Techniques to Improve the Denoising for Wind Profiler Time Series Data

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Abstract**—**The lower atmospheric signals, which are processed in the present work has been obtained from the LAWP radar at the National Atmospheric Research Laboratory (NARL), Gadanki, India. The Radar wind profiler is most suitable remote sensing tool for measuring the height profile of wind vector with high resolutions in both time and space in all weather conditions. The term wind profiling radar is often used to emphasize the operational applications of the clear air radar technique and operating at lower and middle UHF bands. These radars can measure the wind profiles in the first few kilometers of the atmosphere. They include boundary layer convergence processes and their relationship to atmospheric convection, mountain drainage flows and urban pollution studies. This paper discusses denoising the wind profiler data using Empirical Mode Decomposition (EMD), Peak Detection Technique (PDT) and Daubechies wavelets. Effective Doppler shift for LAWP data is obtained by using Db11 wavelet and compared with the different signal processing techniques. The Result shows that there is an effective doppler shift after using Db11 wavelet for LAWP signals.

Keywords**—** Daubechies, Doppler Beam Swinging, Wind Profiler, Signal to Noise Ratio, Thresholding.

I. Introduction

THE Lower Atmospheric Wind Profiler is used for conducting research in the lower atmosphere [1]. National Oceanic and Atmospheric Administration (NOAA) developed the technology for operational wind profilers, and in the early 1980s deployed the Colorado wind-profiling network consisting of five VHF and one UHF radars. The atmospheric radars of interest in the current study are known as clear air radars and they operate typically in the VHF (30 –300 MHz) and UHF (300 MHz –3GHz) bands. The National Atmospheric Research Laboratory (NARL) at Gadanki (13.47°N,79.18°E) near Tirupati, India, has been operating this wind profiler at 1280 MHz. This system which is the first of its kind in India, has been configured with a simplified active array, that exhibits high sensitivity. This wind profiler used for studying the dynamics and structure of the lower atmosphere. These radars employ bi-phase coding with complementary codes, to achieve better range resolution with a maximum average power. Wind profilers have been developed in the recent past by research and commercial groups for applications ranging from air quality studies to climate monitoring. It can measure the complete Doppler spectrum of atmospheric targets with a time resolution on the order of 1 min and a range resolution of about 100m. It is useful in atmospheric boundary layer studies.

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The extension of the wind profiler technology to the lowest portion of the atmosphere is very important. Wind profiles are very important for studying meteorological phenomena and for weather forecasting. These wind profilers receive the echoes from the atmosphere in the height range from about 0.1Km to 4-5Km. These wind profiler radars are coherent and very high sensitive. These radars are pulse Doppler Radars and works on the principle of the doppler effect.

II. Lower Atmospheric Wind Profiler Radar

Lower Atmospheric Wind Profiler (LAWP) Radars are extensively used for obtaining the wind information in all weather conditions. These radars have the capability for probing the atmosphere, wind profiling. These radars are also called doppler radars. Doppler radars can be used for meteorological research. Wind profilers are expected to have a growing impact upon weather forecasting, atmospheric research, environmental pollution monitoring, climate, air traffic control and many more. It is therefore important that the wind measurements of these radars are both accurate and reliable. The minimum height limitation arises from various factors like receiver overload due to strong clutter and internal reflections in large antenna arrays, the inherent inability of large antenna operating in this frequency range to form well-defined beams in the first few kilometers above the array and the limitation of bandwidth at these frequencies. The operating frequency band of LAWP radar is 900-1400 MHz. These radars are popular for measuring the wind vector by making use of variations in amplitude and frequency of radio waves which are transmitted from a radar system. The features of high spatial resolution and fast system recovery time require operation at frequencies near 1000 MHz.

LAWP radar being extensively used for atmospheric research and operational meteorology and has applications beyond wind profiling. These data may be used to estimate the Moments, Noise Levels and Doppler shift [2]. LAWP radar can be used to distinguish the clear-air scattering from the precipitation scattering arising from cloud and rain drops. Since they provide almost continuous measurement of wind over a range of altitudes, they provide detailed information on vertical structure and wind variability. Vertically directed beams provide for direct measurement of vertical motions. In addition to wind and wind variability, the Doppler wind profiler provides measurement of signal strength and Doppler spectral width.

