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Removal of RFI and Clutter in Atmospheric Radar Power Spectra

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Abstract.
Wind Profilers (WP) are coherent pulsed Doppler radars used for vertical wind profiling of the atmosphere. They operate in VHF /UHF frequencies. They obtain echoes from atmospheric targets and perform Doppler analysis to derive wind velocities at different heights. The echoes received from atmospheric targets are very weak and often contaminated by noise, clutter and radio frequencies interference (RFI). The wind profile estimation is greatly improved, if all the non-atmospheric echoes are removed before processing. In order to handle large volume of data, an automated process is required for this purpose. Almost all the RFI and clutter removal techniques in use are computationally complex and some of these algorithms use variables which change with radar operating parameters and environment. This paper presents an objective algorithm of RFI and clutter removal that could be used as an automated process for cleaning of the Doppler power spectra. This approach mathematically formulates the technique which is intuitively followed by human experts. The performance of this algorithm was successfully tested on the mesosphere–stratosphere–troposphere (MST) radar and Lower Atmospheric Wind Profiler (LAWP) radar located at Gadanki, India. The paper presents representative illustrations of these test results.

Keywords: Doppler Profile, Clutter, RFI, Spectral analysis.

INTRODUCTION

Wind profiler (WP) radars are primarily designed to provide wind profile measurements. It divides vertical atmospheric range into sections known as range-bins. The standard form of data is the Doppler power spectra. It is conventionally presented as a stack of power spectra of range bins as shown in Fig 1 to 5. Each Doppler spectrum contains positive and negative frequency components. The radial wind velocity or the wind velocity target along the radar beam is computed from the mean Doppler frequency shift. The components with positive Doppler frequencies correspond to velocities approaching the radar and negative frequencies indicate receding target velocities. WP radar operates at least three non-planer beams. Three dimensional (3-D) wind data is obtained by processing the echoes from at least three non-coplanar beams1, 2. Atmospheric parameters like target reflectivity, wind speed and wind turbulence could be extracted from the first 3 moments of uncontaminated Doppler spectrum. The signal strength of the atmospheric echoes is weak, with approximate power of -110 to - 140 dBm. In most observations, the contamination from non-atmospheric echoes like noise, ground clutter, moving targets and Radio Frequency Interference (RFI) co-exist with the atmospheric echoes. These signals are strong and hence identifying the atmospheric echoes and tracing Doppler profile becomes difficult. Radars operate for long hours and generate a large volume of data. Processing this large volume of data by human experts is impractical.

The existing methods of clutter and RFI removal can broadly be categorized into two classes; namely, Fuzzy logic (FL) /artificial intelligence (AI) based methods and Time Domain Filtering methods. Time domain filtering has been a direct approach for the removal of clutter and RFI. Some of these methods are reported in Reddy[3], Sreenivasulu [4] and May et al [5].
Following sections presents four approaches that are in use for the clutter and RFI removal.

NCAR Improved Moments Algotirthm (NIMA) Method[6]

This method has been developed by National Centre for Atmospheric Research (NCAR) at Boulder Colorado, USA. It computes various parameters like gradient, curvature, power density ratio, asymmetry, radial velocity of each spectral component of the Doppler power spectra and assigns weights using membership functions. The weighted mean is subjected to a threshold and the component is classified into the target types. This information is plotted in two dimensions showing the trails of clutter, RFI and weather echoes etc. After this exercise, the undesired components can be separated. The membership functions and thresholds are finalized after prolonged observations and training using the data. Also, the key decision parameters are specific to particular radar and often to the weather conditions. Though the method has showed one of the best results, this method is computationally complex and the weights need to be varied depending on the type of radars used.

Fuzzy Logic based Methods [7],[8],[9]

These methods use concepts of Fuzzy Logic decision making. These methods, in the same manner as NIMA, analyses each Doppler component and determine whether it belongs to Clutter, RFI or wind by combinational evaluation of membership functions. This method also requires parameter changes depending on the data and environment. Bianco [7], Cornman [8] and Allabaksh [9] have reported algorithms based on Fuzzy logic.

