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Retrieval of Mesospheric Neutral Wind Based on AgileDARN HF Radar

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Abstract—In this paper, the inversion method of mesospheric neutral wind is studied based on mid-latitude AgileDARN HF radar. Firstly, the meteor target observation method is carried out using 7.5 km range resolution and 2 s integration time. Then, the method of extracting the meteor echo from the data according to the doppler characteristics of the meteor is studied. Finally, the meridional and zonal components of mesospheric neutral wind are obtained by singular value decomposition method based on doppler velocity of meteor echo. The data analysis shows that the meteor echo has the highest incidence in the morning of local time and the lowest incidence in the evening of local time. The semi-diurnal characteristics of tidal waves can be seen from the meridional and zonal components of mesospheric neutral wind. Aiming at the ambiguity of elevation Angle measured by AgileDARN HF radar, a method is proposed to reduce the ambiguity of elevation angle, and the wind field profile of mesospheric neutral wind along altitude is obtained, which lays a foundation for the subsequent study of gravity wave, tidal wave, and planetary wave based on mesospheric wind field.

1. INTRODUCTION

Mesospheric neutral winds are produced by the complex interaction of the earth's atmosphere [1–3]. The fluctuation of mesospheric neutral wind is of great value to the study of gravity waves, tides, and planetary waves [4]. A large number of meteoroids enter the Earth's atmosphere every day [5]; meteoroids interact with the atmosphere to form ionized meteor trails; and part of the signals emitted by radar are reflected back when they meet the meteor trails and are received by radar to form meteor echoes. Driven by neutral wind, the drift of meteor trails produces Doppler velocity; therefore, meteor echo can be used to invert the neutral wind [6, 7]. VHF meteor radar is a special equipment for meteor observation. It can invert mesospheric neutral wind through doppler velocity of observed meteor echo; however, Very High Frequency (VHF) radar can only obtain local wind field characteristics [8]. Therefore, different remote sensing equipment, such as satellites and sondes, also carries out meteor observation, in order to obtain a wider area and more reliable wind field characteristics [9].

Super Dual Auroral Radar Network (SuperDARN) HF radars are mainly located in the middle, high, and polar regions of the northern and southern hemispheres. Their main detection targets are ionospheric plasmas and irregularities, with the aim of obtaining convection diagrams at global scale [10]. Hall et al. first found Grainy Near Range Echoes (GRNEs) in SuperDARN HF radar data, which occur at slant ranges less than 500 km and are independent of the intensity of geomagnetic activity [11]. The number of GRNEs detection rates reaches its maximum in the local morning and minimum near the local evening [11]. Based on these characteristics, Hall et al. believed that the echo was formed by the backscattering of the meteor trails, which was meteor echo, and retrieved the atmospheric wind field based on the meteor echo doppler velocity. Based on the studies of Arnold et al. the

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characteristics of SuperDARN HF radar meteor echoes can be summarized as close range, altitude in ionospheric regions D and E, low LOS doppler velocity, and low spectral width [12–14]. Since then, many scholars have tried different meteor echo extraction algorithms based on SuperDARN HF radar [15, 16]. Based on the extracted doppler velocity of meteor echo, studies on mesospheric neutral wind, atmospheric temperature inversion, semi-diurnal tide, gravity wave, and other aspects have been carried out [14, 17, 18], and a lot of research results have been achieved.

Although SuperDARN has made great achievements in mesospheric neutral wind inversion, the extraction of meteor echoes is based on SuperDARN normal observation model data with poor temporal and range resolution. In order to improve the observation accuracy of the meteor target, this paper designs the observation parameters of the meteor, according to the characteristics of the meteor target, without changing the hardware and software of the radar system based on the digital characteristics of the AgileDARN. Firstly, the meteor target observation was carried out with a range resolution of 7.5 km and an integral time of 2 s. Then, the meteor echo extraction algorithm is systematically analyzed by using the meter observation data by AgileDARN, and the statistical characteristics of echo number with different parameters such as echo power, doppler velocity, and spectral width are obtained. The occurrence rate of meteor echo within 24 hours is analyzed, which shows that there is the maximum meteor incidence in the local morning and the minimum incidences in the local evening. Finally, based on the doppler velocity of meteor echo, the inversion method of mesospheric neutral wind is carried out, and the meridian and zonal components of neutral wind are obtained. A method to reduce the ambiguity of echo elevation angle is proposed, and the profile of atmospheric neutral wind field along the height is obtained.