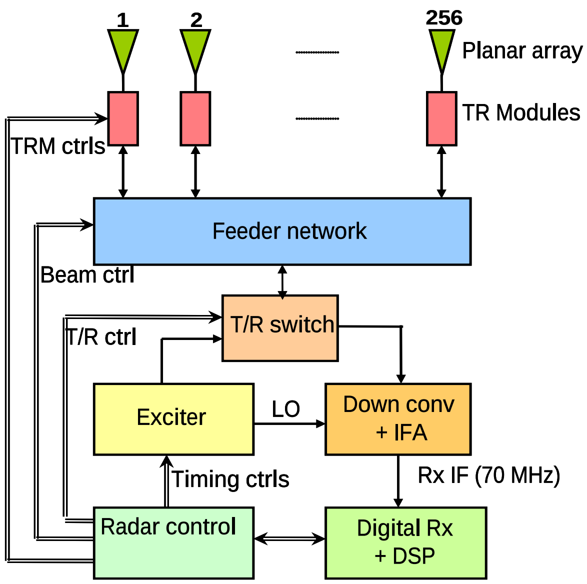


Fig. 1 Block diagram of LAWP Radar

LAWP Radar system Specifications :

- Operating frequency is 1280 MHz
- Wind profiling Technique is Doppler Beam Swinging.
- Minimum height range is 100m
- Maximum height range is about 3-6 km in clear air and up to 12 km during precipitation
- Type of Antenna is Active patch array 16 x 16 (2.8m x 2.8m)
- Type of Tx/Rx is Solid-state TR modules (256)
- Pulse length range is 0.25μs to 8 μs
- System recovery time is < 0.5μs

A. Doppler Beam Swinging

To measure the atmospheric winds the wind profilers use either Spaced Antenna (SA) technique or Doppler Beam Swinging (DBS) technique. These systems operate with DBS technique with three fixed beams (Vertical, East-West, and North- South) to derive the components of the wind vector. The SA technique employs a single vertical beam, but receives the echo with multiple receivers.

Most commonly used technique for wind profiling is the DBS technique. One antenna beam is pointed toward zenith, and other two beams are pointed at off zenith angles in the range 10^{o} - 20^{o} off zenith with orthogonal azimuths as shown in figure 2. Spaced Antenna technique measures the temporal and spatial variation of field pattern of radar signals which are partially reflected or scattered from refractive index irregularities in the atmosphere. The antenna is pointed vertically. The spectral or complex autocorrelation analysis yields an estimate of the vertical velocity.

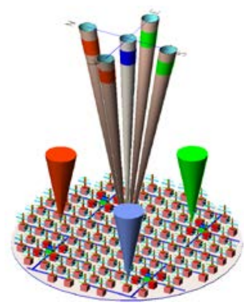


Fig. 2 Antenna Configuration for Doppler Beam Swinging Technique

The wind profiler is operated in a pre-selected sequence of beam directions. Comparison of received echo with the transmitted pulse permits the determination of the Doppler frequency. The beam pointing sequence is repeated for every 1-5 min. For each height, the radial velocities measured from the three beams are used to derive the east-west (zonal), north-south (meridional), and vertical components of the wind, U, V and W respectively.

If the beams are oriented to the east at zenith angle θ_1 (beam 1), to the north at zenith angle θ_2 (beam 2) and to the vertical θ_3 (beam 3), the radial velocities along these three beams are

$$\begin{aligned} V_{R1} &= U\,Sin(\theta_1) + WCos(\theta_1) \\ V_{R2} &= U\,Sin(\theta_2) + WCos(\theta_2) \\ V_{R3} &= W \end{aligned} \tag{1}$$

III. DATA PROCESSING

The received signals are Doppler shifted from the transmit frequency due to the motion of the atmosphere. It is converted into a quadrature base band signal using the down converter and quadrature detection. The demodulated quadrature signals, which represent the combination of signal plus noise, are sampled at regular intervals. An echo due to a single pulse is of no use as the received signals are normally weaker than the back ground noise and clutter. Here, signal processing steps are required to extract the weak signals from the noisy and clutter environment and to derive the atmospheric parameters. The Data processing steps include pulse compression, coherent integration, spectral processing steps like clutter removal, incoherent integration etc.