Notch filter Method [10]

This method is specifically proposed for RFI removal. In this method the frequency location of RFI is identified from the power spectral data. Then a notch filter is used in the time domain to remove the RFI component. The data is taken for further processing by converting back to the frequency domain and subjected to the established Doppler profile extraction method [11]. This process is computationally complex, and requires time domain data. It often fails to remove the RFI signals which present themselves in slightly different frequencies. Such interference appears as an off-vertical line on the Range-Doppler plane. This method requires the change in the Notch filter frequency depending on the location of RFI. This poses a serious limitation for the method to be used as an objective and automated algorithm.

Wavelet Transform based method [12]

This method applies the wavelet transform based filtering technique, on the time domain I and Q signal data. It has reported better performance especially when the Doppler frequency corresponding to the wind is low and the profile is very near DC frequency. This method indirectly works on the characteristics of clutter. Generally, clutter has higher amplitude than the atmospheric signal. The method uses a threshold value to decide whether the component is a clutter. This threshold value is required to be changed depending on the radar.

An algorithm capable of imitating human skill is likely to be most effective as an automated program. With this motivation, an objective method is developed to remove clutter and RFI from Doppler spectra of wind profilers. A method is called objective if it does not require tuning of parameters when operated on different radars and in different conditions. This paper presents a method that can be used for the removal of the said purpose. The method is computationally simple. It identifies Clutter and RFI components by searching for the defined characteristics or signature in the Range-Doppler plane and replaces them by noise components present in the spectra. The algorithm is tested on different atmospheric conditions and two types of radars.

RESEARCH METHOD

It is well known[6],[7] that clutter and RFI show specific characteristics or signature on the Doppler power spectra. Experienced radar operators identify the clutter and the RFI components by visually locating these signatures. The algorithm formalizes this visual searching skill by using correlation of signature in terms of loosely defined features.

Criterion for Clutter Identification

The clutter components are the echoes due to terrestrial components like buildings, trees and moving vehicles. These objects are either stationary or moving at low relative radial velocity with the radar beam. The movements of these objects are approaching as well as receding with near-equal probability. As a result, they appear as symmetrically placed components at low altitudes and low Doppler frequencies. The clutter generated due to the components is located within low range of less than 6.5 km and moving with radial velocity lesser than 20 ms^{-1}. The power spectral components are arranged in a 2-D matrix and a typical component S(i,j) is the power of the jth Doppler component of ith range bin. Therefore, S(i,-j) is the image component. It is observed that the clutter components are symmetrical but have slightly different power spectral density (PSD). After analyzing 1000 data sets of Doppler spectra consisting of clutter, it was found that the symmetrical components of the clutter differ in power by a maximum of 35 percent. Expression (1) shows mathematical formulation of this condition.

$$\text{abs}(S(i,,j)-S(i,-j)\leq 0.35\times(S(i,j)+S(i,-j))/2 \quad (1)$$

Where, *i* and *j* are the indices for range and Doppler.

The term on the left is the power difference in the symmetrical components. The condition limits the PSD variation to be within 35% of the average value of the two components. The algorithm searches for symmetrically located Doppler components with these constraints. This symmetry condition and location constraints for the Doppler component, are combined with logical 'AND' to determine whether it is a clutter, as given in equation 2,3and 4. The mathematical formulation of these conditions requires quantification of range bins and Doppler bins. These numbers need to be computed from the radar operation parameters. This is explained with the examples given below. The operating parameters of Indian MST radar and LAWP radar (located at National Atmospheric Research Laboratory (NARL, Gadanki, India) are given in table 1.

Table 1: Operating parameters of MST Radar and LAWP radar (location: 13.4^{0}N, 79.17^{0}E)

Parameter	Parameter value (MST)	Parameter value (LAWP)
Transmission Frequency	53 MHz	1280 MHz
Average power	40 KW	0.3KW
Operation mode	DBS, 6 Beams, N10,E10,S10,W10, Zx,Zy.	DBS, 3 Beams, Zenith, and 14.2^0 down at NE, SW.
Pulse width	16 µs; binary coded baud, of 1 µs.	1 µs
Coherent Integration	64 (Time domain averaging)	32 (Time domain averaging)
FFT points	512	512
Doppler Resolution	0.0305 Hz.	1.22 Hz.
Sampling Start (after Tx)	24 µs	5 µs
No. of range bins	150	150
Maximum radial velocity	±22.11 ms-1	±30 ms-1
Radial velocity resolution	0.08636 ms-1	0.1464 ms-1
Inter pulse period	1000 µs	50 µs

