

Detection and study of boundary layer height in Beijing urban area using atmospheric aerosol lidar

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Abstract: A multi-wavelength aerosol lidar (MWAL) with 355 nm, 532 nm and 1064 nm has been developed and deployed for operational observations at Haidian District Meteorological Service of Beijing. The structure design, specifications, observation campaign and detection principle of the MWAL are presented and the retrieval method of boundary layer height is introduced. By comparing it with the data of digital radiosonde, it is verified that the first normalized gradient of range corrected signal can more accurately retrieve boundary layer height. The typical daily variation characteristics and influencing factors of urban boundary layer height are analysed through observation examples, and the monthly mean value of boundary layer height in 2019 is acquired and analysed.

1. Introduction

The atmospheric boundary layer (ABL) is the lowest layer of the atmosphere directly affected by the ground, serving as a bridge for material and energy exchange in the earth atmosphere system. The relationship between the ABL and human activities is the closest and most direct, and air pollution problems mainly occur in the ABL [1,2].

Because the ground is the main source of aerosols, the concentration of aerosols in the ABL is significantly higher than that in the free atmosphere above the ABL. The vertical structure of the ABL is closely related to the spatial distribution of aerosols [3].

The urban area of Beijing has typical urban underlying surface characteristics. Studying the structure of the ABL in the urban area of Beijing will help to understand the structural characteristics of the urban ABL, play an important role in evaluating the distribution and diffusion of atmospheric pollutants, and have important significance for urban meteorological research and meteorological support [4,5].

Lidar provides a new technical method for the study of ABL, which can use the vertical profile data of atmospheric aerosols to retrieve the the boundary layer height (BLH). By utilizing long-

term observation data from lidar, the spatiotemporal distribution characteristics of the ABL can be obtained [6,7].

A multi-wavelength aerosol lidar (MWAL) with 355 nm, 532 nm and 1064 nm designed and developed by Institute of Oceanographic Instrumentation, Qilu University of Technology (Shandong Academy of Sciences) was deployed at Haidian District Meteorological Service of Beijing for operational observations. The structure, specifications, observation campaign and detection principle are presented. The retrieval method of BLH is introduced and compared with the data of GTS1 digital radiosonde to verify the reliability of the method. Through long-term continuous observation, the daily and monthly variations of the ABL in the urban area of Beijing are analysed.

2. The Aerosol Lidar and Observation Campaign

The aerosol lidar with three-wavelength lasers of 355 nm, 532 nm and 1064 nm has been developed by the Institute of Oceanographic Instrumentation, Qilu University of Technology (Shandong Academy of Sciences) for automatic observations of tropospheric aerosols and clouds. The echo signals are received by a Schmidt-Cassegrain telescope with a diameter

of 12 inch. The optical receiving system has six channels, which respectively obtain elastic scattering signals at 355 nm and 1064 nm, the 532 nm parallel polarization (532 nm-P) and perpendicular polarization (532 nm-S) signals, and N₂ Raman scattering signals at 387 nm and 607 nm. The optical structure of MWAL is shown in Figure 1.

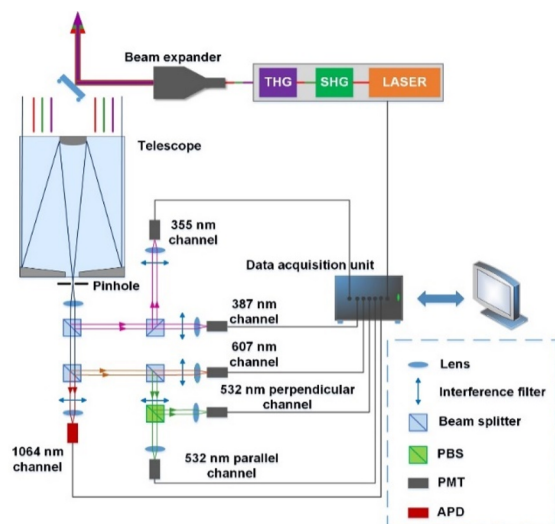


Figure 1. The structure of MWAL

The specifications of MWAL are shown in Table 1.

Table 1. The Specifications of MWAL

Parameters	Specifications
Transmitter	
Laser type	Lamp-pumped Nd:YAG
Wavelength	355 nm, 532 nm & 1064 nm
Pulse energy	40 mJ@ 355 nm, 30 mJ@532 nm, 60 mJ@1064 nm
Pulse duration	10 ns
Repetition frequency	20 Hz
Beam divergence	200 μrad
Receiver	
Type	Schmidt-Cassegrain
Diameter	300 mm
Field of View	500 μrad
Range resolution	15 m
Receiving channels	355 nm, 387 nm, 532 nm-P, 532nm-S, 607 nm & 1064 nm
Detector type	APD for 1064 nm; PMT for 355 nm, 387 nm, 532 nm-P, 532nm-S & 607 nm

The MWAL is deployed at the Haidian Park Observation Site (39° 59' N, 116° 17' E) of the Haidian District Meteorological Service (HDMS) of Beijing to conduct all-day operational observations. The GTS1 digital radiosonde carried by hydrogen balloon is usually released at 7:15 and 19:15 local time every day to obtain the profiles of the meteorological elements such as temperature, humidity, wind, and pressure.

