Research on Multi-pulse Splicing Algorithm for Coherent Wind Lidar

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Abstract:
In the field of pulsed coherent wind data processing, it is an ongoing challenge to effectively balance the accuracy of wind speed resolution while ensuring the accuracy of range resolution. In traditional methods, to maintain a high range resolution, it is often necessary to limit the number of data points in the range gate, which inevitably leads to a reduction in the Fourier transform spectral resolution and, in extreme cases, the loss or omission of key characteristic signals. In response, zero-padding or interpolation methods are usually used for processing, but since these methods do not really increase the amount of information in the data, their effects are not significant. To break through this limitation, a multi-pulse coherent splicing algorithm is proposed, which coherently splices multiple groups of adjacent pulse signals, thus maintaining both a high range resolution and a wind speed resolution. Numerical simulations and actual experiments are used for verification, and the results show that the performance of this algorithm is better than that of the traditional incoherent accumulation algorithm and can effectively serve the actual detection of the wind field.

Keywords: coherent wind detection, lidar, multi-pulse splicing, coherent splicing

INTRODUCTION

With the growing global demand for clean energy and the continuous advancement of meteorological scientific research, technologies for accurately measuring the atmospheric wind field have become increasingly important. As an advanced wind field measurement device, the coherent wind-measuring lidar, with its advantages of high precision, high spatio-temporal resolution, and non-contact measurement, has demonstrated great application potential in fields such as wind power generation [1, 2], weather forecasting [3], and aerospace [4]. The coherent wind-measuring lidar measures wind field information by emitting laser pulses, receiving the back-scattered light from aerosol particles in the atmosphere, and utilizing the Doppler effect. It can calculate the wind speed in the entire line-of-sight direction and can be used to detect wind speed information from tens of meters to several kilometers [5]. The minimum range resolution of a pulsed-mode laser coherent wind-measuring radar is jointly affected by the pulse width of the emitted laser and the length of the range gate.

Early research on coherent wind-measuring lidars mainly focused on the verification of basic principles and the preliminary construction of the system [6, 7]. The main intermediate-frequency signal processing algorithms for the radial echo of the pulsed coherent laser wind-measuring radar beam include: Fast Fourier Transform (FFT), pulse - pair algorithm, multi-pulse-pair algorithm [8] (poly-pulse pair), and maximum-likelihood algorithm [9] (ML), etc. The Fast Fourier Transform method mainly divides the echo time-domain signal using a fixed-length range gate according to the radar range resolution requirement, then performs FFT on the signal of each range gate and calculates the intermediate-frequency value of that range gate. Finally, the radial wind speed value of the beam in that range segment is calculated according to the Doppler shift formula [10]. The method of dividing fixed - length range gates is simple and easy to implement, and it is the method used by most laser wind- measuring radars at home and abroad. The United States' FiberTek company developed a pulsed laser wind-measuring radar for observing aircraft turbulence and wake. Its range resolution is 40-120 m, determined by the length of the divided range gates, and it can achieve wind speed measurements of 20-200 m/s with a wind speed resolution of 0.1 m/s [11]. The Windcube series of commercial laser wind - measuring radars, developed by the French company Leosphere, is mainly used for aircraft wake vortex detection, airport air traffic optimization, wind energy applications, atmospheric research, and meteorological monitoring. Windcube divides range gates with a fixed length, and the optional minimum range resolution is 25 meters, with a wind speed measurement error of less than 0.5 m/s [12]. The Wind Imaginer laser wind-measuring radar system developed by the United States' Lockheed Martin company in 2015 is mainly applied to wind field scanning and vortex detection. This system has a sampling rate of 750 MHz, a repetition frequency of 3-20 kHz, a pulse width of 50-400 ns, and a range resolution of better than 15m [13]. A certain type of laser wind - measuring radar developed by the Southwest Institute of Technical Physics is mainly used for airport wind shear change warning. It can adjust the minimum range resolution to 30 meters, has an average wind speed variance of 0.42 m/s, and a measurement range of 10 kilometers [14].