Starting range for the MST radar is 3.6 km. The range resolution is 0.15 km. Therefore the range bin threshold (RBth) works out to be the 20th range-bin; (6.5-3.6)/ 0.15 ≈ 20. The beam dwell time of the observation is 32.768 seconds. This makes Doppler resolution to 0.03052(≈1/32.768) Hz. For 53 MHz (λ= 5.66m) radar, corresponding velocity resolution is 0.086 ms-1(≈ 5.66/2 × 0.03052).The radar operates with the beam tilted at 10^0 from zenith. The radial velocity corresponding to the horizontal velocity threshold (20ms-1) works out to be 3.472ms-1 (≈20 × sin10^0). The corresponding Doppler bin threshold (DBth) is the 40th Doppler bin (DB); 3.472/0.086 ≈ 40. The algorithm includes a program to captures the radar operational settings from the data header file and computes RBth and DBth using the expressions given in equation (2) and (3). The descriptions of the symbols in equations (2) and (3) and the units are as follows: Range upper limit: (Rul) is in km, radial velocity (Vr) is in ms^{-1}, window start time (twst) is in µs
and beam dwell time (tbd) is in seconds. The expression (4) gives the condition applied on spectral components. The spectral components satisfying this condition are classified as clutter components.

RBth = (Rul- (twst × Δr)) ⁄ Δr (2)

DBth = Vr× (tbd)/ (λradar /2) -1 (3)

Where Δr is the range resolution

(i ≤ RBth) && (abs (j) ≤ DBth) && (abs (S (i,j)
- S (i,-j) ≤ 0.35 ×S(i,j) + S (i,-j)) / 2) (4)

For the LAWP radar twst is 5 µs and Δr is 0.15 km. Using equation 2, for the radar under test, we get RBth = 38. Similarly the tbd is 0.82s and λradar is 0.234m. The beam tilt in LAWP is 14^0 from zenith. Hence the Vr is 4.84 ms^{-1}, ≈20 x sin14^0. Using equation 3 we get DBth for the radar is 34. Also, the computed values of RBth and DBth are 25 and 38 respectively. Hence, it can be seen the same program could be used in wind profiling radar for identification of clutter components.

Identification of Radio Frequency Interference

RFI is a disturbance asynchronous with the radar PRF. It occurs at any arbitrary frequency. This signal leaks into the receiver and presents itself at almost the same frequency component in Doppler spectra of all the range bins. On the range-Doppler plane this appears as a vertical or near vertical line of prominent peaks having near-equal PSD. It was observed from data sets of large volume of Indian MST radar data, that the RFI disturbance is always present for more than 10 µs with PSD variation less than 12.5% of the average PSD and negligible change in frequency. This corresponds to 10 or more range bins (RB) of the MST radar and also for the LAWP. The algorithm searches whether the value of S*(i, j)* for more than 10 consecutive range-bins *'i'* values are near-equal for *'j'*, or *'j-1'* or *'j+1'* Doppler bins. Mathematically this conditions can be written as *"if the mean (M) and standard deviation (V) of the set 'S(i, j)'; from 'i' to '(i+10)' and for 'j' or ' j-1' or 'j+1',have a ratio more than 8 (corresponds to 12.5% variation) the components are identified as RFI"*. In other words this condition checks whether the standard deviation of the PSD for 10 consecutive range bins is within 12.5 %. If this condition is satisfied, the set of spectral components are classified as RFI. Mathematically, the program checks the true condition of the equation (5). The left side of equation (5) uses the mathematical formula for mean and the right side is standard deviation.

$$\frac{1}{10}\left(\sum_{k=i}^{i+10} S(k,\ j)\right) \geq 8 \times \sqrt{\left(\frac{1}{10}\sum_{k=i}^{i+10}\left(S(k,\ j) - \left(\frac{1}{10}\left(\sum_{k=i}^{i+10} S(k,\ j)\right)\right)\right)^{2}\right)} \qquad (5)$$

Thus the clutter and RFI could be identified by searching for their characteristics features.