In general, the echo power due to a single pulse is very weak compared to the noise power and echoes received over a large number of successive pulses are averaged to improve the detection capability. Therefore, a large number of pulses need to be transmitted within the given integration interval.

Otherwise, radar should be able to transmit pulses at a fast rate for better detection.

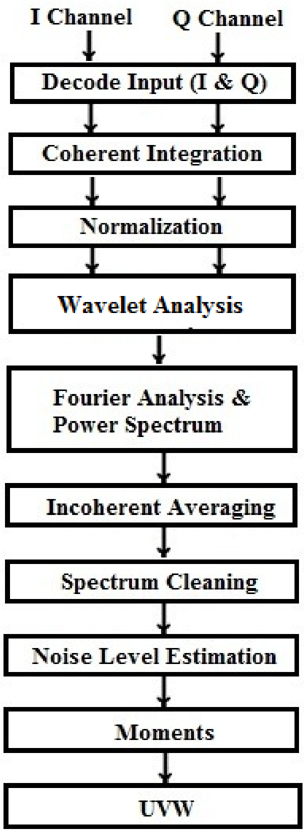


Fig. 3 Data processing steps of LAWP Radar

Coherent Integration is a low pass filtering process achieved by adding the complex digital data samples for a pre-defined number of pulses. Coherent integration has the advantage that it reduces the data rate by up to two orders of magnitude and it improves the detectability of echoes with low signal to noise ratio, since the average transmitter power can be used. After coherent integration, elimination of non fading ground clutter is carried out by applying a very narrow band notch filter that removes any zero frequency bias in every range gate without attenuating the zero frequency component of the atmospheric echo.

The maximum range capability of the radar wind profiler is directly proportional to the square root of the average transmit power, which is the product of peak power and duty ratio (τ /T), where T is the inter-pulse period. The Profiler's Range Resolution is equal to $c\tau$ /2. The best range resolution is obtained with short pulse length, but the profiler's height coverage will be minimum due to low average transmit power. The time series complex data {(I_i, Q_i), i = 0, 1. . . N_{FFT} - 1} is subjected to FFT to obtain the complex Doppler spectrum {(X_i, Y_i), i = 0. . . N_{FFT} - 1} of the received echoes. I_i and Q_i are the in-phase and quadrature components in time series data, X_i and Y_i are the real and imaginary components of the complex Doppler spectral data, and N_{FFT} is the number of time series points.

IV. EMPIRICAL MODE DECOMPOSITION

The Empirical Mode Decomposition (EMD) is an adaptive method to decompose any data into a set of Intrinsic Mode Function (IMF) components, which become the basis representing the data. Because of the adaptive nature of the basis, there is no need for harmonics. EMD is ideally suited for analyzing data from non stationary and nonlinear processes. EMD offers a totally different approach to data decomposition, to study the characteristics of the noise which is present in the signal.

EMD method is an algorithm for the analysis of multi component signals that breaks down into a number of amplitude and frequency modulated zero mean signals, termed intrinsic mode functions (IMFs) [5]. EMD adaptively decomposes a multi component signal $x(t)$ into a number L of the so-called IMFs $h^{(i)}(t),\ 1 \le i \le L$.

$$x(t) = \sum_{i=1}^{L} h^{(i)}(t) + d(t) \tag{2}$$

Where $d(t)$ is a reminder that is a non-zero-mean slowly varying function with only few extreme.

Each one of the IMFs, the i th one $h^{(i)}$, is estimated with the aid of an iterative process, called sifting, applied to the residual multi component signal

$$x^{(i)}(t) = \begin{cases} x(t) & i=1 \\ x(t) - \sum_{j=1}^{i-1} h(j)(t) & i \ge 2 \end{cases} \tag{3}$$

Although the term local mean is, especially for multi component signals, somewhat vague, in the EMD context means that its subtraction from $x^i(t)$ will lead to a signal, which is actually the corresponding IMF,

i.e., $h^{(i)}(t) = x^{(i)}(t) - m^{(i)}(t)$ (4)

EMD Algorithm

Given a non stationary signal $x(t)$, the EMD algorithm can be summarized into the following steps:

Step (1): Finding the local maxima and minima: then connecting all maxima and minima of signal $x(t)$ using cubic splines to obtain the upper envelope $x_u(t)$ and lower envelope $x_l(t)$, respectively.

