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Performance Comparison of Various Spectral Estimation Algorithms on MST Radar Signal Processing

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Abstract: The Indian Mesosphere-Stratosphere-Troposphere (MST) radar, located at National Atmospheric Research Laboratory (NARL), Gadanki (13.5° N, 79.2° E), India, serves the purpose of providing information regarding atmospheric movements. In order to obtain wind information, the signals collected from the MST radar are to be analyzed, which mainly involves the estimation of the power spectrum. This paper discusses signal processing of MST radar data. Signal processing was done to translate from a time domain to spectrum estimation by using various methods like multi-band wavelets, iterative principal component analysis, and multi-snapshot semiparametric algorithm. We present a performance comparison of radar signal processing using different proposed algorithms. For comparing the performance evaluation, we applied proposed algorithms to the MST radar data for estimating the Doppler spectrum and thus, in turn obtaining the Doppler frequencies. The wind parameters such as Zonal *U*, Meridional *V*, and Wind velocity *W* are estimated from the Doppler frequencies. Finally, results have been validated with the Global Positioning System (GPS) Radiosonde data.

Keywords: MST radar, Doppler Estimation, Estimation of Covariance Matrix, Multi-Snapshot Covariance, spectral analysis, and GPS.

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1. Introduction

The Indian MST radar was developed with an active phased array antenna consisting of 1024 Yagi-Uda antenna elements and operated at a frequency of 53MHz. The pulse Doppler radar is used to detect the moving and stationary targets. The MST radar is one of the most significant Earth's atmospheric radar for the detection of dynamic changes in the atmosphere. The radar can receive the echo signals based on mechanisms, like an Isotropic backscattering and Fresnel Reflections from the earth's atmosphere at VHF and UHF bands. The Doppler radars can be operated with high peak power and large antenna array aperture to detect the weak backscattered signals from the long-range atmosphere. The National Atmospheric Research Laboratory (NARL), Gadanki, (A.P) provides wind information by using MST radar for the earth's atmospheric regions of the troposphere, stratosphere, and mesosphere. The MST radar gives atmospheric raw data starting from a height of 3.6 km to 26 km with a resolution of 150 m. At present, there is a lot of literature about the Doppler spectrum estimation for the MST radar data. An adaptive estimation technique is presented in [1] to estimate the Doppler spectrum. In this technique, certain parameters were used to adaptively track the radar signal in the range-Doppler spectral frame. Multi-taper spectral estimation [2] and Bispectral-based estimation [3] have been applied to radar data, which have high computational cost and broadened spectral peak respectively. Other algorithms such as cepstral thresholding [4], wavelet-based denoising [5] and principal component analysis (PCA) [6] are also used for spectral estimation of the MST radar data. Recently, the SPICE algorithm [7] has been applied to MST radar data to compute the Doppler spectrum. The existing method, ADP [8] used at NARL is not estimating Doppler profile accurately at higher altitudes. So there is a need for efficient spectral algorithms for processing radar signals at higher altitudes and also at low SNR conditions.

2. Proposed Algorithms

In this section, we present three different methods to solve the spectral estimation problem for the radar data. The summarized algorithms are discussed as follows.

2.1) Multi-band Wavelets

This subsection provides one of the proposed algorithms used in the research to process MST radar signals [9]. The steps involved to implement the algorithm are as follows:

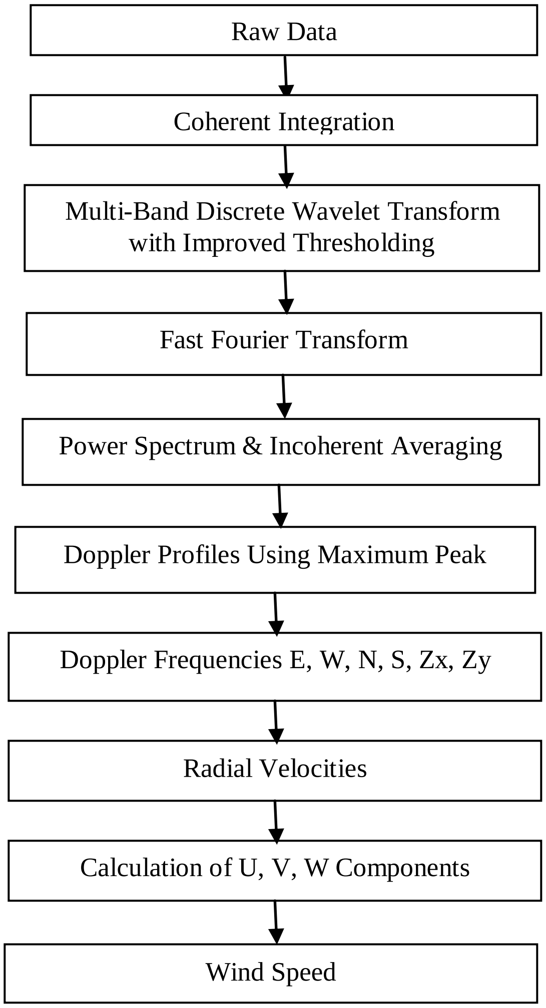

Fig.1. Flowchart of the proposed algorithm using multi-band wavelets.

