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Characteristics of heterodyne lidar echoes in different polydisperse aerosol environments

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ABSTRACT

The characteristics of heterodyne lidar echoes are related to both the polydisperse aerosols and the polarization state of emitted laser. Based on the database of optical properties of aerosols and clouds(OPAC), we have numerically simulated the backscattering process of photons in different polydisperse aerosol environments using the semi-analytic Monte Carlo method. Then, the backscattering properties of five typical aerosol components in four environments are analyzed within the wavelength range of 1.4–2.1 μm, and the emitted lasers are linear polarized light (LPL) and circular polarized light (CPL). The simulation results show that the degree of polarization (DoP) of lidar echoes is larger by using LPL in the four typical aerosol environments and that the returned photon numbers are less affected by the polarization state of emitted laser pulses. Finally, to achieve the same detection performance, the required laser power ratios are discussed in detail under typical humidities, which is of reference value to the designs and performance analyses of heterodyne lidar systems for atmospheric environment observations with long range and high accuracy.

1. Introduction

Lidar has relatively high temporal–spatial resolution and measurement accuracy, which is a powerful tool for the remote sensing of atmospheric environment. In such applications, the greenhouse gases concentrations and atmospheric wind field can be measured based on the intensity and frequency shift of lidar echoes that are scattered by atmospheric aerosols. To improve the detection range and measurement resolution, the research on heterodyne (coherent) lidars has become increasingly active, especially the coherent Doppler lidar (CDL) and coherent differential absorption lidar (CDIAL), which have been widely adopted in observations of atmospheric wind [1], turbulence [2], aerosol concentration [3], atmospheric constituents [4,5] and air pollutants [6]. The heterodyne detection is used because it has good noise-reducing ability and can achieve nearly quantum limit detection [7]. Different from the direct detections, there are many matching conditions need to be met, such as the matching of polarization and wavefront [8]. In this paper, we mainly focus on the polarization and intensity properties of lidar echoes backscattered by polydisperse aerosol particles.

Generally, the polarization properties of lidar returns are influenced by many factors [9,10], such as the state of polarization (SOP) of incident beam and the scattering particle parameters including the particle number density, size distribution, shape, humidity [11] and complex refractive index (CRI). The polarization mismatch between the lidar return and local oscillator (LO) can reduce the coherent efficiency and thus deteriorate the detection performance [12]. To solve this mismatch, comprehensive studies of

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the polarization diversity reception (PDR) have been carried out [13,14], which prove the validity of PDR. However, the degree of polarization (DoP) imposes the upper limit that the backscattered light can be effectively utilized in heterodyne detection [15], which needs to be explored in depth. In previous research, the polarization properties of backscattered light are analyzed mainly based on the monodisperse particles [16–18] or the same type of particles with different sizes [9], in which the Monte Carlo (MC) method is widely used. Nevertheless, in actual atmospheric environments, there are obvious variations in the aerosol components and particle size distributions, which are polydisperse [19], and the backscattering properties change a lot with the aerosol particle parameters. As a result, the analyses of scattering properties based on monodisperse aerosols may bring big errors than that using polydisperse aerosols. Moreover, in practical heterodyne lidar systems, the emitted lasers are usually linearly polarized light (LPL) [3] and circularly polarized light (CPL) [4] due to the structures of optical transceivers, and the polarization properties of the backscattered field could be different under diverse SOPs of incident lasers. Thus, a more realistic and practical analysis of lidar echoes is needed in different polydisperse aerosol environments.

In this paper, the echoing characteristics in four typical aerosol environments are investigated based on the OPAC (Optical Properties of Aerosols and Clouds) database [19], which provides the optical parameters of 10 kinds of aerosol particles and 10 typical aerosol environments at 61 wavelengths. It is convenient to use OPAC to model climate relevant optical properties of atmospheric particulate constituents for individual cases. The optical characteristics in OPAC database are calculated with the Mie theory, and the components in each aerosol environment are applicable to the average conditions. The quantitative investigations on the backscattering process of polarized light in aerosol environments are conducted by considering different aerosol species, radius, humidity and the SOPs of emitted lasers. The DoP and backscattered photon numbers are discussed in detail, which offers the reference for understanding the depolarization behavior of atmospheric aerosols better and improving heterodyne lidar performances.

2. Theoretical background

2.1. Heterodyne lidar for atmosphere detection

The pulsed heterodyne lidars for atmospheric detection have similar structures which are shown in Fig. 1(a). Optical fiber devices are widely adopted to improve the system compactness and the anti-interference ability. The lidar returns are coupled into fiber and then mixed with LO to achieve the heterodyne detection. The LO is frequency-shifted by the acousto-optic modulator (AOM). There are two kinds of optical transceivers which are shown in Fig. 1(b) and (c). In the all-fiber heterodyne lidar systems, the fiber circulator is used to achieve the isolation between receiver and transmitter, and the output laser is LPL. The isolation can be also realized by PBS (polarization beam splitter) and wave-plates, and the emitted light is CPL. Heterodyne lidar with the pulse width of τ has the spatial resolution of $\Delta R = c\tau/2$, and the backscattering properties at different ranges can be measured. In actual atmosphere, there are also multi-scatterings between aerosol particles, which reduces the DoP of the backscattered field.

The PDR method can be used to improve the matching degree of LO and signal, and thus the depolarization ratio is not the focus of this paper. The detailed PDR structure in Fig. 1(a) can be found in our previous work [13], and the improvement of conventional PDR is achieved by monitoring the power of LO after the two outputs of PBS, making it valid in situations where the LO and scattered field are both elliptically polarized light (EPL) and LPL.

2.2. Monte Carlo method and simulation

The Monte Carlo method has great flexibility and the number of simulated samples can be adjusted according to the required precision. The results of Monte Carlo simulation have shown good agreements with experiment measurements [20,21]. In the scattering simulation of polarized light, we assume that the polydisperse aerosols are well mixed. The aerosol particles in each

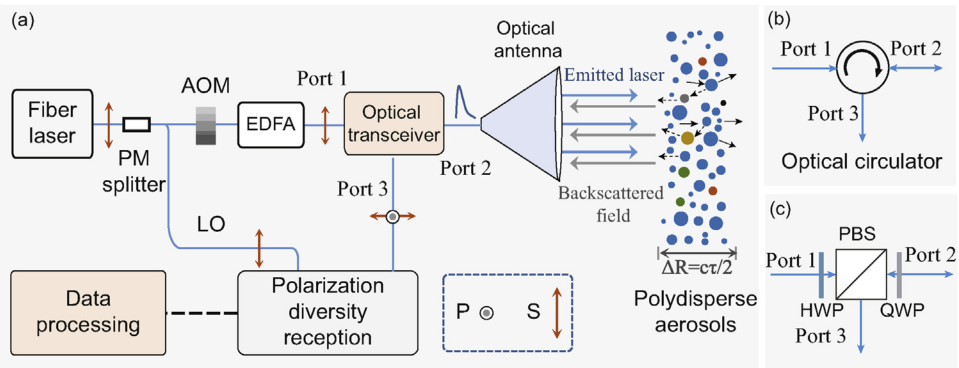

Fig. 1. Typical structures of the pulsed heterodyne lidars based on the backscattered field of polydisperse aerosols. (a) Structures of heterodyne lidar system using optical fiber devices; (b) the optical transceiver based on optical fiber circulator, the emitted laser is LPL; (c) the optical transceiver based on PBS, quarter wave plate (QWP) and half wave plate (HWP), the emitted laser is CPL.