Currently, the commonly used Doppler shift estimation algorithms mainly include the pulse-pair algorithm, recursive adaptive filtering frequency estimation method, periodogram maximum method, and maximum-likelihood estimation method [15]. The pulse-pair algorithm is relatively simple to calculate and does not require prior information such as signal spectral width and signal-to-noise ratio. However, the estimation performance of this algorithm will severely degrade at low signal-to-noise ratios, limiting its application in coherent wind-measuring lidars. The recursive adaptive filtering frequency estimation method is a method that first removes abnormal data values and then performs frequency optimization estimation under low signal-to- noise ratio conditions. This method improves the reliability of the data and the accuracy of frequency estimation to a certain extent. The periodogram maximum method is a commonly used frequency estimation method. By non-coherently accumulating and averaging the multi-pulse periodogram, the influence of noise can be eliminated, achieving good estimation accuracy. However, when the length of the sampled data is small, the spectral resolution will be reduced, and when the length of the sampled data is large, the time resolution of wind speed estimation will be reduced. Compared with the above algorithms, the maximum-likelihood estimation method has the best estimation performance closest to the Cramér-Rao bound when the signal-to-noise ratio is high and the sampled data sequence is large. However, the computational complexity increases when the data sequence is large, limiting the update rate of wind speed data.

With the development of technology, researchers have started to focus on how to optimize measurement algorithms to improve system performance. In wind field measurements, the measurement accuracy of a single pulse is often limited by factors such as noise [16]. In practical applications, in order to improve measurement accuracy and resolution, multi-pulse splicing algorithms are often required. The multi-pulse splicing algorithm aims to obtain more accurate and continuous wind field data by processing and combining the echo signals of multiple transmitted pulses. The emergence of the multi-pulse splicing algorithm provides an effective way to solve this problem. By coherently or non-coherently accumulating the echo signals of multiple pulses [17], the influence of noise can be reduced and the signal-to-noise ratio can be improved. However, the current multi-pulse splicing algorithms still face some challenges. On the one hand, the complexity of the atmospheric environment, such as the inhomogeneous distribution of aerosols and atmospheric turbulence, will interfere with the echo signals, affecting the accuracy and stability of the multi-pulse splicing algorithm. On the other hand, with the continuous expansion of the application scenarios of coherent wind-measuring lidars, the requirements for measurement accuracy and real-time performance are also getting higher and higher. The existing algorithms still have a certain gap in meeting these demanding requirements.

Therefore, in-depth research on the multi-pulse splicing algorithm of coherent wind-measuring lidars has important theoretical and practical significance. This paper aims to systematically study the multi-pulse splicing algorithm, analyze the advantages and disadvantages of existing algorithms, and explore new algorithm ideas and methods to improve the measurement performance of coherent wind-measuring lidars in complex environments, providing technical support for their wider application in various fields.

COHERENT WIND LIDAR ECHO SIGNAL PROCESSING

Coherent Wind Lidar Echo Signal Model

The echo signal received by the coherent lidar system is the superposition of the backscattered signals from a large number of aerosol particles within the detection range. It can be simply described as a complex Gaussian random process with zero mean. After the backscattered signal is mixed with the local oscillator light, it is converted into an electrical signal by a balanced detector and then sampled. A sequence of N sampling data is obtained, and the p-th data sequence can be expressed as:

$$z_p = s_p \exp(2\pi fi * T_s \mathrm{p}) + n_p \quad (1)$$

In Equation (1), s_p is the signal in the echo, f is the Doppler frequency, T_s is the sampling interval, and n_p is the uncorrelated noise in the p-th data sequence. Let n_q be the uncorrelated noise in the q-th data sequence, then its statistical property is $\langle n_p n_q \rangle = 0$, where p and q are the sequence numbers of the sampling data.