The rest of this paper is organized as follows. Section 2 introduces the algorithm analysis, including meteor echo doppler velocity and spectral width calculation method, meteor echo extraction algorithm, atmospheric neutral wind inversion method. The data processing results, such as meteor echo power characteristics, meteor echo statistical characteristics, and neutral wind inversion results are presented in Section 3. In Section 4 we conclude the paper.

2. ALGORITHM ANALYSIS

2.1. Calculation Method of Meteor Echo Parameters

The meteor echoes received by SuperDARN are mainly underdense meteor echoes [11], and the echo power received by the radar declines exponentially due to the diffusion of meteor trails [19]:

$$P(t) = P_0 e^{-\frac{t}{\tau}} \tag{1}$$

where $P(t)$ represents the echo power at time t, P_0 the initial power of the meteor trail, and τ the attenuation coefficient. The attenuation coefficient can be obtained from the meteor diffusion coefficient, i.e.,

$$\tau = \frac{\lambda^2}{32\pi^2 D} \tag{2}$$

where D is the diffusion coefficient, in m/s, and λ is the working wavelength of radar.

AgileDARN HF radar transmits signals with unequal interval multi-pulse sequences [20]. In the process of echo signal, the autocorrelation of the sampled signal is calculated to get the autocorrelation function, and the doppler frequency is obtained by the least square fitting of the phase of the autocorrelation function. Then the Doppler velocity can be calculated.

Assuming that the phase of the autocorrelation function is ψ and the phase delay time t, the Doppler velocity is

$$V_d = \frac{\lambda}{4\pi}\frac{\partial \Psi}{\partial t} \tag{3}$$

SuperDARN observations of meteor echoes are mostly underdense meteor echoes, and Lorentz fitting of the underdense meteor spectrum has good performance [12]. By taking logarithm of echo power and then performing least square fitting, the fitting slope is obtained as α, and the spectral width is

$$\omega = \frac{\lambda}{4\pi\alpha} \tag{4}$$

2.2. AgileDARN HF Radar Meteor Target Observation Method

AgileDARN HF radar is an all-digital phased array radar, which is composed of a 16-element main antenna array and a 4-element sub-antenna array. The main antenna array sends and receives signals, while the sub-antenna array only receives signals. The main antenna array and sub-antenna array realize interferometric elevation measurement [21]. The main observation target of AgileDARN is ionospheric plasma and irregularity, and in order to achieve large-scale observation of ionospheric plasma and irregularity, the pulse width of AgileDARN is 300 µs; the corresponding range resolution is 45 km; and the detection range is 180 km–4500 km under the common observation mode. The operating frequency is 8–20 MHz, which can be selected according to the electromagnetic environment of the station, and generally, it is 10.4 MHz. The field of view is 78°, and the duration of a cycle is 1 min.

It is known that when meteoroids enter the Earth's atmosphere, ablation produces approximately cylindrical ionized meteor trails, which are about $0.5 \sim 4.5$ m in diameter and $10 \sim 25$ km in length (a few meteor targets are $30 \sim 50$ km in length) with a duration of about $0.1 \sim 10$ s [22, 23]. It can be seen that the parameters of the common observation mode cannot effectively observe the meteor target.

