Wavelet transform based methods for removal of ground clutter from the radar wind profiler data

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Abstract:
Various non–atmospheric signals contaminate radar wind profiler data introduce bias in moments and wind velocity estimation. Especially in UHF wind profilers ground clutter severely degrades wind measurement. Detection of weak signal in a noisy environment is an important problem in atmospheric radar systems. It is important to improve the SNR at higher altitudes. Wavelet analysis is a powerful tool to differentiate the characteristics of the ground clutter from the atmospheric turbulence echo at the time series data level. In this paper we proposed a new method based on wavelets for removing ground clutter from the data.

Key Words: Wavelet transform, Ground clutter filtering, Signal processing

I INTRODUCTION

Radar Wind Profiler (RWP) is a powerful remote sensing tool to probe the atmospheric wind velocities. RWP employ the Doppler beam swinging (DBS) technique, which uses three or five beams, one beam is transmitted in vertical (Zenith) direction and two (or four) off vertical beams are transmitted in orthogonal directions. Due to the irregularities of atmospheric refractive index, a portion of the transmitted signal back scattered [1] and received by the radar. The irregularities move with wind as it changes its speed and direction with time. Thus the backscattered signal is shifted in frequency called Doppler shift. This frequency shift is used to measure the atmospheric wind velocities. Generally back scattered signal is contaminated with echoes from various stationary targets such as trees, power lines, hills, etc., called ground clutter. Echoes from moving targets such as birds and air planes called as intermittent clutter. The contaminating signals are very strong and dominate the genuine atmospheric echoes.

II DATA AND CLASSICAL SIGNAL PROCESSING

Lower Atmospheric Wind profiler (LAWP) radar [2,3] located at National Atmospheric Research Laboratory (NARL), Gadanki, India, operates at 1280 MHz frequency with a power aperture product of 1600 W-m^2. Important specifications of LAWP are given below:

Frequency	:	1280 MHz
Band Width	:	1.5/3/6 MHz
Technique	:	DBS
Antenna	:	8x8 array (1.4 m)
Peak power	:	0.8 kW @ 10%DR
Pulse width	:	0.25 – 8 µs
Noise figure	:	3 dB
Max range coverage	:	3-6 km

LAWP provides atmospheric echoes in the height range from 100m to 4-5 km in clear air. Since the radar site is surrounded by power lines and hills, the received signal severely contaminated with the unwanted signals which results bias in the wind estimation.

Figure-1 shows the classical signal processing steps (existing method) involved in wind velocity measurements. Coherent integration is performed on the data collected by radar, it improves signal to noise ratio (SNR) and also reduces the data volume size. The conventional clutter rejection algorithm is used to remove the DC/clutter from contaminated data, the DC spectral point, which is zero Doppler frequency point and several points around it are replaced with the mean of the instantly followed adjacent points [4]. But this type of processing is unable to remove the total ground clutter and also produces substantial bias in the wind estimation. Windowing is applied to the data (generally Hanning (or) Hamming) which reduces the spectral leakage and picket fence effects. Doppler spectrum of the data is computed using fast Fourier transform (FFT), several Doppler spectra are averaged (incoherent averaging) to improve the detectability. Noise level is estimated using Hildebrand and Sekhon method [5], the spectrum above the first crossing of the noise level [6] is taken as the signal power, peak picking algorithm is implemented which picks only the true atmospheric signal and finally moments are computed using the following equations.

$$\text{Signal Power} = M_0 = \sum_{i=k_1}^{k_2} \tilde{p}_i$$

$$\text{Mean Doppler} = M_1 = \frac{1}{M_0}\sum_{i=k_1}^{k_2} \tilde{p}_i f_i$$

$$\text{Doppler Variance} = M_2 = \frac{1}{M_0}\sum_{i=k_1}^{k_2} \tilde{p}_i \left(f_i - M_1\right)^2$$

$$\text{Doppler Width} = 2\sqrt{M_2}$$

$$\text{SNR} = 10\log\left[\frac{M_0}{N_{FFT} * N_0}\right] \text{dB}$$

Where k_1 = Lower Doppler point of index from the peak point, k_2 = Upper Doppler point of index from the peak point, $f_i = \frac{(i-N/2)}{(IPP*n_i*N)}$