The key innovation of the algorithm is formulating mathematical expressions with experimentally identified parameters to define the signature of specific echo. This approach reduces the computational complexity significantly compared to the two methods namely NIMA and FL methods. Another useful feature of this algorithm is automatic conversion of atmospheric thresholds into *DB* and *RB* using radar operating parameter values. This feature allows the algorithm adapt to any radar and for any atmospheric condition.

RESULTS AND ANALYSIS

This algorithm was applied to the simulated data as well as to various data sets of the Indian MST radar and LAWP radar. Various cases of power spectra contaminated with RFI and clutter were subjected to this algorithm. After identifying and removing the clutter and RFI, the data was subjected to Doppler profile estimation by Multi-parameter Cost Function method [13] Figure. 1 to 5 shows the results whose detailed explanation is given below:

(i) Clutter components of different strengths varying from 1/10th to 10 times the strength compared to the weather signal were introduced in the Doppler spectra. The Doppler position of the clutter components was also varied. In some samples the clutter components coincided with the weather components. 25 such samples were created. Experiments on all these data showed consistent profile tracing. One sample case each are presented in Figure. 1 (a) and Figure. 1 (b)

(ii) Similarly 25 data sets of RFI with different signal strengths and spectral location are generated and experimental results were evaluated. One representative example is given in Figure 2 (a) and Figure 2 (b).

(iii) 25 Data sets with both RFI and clutter were generated. The performance of the algorithm was evaluated on the data. A critical case of RFI removal where it interferes with the wind echo is shown in Figure. 3 (a) and Figure. 3 (b).

(iv) About 100 sets of contaminated data from real MST radar data were selected. 30 of these data sets had clutter, 60 sets had RFI and 10 sets had both RFI and clutter. The method was applied to all these data sets and sample results are given in Figure 4(a), Figure 4(b), Figure 4(c) and Figure 4(d).

(v) Around 20 sets of LAWP radar data were selected having clutter. A representative example is given in Figure 5(a) and Figure 5(b).

After removing the unwanted signals the data were visually analysed to check whether quality of the weather signal is affected by the cleaning process. Visible degradation of power spectra was observed in approximately 50 out of 1000 data sets of MST radar and 20 out of 200 data sets of LAWP. However, it was possible to extract Doppler profile correctly from all the cleaned datasets. The efficacy of this method is established as the Doppler profile tracing in all the examples are greatly improved.