Step (2): Computing local mean value $m_1(t) = \frac{1}{2}(x_u(t) + x_l(t))$ of data X(t), subtracting the mean value from signal $x(t)$ to get the difference:

$$h_1(t) = x(t) - m_1(t) \tag{5}$$

Step (3): Regarding $h_1(t)$ as new data and repeating steps (1) and (2) for k times, the value of $h_{1(k-1)}(t)$ and $h_{1k}(t)$.

$$h_{1k}(t) = h_{1(k-1)}(t)x(t) - m_{1k}(t) \tag{6}$$

It is terminated until the resulting data satisfies the two conditions of an IMF, defined as $c_1(t) = h_{1k}$ and The residual data

$$r_1(t) = x(t) - c_1(t) \tag{7}$$

Step (4): Regarding $r_1(t)$ as new data and repeating steps (1), (2) and (3) until finding all the IMFs. The sifting procedure is terminated until the nth residue $r_n(t)$ becomes less than a predetermined small number or the residue becomes monotonic.

Step (5) Repeat steps 1 through 4 until the residual no longer contains any useful frequency information. The original signal is, of course, equal to the sum of its parts. If we have 'n' IMFs and a final residual $r_n(t)$. Finally the original signal $x(t)$ can be expressed as follows:

$$x(t) = \sum_{i=1}^{n} c_i + r_n \tag{8}$$

V. Peak Detection Technique

Identifying and analyzing peaks or spikes in a given time series is an important in many applications. This technique is useful in many application areas like bioinformatic, mass spectrometry, signal processing, image processing requires peak detection. Peak detection technique can able to detect peaks in variant environments, independent of the average magnitude of the peak signal. To reduce the effect of noise, it is required that the local signal to noise ratio should be over a certain threshold.

Thresholding can be used to find the local maxima for signal portions which exceeds the threshold level. With this technique, effective doppler shifts can be obtained. Peak detection technique is one of the methods for reducing the probability of false detection. The advantage of this algorithm is better height coverage and effective doppler shift.

Computing the Threshold automatically by adapting it to the noise levels in the time-series as

$$Threshold = (max + abs\_avg)/2 + K * deviation \tag{9}$$

Where *max* is the maximum value in the time-series, *abs_avg* is the average of the absolute values in the time series, *K* is the influence factor of the deviation, and *abs_dev* is the mean absolute deviation.

$$abs\_avg = \frac{\sum_{i=1}^{N} |P_i|}{N} \tag{10}$$

$$deviation = \frac{\sum_{i=1}^{N} |P_i - avg|}{N} \tag{11}$$

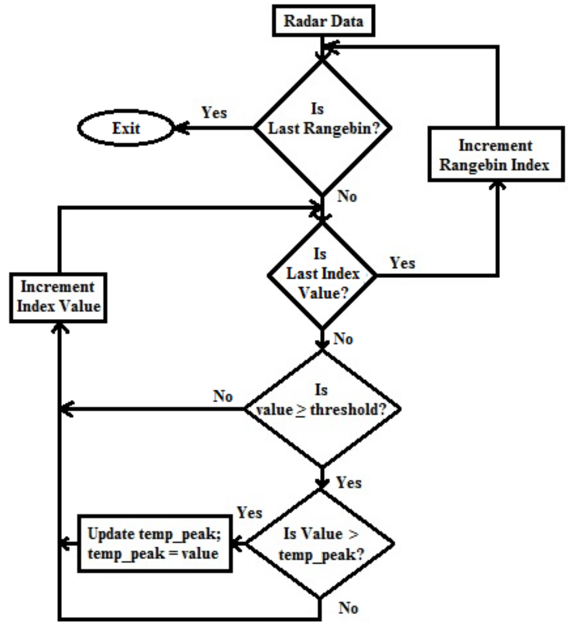


Fig. 4 Flow diagram of the Peak Detection Technique

If the deviation is very low, the threshold will nearly be in the middle of maximum value and the average value.

