Analysis of Observation Performance of a Mobile Coherent Doppler Wind Lidar Using DBS Scanning Mode

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Abstract. The Coherent Doppler Wind Lidar (CDWL) is one of the important remote sensing devices for atmospheric boundary layer wind field observation, it has broad application prospects in the fields of meteorological monitoring and warning, air pollution transportation and aviation safety. In order to test the observation performance of the CDWL using Doppler beam-swinging (DBS) scanning mode, description of the CDWL is introduced, and the main influencing factors of the CDWL observation accuracy is studied, the comparative observation experiments were carried out at the Anqing National Conventional Sounding Station (30°37″ N, 116°58″ E) during the course of Typhoon Rumbia (No. 18, 2018) from August 16 to August 26, 2018. The results show that: the wind observation accuracy is determined by the carrier-to-noise ratio (CNR) of the CDWL. In the precipitation conditions, the effective data acquisition rates of 1.5km and 2.0km detection height are only 46.2% and 38.8%, respectively, and it was even difficult to continue operation. Under clear sky conditions, it could operate continuously, and the effective data acquisition rates of 1.5km and 2.0km detection height were 85.4% and 64.4%. In addition, the correlation of wind direction and wind speed between the CDWL and the conventional sounding system (L-band secondary wind-finding radar) was 1.041 and 0.982, and the consistency is good. Based on the sounding, the wind direction and wind speed errors of the CDWL during the comparison experiment were 0.82m/s and 9.3°.

Keywords: Coherent Doppler Wind Lidar (CDWL), Observation performance, Doppler beam-swinging (DBS) scanning, Wind direction and Wind speed, Comparison experiment

1. Introduction

The character of the boundary layer in severe convective storms, especially under low-level mesocyclones and in tornados is critical to our full understanding of tornado dynamics and tornadogenesis. Currently, our knowledge of the boundary layer is based almost on numerical simulations and theory under highly idealized conditions [1,2], there are few fine observations of the wind field profile at low levels. According to the literature [3-5], the instruments widely used in low-level wind and wind shear observation mainly include: ultrasonic anemometer, Doppler acoustic radar and microwave weather radar. However, the ultrasonic anemometer is a point measuring instrument, which can only be used to obtain the wind speed information of a single point in space, and cannot...
obtain the spatial distribution of the entire wind field, so its application in wind shear measurement is limited. The Doppler acoustic radar has insufficient measurement capabilities near the ground, and can only measure wind field information at a height of several tens of meters; at the same time, its beam direction is fixed and immovable, and it can only measure above the radar. The observation signals of the microwave weather radar are mainly the scattering signals of large particles such as rain, snow and ice. The observation performance of the microwave weather radar is low in the weather with clear sky and few clouds or the environment with low aerosol density. At the same time, the microwave weather radar is relatively large, has poor mobility and poor range resolution.

The Coherent Doppler Wind Lidar (CDWL) is one of the important remote sensing devices for atmospheric boundary layer wind field observation with high temporal and spatial resolution [6-8]. It has broad application prospects in the fields of meteorological monitoring and early warning, air pollution transportation and aviation safety. However, precise wind field measurement under rainy conditions is a challenge, due to the presence of interfering signals from raindrop reflections.

In this work, the main factors affecting CDWL observation performance is analyzed, the accuracy of CDWL is evaluated by comparison with the sounding.

2. Observation Principles and Methods

During lidar observation, laser beams are emitted along the true north, true east, and zenith directions, and the lidar backscattered signal is processed to obtain the basic data along different beam directions and different distances. Let \( v_{nx}, v_{xe}, v_{nz} \) be the observed values of the radial velocity of the three beams along true north, true east, and zenith respectively, the sign is defined as positive when the movement is toward the lidar, and vice versa. \( u, v, w \) are the projection components on the true east, true north, and vertical coordinate axes respectively, pointing to the true east, True North, and Zenith are positive. Under the assumption of uniform atmospheric level, the relationship between the radial velocity and the three components of \( u, v, w \) can be derived from the geometric relationship as:

\[
\begin{align*}
    u &= \frac{v_{nx} - v_{nz} \cos \theta}{\sin \theta} \\
    v &= \frac{v_{xe} - v_{ez} \cos \theta}{\sin \theta} \\
    w &= v_{nz}
\end{align*}
\]  

(1)

In the formula (1), \( \theta \) is the deflection angle, that is, the angle between the oblique beam and the vertical beam. In meteorology, wind speed is often broken down into horizontal wind and vertical wind. The horizontal wind speed is denoted as \( V_H \), the horizontal wind direction is denoted as \( \alpha_H \), and the direction of the horizontal wind is specified as the wind direction of the horizontal wind. The azimuth angle is represented by \( \varphi \), and the horizontal wind direction is \( \alpha_H = \varphi + \pi \), and the relationship between the components of horizontal wind \( V_H \) and \( u, v \) can be obtained as:

\[
\begin{align*}
    V_H &= u \sin \varphi + v \cos \varphi \\
    \alpha_H &= \varphi + \pi; \quad \varphi = \arctan \frac{u}{v}
\end{align*}
\]  