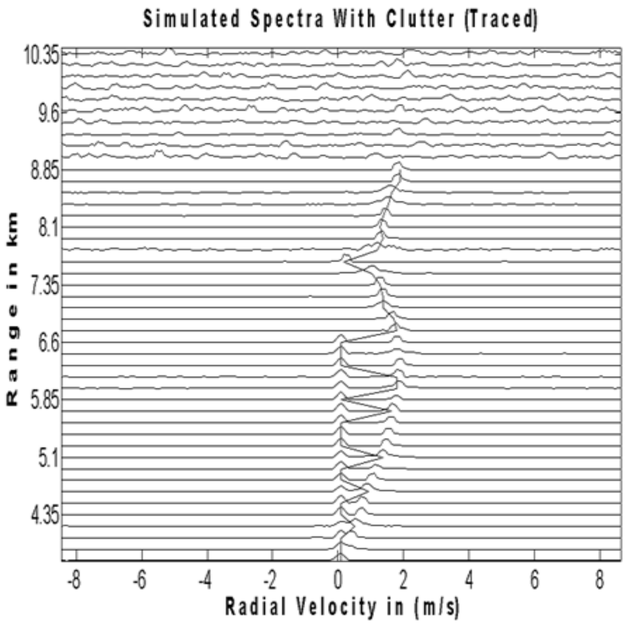

Fig 1(a) Simulated data with clutter

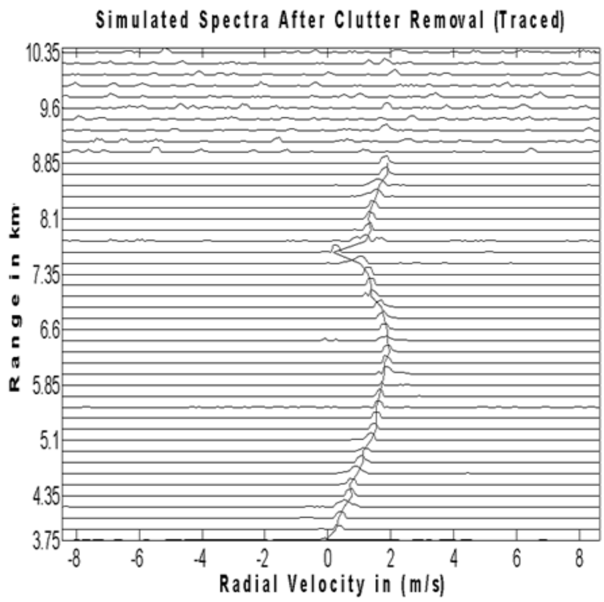

Fig 1(b) Simulated data after clutter removal

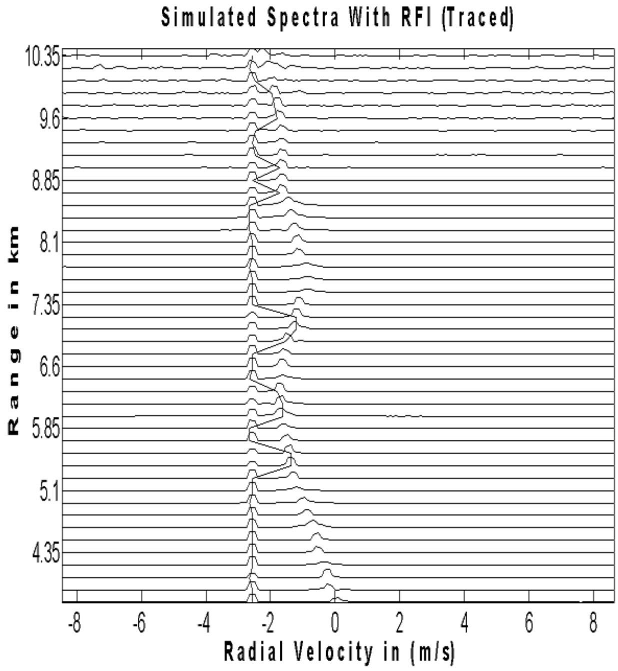

Fig 2(a) Simulated data with RFI

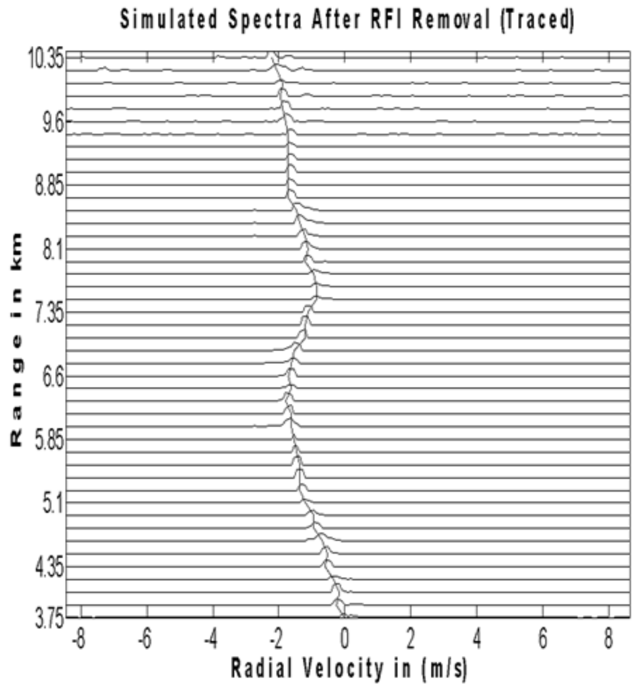