When the number of sampling samples is relatively large, for N sampling data sequence samples, a discrete Fourier transform is performed. After the signal z undergoes a discrete Fourier transform, the signal power spectrum estimate of the p-th sample sequence obtained by using the fast Fourier transform algorithm is

$$u_p = \frac{1}{N}\left|\sum_{k=0}^{N-1} z_k \exp(-j\frac{2\pi pk}{N})\right|^2 \tag{2}$$

For the data segment of the specified range gate in the echo signal, N represents the number of sampling points within a range gate, and its corresponding energy is relatively limited. Under this assumption, first, the obtained data is directly subjected to FFT, then the square operation is performed on the transformed amplitude, and finally, the arithmetic mean is taken. By performing incoherent accumulation on multiple groups of pulse echoes and combining the Fast Fourier Transform algorithm to reduce the amount of calculation and calculation time, the power spectrum of the wind field echo signal within the corresponding range gate is obtained, and thus the corresponding wind field information is calculated.

Range Resolution and Spectrum Resolution of Coherent Wind Lidar

Velocity resolution and range resolution are two core performance parameters of a coherent wind lidar, and these two parameters directly determine the capture accuracy and analysis ability of the radar system for wind field information. The level of velocity resolution directly affects the sensitivity and accuracy of the radar system to wind speed changes.

$$\Delta V = \lambda \frac{\Delta f}{2} \tag{3}$$

where ΔV is the velocity resolution of the coherent Doppler wind lidar, and Δf is the estimation error of the Doppler shift. It can be seen from the above equation that the velocity resolution of the laser wind lidar is related to the spectrum resolution of the echo signal. Under the condition that the laser wavelength is constant, the velocity resolution is positively correlated with the spectrum resolution.

Regarding the range resolution of the radar, let the time interval from the emission to the reception of the pulsed laser be Δt. The range gate width dL is such that the minimum resolvable distance δL in the pulsed lidar is determined by the pulse width τ. The range resolution refers to the minimum interval that a coherent wind - measuring lidar can distinguish between target objects at different distances when detecting the wind field.

$$\Delta L = dL + \delta L = c\frac{(\Delta t + \tau)}{2} \tag{4}$$

where c is the speed of light and τ is the laser pulse width. When the distance between two target objects is less than δL, their echo signals will overlap, and the data processing system cannot distinguish the two pulse signals, resulting in errors in distance measurement.

Due to the interference of noise and its influence on the reception efficiency of the echo signals of aerosols and atmospheric molecules, the carrier-to-noise ratio of the lidar will be low. Accurately estimating the power spectrum is very critical for improving the detection accuracy of the radar system. For the Fast Fourier Transform (FFT), increasing the data length by adding zero-value points at the end of the signal data is a commonly used technique to improve the spectrum resolution. The core idea of this method is to reduce the interval between adjacent spectral lines in the spectrum by increasing the number of sampling points, thereby improving the estimation accuracy of the spectrum. Usually, to ensure the calculation efficiency of the FFT algorithm, the number of points participating in the FFT algorithm needs to satisfy the power index of two. In order to have sufficient range resolution ability, the selected data length participating in the FFT needs to be relatively short, but the relative insufficiency of the selected data length will result in insufficient spectrum resolution. For this, generally, a processing algorithm of zero-padding or interpolation is adopted to supplement the data length to the power index of two as close as possible. However, although the data segment processed by either zero-padding or interpolation is calculated by the FFT algorithm, although the data length is increased under the premise of ensuring the range resolution, so that the spectrum resolution is higher and the spectrogram looks smoother and more continuous. However, this operation does not reduce the power of the noise or increase the power of the signal, nor does it actually increase the effective amount of information. Therefore, neither the FFT combined with the zero-padding nor the interpolation algorithm can improve the signal-to-noise ratio of the spectrum analysis.