AgileDARN HF radar is a digital array radar, and the hardware is designed by FPGA [21]. It can deliver different parameters to corresponding registers through control software without changing the radar system, so as to realize the change of working mode. Taking advantage of this characteristic, we designed the observation parameters of the meteor target: pulse width is 50 µs (corresponding range resolution of 7.5 km); integration time is 2 s; detection range is between 75 km and 750 km. Parameters of AgileDARN HF radar to observe meteor targets are shown in Table 1.

Table 1. Working parameters of AgileDARN observing meteor targets.

Parameters	Value
Frequency band	10.4 MHz
Pulse width	50 µs
AD start sampling time	500 µs
Number of gates	100
Field of overview	78°
Number of beams	24
Beam width	3.25°
Temporal resolution	1 min
Integration time	2 s
Range resolution	7.5 km
AD sampling range	75 km $\sim$ 750 km

2.3. Meteor Echo Extraction Algorithm

Meteor echo extraction is the basis of neutral wind inversion. SuperDARN HF radar picks up meteor echoes based on the following characteristics [24]: located at relatively close range units, typically within 500 km at slant range, at the height of the ionosphere D and E layers, generally within 150 km, the echo power of the meteor is greater than 3 dB; the Doppler velocity is in the range of -50 m/s $\sim$ 50 m/s; and the spectrum width is in the range of 1 m/s $\sim$ 50 m/s.

However, the above meteor echo filtering thresholds are not completely applicable to AgileDARN. In order to effectively extract the meteor echo from AgileDARN HF radar data, the above parameters of meteor echo extraction are improved in this paper: the power threshold of meteor echo extraction is set to 10 dB to reduce the influence of interference, and other parameters remain unchanged. The parameters of the AgileDARN HF radar to extract the meteor echo are shown in Table 2. The echo that meets all thresholds in Table 2 is the meteor echo.

Table 2. Extracting meteor echo parameter threshold.

Meteor Extraction Parameters	Values
Power (dB)	≥ 10
LOS Doppler Velocity (m/s)	± 50
Spectral Width (m/s)	> 1 and < 50
Altitude (km)	≥ 70 and < 150
Slant Range (km)	≤ 450

2.4. Neutral Wind Inversion Algorithm

Assume that the neutral wind velocity is uniform within the 24-beam range scanned by AgileDARN HF radar. The radial Doppler velocity measured by AgileDARN radar is related to the specific direction of the radar K vector in the scatterer, which is related to beam direction and range gate and independent of time. The relationship between the radial Doppler velocity of meteors observed by radar and the actual neutral wind velocity is as follows [25]:

$$v_i = \vec{v} \cdot \hat{e}_i = v_n \cos\theta_i + v_e \sin\theta_i \tag{5}$$

As shown in the formula, v_i indicates the radial doppler velocity component of the i-th beam, $\hat{e}_i$ the unit vector of the beam, $\vec{v}$ the actual neutral wind velocity vector, v_n the north-south component of the neutral wind, which is the meridional wind, v_e the east-west component of the neutral wind, which is zonal wind, and θ_i the i-th beam azimuth. The relation between v_i and LOS velocity v_{los} is

$$v_i = \frac{v_{los}}{\cos(\alpha)} \tag{6}$$

where α represents the elevation angle.

It can be seen from Equation (5) that the equation has only two unknown parameters, and the solution equation of the Doppler velocity component of the two beam locations can determine v_n and v_e. However, the doppler velocity measured by radar is interfered by noise, so the least square fitting method is used to solve the 24 beams of AgileDARN. Equation (5) can be obtained by writing it in matrix form

$$\begin{bmatrix} v_0 \\ v_1 \\ \vdots \\ v_{24} \end{bmatrix} = \begin{bmatrix} \cos\theta_0 & \dots & \sin\theta_0 \\ \vdots & \ddots & \vdots \\ \cos\theta_{24} & \dots & \sin\theta_{24} \end{bmatrix} \begin{bmatrix} v_n \\ v_e \end{bmatrix} \tag{7}$$

