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Two-wavelength Lidar inversion algorithm for determining planetary boundary layer height

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ABSTRACT

This study proposes a two-wavelength Lidar inversion algorithm to determine the boundary layer height (BLH) based on the particles clustering. Color ratio and depolarization ratio are used to analyze the particle distribution, based on which the proposed algorithm can overcome the effects of complex aerosol layers to calculate the BLH. The algorithm is used to determine the top of the boundary layer under different mixing state. Experimental results demonstrate that the proposed algorithm can determine the top of the boundary layer even in a complex case. Moreover, it can better deal with the weak convection conditions. Finally, experimental data from June 2015 to December 2015 were used to verify the reliability of the proposed algorithm. The correlation between the results of the proposed algorithm and the manual method is $R^2 = 0.89$ with a RMSE of 131 m and mean bias of 49 m; the correlation between the results of the ideal profile fitting method and the manual method is $R^2 = 0.64$ with a RMSE of 270 m and a mean bias of 165 m; and the correlation between the results of the wavelet covariance transform method and manual method is $R^2 = 0.76$, with a RMSE of 196 m and mean bias of 23 m. These findings indicate that the proposed algorithm has better reliability and stability than traditional algorithms.

1. Introduction

The planetary boundary layer (PBL) is the layer of the Earth's surface atmosphere, which is directly influenced human activity, and by surface atmospheric conditions [21]. The PBL has a considerable impact on local and regional environmental health and is important in weather forecasting model [19]. The heating process of solar radiation for the surface is also achieved through PBL dynamics. Furthermore, atmospheric activity in the PBL will affect cloud nuclei propagation and pollutant dispersion [6]. Therefore, the PBL is extremely significant for environmental health and human activities. It is also essential for conducting continuous observation of the boundary layer height (BLH) with accurate means of detection.

The vertical structure of the atmospheric boundary layer includes the near-surface layer, mixed layer and entrainment layer [21]. Aerosol particles are abundant within the boundary layer. Moreover, there is free atmosphere with mostly atmospheric molecules and few aerosol particles above the boundary layer. Currently, a variety of remote sensing detection technologies are used for boundary layer observation, including acoustic (sonic detection and ranging), optical (Lidar, ceilometers) and electromagnetic (radiosondes, Doppler radar) remote sensing [22]. Radiosonde is the most common measurement technique used for thermodynamic profiles. Radiosonde data can be used to determine BLH based on the vertical profiles of meteorological parameters [27]. However, the spatial resolution of this method is very low. The Lidar system has become a major means in the study of the boundary layer because of its active remote sensing equipment, which have a high temporal and spatial resolution. It can be used to investigate the evolution, optical and physical properties of the main components of the atmosphere [5,15,18]. Traditional Lidar algorithms depend on the aerosol concentration to calculate BLH. The maximum gradient position is regarded as the BLH. The Lidar algorithm for retrieving the BLH mainly includes the gradient method [11], wavelet covariance transform (WCT) method [2], and ideal profile fitting method [12]. The gradient method defines the maximum gradient position of the aerosol profile as the top of the boundary layer. WCT method can reduce the impact of noise because the operator can choose an appropriate base function and set an appropriate threshold. The ideal profile fitting method, developed by Steyn et al. [23], is an effective method for delineating well-mixed boundary layers. These methods are based on the single wavelength Lidar signal to

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calculate BLH. This means that those methods detect the BLH using aerosols as tracers, and that BLH is inferred from the aerosol concentration profile [1,5,13]. However, when the vertical distribution of aerosols becomes nonuniform or is affected by multi-layer aerosols, determining BLH accurately using these Lidar algorithms becomes difficult [24,25]. Therefore, more robust and effective algorithms are needed to alleviate this problem.

In recent years, the multi-wavelength Lidar has been widely used in atmospheric research. Aerosol color ratio and depolarization ratio can be obtained through dual-wavelength information. Sugimoto [20] investigated dust and anthropogenic aerosol plumes by using two-wavelength polarization Lidar, and showed that the properties of atmospheric particles differ at different heights. Burton [3] indicated that different types of aerosols have different color ratio and depolarization ratio. Groß [10] classified aerosols based on airborne high spectral resolution Lidar observations, and found that the same aerosol type can be together in a cluster. Lu [17] analyzed the atmospheric vertical characteristics based on a two-wavelength Lidar inversion algorithm. The multi-wavelength information can reduce the parameters of the hypothesis in atmospheric studies. For this reason, multi-wavelength information can be used to calculate BLH.

In the current research, we proposed a two-wavelength Lidar inversion algorithm to determine BLH based on the particle distribution. The algorithm is called the particle distribution method (PDM) in following text. The aerosol color ratio and depolarization ratio were used to establish the particle distribution, which were then used to retrieve BLH. Next, the algorithm was used to determine the BLH under different boundary layer mixing state. Experimental results demonstrate that the PDM algorithm is more stable in determining the BLH compared with traditional methods. In particular, it can identify the boundary layer accurately under weak convection condition where the traditional methods cannot be applied. Finally, experimental data from June 2015 to December 2015 verified the stability of the algorithm. The results indicate that the new method not only possesses better feasibility than traditional methods, but also maintains comparable stability.