(2)

Combining formulas (1) and (2), and \( V_v = \frac{1}{2}\sqrt{\frac{f}{f}} \), it is well known that the estimation accuracy of wind is also the estimation accuracy of Doppler shift [9]. Usually, under clear sky conditions, lidar receives aerosol backscattered echo, and the power spectrum is basically aerosol spectrum. But under precipitation conditions, the received backscattering signal may contain two components [10], the aerosol and rainfall signal. From the Doppler power spectrum, two peaks can be observed if the wind
and the rainfall velocities are different. A two-component Gaussian model is often used to fit the two-peak spectrum. A least squares fit is applied to determine model is often used to fit the two-peak spectrum [11-12], and applied to determine the Doppler frequency shift, signal power and spectral width information from the wind and precipitation signals.

3. Instrument
The CDWL is composed of lasers, telescopes, photodetectors, digital signal processors and terminal software. The CDWL is a mobile portable system with a telescope aperture of 80mm, working wavelength of 1.548nm, transmitting pulse energy of 110uJ, pulse repetition frequency of 10 kHz, and spatial resolution of 60m (figure 1; table 1), the system adopts all-optical fiber technology and fast digital signal processing technology to achieve the miniaturization of the CDWL system, and works in a Doppler beam-swinging(DBS) scanning mode which has three pointing directions, the one is vertical direction, while the other two are north and west with an elevation angle of 60°, then realizes the function of real-time estimation of wind speed and direction from three radial wind profiles based on the assumption of horizontally homogeneous wind field.

![Figure 1. The CDWL configured at Anqing National Conventional Sounding Station (30°37″ N, 116°58″ E)](image)

| Parameter                | Value             |
|--------------------------|-------------------|
| Wavelength               | 1548 nm           |
| Pulse duration           | 300 ns            |
| Pulse energy             | 110 uJ            |
| Repetition frequency     | 10 kHz            |
| Diameter of telescope    | 80 mm             |
| Spatial resolution       | 60 m              |
| Temporal resolution      | 2 s               |
| Maximum range            | 15 km             |
| Azimuth scanning range   | 0-360°            |
| Zenith scanning range    | 0-90°             |
4. Comparison Experiments

To assess the observation performance of the CDWL, the comparison experiment is carried out during the course of Typhoon Rumbia (No. 18, 2018) from August 16 to August 26, 2018, at the Anqing National Conventional Sounding Station (30°37′N, 116°58′E). The wind speed and direction were measured by tracing the GTS1 digital radiosonde carried by weather balloons using L-band secondary wind finding radar. Figure 2 shows the time-sections of CNR observed vertically, horizontal wind direction, and wind speed on 19 and 21 Aug. 2018. The value of CNR directly affects the recognition of Doppler frequency shift, and it is susceptible to interference from cloud and rain particles. We find that precipitation occurs, the data acquisition rate is low. In contrast, it is relatively high in the absence of precipitation. The effective data acquisition rates of 1.5km and 2.0km detection height are only 46.2% and 38.8% during the typhoon-induced precipitation, however they are 85.4% and 64.4% in fine weather. Figure 3 shows the horizontal wind and direction profiles measured by Doppler wind lidar and sounding on August 21th, 2018, their trends are basically the same. Through correlation analysis, the correlation between the wind direction and wind speed data obtained by the two devices is 1.041 and 0.982. Statistical analysis of 398 pairs of data collection during the comparison experiment as shown in figure 4, the wind direction and wind speed errors of the CDWL are 9.3°and 0.82m/s.

Figure 2. Continuous observation results on August 19th and 21th, 2018. (a) Time-height plot of vertical radial CNR, (b) horizontal wind speed and (c) horizontal wind direction.
Figure 3. Wind profiles measured by the CDWL and sounding on August 21th, 2018.

Figure 4. Statistics of the error in wind measurements between the CDWL and Sounding. (left) Histogram distributions of wind speed error, (right) wind direction error.

4. Conclusions
From the results of comparative observation experiments, the CDWL using a DBS scanning mode has superior wind detection capabilities and high comparability. The wind observation accuracy is determined by the CNR of the CDWL. In the precipitation conditions, the effective data acquisition rates of 1.5km and 2.0km observation height are only 46.2% and 38.8%, respectively, and it was even difficult to continue operation. Under clear sky conditions, it could operate continuously, and the effective data acquisition rates of 1.5km and 2.0km detection height were 85.4% and 64.4%. In addition, the correlation of wind direction and wind speed between the CDWL and sounding was 1.041 and 0.982. Based on the sounding, the wind direction and wind speed errors of the CDWL during the comparison experiment were 0.82m/s and 9.3°. However, the back-scattered echoes are easily affected by cloud and rain particles, which make the data acquisition rate in the precipitation period lower. In the future, we will combine multiple observation instruments, and study the echo power spectrum of aerosol, cloud and rain particles, and improve low-level wind field observation capabilities under complex conditions.

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