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SMOOTHED DOPPLER PROFILE IN MST RADAR DATA- THE MODIFIED CEPSTRUM APPROACH

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ABSTRACT

The concept of cepstrum thresholding (CT) is applied to estimate smoothed nonparametric spectrum. The CT method is applied to Mesosphere, Stratosphere and Troposphere (MST) radar data for spectral cleaning. This method is not superior as compared with the conventional Periodogram method. So, to enhance the spectral visibility in Doppler Profile (DP), the CT technique is modified. The modified cepstrum (MC) is developed and implemented, to validate, it is applied to radar data. An adaptive spectral moment's estimation technique is utilized for analyzing the Doppler spectra of the MST radar signals. From the Doppler frequency components, the radial velocities in the direction of the zonal (U), meridional (V), and vertical (W) are estimated. In turn, the wind velocity is estimated from U and V components. The proposed method works well even at higher altitudes and results are compared with the traditional methods such as Peak detection technique and the matched filter.

Keywords: MST radar, cepstrum thresholding, doppler shift, matched filter, spectral peak detection, spectral moments.

1. INTRODUCTION

National Atmospheric Research Laboratory (NARL) at Gadanki (13.47°N, 79.18°E), India has been operating 53 MHz atmospheric Mesosphere, Stratosphere and Troposphere (MST) radar for studying structure and dynamics of lower, middle and upper atmosphere [1-4]. MST Radar provides estimates of atmospheric winds on a continuous basis with high temporal and spatial resolutions. MST Radar uses the echoes obtained over the height range of 1-100 Km to study winds, turbulence. The Indian MST Radar is operational for scientific studies of the atmosphere in the height range of 2-20 km (troposphere and lower stratosphere), 60-90 km (mesosphere), 100-150 km (E region) and 150-800 km (F region). The echoes from the atmosphere are due to neutral turbulence in the lower height regions and due to the irregularities in electron density in higher altitudes.

The method adopted for identifying the signal and computing the three low-order spectral moments is central to the problem of extracting information from the Doppler spectrum of the MST radar signal. The conventional method of analyzing the MST radar spectral data is based on identifying the most prominent peak of the Doppler spectrum for each range gate and computing the three low order spectral moments and signal-to noise ratio (SNR) using the expressions given by [5]. Various methods were proposed to identify the Doppler profiles under a wide range of signal to noise ratio (SNR) conditions [6-10]. All these techniques are not superior at low SNR conditions.

The method of adaptive moments estimation was presented to perform consistently well at distinct SNR conditions of atmospheric signals [11]. The method is applied to the radar spectral data and the results are presented for low and high SNR conditions. The method has certain limitations in its application such as (1) under severe weather conditions, the algorithm fails to estimate the moments properly which is mainly due to the difficulties arising from the multiple echoes (2) the algorithm involves five sets of moments estimation and six iterations for the final moments extraction. This introduces complexity in computation.

The research work carried by S. Varadarajan of S V University, 2004 has overcome the above limitations using wavelet denoising the time series data priori to spectrum processing. To fix the threshold, the cross validation scheme was used. The spectral visibility range of the Doppler profile using wavelet denoising is increased to 18Km at the expense of computational complexity.

In this paper, an attempt has been made to apply the concept of Cepstrum Thresholding (CT) for smoothed spectrum estimation [12]. The CT method is applied to radar to for the Doppler profile. It is observed that no superior than the existing techniques. To achieve better spectral cleaning, the cepstral coefficients are weighted by a Hamming or Hanning window. Since the higher indexed cepstral coefficients are related to rapid fluctuations in estimated spectrum, the windowing process is performed by retaining the lower indexed cepstral coefficients and modifying the higher indexed cepstral coefficients. The modified cepstrum (MC) approach is applied to the MST radar data. In this approach, the wavelet denoising, dc removal, averaging operations are not used in the estimation of Doppler profile.

The theory of the smoothed spectrum estimation using the MC is presented in section 2. A stepwise description of the algorithm applied to the MST radar data is given in section 3. The results and discussion are in section 4 and the important conclusions are in section 5.