By simplifying the above formula we would get

$$A \cdot x = b \tag{8}$$

That is

$$\begin{bmatrix} v_0 \\ v_1 \\ \vdots \\ v_{24} \end{bmatrix} = b, \quad \begin{bmatrix} \cos\theta_0 & \dots & \sin\theta_0 \\ \vdots & \ddots & \vdots \\ \cos\theta_{24} & \dots & \sin\theta_{24} \end{bmatrix} = A, \quad \begin{bmatrix} v_n \\ v_e \end{bmatrix} = x$$

According to the singular value decomposition theory, we can obtain that for any $M \times N$ matrix A, we can write the orthogonal matrix U of column $M \times N$. The product of the diagonal matrix W of $N \times N$ and the transpose matrix V of $N \times N$ [24], i.e.,

$$A = UWV^T \tag{9}$$

where matrices U and V satisfy: $U^T \cdot U = V^T \cdot V = 1$. Equation (8) can be solved by using Equation (9)

$$x = V \cdot W \cdot U^T \cdot b \tag{10}$$

The above equation can be written as

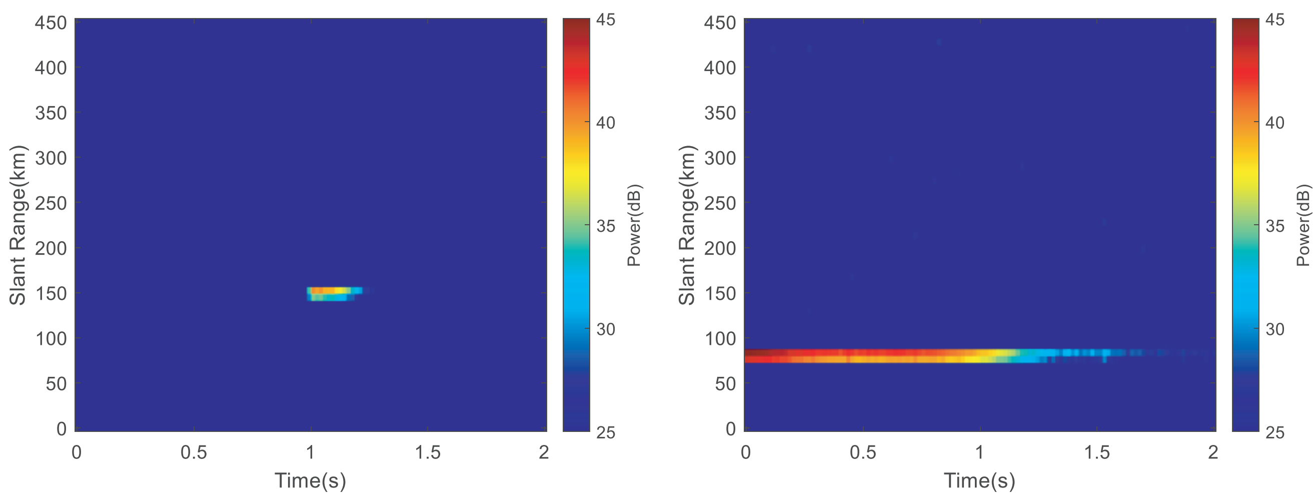
$$x = \sum_{i=1}^{M} \frac{U_i b}{w_i} V_i \tag{11}$$

where w_i is the element of matrix W. When there are more equations than unknowns, we can find the least squares solution of the linear overdetermined equations to get the meridional and zonal components of the neutral wind [25].

3. DATA PROCESSING RESULTS

3.1. Typical Meteor Echo Characteristics

Figure 1 shows the variation characteristics of typical meteor echo power observed by AgileDARN HF radar. Figure 1(a) shows a short meteor echo with a duration of about 0.3 s, and Figure 1(b) shows a long meteor echo with a duration of about 2 s. It can be seen from the figure that the power of the meteor's echo changes from weak to strong and then gradually weakened, indicating the process of the meteor from entering the radar field of view to gradually disappearing.