MULTI-PULSE SPLICING FOR COHERENT WIND DATA PROCESSING

To improve the signal-to-noise ratio of the data of the specified range gate of the echo signal, the data of the range gates corresponding to multiple consecutive groups of pulses are spliced to reach the specified data length that meets the requirements. At a high sampling frequency, considering that the change of turbulence is small within multiple consecutive sampling times, it can be assumed that the wind speed is relatively constant during the detection time of the selected multiple groups of pulses. In this way, by splicing the actual wind speed information data of multiple segments, the power of the wind speed signal to be measured can be directly increased. The multi-pulse range gate splicing algorithm, while ensuring the range resolution ability, increases the data length by splicing the actual wind speed pulse data, which can further improve the signal-to-noise ratio of the spectrum analysis.

Considering that the splicing of any two groups of pulse data may introduce frequency interference at the junction, the initial phases of adjacent pulse signals are aligned in the time domain. This operation will not change the result of the FFT transformation but can effectively eliminate the possible introduced frequency interference. Considering that the calculation and processing of the phase discrimination operation for the initial phase of each pulse signal are too complex [18], a time-domain signal shift alignment method based on the correlation coefficient is proposed. The correlation coefficient characterizes the correlation between two variables. The correlation coefficient selected here is the Pearson correlation coefficient, and its calculation method is the covariance of the two variables divided by the product of the standard deviations of the two variables respectively. The positive and negative signs of the correlation coefficient represent positive and negative correlations respectively. The larger the absolute value of the correlation coefficient, the stronger the correlation. Numerically, the larger the correlation coefficient, the stronger the positive correlation between the two variables. This method first requires setting a reference of the same length as the pulse signal. Then, based on the principle of maximizing the correlation coefficient, search and calculate before and after to perform the shift alignment, and sequentially complete the shift operations for all pulses. Accordingly, the elimination of the initial phase differences can also be achieved, thereby increasing the amplitude intensity of the multi-pulse accumulated average signal.

COHERENT WIND DATA PROCESSING BASED ON MULTI-PULSE SPLICING

The coherent wind data processing algorithm based on multi-pulse splicing involves the effective integration of wind speed information in multiple pulse signals to improve the accuracy and spatial resolution of wind measurement data. For the collected multi-pulse coherent wind measurement data, in order to obtain information such as the spatial resolution of the wind field, it is necessary to divide the range gates for each single-pulse echo signal during the echo signal reception period. After the synchronous acquisition card starts working, the height corresponding to each sampling point is determined according to the sampling frequency of the acquisition card, so as to divide the range gates.

Simulation of Multi-Pulse Range Gate Splicing

In the simulation software, the wind speed signal is simulated in the form of signal expression $y = \sin(2 * pi * f * t + b) + a$. Here, a represents the amplitude noise and b represents the phase interference. The sampling frequency is selected as 400 MHz, the characteristic frequency f is taken as 40 MHz. The added noise a is white Gaussian noise with a power of 10 dBW, and the value of the phase b is a random interference within the range of $[-\pi, \pi]$. Taking 15m as a range gate, the signal length of each range gate is 40 points.