When K= 0.5, Then the Threshold equation can be rewritten as

$$Threshold = \frac{\max}{2} + abs\_avg \tag{12}$$

Where

$$abs\_avg = \frac{\sum_{i=1}^{N} |P_i|}{N} \tag{13}$$

The Threshold can be calculated based on the above equations.

The ground clutter can be removed from the wind profiler data by applying the thresholding. First the peak value can be identified in each and every range bin and stored these peak values in an array.

VI. Wavelet Transforms

The key to the effectiveness of the wavelet decomposition based denoising, therefore, is in the ability to find a wavelet basis function that has a functional form close to that of the signal of interest. In the case of atmospheric radars, standard wavelet such as Daubechies was used to analyze wind disturbances and to remove ground and intermittent clutters. However, it is possible to improve the effectiveness of the denoising process if a better wavelet is designed. The application of wavelet analysis in radar systems has become an active research area. Wavelet analysis is used to detect radar pulse edges. The noise is removed by thresholding the wavelet transform coefficients of the received RF radar pulses.

The Wavelet transform performs a correlation analysis, therefore the output is expected to be a maximal when the input signal most resembles the mother wavelet.

Wavelet decomposition of a signal y(t) is

$$y(t) = \sum_{s} a_{u0}(s)\,\phi_{u0,s}(t) + \sum_{u}\sum_{s} d_{us}(s)\,\psi_{u,s}(t) \tag{14}$$

$$\phi_{u,s}(t) = 2^{u/2}\ \phi(2^{u}t - s) \tag{15}$$

$$\psi_{u,s}(t) = 2^{u/2}\ \psi(2^{u}t - s), \qquad (u, s\ \in\ Z) \tag{16}$$

u is the dilation parameter and s is the translation parameter. $\phi(t)$ and $\psi(t)$ are called scaling and wavelet functions respectively. a_{u0} and d_{us} are called wavelet coefficients.

Wavelet technique is one of the most important method for removing noise and extracting signal from any data. Mallat defines a wavelet as a function of zero average,

$$\int_{-\infty}^{\infty} \psi(t)dt \ = \ 0 \tag{17}$$

Which is dilated with scale parameter s, and translated by u:

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-u}{s}\right) \tag{18}$$

The aim of this study is to investigate the wavelet function that is optimized to identify and de-noise the radar signal.

A. Daubechies

Daubechies classic technique for finding orthogonal wavelet bases with compact support is often used as the default in many wavelet applications. However, the wavlets produced are independent of the signal being analyzed. The wavelet design techniques were developed to build non orthogonal wavelet bases from a library of existing wavelets in such a way that some error cost function is minimized.

The scaling function for Daubechies exist up to order 20. Higher order Daubechies functions are difficult to describe with an analytical expression. The Daubechies wavelets are chosen to have the highest number of vanishing moments. The wavelet based denoising process is shown in figure 5.

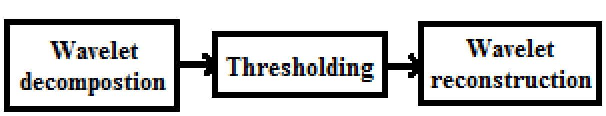


Fig. 5 Block diagram of Wavelet based de-noising

The properties of this wavelet are asymmetric, orthogonal and bi-orthogonal. In this paper, Db11 has been used to improve the SNR for the Lower Atmospheric signals. Db11 wavelet is shown in figure 6.

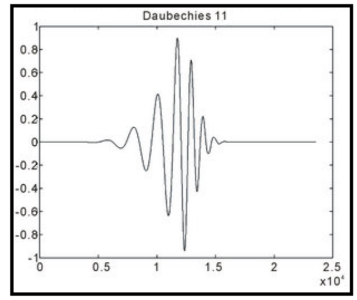


Fig. 6 Db11 wavelet

A. Thresholding

The problem of estimating a signal that is corrupted by noise has been interest to many researchers. The problem is to recover the original signal from the noisy data. Wavelet thresholding is a signal estimation technique for signal denoising. It removes noise by killing coefficients that are insignificant relative to some threshold. The efficiency of wavelet denoising depends heavily on the choice of a thresholding parameter. The selection of the threshold value plays an important role in denoising process.

