THE SIGNAL PROCESSING BY EMPIRICAL MODE DECOMPOSITION FOR INCOHERENT DOPPER WIND LIDAR BASED ON IODINE FILTER

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ABSTRACT

The atmospheric wind field can be retrieved from the combined Mie and Rayleigh backscattering by use of an incoherent Doppler lidar. In this paper, we present a detailed analysis of the signal processing and wind field retrieving from backscattered lidar signal. The backscattering lidar signal can be denoised based on the method of Empirical Mode Decomposition (EMD). And a new approach is proposed to eliminate the edge problem that comes with EMD. The Signal-to-Noise Ratio (SNR) by using the EMD method is improved no less three times than the original's. The result of wind field retrieving shows that this denoising method is effective and superior to traditional method.

1. INTRODUCTION

Our mobile wind lidar system is a useful tool to measure the wind utilizing direct detection Doppler lidar techniques. The atmospheric wind field can be retrieved from the combined Mie and Rayleigh backscattered signal.[1] The backscattering signal is attenuated due to noise and interferences, such as stochastic turbulences, background noise, dark current, electronics readout noise and atmospheric turbulence. In order to improve the detected distance and the signal-to-noise ratio (SNR), lidar researchers usually use the multiple-pulse average or running-average approach to smooth the lidar signal. [2-4]

As we known, the noise in backscattering signal of lidar contains different frequency, so the conventional Fourier spectral analysis is not useful in lidar signal. Because noise is non-stationary, setting a cut-off frequency maybe loose the sudden change of signal, The popular moving average approach also can remove some noise, but it sacrifices the range resolution. And the wind needs to be showed immediately, so signal processing calls for rapid and efficient techniques.

In this paper, we present a new method to process signal for wind lidar, Empirical Mode Decomposition (EMD), which is developed by Huang et al. for adaptively representing non-stationary signals as a sum of Intrinsic Mode Function (IMF).[5, 6] We propose another method to solve the edge problem with EMD, which is more suitable for lidar signal. In this work, the lidar data obtained from our Doppler lidar are analyzed by EMD method. We show the denoising result, SNR, and the retrieving wind field to valuate its effect and superiority.

2. EMPIRICAL MODE DECOMPOSITION

Huang et al. introduce a new method to deal with both non-stationary and nonlinear data. The essence of the method is to identify the intrinsic oscillatory modes by their characteristic time scales in the data empirically, and then decompose the data accordingly to obtain a series of Intrinsic Mode Function (IMF).

By virtue of the IMF definition, the decomposition method can simply use the envelopes defined by the local maxima and minima separately. Once the extrema are identified, all the local maxima are connected by a cubic spline line as the upper envelope. Repeat the procedure for the local minima to produce the lower envelope. The upper and lower envelopes should cover all the data between them. Their mean is designated as m_1, and the difference between the data and m_1 is the first component, h_1, i.e.

$$X(t) - m_1 = h_1 \tag{1}$$

The sifting process serves two purposes: to eliminate riding waves; and to make the wave-profiles more symmetric. Toward this end, the sifting process has to be repeated more times. In the second sifting process, h_1 is treated as the data, then

$$h_1 - m_{11} = h_{11} \tag{2}$$

Now all the local maxima are positive, and all the local minima are negative, but many waves are still asymmetric. We can repeat these sifting procedure k times, until h_{1k} is an IMF, that is

$$h_{1(k-1)} - m_{1k} = h_{1k} \tag{3}$$

the result is shown in figure 2 after nine siftings. Then, it is designated as

$$c_1 = h_{1k} \tag{4}$$

the first IMF component from the data.

