the sea surface[3]. These studies play a crucial role in estimating upper ocean primary production and understanding the spatial distribution of specific constituents.

Traditionally, remote sensing technologies have been used to observe the color of the ocean and extract information about its constituent properties. Optical properties and particle distribution serve as key parameters for estimating primary production and quantifying the spatial distributions of specific constituents using satellite observations[4]. Inherent optical properties (IOPs), such as the volume scattering function (VSF) [5], polarization[3], and absorption coefficient[6], play a vital role in optical oceanography. However, direct measurement of these parameters presents practical challenges, leading researchers to study suspended particles using in situ detection equipment and sample collection analysis[7-10].

The classification and characterization of suspended particulate matter in water are crucial for understanding various environmental processes, such as sediment transport, water quality assessment, and ecosystem health[11]. Particles in water can exhibit diverse shapes, ranging from irregular aggregates to well-defined geometric forms, each carrying unique information about their origin, behavior, and potential impact on aquatic systems[12]. Accurate identification and classification of different particle shapes are crucial for unraveling the complex dynamics of suspended matter in water[13].

The fundamental issue in optical remote sensing of the ocean is how light propagates in water. The study of light scattering by suspended particles in water forms the basis of ocean optical remote sensing. The significant differences in size distribution and morphology of suspended particles pose great challenges for the inversion and quantitative analysis of remote sensing data. In addition to absorption and scattering, the interaction between light and suspended particles in water also involves changes in the polarization state of light. Describing the polarization scattering characteristics of suspended particles in water as comprehensively as possible is a fundamental problem in both active and passive remote sensing. One of the main difficulties in polarized scattering of suspended particles is the lack of instruments for fast measurement of complex water samples or natural water bodies under field or laboratory conditions.

Motivated by these advancements, this paper presents a novel and compact polarized ocean Scheimpflug lidar system designed for profiling water mediums and distinguishing polarization features of suspended particles. The laboratory-based demonstration system offers an effective measurement polarization information detection with very high spatial and temporal resolution. This research combines field laboratory experiments to evaluate the performance and limitations of ocean lidar systems for suspended particle detection. Specific objectives include developing robust algorithms for retrieving particle properties from lidar signals, investigating the influence of environmental factors on particle scattering characteristics, and assessing the accuracy and reliability of lidar-derived particle measurements through comparison with in-situ data.

In summary, the laboratory experiment on ocean lidar and the utilization of shipborne lidar data for calibration purposes are crucial for the data inversion and system calibration of spaceborne ocean lidar. The detection of polarization characteristics further enhance the capabilities of spaceborne lidar in studying the marine environment. The calibration process involves comparing shipborne and spaceborne lidar measurements to establish accurate calibration parameters for the spaceborne lidar system

2. Specification and methodology

A typical lidar system includes a laser transmitting system, a receiving system and a photoelectric detection system. In this sector, the detailed specifications of the polarized ocean Scheimpflug lidar system would be introduced.

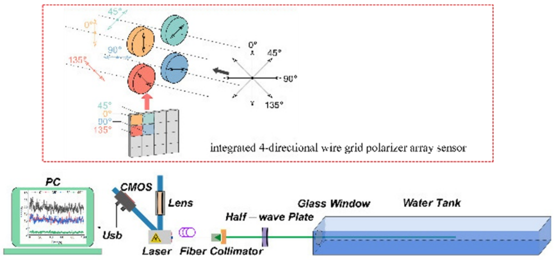


Fig. 1. Schematic of the polarized ocean Scheimpflug lidar system.

The system schematic and equipment selection are shown in Fig. 1 The light source of the system was a 532-nm continuous-wave diode-pumped lasers (DPL) with a nominal power of about 50 mW, and the polarization extinction ratio of the laser beam is beyond 100:1 (Cobolt Calypso 04-01, Cobolt Inc., Solna, Sweden). The lasers emit a laser beam of high quality, characterized by stability, with its power stability being less than 2% under various operating conditions. The detection stability of the system is greatly affected by the radiant power fluctuations of a laser over a short period of time, and the results of subsequent long-duration detection experiments have been analyzed to address this issue. The laser beam has been collimated achromatic fiber collimator (PAF2-7A, Thorlabs Inc., USA) and transmitted into the water medium. The backscattering light was collected by a 25.4 mm plane convex glass with a focus length of 10 cm. The CMOS sensor was mounted at 45°, which accommodated both near and far signals, tilted to the glass plane to satisfy the Scheimpflug principle. The imaging detector utilized in this system is a monochrome 5.0 Megapixel CMOS sensor with integrated 4-directional wire grid polarizer array (CS505MUP1 Thorlabs Inc., USA). Integrating the polarizers between the microlenses and photodiodes minimizes crosstalk and increases alignment accuracy between the polarizer orientations and their respective pixels. Each pixel is covered with one of four linear polarizers with orientations of 0°, 45°, 90° , and 135°. The size of the monochrome CMOS sensor was 2448 × 2048 pixels (approximately 5.0 Megapixel, pixel size: 3.54 μm × 3.54 μm). The quantum efficiency was approximately 72% and the polarization extinction ratio is beyond 291:1 at 532nm.

Stokes method describes polarized light by a four-dimensional vector, which contains information on the intensity and polarization of the light, all parameters are the average of the light intensity on the time scale, this vector S can be expressed as

$$S = [S_0 \quad S_1 \quad S_2 \quad S_3]^T \tag{1}$$

S_0 is the light intensity information, S_1 and S_2 are the linearly polarized light components in the x-axis and 45 ° directions, and S_3 is the circularly polarized light component. If we only consider the linearly polarization parts of the Stokes parameter, we can define the scattered polarizations by Q parameter, U parameter, expressed as

$$Q = S_1 / S_0 \tag{2}$$

$$U = S_2 / S_0 \tag{3}$$

Spherical or irregular silicon dioxide particles were selected as experimental subjects, and their morphology can be obtained from the microscope images in Fig. 2.