2. Instrumentation

The two-wavelength polarization Lidar system used in this study is located at Wuhan University (114°21′E, 30°32′N), China, on the roof of the Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing. The instrument is positioned 39 m above sea level and is surrounded by buildings [26]. The two-wavelength polarization Lidar system consists of a laser transmitter system, a receiving telescope, and data acquisition and processing sub-systems. The Lidar transmitter functions at 532 and 355 nm with the aid of a ND: YAG pulse laser. The signals are detected by the photomultiplier tubes (PMTs) and are fed into an amplifier. The outputs of the amplifier are connected to a PC-based data acquisition system. The system provides a backscatter signal with a temporal resolution higher than 1 s and a vertical spatial resolution higher than 7.5 m. In terms of instrument calibration, the channel gain constant is measured every day before signal acquisition begin. We cover the receiving telescope and construct the system in normal working conditions. When the system is in a stable working state after five minutes, the data collected by Licel are used as the channel gain constant. Then, the acquired signal subtracts the gain constant to correct the acquired signal. The 45°-calibration with a polarizing sheet filter was applied to calibrate the depolarization channels under a cloudless weather condition [9]. A polarizing sheet filter was placed before the polarizing prism when calibrate the depolarization channels. According to rotate the angle of polarizing sheet filter, the polarizing signal from the parallel (//) or perpendicular (⊥) channel could be obtained. The ratio of the signal intensity of the parallel and perpendicular channel is the calibrated constant of the depolarization channel. Additional details can be seen in a previous study [16]. Experimental data acquired from the Wuhan University ground-based Lidar system from June 2015 to December 2015 tested the proposed algorithm.

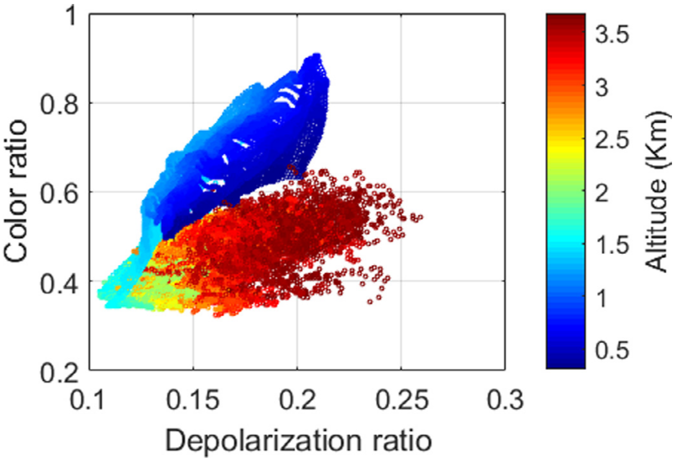

Fig. 1. Scatter plots of color ratio and depolarization ratio on 7 December 2015. The color bar represents the altitude information. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

3. Methodology

3.1. Theory

The development of Lidar system provided the more wavelength information in the study of the boundary layer. Sugimoto's [20] research shows that atmospheric particles at different heights have different color ratio and depolarization ratio. Our previous research indicates that particles with large color ratio are distributed in the near ground (below 2 km); the distribution of the depolarization ratio is uniform over the vertical structure [16]. Fig. 1 shows the relationship between color ratio and depolarization ratio. The color bar represents the altitude. The distribution shows that different particles are distributed in different areas. Most of the particles in the upper atmosphere (above 1500 m) are molecular particles, and are therefore concentrated in the red area with a low color ratio. However, atmospheric particles near the ground (below 1000 m) are mainly aerosol particles, and are concentrated in the black area, with a high color ratio. Similar particles gather together. Therefore, we aimed to determine the top of the boundary layer based on the particles distribution.

3.2. Method

An algorithm based on the particles distribution was proposed to calculate the top of the boundary layer. Fig. 2 shows the flowchart of the PDM algorithm. First, the color ratio and the depolarization ratio are used to form the sample sequence x(i). Second, according to the clustering algorithm, the sample sequence is divided into two categories. The categories sequence f(i) is then used to calculate the BLH. Finally, the centroid of the cluster is employed to confirm the threshold value that will be used to filter the point of error. The more detailed procedure is as follows:

The single channel Lidar equation can be written as ([7,8]; 1984):

$$P(i) = CP_0 i^{-2}[\beta m(i) + \beta a(i)]\exp[-2\int_0^i [\alpha m(i) + \alpha a(i)]di] \tag{1}$$

where i is the altitude, $P(i)$ represents the received Lidar signal, C is a channel calibration constant, P_0 is an output pulse energy, $\beta_m(i)$