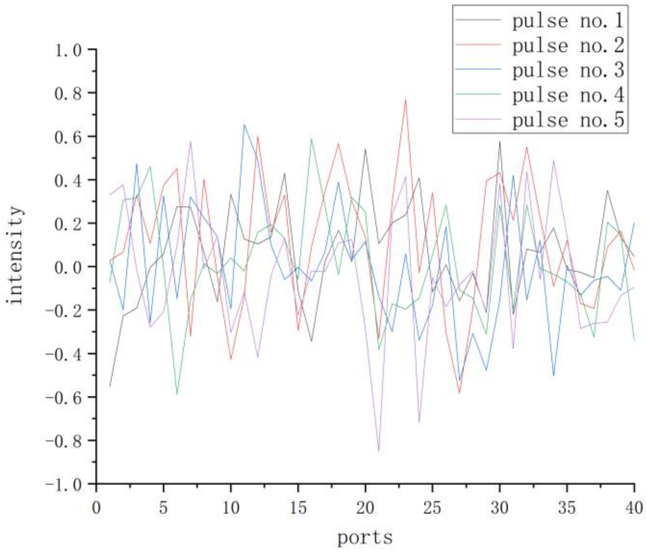

Figure 1. Time-domain data of 40 sampling points in 5 consecutive groups

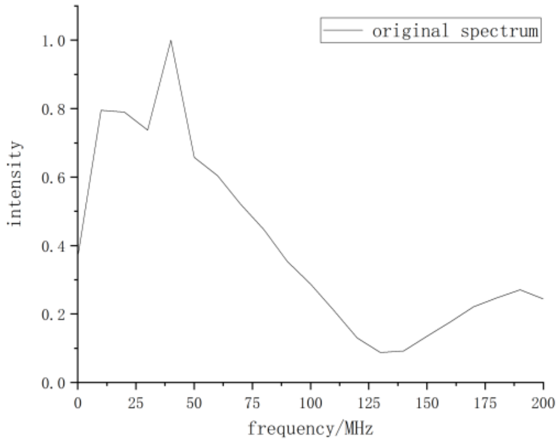

Figure 2. Spectrum accumulation of 1000 groups of FFT transformations without zero-padding

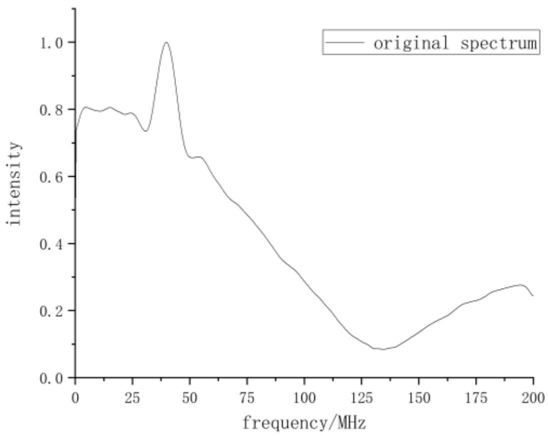

Figure 3. Spectrum accumulation of 1000 groups of FFT transformations with zero-padding

Figure 1 shows the time-domain signal diagram of 40 points included in a specified range gate corresponding to 5 consecutive pulse serial numbers. Figure 2 shows the spectrum data after directly performing the Fast Fourier Transform on 40 data points. Due to the small number of points, the spectrum is relatively dispersed. Through simple spectrum analysis, the characteristic frequency value is 40 MHz. In order to improve the sampling accuracy, the zero-padding FFT method is used for data processing, and the results are shown in Figure 3. It is the spectrum after performing a 1024-point FFT transformation after zero-padding. It is found that the peak data directly obtained after zero-padding is 39.844 MHz. Compared with the result before zero-padding, there are differences between the two. Considering that the spectrum sampling accuracy is 0.39 MHz, the measurement results are within the allowable error range. Therefore, it can be seen that the adjacent spectrum intervals become much smaller after zero-padding, and the spectrum accuracy is improved.

The zero-padding FFT transformation algorithm depends on the accumulation of a large number of groups of pulses to effectively calculate the characteristic frequency. When processing echo data with a low signal-to-noise ratio, it is prone to incorrect results or failure to detect the characteristic frequency due to the interference of noise. Here, the 1000 groups of pulse range gate data involved in the accumulation are changed to 100 groups of data.