Overall, c_1 should contain the finest scale or the shortest period component of the signal. We can separate c_1 from the rest of the data by

$$X(t) - c_1 = r_1 \tag{5}$$

Since the residue, r_1, still contains information of longer period components, it is treated as the new data and subjected to the same sifting process as described above. This procedure can be repeated on all the subsequent r_j s, and the result is

$$r_1 - c_2 = r_2, \ldots, r_{n-1} - c_n = r_n \tag{6}$$

The sifting process can be stopped by any of the following predetermined criteria: either when the component, c_n, or the residue, r_n, becomes so small that it is less than the predetermined value of substantial consequence, or when the residue, r_n, becomes a monotonic function from which no more IMF can be extracted. Even for data with zero mean, the final residue can still be different from zero; for data with a trend, then the final residue should be that trend. By summing up equations (5) and (6), we finally obtain

$$X(t) = \sum_{i=1}^{n} c_i + r_n \tag{7}$$

Thus, we achieved a decomposition of the data into n-empirical modes, and a residue, r_n, which can be either the mean trend or a constant.

3. PROCESSING LIDAR SIGNAL BY EMD

The lidar signal is composed of useful data and noise. The original backscattering lidar signal from energy reference channel is given in Fig.1. From the picture, we can see that the dynamic range of lidar signal can reach 10^5, and the lidar signal is a typical attenuated function with altitude**.** Because the number of photon decreases rapidly and the noise increases at far distance, the SNR and accuracy of high altitude atmosphere is much lower than of the low altitude. Therefore, we need to use the appropriate method to denoise and to improve the accuracy of wind field.

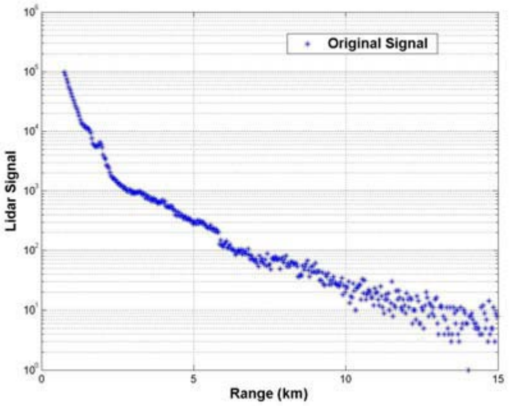

Fig.1. The typical signal of lidar

After analyzing the signal, we use EMD method to decompose the time series data into a series of IMF with a zero local mean, which is showed in Fig.2.

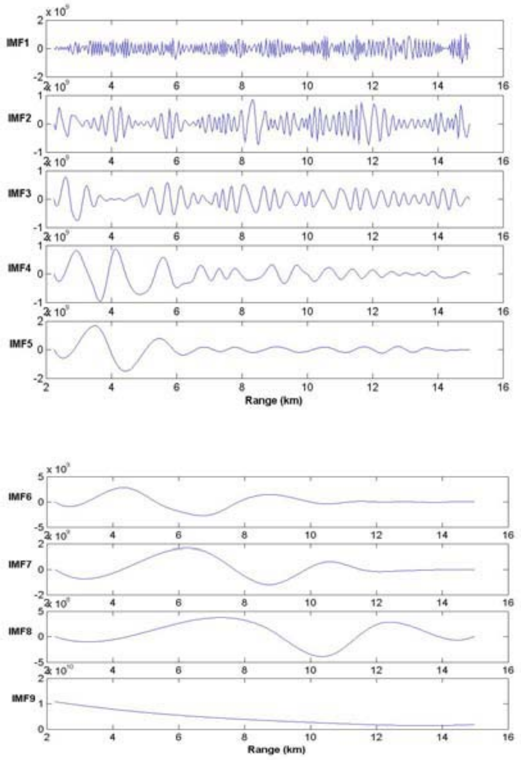

Fig.2. The first 9 IMFs of the lidar signal

In Fig.2, IMFs are ordered from high to low frequency although they will rarely have a constant frequency. We assume the high frequency IMFs to contain only noise and fluctuation. Whereas the energy of the high frequency IMFs are of little weight in the total backscatter, it is still practicable to improve SNR by subtracting high frequency modes from the data. In addition, high order IMFs often contain small spatial (or time) scale fluctuations that are much less than that of the wind speed we concerned. Therefore, high frequency modes can also be removed to get proper signal resolution. Denoised signal here is achieved by subtracting the first two IMFs from the original signal, showed in Fig.3.