Fig 2(b) Simulated data after RFI removal

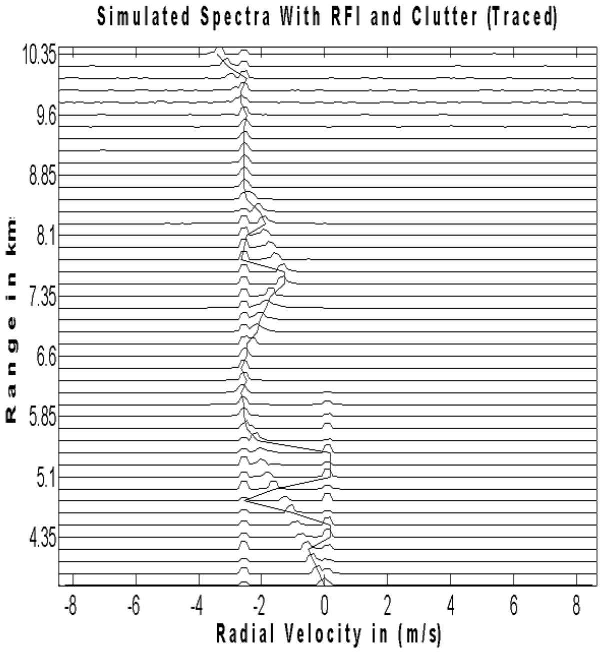

Fig. 3(a) Simulated data with RFI and clutter

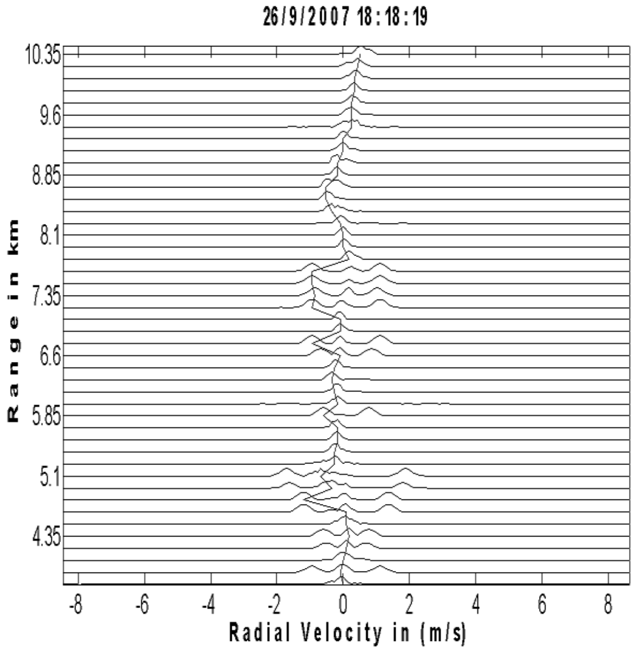

Fig. 4(a) MST radar data with clutter

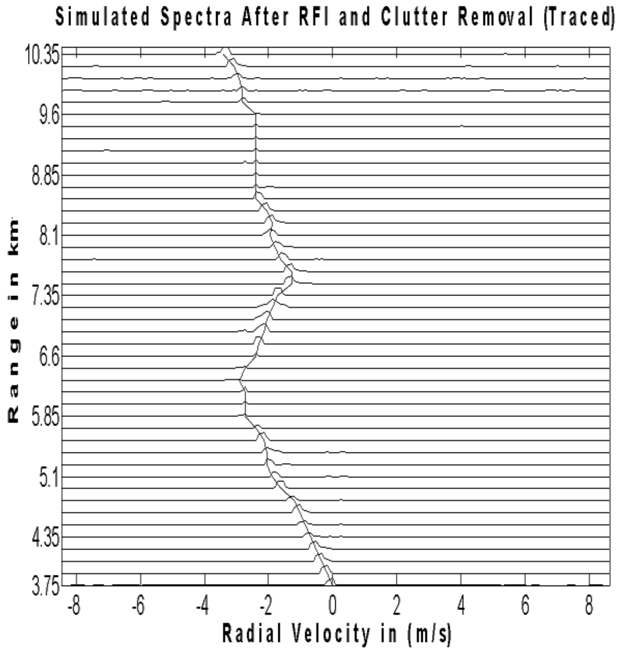

Fig. 3(b) Simulated data after clutter and RFI removal