IPP = Inter Pulse Period,
N = Number of FFT Points,
L = Noise level,
n_i = Number of coherent integrations,
p_i = Signal power at corresponding FFT point.
Radial velocity computed using mean Doppler for three (or five) beam positions.
Radial Velocity $V_D = -(f_D*\lambda)/2$ m/s.
f_D =Mean Doppler, λ = Wavelength

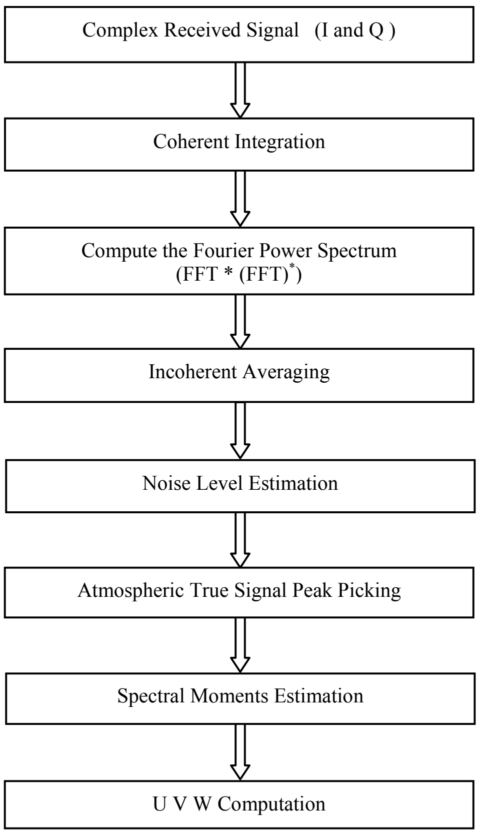

Figure 1. Classical signal Processing steps for wind velocity measurement

III WAVELET TRANSFORM AND ITS DECOMPOSITION

Wavelet is a short wave localized in time domain and frequency domain, wavelet transform uses multi resolution technique by which different frequencies are analyzed with different resolutions. High frequency components give good time resolution and poor frequency resolution, while low frequency components give good frequency resolution and poor time resolution [7]. Most of the signal characteristics match with this property [8]. Wavelet decomposition divides a signal into a set of basis functions called wavelets. Wavelet has the goal of highlighting particular properties of the signal. Wavelet decomposition of a signal y(t) is

$$y(t) = \sum_k a_{j0}(k)\, \phi_{j0,k}(t) + \sum_j \sum_k d_{jk}(k)\, \psi_{j,k}(t)$$

$$\phi_{j,k}(t) = 2^{j/2}\phi(2^j t - k)$$

$$\psi_{j,k}(t) = 2^{j/2}\psi(2^j t - k), \quad (j,k \in Z)$$

j is the dilation parameter and k is the translation parameter.

$\phi(t)$ and $\psi(t)$ are called scaling and wavelet functions respectively. a_{j0} and d_{jk} are called wavelet coefficients.

Wavelet decomposition is computed by successive low pass and high pass filtering steps. In figure 2(a) the signal denoted by a sequence y[n], where n is an integer, passes through successive low pass (G0) and high pass filters (H0). High pass filter produces detail information $d_1[n]$, while the low pass filter produces coarse approximations $a_1[n]$ at level one. To further improve the wavelet decomposition level, approximation coefficients again passed through a set of low pass and high pass filters. This process continued until the desired level is reached. The maximum number of levels depends on the length of the signal.

$N = 2^j$

N = length of the signal, j = maximum number of levels
The inverse process is used to reconstruct the original signal. G0, H0 are analysis filters, and G1, H1 are synthesis filters. Figure 2(b) and 2(c) shows the two-level wave decomposition and its reconstruction processes respectively.