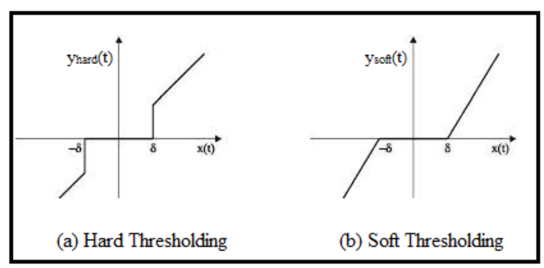


Fig. 7 Thresholding

There are different ways to apply the threshold to the wavelet coefficients. The signal is composed into L levels before thresholding is applied. The two types of thresholding are one hard threshold is a "keep or kill" procedure and is more intuitively appealing and other soft thresholding shrinks coefficients above the threshold in absolute value. The second one provides smoother results in comparison with the hard thresholding. Soft thresholding avoids the discontinuities by shrinking the coefficients.

For all these reasons, the suitability of one or the other method depends on each particular application. Thresholding can be applied manually by selecting the desired coefficients at different levels.

B. Reconstruction

Reconstruction of the signal using the appropriate coefficients of level N and the modify the detailed coefficients of level from 1 to N.

Procedure to Denoise the LAWP signals using Db11 Wavelet

Denoising is applied to LAWP Radar data on 20th August 20, 2014.

An Algorithm for Doppler profile using Db11 wavelet:

- DC removal from the raw data using Hilbert transform technique.
- Computation of FFT for the raw data.
- SNR is computed for each range bin.
- The raw data is de-noised using Db11 wavelet.
- The above two steps 2 and 3 are repeated until

all range bin data were processed.

VII. Results

Doppler shift results of LAWP data on 20th August 2014 in South direction before denoising and after denoising using EMD shown in Figure 8 and Figure 9 respectively.

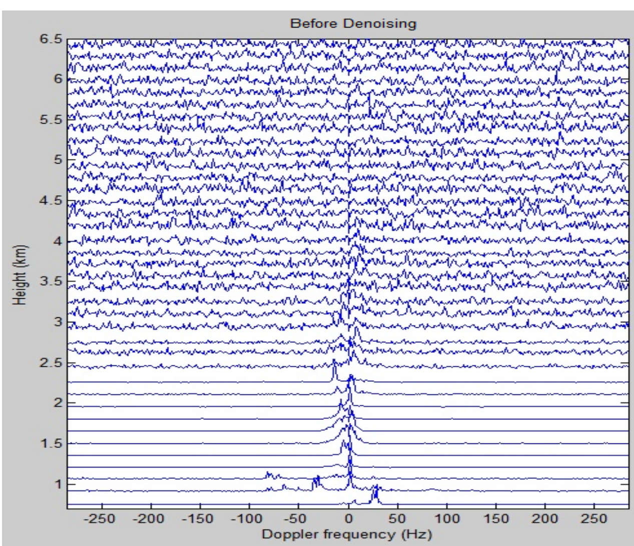


Fig. 8 Before de-noising

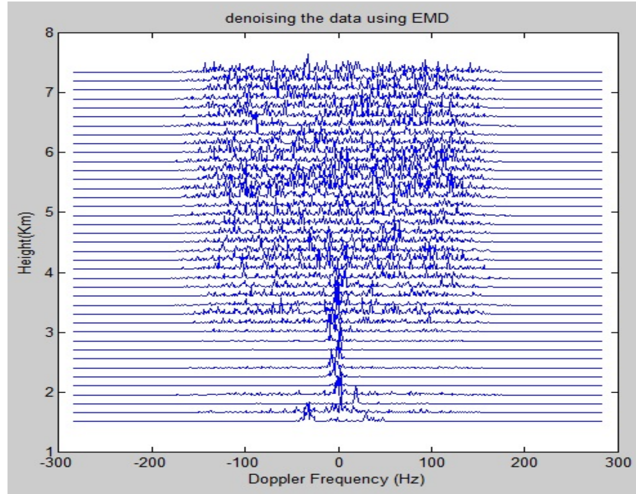
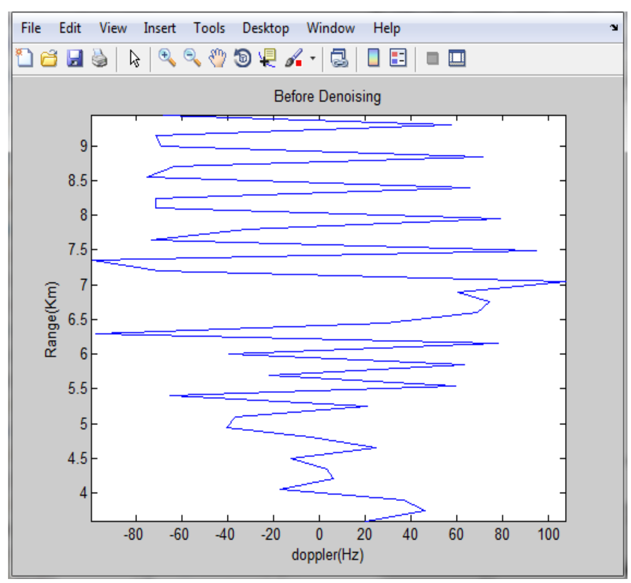