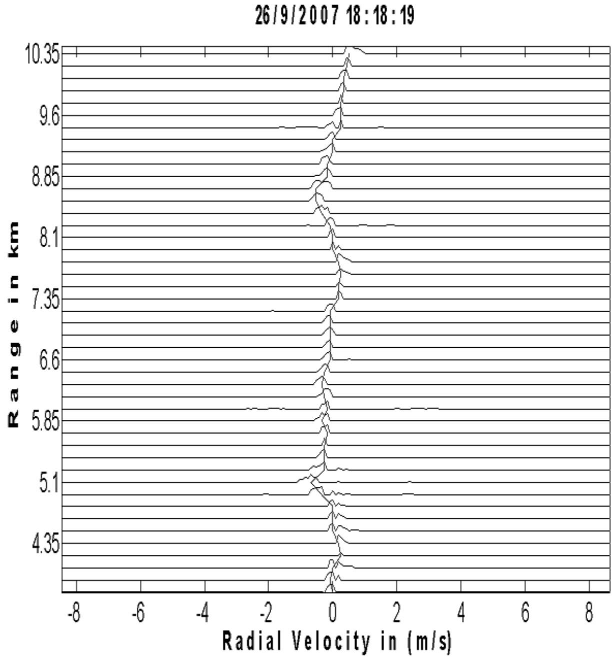

Fig. 4(b) MST radar data after clutter removal

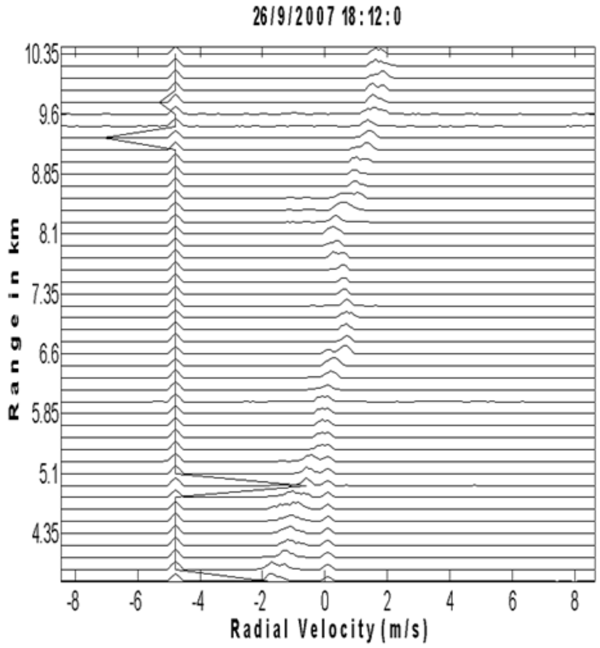

Fig. 4(c) MST radar data with RFI and clutter (Dominating signal near 0 m/s)

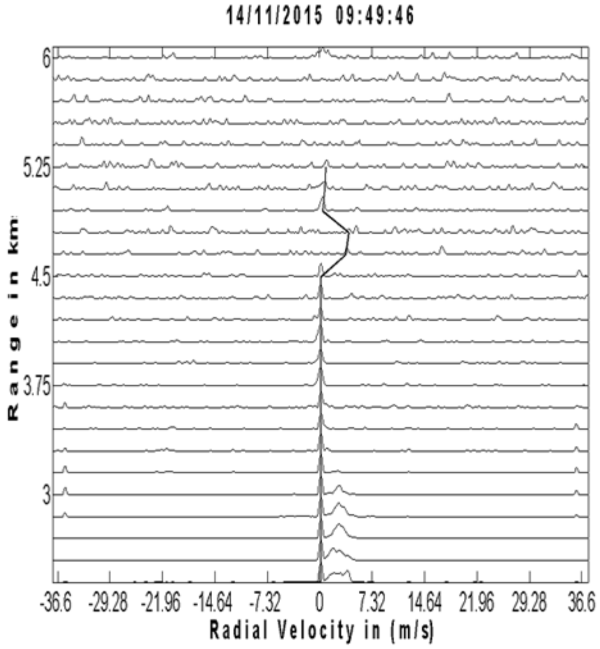

Fig. 5(a) LAWP radar data with clutter (Dominating signal near 0 m/s)