(a) (b)

Figure 1. Typical meteor echo characteristics observed by AgileDARN HF radar.

3.2. Analysis of Echo Statistical Characteristics

The slant range of AgileDARN observation is 75 km $\sim$ 750 km, and we choose the slant range 75 km $\sim$ 450 km as the meteor echo filtering range. After determining the slant range of meteor echo, the echo power, Doppler velocity, and spectrum width are calculated, and then filter out the meteor echo according to the threshold set in Table 2.

Figure 2 shows the statistical histogram of the number of echoes filtered by echo power, Doppler velocity, and spectral width. Figure 2(a) is the histogram of the number of echoes distributed with power; Figure 2(b) is the histogram of the number of echoes distributed with Doppler velocity; and Figure 2(c) is the histogram of the number of echoes distributed with spectral width. In Figures 2(a), (b), and (c), the blue line represents the echo after simple data preprocessing such as noise elimination; the red line represents the echo with an echo power greater than 10 dB; the yellow line represents the echo data with a Doppler velocity between -50 m/s and 50 m/s with a power greater than 10 dB; and the purple line represents the meteor echo, which meets all thresholds in Table 2. Figure 2(d) shows the time distribution histogram of the number of meteor echoes extracted within 24 hours. It can be seen from the figure that the number of meteors observed in the local morning is the largest, and the