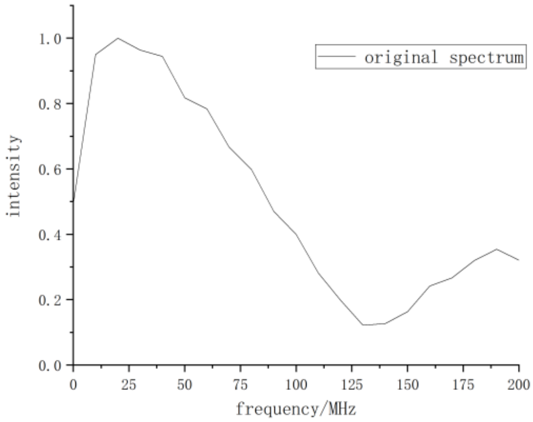

Figure 4. Spectrum accumulation of 100 groups of FFT transformations without zero-padding

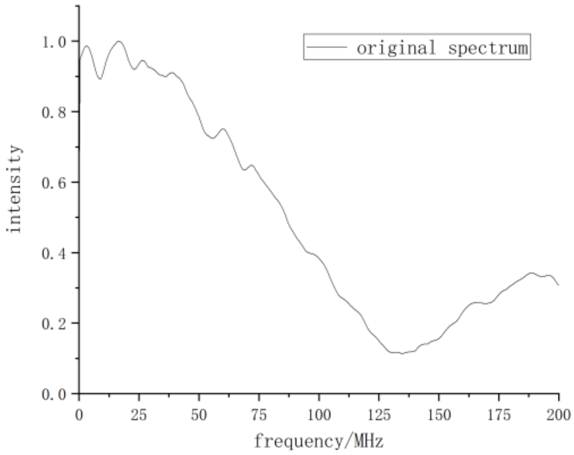

Figure 5. Spectrum accumulation of 100 groups of FFT transformations with zero-padding

Figure 4 shows the spectrum accumulation results of 100 groups of FFT transformations without zero-padding operation, and Figure 5 shows the spectrum accumulation results of 100 groups of FFT transformations with zero-padding operation. It can be clearly seen that neither of them can accurately calculate the 40 MHz characteristic frequency in the echo simulation signal. Through multiple experiments, it can be seen that the zero-padding FFT transformation algorithm does not actually increase the amount of information, so it cannot improve the signal-to-noise ratio of spectrum analysis.

Since the zero-padding FFT transformation algorithm does not actually increase the amount of information, in order to effectively improve the signal-to-noise ratio of the specified range gate data of the echo signal, it is proposed to splice the range gate data corresponding to multiple consecutive groups of pulses to increase the data length and perform FFT transformation to obtain the characteristic frequency. For the specified range gate data corresponding to the above 100 groups of pulses, splicing can obtain 4000 data points. At this time, the expansion of data points does not sacrifice the range resolution ability of the system. Through zero-padding processing, the data is directly supplemented to 4096, and 1024 data points are selected for fast Fourier transform to obtain the spectrum accumulation result shown in Figure 6. However, in actual operation, due to the differences in the initial phases of different pulses, new characteristic frequencies with relatively high intensities will be introduced at the junctions of the range gate splicing corresponding to multiple groups of pulses, which will affect the final spectrum analysis and calculation. This needs to be removed in the preprocessing of time-domain alignment. The proposed coherent accumulation algorithm based on time-domain alignment mainly uses the correlation coefficient to match and compensate the modulation of the pulse signal to achieve the alignment of the initial phases between echoes. After performing time-domain alignment on the specified range gate data corresponding to the above 100 groups of pulses, the same splicing operation is performed again. 1024 data points are selected for fast Fourier transform to obtain the spectrum accumulation result shown in Figure 7.