From the result we find that the low altitude of the signal is no longer availability. This is obviously showed in Fig.4 where ORG is the original data and EMD1 is the data processed by EMD directly.

Because data sequence at the two ends is dispersed when the maximum and minimum envelopes are fitted by the cubic parametric spline function, the signal below 1500 meters processed by EMD deviates from the original signal greatly. And because of the repeating treatment, the whole result of data processing would be seriously deviated from the original data sequence. For a long data sequence, giving up the ends data can reduce the deviation. The lidar data is long enough comparatively, but the former end of the data series is useful for wind lidar that cannot be discarded. On the other hand, the data of the latter end of the sequence can be given up because of its very low SNR. We should expand the data sequence to reduce the deviation.

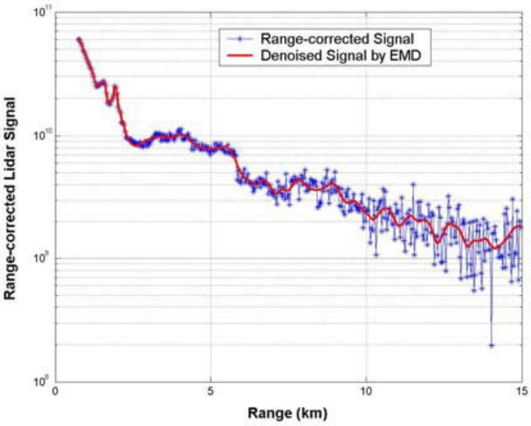

Fig.3. Denoised lidar return signal by EMD

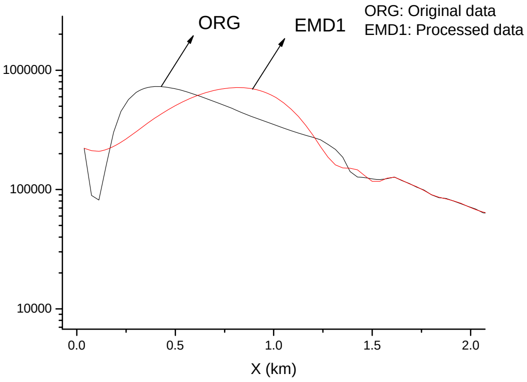

Fig.4. Comparing the raw data with the processed data by EMD (low altitude)
ORG: raw data; EMD1: processed data by EMD method directly

A method for data expansion is proposed as follows. The lidar equation can be expressed as

$$P(\lambda,r)=p_0\frac{A}{r^2}E\beta(\lambda,r)\exp[-2\int_0^r\alpha(\lambda,r')dr'] \quad (8)$$

In Eq. (8), *P(λ, r)* is received power; P_0 is transmitted pulse power; A is aperture of telescope, E is efficiency of optics and electronics; $\beta_{.}$ is the backscatter coefficient of atmosphere; *α(λ, r')* is the extinction coefficient .We use this formula to expand the data sequence,

$$\ln(P(r))=kr+b \quad (9)$$

Where k and b are constants that are determined by the lidar data sequence.

We find the maximum of the data sequence firstly and then expand the data series from the maximum to lower altitude with Eq.9.

To compare the data processed by EMD after expanding the original data with data processed by EMD directly, we express the results in detail at low altitude in Fig.5 where ORG is the original data while EMD1 is the data processed by EMD directly and EMD2 is the data processed by EMD after expanding the original data. We can see that EMD2 is well consistent with ORG while EMD1 is not yet. We can see the result is comparatively good in low altitude from 0.1 to 1 km. So we conclude that this data expanding method can properly solve the edge problem.

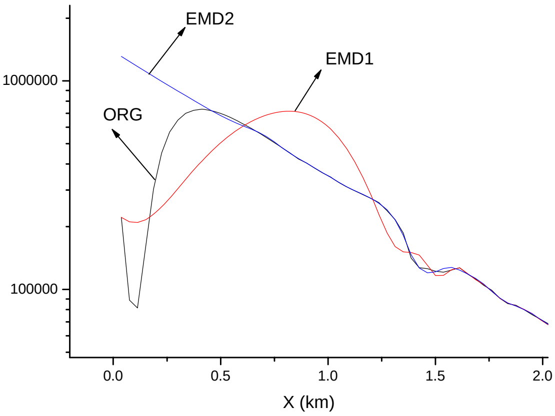

Fig.5. Comparison of different results (at low altitude)
ORG: original data; EMD1: data processed by EMD directly; EMD2: data processed by EMD after expanding the original data.