IV REMOVING GROUND CLUTTER

This section demonstrates ground clutter removal using wavelet filtering. Recently much work was done for removing clutter from the radar wind profiler data, such as clutter fences [9], least squares approach [10], DC removal [6], genuine wind echo using as the reference at user specified height and searching for ground clutter way down to the lowest height [11], consensus averaging [6] and half plane subtraction [12]. These techniques are ineffective to eliminate complete clutter contamination and not suitable for all atmospheric conditions, hence introduce bias in the wind estimation.

The backscattered atmospheric turbulent signal A(t) is contaminated with clutter and noise and given by
A(t) = S(t)+C(t)+N(t)
A(t) = total back scattered signal, S(t) = clear air signal, C(t) = clutter, N(t) = Noise.
The time and frequency localization property of the wavelets is useful to differentiate the clutter and clear air signal. Jordan [13] used dubechies 20 (db20) for ground clutter elimination which has good match with the ground

clutter characteristics. Lehmann [14] used db2 wavelets, Wei-hau [15] used db20 wavelets for clutter removal according to the regularity condition of the signal. In this paper for 1280 MHz radar wind profiler signal, db20 wavelets are suitable. Donoho [16], Donoho and Johnstone [16, 17] introduced wavelet based thresholds (soft and hard) to denoise the data. Hard and soft threshold functions are given by

$$S_h(y) = \begin{cases} 0, & |y| < \lambda \\ y, & |y| \geq \lambda \end{cases}$$

$$S_s(y) = \begin{cases} 0, & |y| < \lambda \\ y - \dfrac{\lambda y}{|y|}, & |y| \geq \lambda \end{cases}$$

Here 'y' is wavelet coefficient and 'λ' is threshold level,

$\lambda = \sigma\sqrt{2 \log \mathrm{N}}$

$\sigma = \text{median}\ (|d_j|)/0.6745$

d_j = detail coefficients at level j, N = number of wavelet coefficients

The noisy coefficients passed through this threshold, coefficients above and below the threshold level are clipped according to the soft and hard threshold functions. After that, inverse wavelet transform is applied to the clipped coefficients to reconstruct the denoised data.

Von Sachs and Mac Gibbon used level and location dependent threshold and Lehmann [14] used modified hard and soft threshold levels are defined by

$$S_h(y) = \begin{cases} \text{y}, & |y| < \lambda \\ 0, & |y| \geq \lambda \end{cases} \longrightarrow \quad (1)$$

$$S_s(y) = \begin{cases} \text{y}, & |y| < \lambda \\ \dfrac{\lambda y}{|y|}, & |y| \geq \lambda \end{cases} \longrightarrow \quad (2)$$

Here λ is threshold calculated based on minimax, L_2 – rate for the risk of estimation and it satisfy the condition

$\hat{\sigma}_{jk} = \sqrt{\text{var}\,iance(d_{jk})}$ for any positive constant 'C':

$$\overset{SUP}{f} \in F_{22}^{S}(M)\ E\|\hat{f}^{*} - f\|_2^2 = O((\log(n)/n)^{2n/(2s+1)})$$

^ denotes the estimation, d_{jk} denotes detailed coefficients at level j and location k. We applied db20 maxlevel wave decomposition for 1280 MHz radar wind profiler. We used modified soft threshold for removing ground clutter and applied in a different way. In discrete wavelet transform (DWT) the first few values in the time series are wrapped around to compute the last components in the transform called wrap - around effect [13]. Due to this effect we are excepting the first few and last few coefficients for threshold level estimation and used soft threshold given in equation (2). Threshold λ is calculated using only the middle of the coefficients (excepting first few and last few coefficients)

$$\lambda = \sigma\sqrt{2 \log \mathrm{N}}, \qquad \hat{\sigma}_{jk} = \frac{\sqrt{\text{var}\,iance(d_{jk})}}{0.6745}$$

'd' corresponds to the middle coefficients, $\hat{\sigma}_{jk}$ is the approximation of σ. Figures 2(a) and 3(a) represents the I and Q data respectively. After applying the db20 wavelet decomposition to I and Q separately, the decomposed signal clearly differentiates the ground clutter and clear air coefficients. Figures 2(b) and 3(b) shows the decomposed signals corresponds to 2(a) and 3(a) respectively, the first few coefficients have large magnitude marked with dashed line corresponds to the ground clutter, remaining corresponds to the clear air and noise. The above mentioned threshold applied only for these clutter coefficients instead of applying all coefficients; hence it reduces only the clutter without affecting the signal. Inverse wavelet transform is then applied to reconstruct the clutter removed signal.