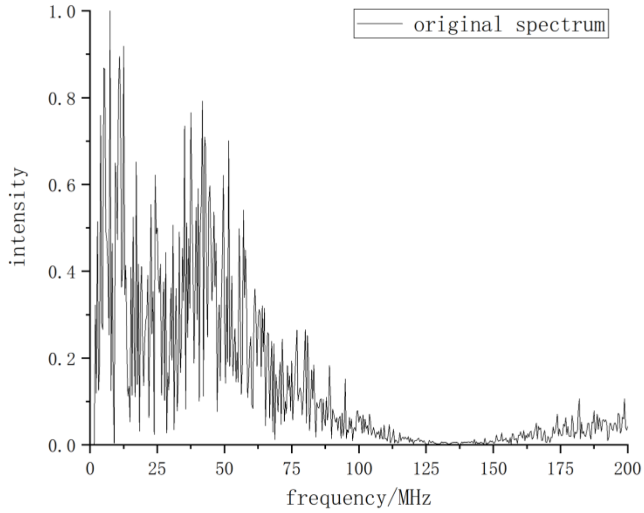

Figure 6. Spectrum accumulation of 100 groups of spliced and zero-padded FFT transformations without alignment

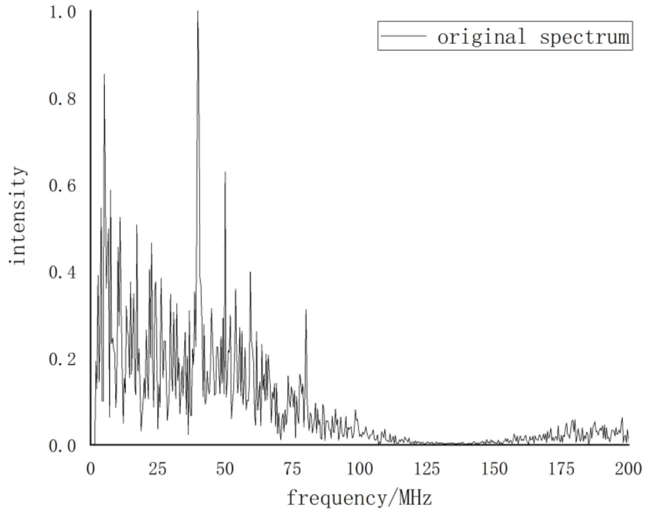

Figure 7. Spectrum accumulation of 100 groups of spliced and zero-padded FFT transformations after alignment

The spectrum accumulation effects shown in Figure 6 and Figure 7 both adopt the splicing operation. Compared with the spectrum accumulation effects obtained by the previous zero-padding operation, since the added data information is the actual wind speed acquisition data, it can be seen that the frequency distribution in the frequency segment where the characteristic frequency is located is more distinct. By comparing the spectrum accumulation effects obtained after processing in Figure 6 and Figure 7, it can be seen that the spectrum distribution after alignment and splicing is obviously more concentrated, and the main spectrum components are significantly enhanced, while the noise and other interference components are effectively suppressed. The splicing algorithm after time-domain shift alignment can effectively improve the signal-to-noise ratio of the final echo signal and can calculate the characteristic frequency from weak signals.

Field Measurement of Multi-Pulse Range Gate Splicing

Actual atmospheric wind field observation data is selected. The central frequency of the constructed coherent wind measurement pulsed lidar system is [central frequency value], the sampling frequency is set to [sampling frequency value], the pulse repetition frequency is [pulse repetition frequency value], and the emitted laser power is set to 300 mW. At this time, taking 6 m as a range gate, the signal length of each range gate is 40 points. The starting point of the detection distance is 135 m, and 100 groups of consecutive corresponding range gate data are intercepted. Similarly, the incoherent accumulation algorithm based on zero-padding fast Fourier transform and the splicing algorithm after multi-pulse time-domain alignment are respectively used for processing. Finally, the data is padded to 4096 data points, and the spectrum accumulation effects obtained are shown in Figure 8 and Figure 9.