2. SMOOTHED SPECTRAL ESTIMATION VIA THE MODIFIED CEPSTRUM

Consider a stationary, discrete-time, real valued signal $x(n), n = 0,1,2,.......,$ with covariance sequence

$\{r_k\}_{k=-\infty}^{\infty}$ and power spectral density (or spectrum) $\phi_p(\omega)$ where $\omega \in [-\pi, \pi]$. In practice, the spectrum $\phi(\omega)$ is estimated from a set of observed samples $\{x(n)\}_{t=0}^{N-1}$ of the signal.

The periodogram estimate of $\phi(\omega)$ is given by [13-14]

$$\hat{\phi}_p(\omega) = \frac{1}{N}\left|\sum_{t=0}^{N-1} x(n)e^{-i\omega n}\right|^2 \tag{1}$$

where the subscript 'p' denotes the periodogram estimate.

$$\text{Let } \omega_l = \frac{2\pi}{N} l, l = 0,......., N-1 \tag{2}$$

denote the Fourier grid of the angular frequency axis. $\hat{\phi}_p(\omega)$ can be computed efficiently by means of a Fast Fourier transform (FFT) algorithm.

The cepstral coefficients are defined as:

$$c_k = \frac{1}{N}\sum_{l=0}^{N-1} \ln[\phi(\omega_l)] e^{j\omega_l k},\ k = 0,1,..........N-1 \tag{3}$$

where it is assumed that $\phi(\omega_l) > 0, \forall l$. The cepstral coefficients have several interesting features, one of which is mirror symmetry:

$$c_{N-k} = c_k,\quad k = 0,1,........., N/2 \tag{4}$$

which mean that only half of the sequence $c_0,.........., c_{N/2}$, is distinct. The other half is obtained from $c_1,.........., c_{(N/2)-1}$, as in (4).

Using the periodogram estimate in (1), a common estimate of the cepstral coefficients is obtained by replacing $\phi(\omega)$ in (3) with $\hat{\phi}_p(\omega)$, which is given in [15].

$$\hat{c}_k = \frac{1}{N}\sum_{l=0}^{N-1} \ln[\hat{\phi}_p(\omega_l)] e^{j\omega_l k} + \gamma\delta_{k,0}, \\ k = 0,...........M, \tag{5}$$

where

$$\delta_{k,0} = \begin{cases} 1 & if\ k = 0 \\ 0 & else \end{cases} \tag{6}$$

M = N/2 and $\gamma = 0.577216...$ (the Euler's constant).

It can be shown that in large samples, the estimated cepstral coefficients $\{\hat{c}_k\}_{k=0}^{M}$ are independent normally distributed random variables [16]:

$$\hat{c}_k \sim N(c_k, s_k^2) \tag{7}$$

$$\text{with } s_k^2 = \begin{cases} \dfrac{\pi^2}{3N} & if\ k = 0,...., M \\ \dfrac{\pi^2}{6N} & if\ k = 1,........., M-1 \end{cases} \tag{8}$$

The cepstral coefficients are weighted by a Hamming or Hanning window. Since the higher indexed cepstral coefficients are related to rapid fluctuations in estimated spectrum, the windowing process is performed by retaining the lower indexed cepstral coefficients and modifying the higher indexed cepstral coefficients. The modified cepstral coefficients are denoted by $\{\tilde{c}_k\}$. The smoothed spectral estimate corresponding to $\{\tilde{c}_k\}$ is given by:

$$\tilde{\phi}_{cep}(\varpi_l) = \exp\left[\sum_{k=0}^{N-1} \tilde{c}_k e^{-j\omega_p k}\right]; \quad l = 0,........N-1 \tag{9}$$

where the subscript cep signifies its cepstrum dependence. The final scaled spectrum estimate $\hat{\phi}_{cep}(\omega_l)$ is then given by:

$$\hat{\phi}_{cep}(\omega_l) = \hat{\alpha}\tilde{\phi}_{cep}(\omega_l), l = 0,......., N-1 \tag{10}$$

where

$$\hat{\alpha} = \frac{\sum_{l=0}^{N-1} \hat{\phi}_p(\omega_l)\tilde{\phi}_{cep}(\omega_l)}{\sum_{l=0}^{N-1} \tilde{\phi}^2{}_{cep}(\omega_l)} \tag{11}$$