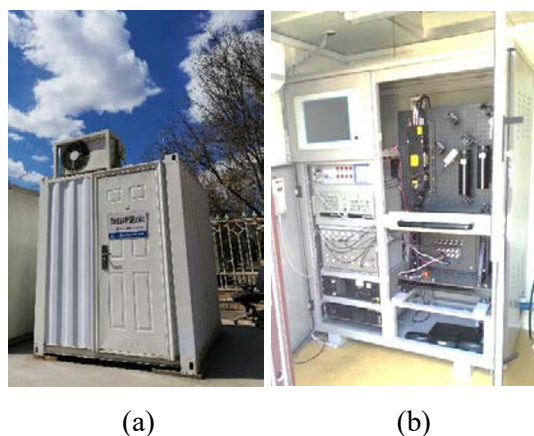


Figure 2. The observation site figure (a) and the internal structure (b) of MWAL

3. The BLH Determination

Generally, there is a very strong temperature inversion at the top of the ABL, limiting the upward diffusion of pollutants and water vapor. Correspondingly, there are very strong positive gradient of potential temperature (PT) and negative gradient of relative humidity (RH) at the top of the boundary layer. Therefore, the temperature and humidity profiles of radiosonde data can be used to obtain the BLH[8].

The high spatial and temporal resolution makes aerosol lidar to be one of the most suitable systems for continuous monitoring the structure of ABL. Generally, the aerosol concentration in the ABL is significantly higher than that in the free atmosphere above the ABL. Accordingly, the gradient of the lidar signal profile exhibits a strong negative peak at the top of ABL. Gradient algorithms are widely used in retrieving the BLH, including the first gradient of raw signal (G-Raw), the first normalized gradient of raw signal (NG-Raw), the first gradient of the RCS (G-RCS) and the first normalized gradient of RCS (NG-RCS). The BLH is defined at the altitude where the gradient reaches a minimum.

The G-Raw can be obtained by

$$D_{G\text{-Raw}}(z) = \frac{\Delta P(z)}{\Delta z}. \quad (1)$$

The calculation method of NG-Raw is

$$D_{NG\text{-Raw}}(z) = \frac{\Delta P(z)}{\Delta z \times P(z)}. \quad (2)$$

The G-RCS can be calculated by the equation:

$$D_{G\text{-RCS}}(z) = \frac{\Delta RCS(z)}{\Delta z}. \quad (3)$$

The calculation method of NG-RCS is shown below:

$$D_{NG\text{-RCS}}(z) = \frac{\Delta RCS(z)}{\Delta z \times RCS(z)}. \quad (4)$$

In this work, we mainly use 1064 nm echo signal for the BLH retrieving, due to its stronger penetration for atmospheric particulate matter compared to 532 nm and 355 nm. As shown in Figure 3, four gradient methods are used to retrieve the BLH and compared with the profiles of the PT and RH to determine the method. The minimum gradient obtained by the G-Raw and NG-Raw methods will cause misjudgment of the BLH. The position of the minimum gradient obtained by the other methods is basically the same, corresponding to the altitude of about 1.375 km. The relative humidity and potential temperature profiles obtained by the digital radiosonde also show significant gradient changes at an altitude of 1.375 km, indicating that 1.375 km is the location of the BLH.

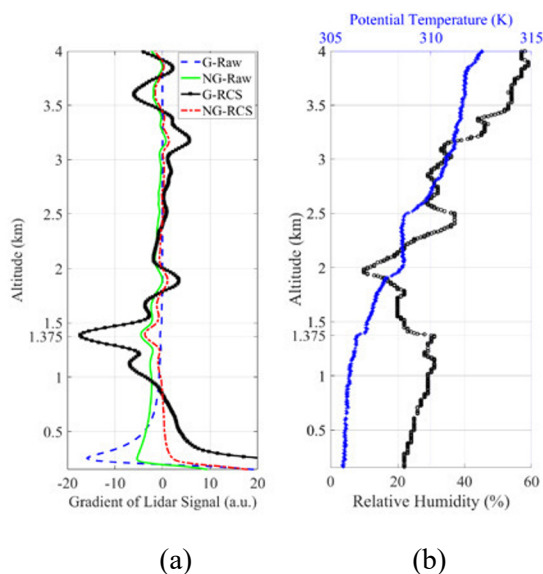


Figure 3. The profiles of gradient signals of lidar (a), PT and RH (b)

Compared to the G-RCS, the NG-RCS method can more effectively suppress signal jitter, so we mainly used the NG-RCS method.

The main retrieving process of the BLH is shown in Figure 4.