A) Iterative Principle Component Analysis

In this subsection, we introduce the new algorithm for power spectrum computation using robust covariance matrix estimation under spiked covariance structure. The term spiked covariance was presented in [10]. Let us consider N samples $\{\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_N\}$, where $\boldsymbol{x}_i$ are K dimensional complex zero mean Generalized Elliptical (GE) distribution random vectors. The spiked covariance model refers to the covariance matrix having the structure

$$\boldsymbol{R} = \sum_{i=1}^{L} p_i \boldsymbol{b}_i \boldsymbol{b}_i^H + \sigma^2 \boldsymbol{I} \qquad (1)$$

where L is an integer that is less than K, and the $\boldsymbol{b}_i$'s are unknown orthonormal basis vectors. This model is directly related to principal component analysis and subspace estimation methods used in many signal processing applications [11]. The steps involved in implementing this algorithm are similar to principal component analysis until the convergence criterion is satisfied. The proposed algorithm (PALG) [12] is summarized in Table 1.

Table 1: PALG

Step	Operation
I	Initialize R_0 to be an arbitrary positive definite matrix
II	Repeat
III	$\boldsymbol{M}_n = \frac{K}{N}\sum_{i=1}^{N}\frac{\mathbf{x}_i\mathbf{x}_i^H}{\mathbf{x}_i^H\boldsymbol{R}_n^{-1}\mathbf{x}_i}.$
IV	Eigen decomposes $\boldsymbol{M}_n$ as $\boldsymbol{M}_n = \sum_{i=1}^{K}\lambda_i\boldsymbol{v}_i\boldsymbol{v}_i^H$, where $\lambda_1 \geq \cdots \geq \lambda_K$.
V	Compute $\hat{\sigma}$, $\hat{p}_i$, $\hat{\boldsymbol{b}}_i$
VI	$\hat{\boldsymbol{R}}_{n+1} = \sum_{i=1}^{L}\hat{p}_i\hat{\boldsymbol{b}}_i\hat{\boldsymbol{b}}_i^H + (\hat{\sigma})^2\boldsymbol{I},$
VII	$\boldsymbol{R}_{n+1} = \hat{\boldsymbol{R}}_{n+1} / \mathrm{Tr}(\hat{\boldsymbol{R}}_{n+1}).$
VIII	$n = n+1.$
IX	Until some convergence criteria is met.

In this algorithm, Blackman-tukey frequency estimation method is used for the principal component spectrum estimate. The equation of the principal component version of the Blackman-tukey frequency estimation method is given by

$$P_{BT}(e^{j\omega}) = \frac{1}{K}\boldsymbol{e}^H\boldsymbol{Re} = \frac{1}{K}\sum_{i=1}^{p}\lambda_i\left|\boldsymbol{e}^H\boldsymbol{v}_i\right|^2 \tag{2}$$

where $\boldsymbol{e}$ is the vector of complex exponentials orthogonal to eigenvectors $\boldsymbol{v}_i$, $i = 1, 2, \ldots, p$ and λ_i denotes eigenvalues of the covariance matrix.

2.2) SPICE$_{\mathrm{MS}}$

In this subsection, we present the multi-snapshot semiparametric algorithm [13]. The summary of the third proposed algorithm of this paper is given in table 2.

Table 2: SPICE$_{\mathrm{MS}}$

Step	**Operation**
I	Find the initial power $\{\boldsymbol{p}_l\}$ using the expression given below $p_l^0 = \boldsymbol{b}_l^*\hat{\boldsymbol{R}}\boldsymbol{b}_l / N \quad l = 1, 2, 3, \ldots\ldots\ldots\ldots\ldots K+N$
II	Compute the Covariance Matrix $\boldsymbol{R}_C$ as $\boldsymbol{R}_C = \boldsymbol{BPB}^*$
III	By using the matrices $\boldsymbol{R}_C$ and $\hat{\boldsymbol{R}}$ evaluate the following equations $\boldsymbol{Q}^{i+1} = \boldsymbol{P}^i\boldsymbol{B}^*\boldsymbol{R}_C^{-1}(i)\hat{\boldsymbol{R}}$ $p_l^{i+1} = \frac{\left\|\beta_l^{i+1}\right\|}{w_l} l = 1, \cdots, K+N.$ $\boldsymbol{R}_C(i+1) = \boldsymbol{BP}^{i+1}\boldsymbol{B}^*$

IV	Check if $\frac{\left\| \boldsymbol{p}^{i+1} - \boldsymbol{p}^{i} \right\|}{\left\| \boldsymbol{p}^{i} \right\|} < 10^{-3}$
V	Iterate III and IV steps until convergence.