3. EXISTING AND PROPOSED ALGORITHMS

3.1 The existing method

The time series raw data (I and Q) has been used and then the coherent integration was performed. It improves the process gain by a factor inter pulse period and also improves the SNR by integrating the detected quadrature due to any other succeeding operation. The variance of the estimate decreases with the use of a window. It also reduces the leakage and picket fence effects. The Fourier analysis characterizes the frequency content of the signal. After performing power spectrum cleaning the Doppler profile is estimated by using max peak detection method. From the profiles the Doppler frequencies are calculated. By using Doppler frequencies radial velocities are calculated, from which the zonal, meridonal and vertical velocity components are calculated.

Wind speed is calculated using zonal and meridonal velocities.

The existing algorithm used in atmospheric signal processing can accurately estimate the Doppler frequencies of the backscattered signals up to certain height. However, the technique fails at higher altitudes and even at lower altitudes when data are corrupted with noise due to interference, clutter etc. Multi taper spectral estimation algorithm has been applied for radar data. This method has the advantage of reduced variance at the expense of broadened spectral peak. The FFT technique for power spectral estimation and adaptive estimates technique for estimating the moments of radar data has been proposed. This method considers a certain number of prominent peaks of the same range gate and tries to extract the best peak, which satisfies the criteria chosen for the adaptive method of estimation. This method failed to give consistent results. Hence, there is a need for development of better algorithms for more accurate estimation of wind parameters.

3.1.1 Estimation of doppler shift for atmospheric radar signals

The atmospheric signals are accompanied with a lot of noise predominantly white Gaussian noise. In order to improve the probability of estimation of the Doppler on the said noise, a good spectral cleaning technique is required to compute the frequencies of the atmospheric signal. The algorithm based on an adaptive data processing technique, consists of sequence of steps given in [11] were used to determine the radar signal Doppler profile.

3.1.2 Moments estimation

There are many methods adapted to find out the noise level estimation. The method implemented here is based on the variance decided by a threshold criterion. The noise level threshold shall be estimated to the maximum level L, such that the set of spectral points below the level 'S', nearly satisfies the criterion: {Variance(S)/Mean(S)^2}<=1 over number of spectra averaged.

The extraction of zero, first and second moments is the key reason for on doing all the signal processing and there by finding out the various atmospheric and turbulence parameters in the region of radar sounding. The basic steps involved in the estimation of moments such as the zeroth moment or Total power, the first moment or Mean Doppler, the second moment or variance (the spectral bandwidth), and Signal to Noise Ratio (SNR) are followed from [5].

3.1.3 UVW computation

Calculation of radial velocity and height

For representing the observation results in physical parameters, the Doppler frequency and range bin have to be expressed in terms of corresponding radial velocity and vertical height.

Height, $H = Ct_R \cos\theta / 2$ meters

Velocity, $V = Cf_D /(2 f_c)$ or $f_D \lambda / 2$ m/sec

where C = the light velocity in free space, f_D = Doppler frequency, f_c = the carrier frequency, λ = Carrier wavelength, θ = Bean tilt angle, t_R = Range time delay.

Computation of absolute wind velocity vectors (UVW)

After computing the radial velocity for different bean positions, the absolute velocity (UVW) can be calculated. To compute the UVW, at least three non-coplanar beam radial velocity data is required. If higher numbers of different beam data are available, then the computation will give an optimum result in the least square method. Line of sight component of the wind vector $V(V_x, V_y, V_z)$ is:

$$V_D = V_{.i} = V_x \cos\theta_x + V_y \cos\theta_y + V_z \cos\theta_z$$

where X,Y and Z directions are aligned to East-West, North-South and Zenith, respectively. Applying least square method, residual $\xi^2 = (V_D - V_{Di})^2$, where $V_{Di} = f_{Di}\lambda / 2$ and i represents the beam number to satisfy the minimum residual. Minimizing residual ξ^2 along X, Y and Z direction leads to Vx, Vy and Vz, which corresponds to U (Zonal), V (Meridonal) and W (Vertical) components of velocity.