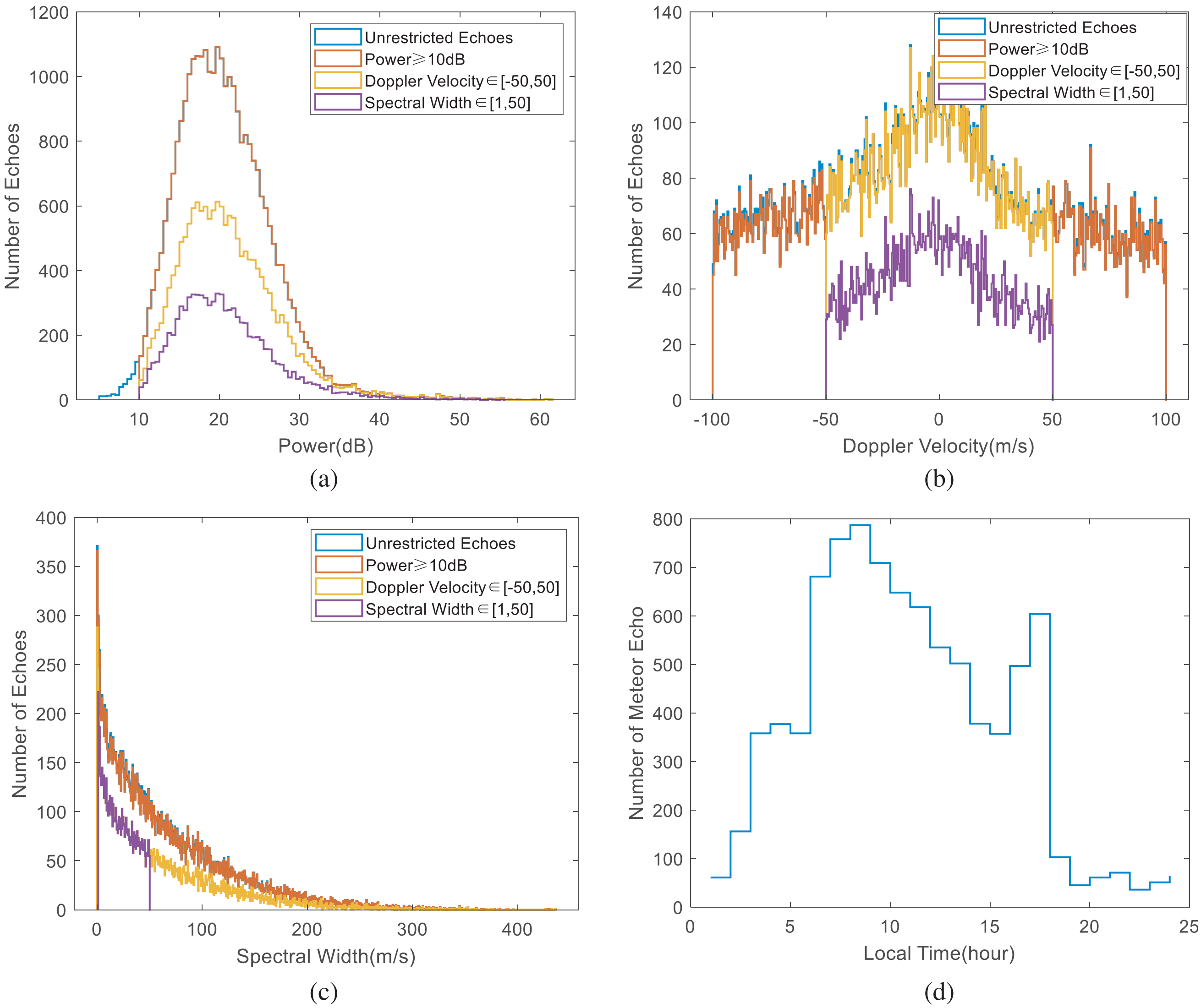


Figure 2. Histogram of the number of echoes.

number of meteors observed in the local evening is the least, which is consistent with the distribution characteristics of the number of meteor echoes observed by a typical SuperDARN HF radar [15].

3.3. Neutral Wind Characteristics

AgileDARN retrieves neutral wind from doppler velocity of meteor echo. Mesospheric neutral wind usually consists of horizontal wind and vertical wind, in middle and low latitudes. The wind speed of vertical wind is much smaller than that of horizontal wind, and the velocity value of vertical wind tends to zero after average [26, 27]. Therefore, we assume that the neutral wind has only a horizontal component. Wind field inversion methods are summarized as follows:

1) Data selection. The meteor echo was extracted according to the parameters in Table 2, and the Doppler velocity of the meteor echo was obtained.
2) Calculate the average doppler velocity per hour. Calculate the average doppler velocity per hour for each beam and range gate.
3) Calculate the wind field component v_{hour} in the horizontal plane according to Equation (6). Since AgileDARN main array and subarray are 100 meters apart, which is more than three times of

the radar wavelength of 28.8 meters (corresponding to 10.4 MHz working frequency), elevation measurement has aliasing. In order to suppress elevation aliasing, the following algorithm is proposed in this paper:

a) Determine that the altitude of the meteor is 70 km $\sim$ 150 km.
b) According to the elevation angle measurement value and the corresponding slant range, multiple corresponding heights can be calculated, $h_i,\ i = 1, 2, \ldots$.
c) If $h_i \in [70, 150],\ i = 1, 2, \ldots$, then record the corresponding elevation angle α.
d) The neutral wind v_{hour} of each range gate is calculated from the measured elevation α combined with formula (6).

4) Calculate the velocity values for all beams. Average the v_{hour} of all the range gates where each beam meteor is located to get the velocity of 24 beams.
5) The meridional and zonal components of the neutral wind are calculated. According to Equation (5), meridional wind and zonal wind of neutral wind can be obtained by singular value decomposition.

Figure 3 shows the meridional and zonal components of neutral wind obtained by inversion of doppler velocity of meteor echoes observed within 24 hours. It can be seen from the figure that the wind velocity changes periodically at the boundary of 12 o'clock, which is consistent with the change characteristics of semi-diurnal tide of tidal wave.