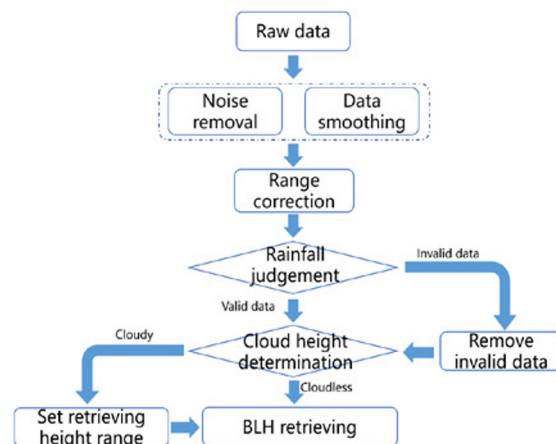


Figure 4. The retrieving process of the BLH

4. Results and Discussion

The BLH varies with time and space. Usually, under clear weather conditions, the structure of the urban ABL has typical diurnal variation characteristics. The nighttime ABL is generally referred to as the stable boundary layer, and its height is lower than that of the daytime ABL. However, at night, due to the presence of residual layers, the BLH retrieved by the gradient method of lidar is usually higher than the stable boundary layer.

Figures 5 and 6 show the Time-Height-Indicator (THI) figures of 24 hours of continuous observation data of lidar on October 27, 2019 and June 16, 2020, respectively, along with the variation curve of the mean value of BLH (black dotted lines in the THI figures). Both figures have diurnal variation characteristics of BLH. During the day, the BLH rises with the increase of temperature, with the mean value of BLH higher than that at night. With the temperature decreasing at night, the BLH gradually decreases.

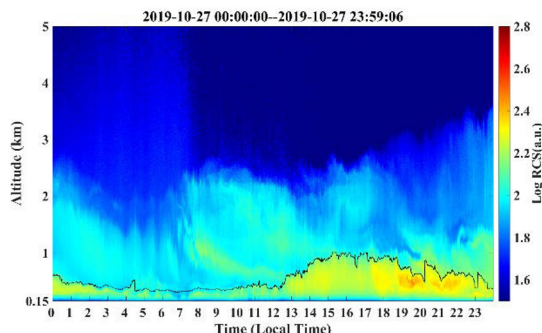


Figure 5. The THI figure of lidar signal on October 27, 2019

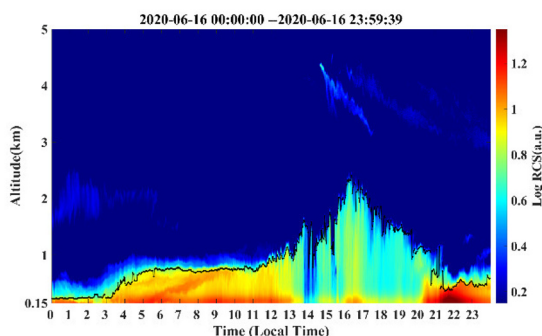


Figure 6. The THI figure of lidar signal on June 16, 2020

Figure 7 shows the maximum (Max-BLH), mean (Mean-BLH), and minimum (Min-BLH) values of the BLH at different times in January. The mean value curve shows that the BLH increases from 11 o'clock and reaches its maximum value at 15 o'clock. The trend of the mean value of BLH is consistent with the daily variation characteristics of the ABL. The mean value of BLH in January 2019 is approximately 0.75 km by calculation.

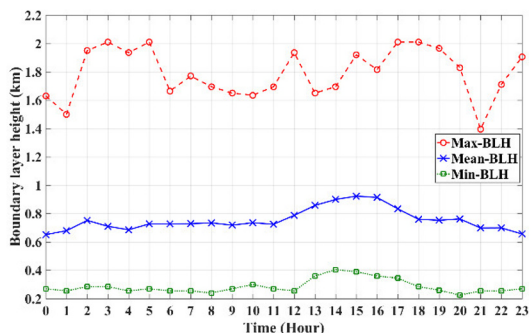


Figure 7. Variation curves of BLH in January 2019

Using effective observation data of MWAL in 2019, the monthly mean value of BLH is acquired, as shown in Figure 8. The average BLH of August is highest, The BLH is lower in

winter and autumn, and higher in spring and summer.

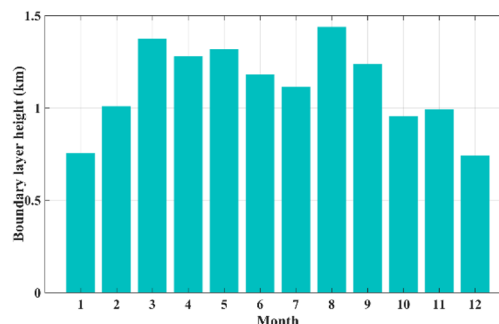


Figure 8. Monthly mean value variation of BLH in 2019

5. Conclusions

This study conducts research on retrieval method and structural feature analysis of BLH using an aerosol lidar, providing research methods and technical solutions for the study of ABL. For future work, we will analyse the retrieval results of BLH using different wavelengths and compare the results of this algorithm with other state-of-the-art approaches.

Acknowledgements

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