Estimation of wind-speed

The winds speed can be calculated by using the formula:

Wind-speed $W = \sqrt{U^2 +}V^2$

The horizontal component of the wind velocity is calculated from the UV components which are estimated from the Doppler frequencies.

3.2 The proposed method

The consistent method to reduce the variance estimate is the CT approach. Stoica and Sandgren (2006) proposed the CT method for the smoothed spectrum estimation [4]. Practically, the variance reduction in spectrum estimation using the CT method is not significant. To achieve better variance reduction, the CT method is modified, called as the MC method. To validate, the MC approach is applied to MST radar data. The algorithm is based on an adaptive window technique, consists of a sequence of steps to determine the radar signal profile, in a Doppler spectral frame.

Step-1: The cepstral coefficients are calculated using FFT for the given time series of data

Step-2: Apply the Hamming or Hanning window on the cepstral coefficients

Step-3: Doppler power spectrum is obtained from the cepstral coefficients

Step-4: The adaptive moment's estimation technique is used to obtain the smoothed Doppler profile.
Step-5: The steps 1 to 4 are repeated for the whole frame in estimating the Doppler frequencies.

After spectral cleaning, the genuine Doppler echoes are selected for drawing Doppler profiles using adaptive window method and maximum slope detection method. The proposed algorithm performs spectral cleaning by multiplying the smoothing window with the cepstral coefficients. Remaining part of the moment's estimation, UVW computation and wind speed calculation are same as that of the existing method.

4. RESULTS AND DISCUSSIONS

The proposed method is applied for the East beam of radar data to extract the Doppler profile. The Doppler profile of the radar data based on FFT and MC is shown in Fig.1. From that, it is clear that Doppler profile using FFT is visible upto 11Km, beyond which the atmosphere noise is dominating the spectral contents. The proposed algorithm is able to smooth the spectral contents of Doppler profile for all heights. The periodogram, the CT and the MC techniques are applied to 5th, 30th, 55th, 80th and 105th bins (for clear comparison purpose, we selected few bins from low range to high range i.e. in incremental steps of 25 from starting 5th bin to 105th bin) of East beam radar data for spectral estimation. From Figs. 2, 3 and 4, it is observed that similar spectral contents are produced by the periodogram and CT methods. The results confirm that the estimated spectra based on MC technique are noise free, smoothed envelope when compared with the above methods. It increases the ability to extract original Doppler frequency from the Doppler profiles.

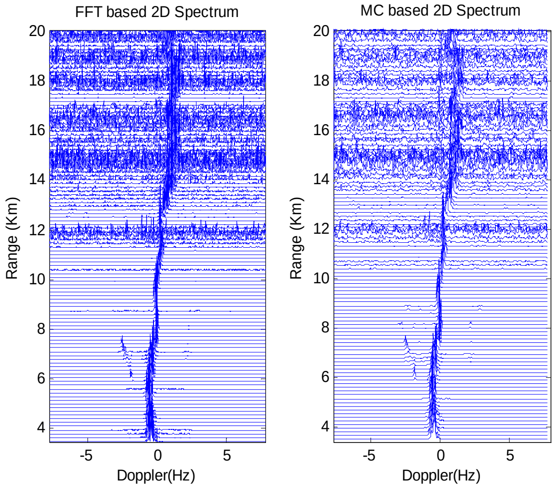


Figure 1 The spectra of East beam dated on 22nd June 2009 using FFT and MC.

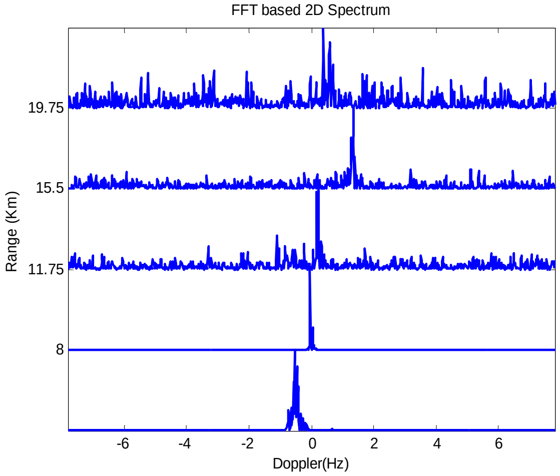


Figure 2 FFT based spectra at various heights.