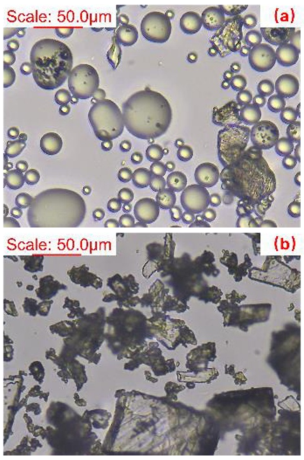
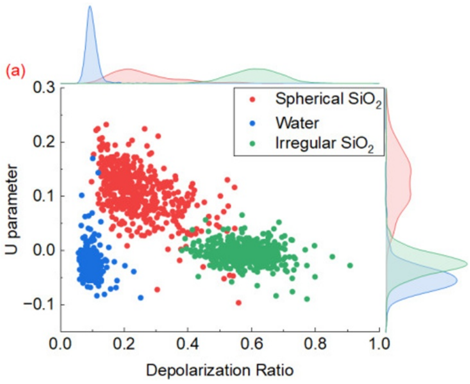


Fig. 2. Images of particles obtained by the microscope. (a) spherical solid silicon dioxide; (b) irregular solid silicon dioxide.

3. Results and Discussion

The difference in depolarization ratio of the three water bodies is very obvious. The depolarization ratio of the water body is about 0.1, and the depolarization ratio distribution of the spherical solid silicon dioxide is relatively flat and concentrated at around 0.22. The depolarization ratio of spherical silica is small and has a certain intersection area with the depolarization ratio of the water medium, which is consistent with the theory of the polarization effect of spherical particles on backscattering signals. At the same time, the irregular shape of silica dioxide leads to a very large depolarization ratio, which is far beyond the tap medium and spherical solid silicon dioxide with a value of about 0.6, showing obvious characteristics that can be used for classification. There is also a small intersection area between the distribution of spherical and irregular solid silicon dioxide depolarization ratios, which may be due to the fact that the depolarization ratios of high-concentration and not very high-purity spherical silica and low-concentration irregular silica are similar. This problem is not easy to control in tank experiments, but it can still prove that polarized ocean Scheimpflug lidar system has great potential for detecting polarization characteristics of suspended particles. The U parameter polarization characterizes the change of polarized backscattering signal in the 45° and 135° direction in Fig. 3 (a) and (b), which can effectively distinguish spherical solid silicon dioxide from other experimental water medium. The combination of depolarization ratio and U parameter can significantly distinguish three different water bodies and suspended particles. The Q parameter and depolarization ratio show completely opposite rules as shown in Fig. 3 (c). The depolarization ratio of irregular solid silicon dioxide is greater than the spherical while spherical solid silicon dioxide is greater than water medium. This is because the more irregular the suspended particle, the worse the linear polarization degree of backscattering signal, but it contains repeated physical meanings of laser backscattering polarization information, its distinguishing effect is not as good as other two parameters combination. Therefore, in different suspended particle experiments, when suspended particle concentration in water medium is high, laser beam polarization characteristics will show obvious distinction. The changes in Q parameter, U parameter and depolarization of beam can better reflect actual situation of particle irregularity in water medium.



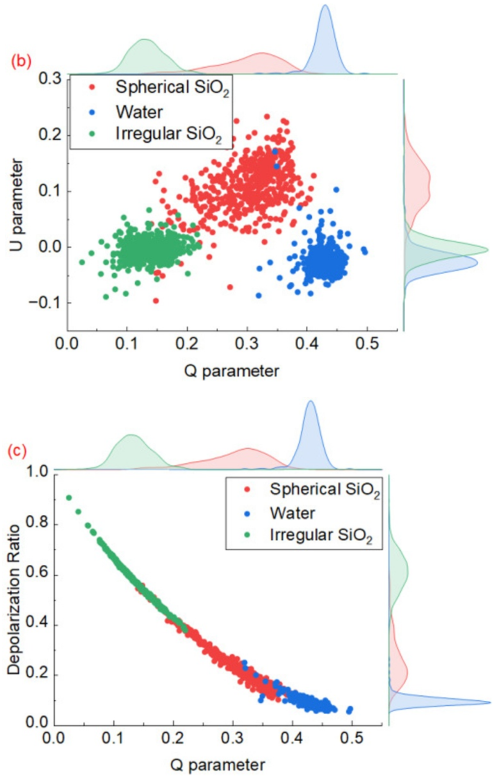


Fig. 3. Marginal distribution curve of optical properties of spherical solid silicon dioxide, water, and irregular solid silicon dioxide: (a) U parameter and depolarization ratio, (b) U parameter and Q parameter, and (c) depolarization ratio and Q parameter.

4. Conclusion

This question focuses on the study of high temporal and spatial resolution remote sensing technology in the detection of backscattered polarization information of suspended particles, and a novel implementation of polarized ocean Scheimpflug Lidar system based on the Scheimpflug principle, utilizing a integrated 4-directional wire grid polarizer array sensor is designed to verify the feasibility of detecting and classifying backscattering characteristics of particles with different sizes and shapes under laboratory conditions. A large number of laboratory detection experiments were completed and microscopic observations were compared and analyzed, and multi-dimensional detection of backscatter polarization information and differentiation of particles of different shapes were achieved.

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