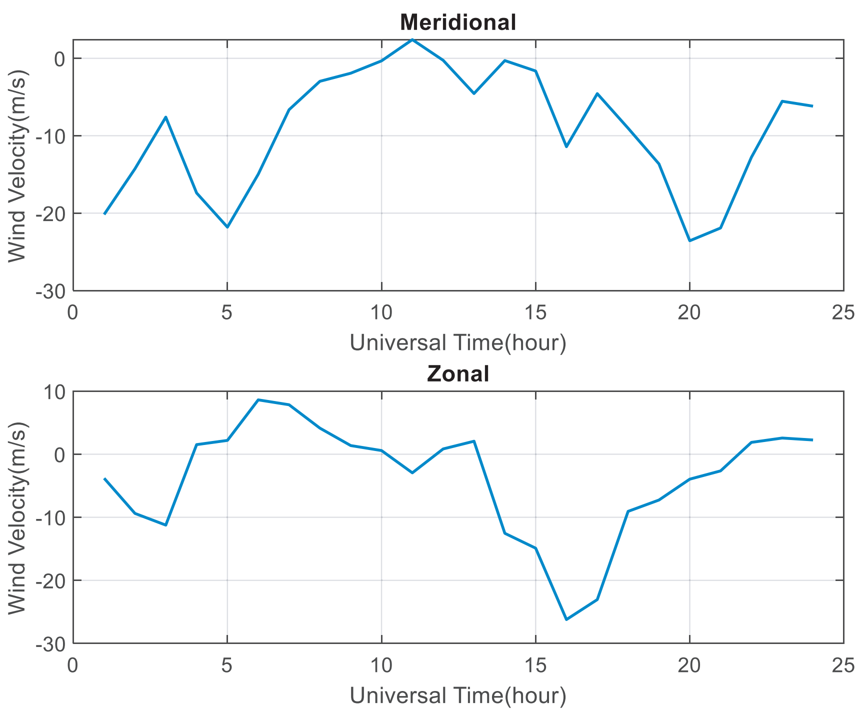


Figure 3. Meridional and zonal wind components.

The meridional wind and zonal wind shown in Figure 4 are the characteristics of the change of neutral wind in the horizontal plane, and normally, the mesospheric neutral wind will have certain characteristics of change in height. In order to obtain the wind field profile of neutral wind along the height, we designed the following inversion method: Firstly, along the height of the meteor 70 m $\sim$ 150 m with 5 km is as the interval. Secondly, the average value of the doppler velocity of the meteor in the distance unit is calculated. Then, the hourly average velocity measured in the corresponding height unit is calculated according to Equation (6). Finally, the meridional and zonal components of the wind field are calculated using singular value decomposition method. Figure 4(a) shows the wind field profile of LOS Doppler velocity along the height within an hour. Figure 4(b) shows the measured value of the