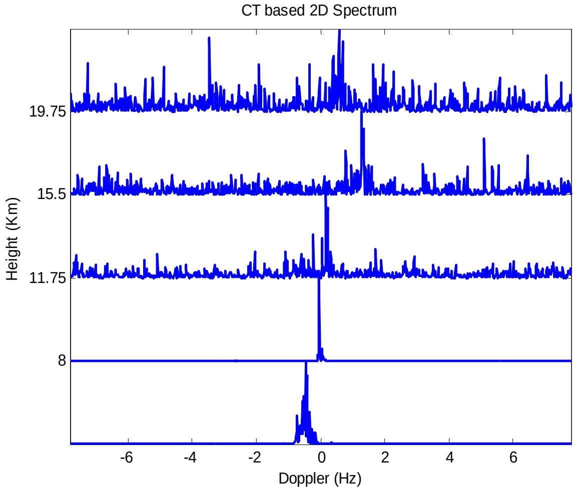


Figure 3 CT based spectra at various heights.

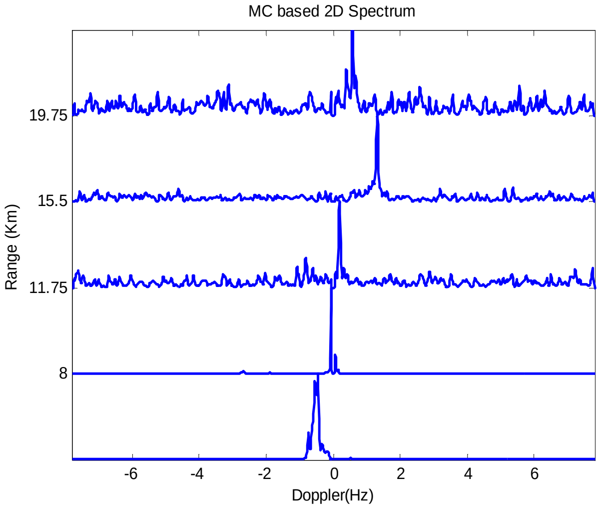


Figure 4 MC based spectra at various heights.

Using the AME technique, the Doppler profiles for these methods are shown in Figs. 5 and 6. The Doppler profile for east beam data using Atmosphere Data Processor (ADP) software is shown in Fig. 7. The estimated Doppler profile using MC method is in agreement with that of the ADP software. From Figs. 8 and 9, it is observed that the wind speed trace using the proposed method is similar to the matched filter and the peak detection technique with AME. To validate the Doppler wind velocity profile estimated by the MC method, independent observation is obtained using radiosonde. Fig. 8(d) shows a sample plot of the comparison of wind velocities of Doppler profile based on FFT, MC and radiosonde data. The results confirm that the estimated wind velocity profile using the proposed method is in line with radiosonde data.

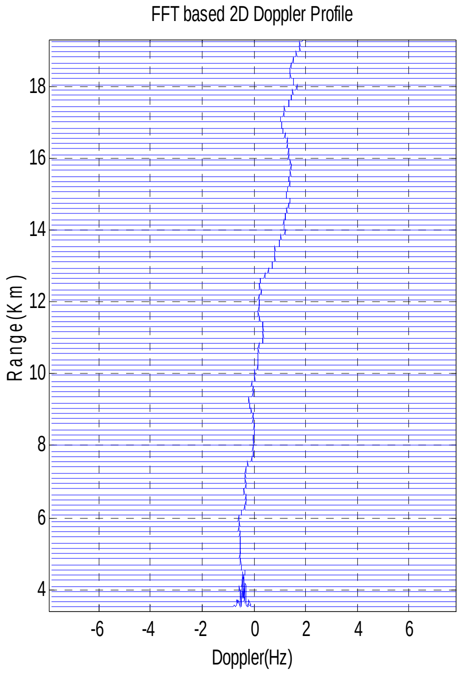


Figure 5 The FFT based Doppler profile of East beam using AME technique.