Fig. 9 After denoising the original data using EMD

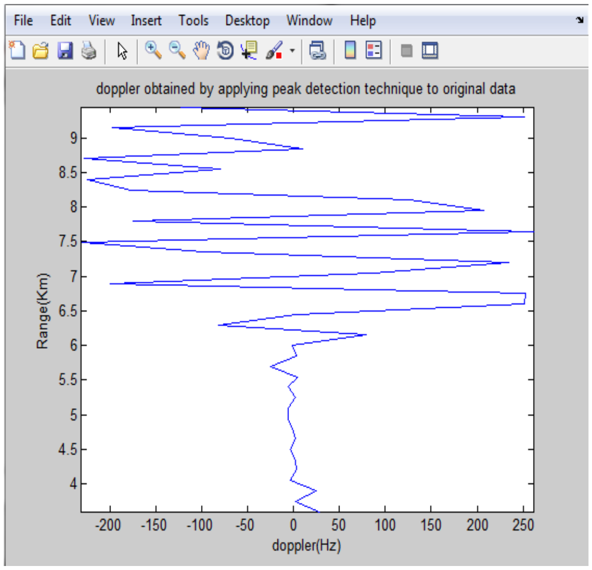
Table 1: Comparison of SNRs of the LAWP data in different dates.

Date	By Using	SNR in dB			
		EAST	**WEST**	**NORTH**	**SOUTH**
19 SEP 2014	FFT	10.2908	8.3036	8.4290	8.5762
	EMD	28.1173	26.555	26.4614	32.2331
20 AUG 2014	FFT	4.4542	6.3965	7.3864	10.3718
	EMD	24.6049	26.1658	24.1997	28.8948
31 MAY 2014	FFT	6.5599	4.0731	4.0123	6.7032
	EMD	26.5085	25.3236	24.5986	27.1046

Doppler shift results of LAWP data on 20th August 2014 in East direction before denoising and after denoising using Peak Detection technique shown in Figure 10.



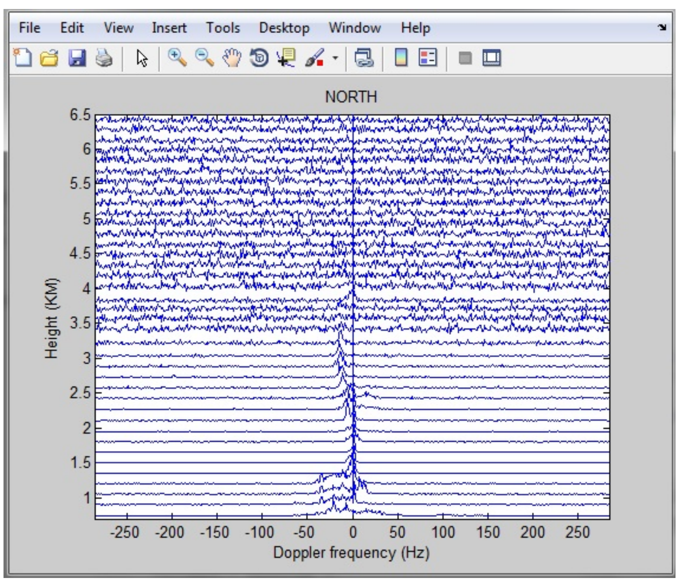
(a)