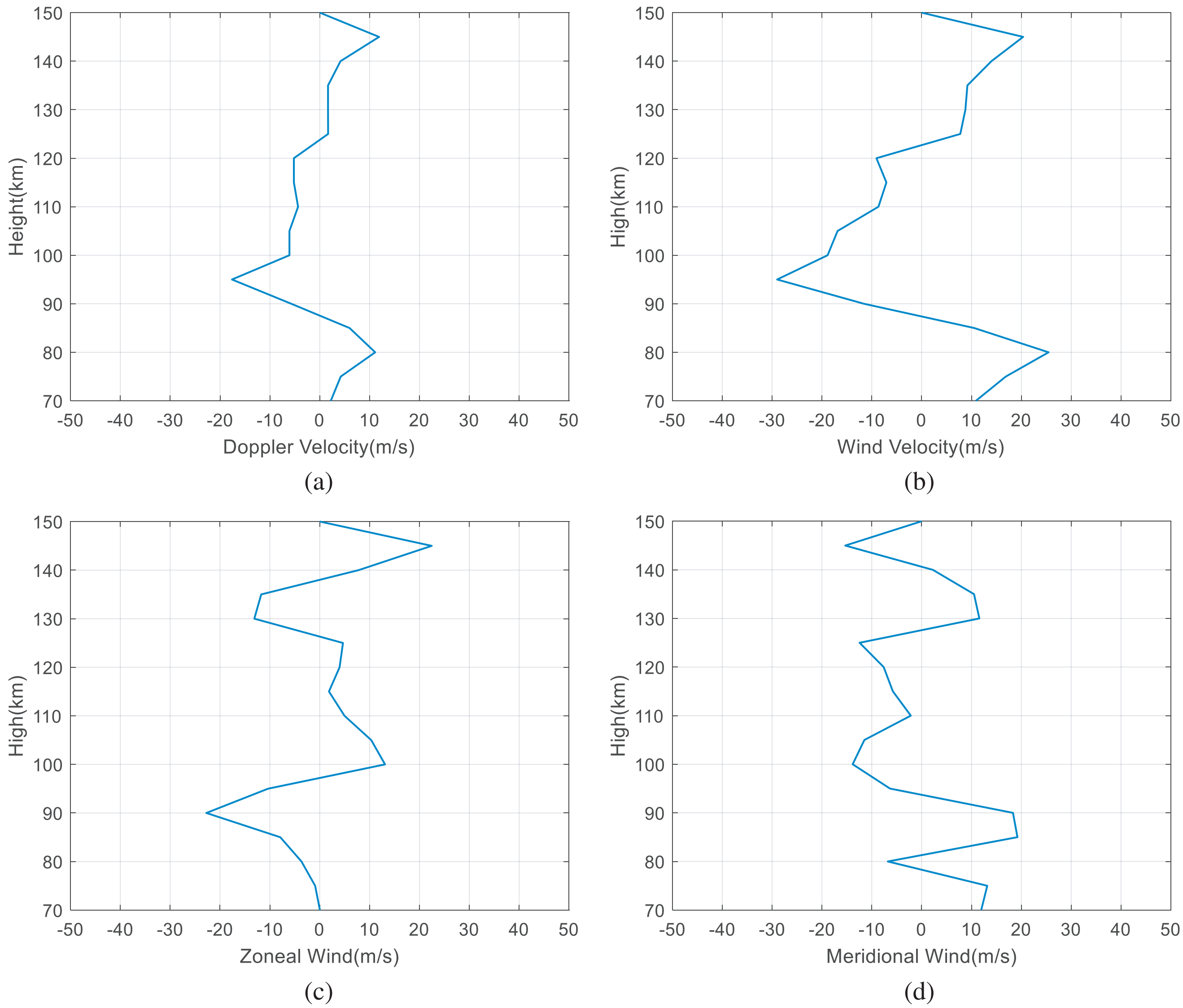


Figure 4. Profile of neutral wind along height.

wind velocity calculated using Equation (6). Figures 4(c) and (d) show the meridional wind and zonal wind of the neutral wind obtained by singular value decomposition. It can be seen from the figure that both meridional wind and zonal wind change between -20 m/s and 20 m/s, and there is no obvious change between 100 km and 120 km.

4. CONCLUSION

In this paper, a meteor echo observation method is designed based on AgileDARN HF radar system, and the meteor echo extraction algorithm is analyzed by using the observation data. The statistical characteristics of the power, Doppler velocity, and spectral width of different echoes in the process of meteor echo extraction are obtained, and the characteristics of the meteor echo distribution over time within 24 hours are obtained. Then, the meridional and zonal components of the neutral wind are obtained based on the singular value decomposition method, and the variation characteristics of the semidiurnal tide can be seen. Finally, a method to reduce the elevation ambiguity is proposed, and the wind field variation characteristics in the altitude range of 70 km $\sim$ 150 km are obtained.

This paper focuses on the inversion method of atmospheric neutral wind based on the meteor echo data observed by AgileDARN HF radar. In the future, long-term wind field inversion method based on the observation data of AgileDARN radar will be carried out by using the algorithm in this paper. The wind field obtained by the wind field inversion algorithm in this paper lays a good foundation for the subsequent study of tides and planetary waves and also expands the application range of AgileDARN HF radar.

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