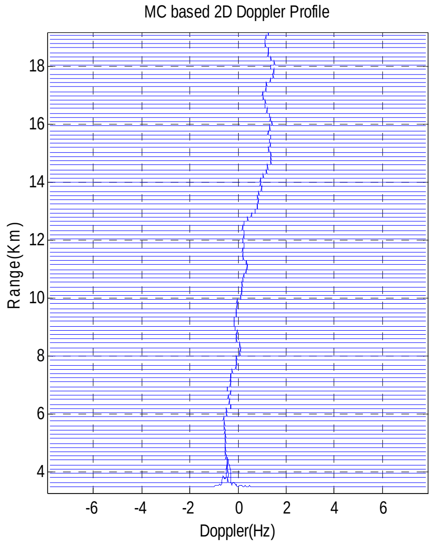


Figure 6. The MC based Doppler profile of East beam using AME technique.

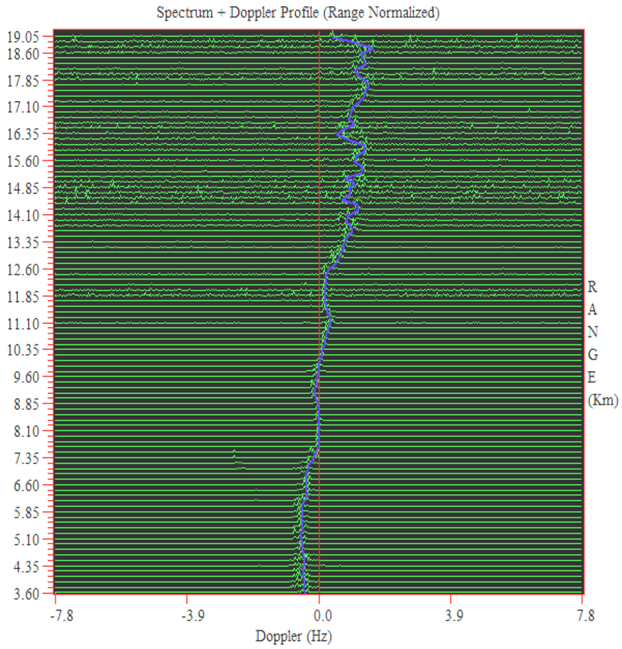
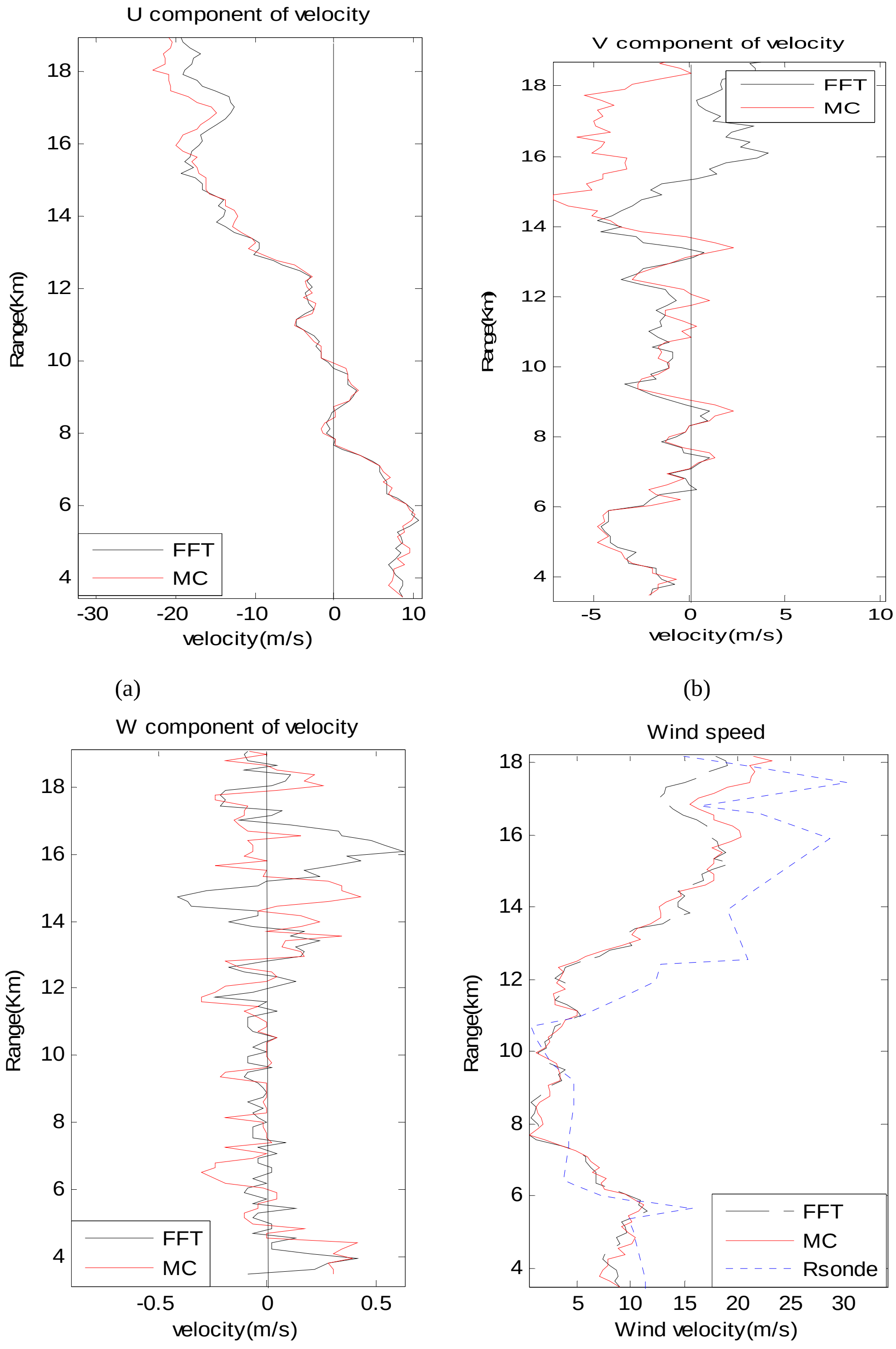