V RESULTS AND DISCUSSION

In phase signal of data collected on 18 May 2010 is shown in fig 2(a) contains the slowly varying trend corresponding to the clutter. In order to eliminate the ground clutter, wavelet decomposition is applied and the decomposed signal is shown in fig 2(b). It has been observed that the first few points have large amplitude marked in dashed line corresponding to the ground clutter. Now, the above mentioned ground clutter removal algorithm has been used to extract the filtered signal, as shown in fig 2(c). It is to be noted that in this extracted signal, the unwanted slowly varying part is completely removed. The original quadrature phase signal along with its decomposed and filtered forms are described in figures 3(a), (b) and (c) respectively. In order to obtain the incoherent integration, the filtered I and Q signals are divided into 8 segments, each having 128 points and a Von Hann window is applied to each, then power spectra are calculated for all the segments. Finally these power spectra are averaged together to get the averaged power spectrum. The spectra corresponding to the original and filtered time series complex data for this particular range bin are shown in fig 4. It may be noticed that the ground clutter which was dominating in case of original data, is completely removed. Figure 5 shows the original and filtered stacked power spectra for all range bins, corresponding to East beam. Figure 6 illustrates the mean Doppler which is shown in red colour.

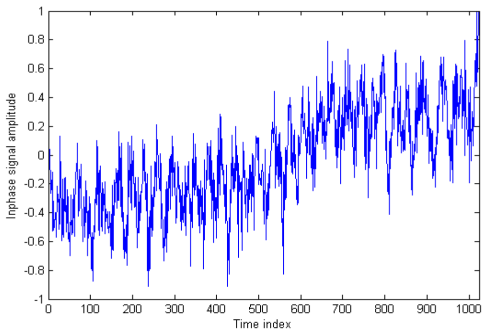

Fig. 2(a). In phase signal for 9th range gate

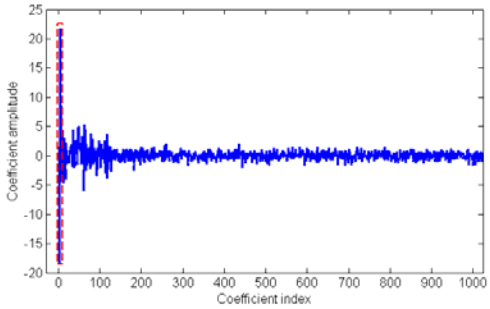

Fig. 2(b). Wavelet decomposed signal of in phase signal

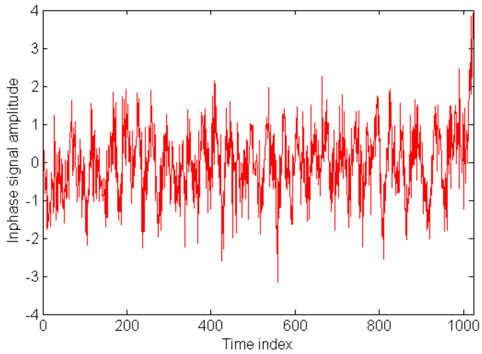

Fig. 2(c). Filtered 9th range gate in phase signal

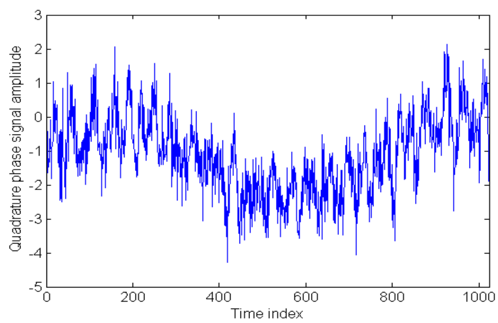

Fig. 3(a). Quadrature (Q) phase signal for 9th range gate

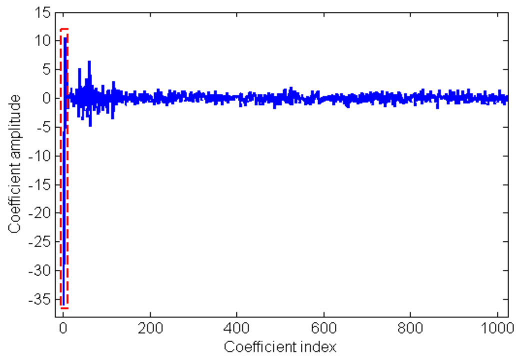

Fig. 3(b). Wavelet decomposed signal quadrature phase signal

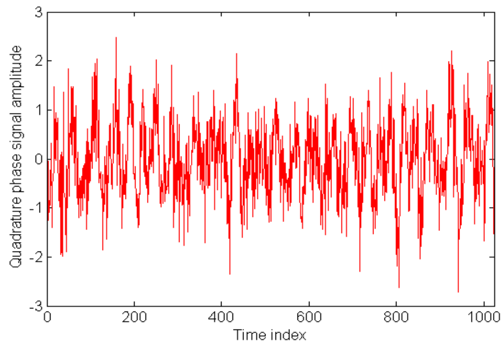

Fig. 3(c). Filtered 9th range gate quadrature phase signal

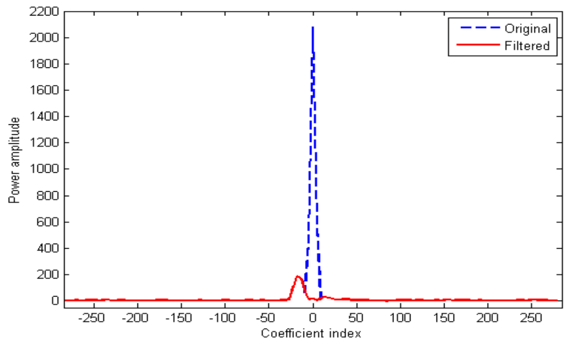

Fig. 4. Power spectra (original and filtered) for 9th range gate

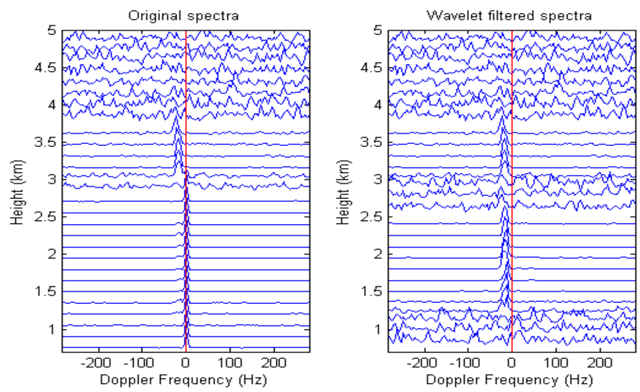

Fig. 5. Power spectra for all range gates (original and filtered) for east beam

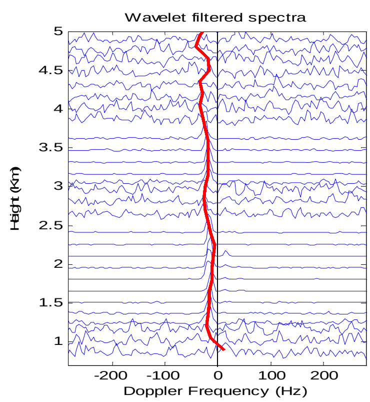

Fig. 6. Power spectra for all range gates with mean Doppler (red colour)

VI CONCLUSION

This paper discusses the performance of wavelet filtering method used to remove the unwanted ground clutter presented in wind profiler data. This method is successfully employed to separate and distinguish the clear air signal from the contamination due to unwanted signals, and improved the reliability of wind measurements.

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