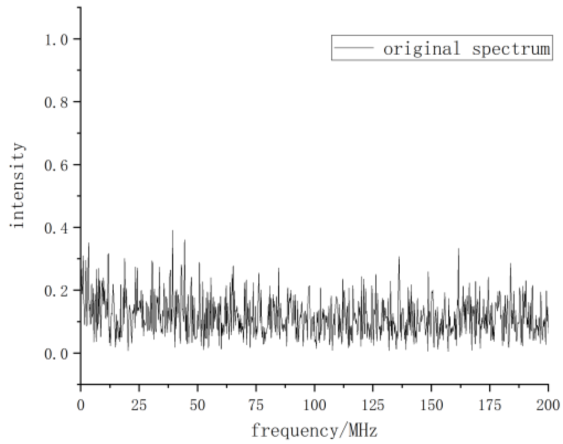

Figure 8. Spectrum accumulation of 100 groups of zero-padding FFT transformations

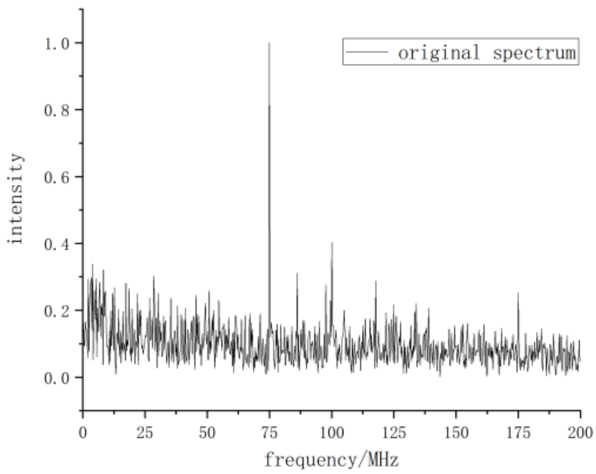

Figure 9. Spectrum accumulation of 100 groups of spliced and zero-padding FFT transformations after alignment

It can be seen that when detecting the wind field information at a short distance under the condition of low-power emission, the interference of noise will greatly affect the calculation of the Doppler shift in the traditional incoherent accumulation algorithm. By aligning and splicing the data of the range gates corresponding to multiple adjacent pulses, relevant wind field information can be effectively and accurately obtained while ensuring the range resolution ability of the system.

In the complex environment of low-power emission, detecting the wind field information at a short distance is particularly crucial. However, the interference of noise in this process cannot be ignored. Due to the characteristics of low-power emission, the signal intensity is relatively weak, which makes the traditional incoherent accumulation algorithm vulnerable to the significant influence of noise when calculating the Doppler shift, thus reducing the accuracy and reliability of wind field information extraction. In response to this, by aligning and splicing the data of the range gates corresponding to multiple adjacent pulses to form a continuous and complete data set, relevant wind field information can be effectively and accurately extracted while ensuring the range resolution ability of the system. In practical applications, this technology can be widely used in fields such as meteorological observation and wind energy resource assessment, providing more reliable technical support for research and applications in related fields.

CONCLUSION

In the data processing of the pulsed coherent wind measurement system, the traditional algorithm identifies the wind speed signal by accumulating the signals of multiple groups of pulses within a specific range gate. However, there is a crucial trade-off in this process: the selection of the range gate length. If the selected range gate is too long, the range resolution ability of the system will inevitably decrease; conversely, if the range gate is too narrow, it may lead to a significant decline in velocity resolution.

To address this challenge, a coherent wind data processing algorithm based on multi-pulse splicing is proposed. The core idea of this algorithm is to effectively integrate the data of the corresponding range gates in adjacent pulses through a well-designed splicing strategy. In this way, we can significantly improve the velocity resolution of the wind field without compromising the actual detection range resolution ability.

The results of numerical simulations and actual experiments show that the multi-pulse splicing algorithm exhibits significant advantages in performance compared to the traditional incoherent accumulation algorithm. This innovative method not only effectively balances the relationship between range resolution ability and velocity resolution but also demonstrates high practical value in actual wind field detection, injecting new vitality into the development of wind field detection technology.

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