Figure 7. Doppler profile of East beam using ADP software.



(a) (b)

(c) (d)

Figure 8: (a) U component (b) V component (c) W component velocities and (d) Wind speed of six beams of MST radar data using adaptive moments estimation technique.

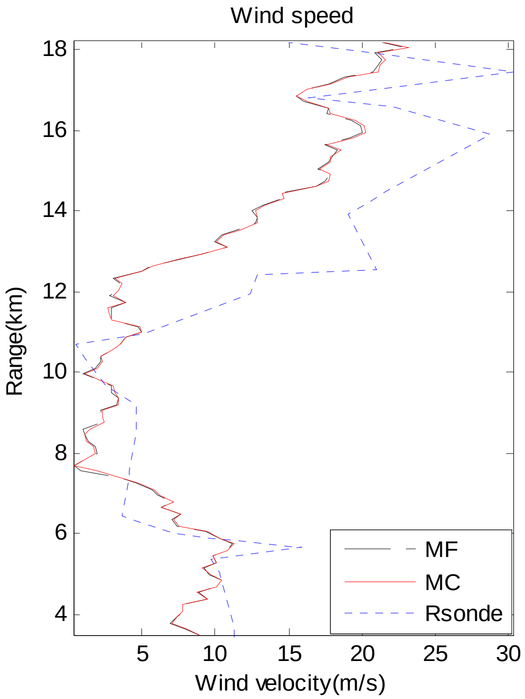


Figure 9. Wind speed of radar data using the matched filter (MF), the MC and wind speed of radiosonde data.

5. CONCLUSIONS

The CT method is applied to MST radar data for the smoothed spectrum estimation. The CT method fails to achieve better spectral cleaning compared with the conventional techniques. The MC method is developed and implemented for the radar data. The existing algorithm could detect upto 11 Km beyond which one has to manually calculate the moments and find the Doppler. The proposed algorithm is able to smooth the spectral contents of Doppler profile for all heights. The numerical results suggest that the proposed method for spectral cleaning of MST radar data is much better than the CT and the periodogram. In addition, the results confirm that the estimated wind velocity using the MC approach is in agreement with the radiosonde data.

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