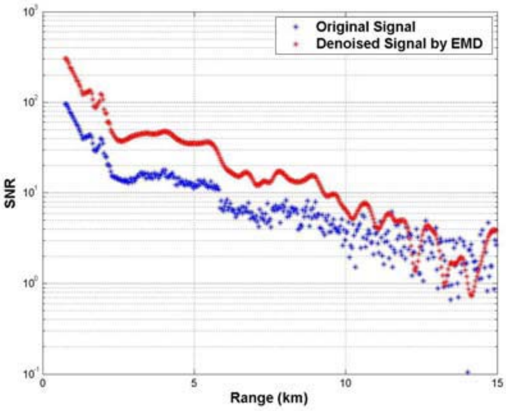

Fig.6. SNR of original and denoised data by EMD

The SNR of original and denoised signal is showed in Fig.6. From the figure, we can see that the SNR of the signal processed by EMD is improved about 3 times more than the original's.

4. RESULT OF WING FIELD RETRIEVING

After denoising, we are able to retrieve the wind field. The results of wind field are showed in Fig.7 and Fig.8. In the figure, the wind speed and direction retrieved from the denoised signal by EMD and original signal are compared. The most of the noise in signal has been eliminated, but the important information, including the change of wind with altitude are reserved. We can conclude that the EMD method is appropriate and effective to retrieve the wind field.

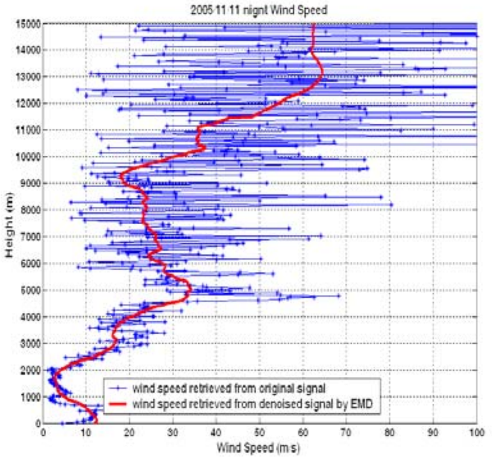

Fig.7. Wind speed retrieved from backscattering signal

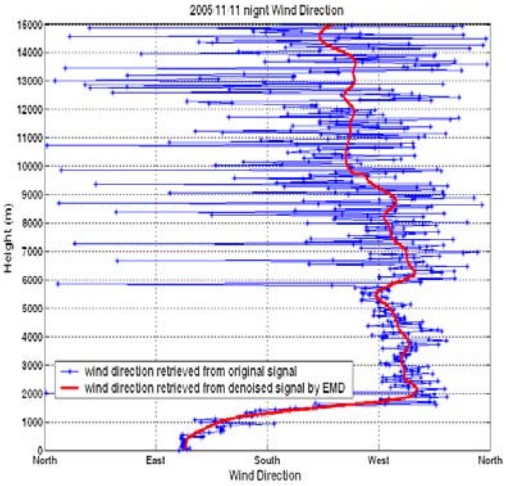

Fig.8. Wind direction retrieved from backscattering Signals

5. CONCLUSION

We can conclude that the EMD method is appropriate and effective to retrieve the wind field. The SNR of the signal processed by EMD is improved about 3 times more than the original's. The wind speed and direction retrieved from the denoised signal by EMD and original signal are compared. The most of the noise in signal has been removed and the error has been eliminated.

6. ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (NSFC)
projects No. 40427001 and No. 60578038; and project 985 of Remote Sensing laboratory of Ministry of Education of China, Ocean University of China.

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