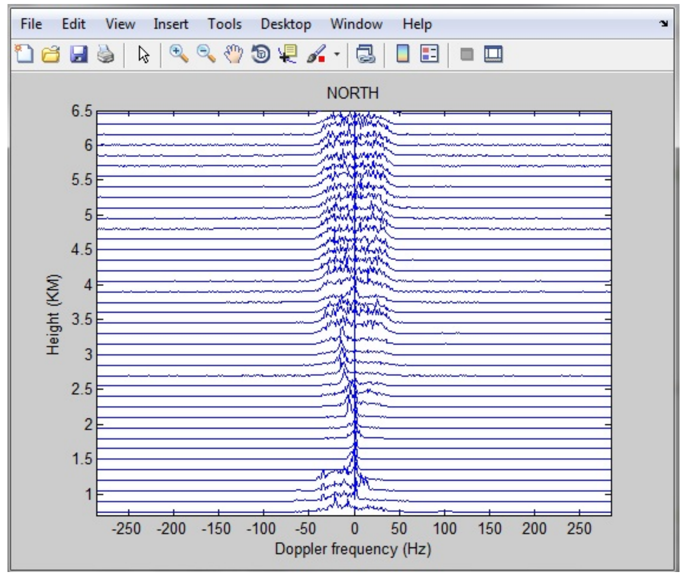
(b)

Fig. 10 (a) Before denoising (b) After denoising using Peak Detection technique.

Doppler shift results of LAWP data on 20th August 2014 in North direction before denoising and after denoising using Db11 Wavelet is shown in Figure 11.



(a)



(b)

Fig. 11 (a) Before denoising (b) After denoising using Db11 Wavelet

Table 2: Improvement in Signal to Noise Ratios after denoising using different Daubechies Wavelets

	East	**West**	**Zenith**	**North**	**South**
Db7	19.503	18.827	19.171	19.289	19.022
Db8	20.126	19.319	19.734	19.675	19.461
Db9	19.384	28.468	19.217	18.751	18.755
Db10	20.248	19.575	20.214	19.789	10.682
Db11	**21.444**	**20.841**	**21.543**	**20.869**	**21.007**
Db12	20.799	19.891	20.687	20.092	20.221
Db13	20.736	19.920	20.706	20.082	20.063

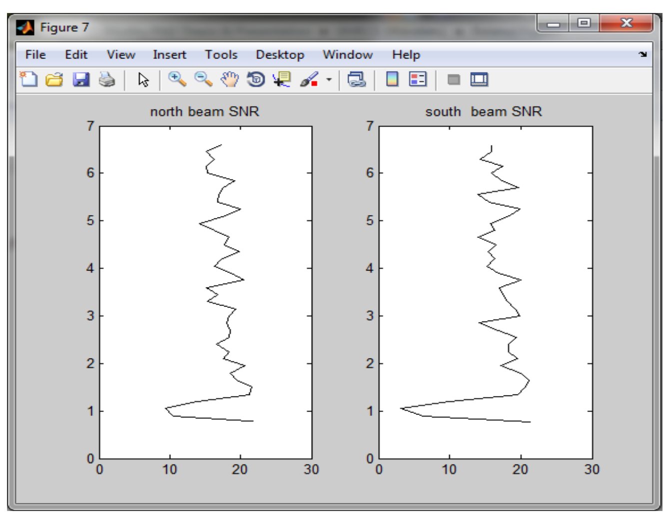


Fig. 12 SNR in North and South directions using Db11 Wavelet

VIII. CONCLUSION

Denoising using Empirical Mode Decomposition, peak detection algorithm and Db 11 Wavelet has been applied on wind profiler time series data and compared. The above results shows that the improvement is observed by comparing before denoising and after denoising by using EMD, peak detection technique and Daubechies Wavelet. From the above discussion, it is concluded that high improvement in signal to noise ratio 21.5 dB is observed after de-noising using Db11 wavelet. Further, the Doppler shift can be effectively improved by using adaptive signal processing techniques like weiner filter, Kalman filter, least mean square algorithm, etc. These adaptive signal processing techniques are widely using for non-stationary signals by compressing the side lobes and to improve the signal to noise ratio.

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BIBLIOGRAPHY

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