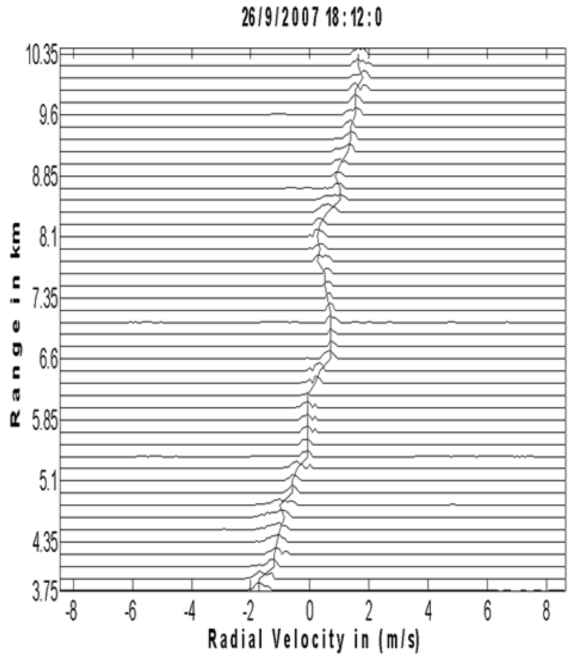

Fig. 4(d) MST radar data after RFI and clutter

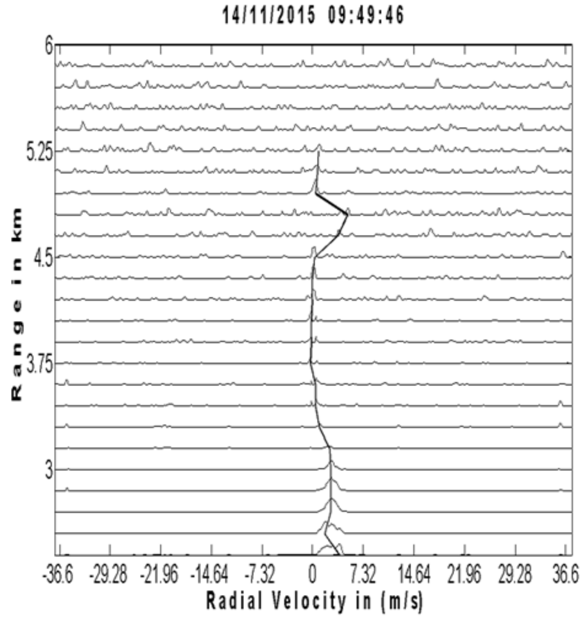

Fig. 5(a) LAWP radar data after clutter removal

RESULTS AND DISCUSSIONS

Computational Complexity

A rough estimate of the computational complexity for a set of M range bins with N point Doppler spectrav for the three approaches mentioned above is as follows.

(i) Assuming that the time domain data is available, Notch filter and wavelet methods require at least M number of N-point correlations. This requires total number of at least M × N^2 Multiply-Accumulate (MAC) operations. Here we have assumed that notch filter is implemented as N point transversal filter. In order to convert back to frequency domain, we need to compute M number of N-point FFTs.

(ii) The Fuzzy logic methods consider minimum of five attributes of spectral components. Therefore it will have minimum of 5 ×M × N computations of exponential functions and M × N MAC operations.

(iii) The newly developed method requires only M × N comparisons.

This comparison is presented in table 2.

Table 2: Comparison of RFI and clutter removal methods

	Notch Filter Method	**Fuzzy Logic Methods**	**Doppler Signature method (Proposed here)**
Input Data	Time and Frequency Domain	Time domain data	Doppler Power Spectra
Computational load Higher level operations	M × N2 MAC and M no. of N point FFTs :	5 M×N Exponential Functions and M ×N MAC Computations	M×N Comparison
Post filtering	Convert back to FFT	Conversion is difficult	No conversion required

Discussions

The newly developed algorithm is tested on approximately 1000 data sets of Indian MST radar and around 200 data set of LAWP radar on various atmospheric conditions. This method is also tried on simulated data with poor SNR, high wind conditions etc. Visual degradation in the profile was seen in approximately 5% of the radar data sets. However the algorithm performed consistently by removing clutter and RFI without affecting the traceability of the Doppler profile in all cases.

This method is computationally simple and is objective in the sense it is capable of adapting to any wind profiler radar without requiring the tuning of parameters. Due to this it can be used as a real-time pre-processing method in any wind profiling radar

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