3. MST Radar Results

NARL provides multiple scans of MST radar data. Each scan cycle have echo signal information from East, West, Zenith-X, Zenith-Y, North, and South beams. Every beam has 150 range bins and each bin contains 512 complex sample points. The Doppler spectrum has been determined using the proposed algorithms for each range bin time series complex data and extracts the Doppler using maximum peak detection method and same would be repeated for all the bins as well as all 6 beams. Once Doppler profiles are obtained, the Doppler velocities v_E , v_W , v_N , v_S , v_{ZX} and v_{ZY} i.e., East, West, North, South Zenith-X and Zenith-Y respectively are calculated by multiplying each of the frequency components of the Doppler profile with $c/2f_{\mathrm{c}}$, where f_{c} is the operating frequency of the Doppler radar and c is velocity of light. The wind velocity components are calculated and finally validated with the GPS [14]. The MST radar data is collected on Feb 09, 2015 from the NARL, Gadanki, Andhra Pradesh. Fig. 2 shows the output SNR calculated from the power spectral density obtained using Periodogram, MWT, PALG and SPICE$_{\mathrm{MS}}$ for the east beam (a) and (b) west beam. From which it is clear that the SPICE$_{\mathrm{MS}}$ is giving better SNR values than remaining methods.

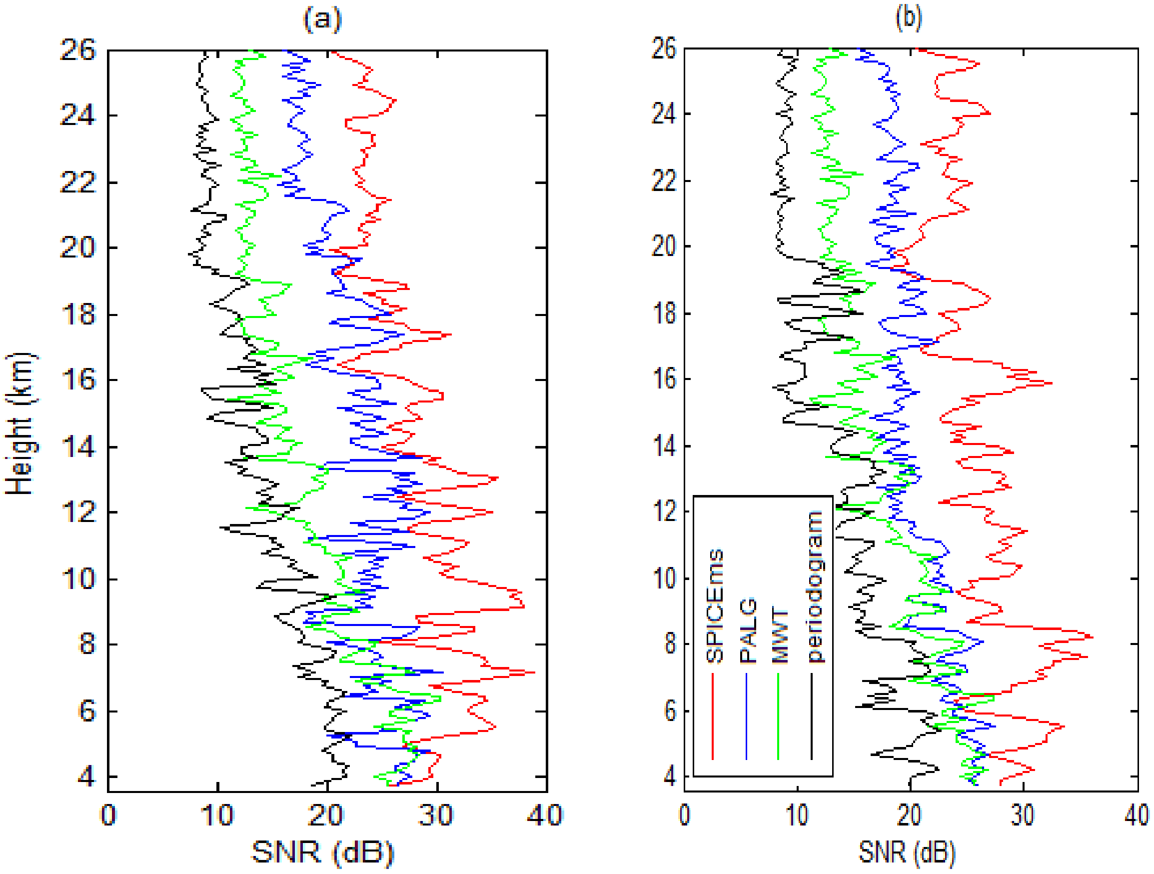

Fig.2. Height profiles of SNR estimated using periodogram, MWT, PALG and SPICE$_{\mathrm{MS}}$ for (a) the east beam and (b) the west beam of Feb 9, 2015 radar data.

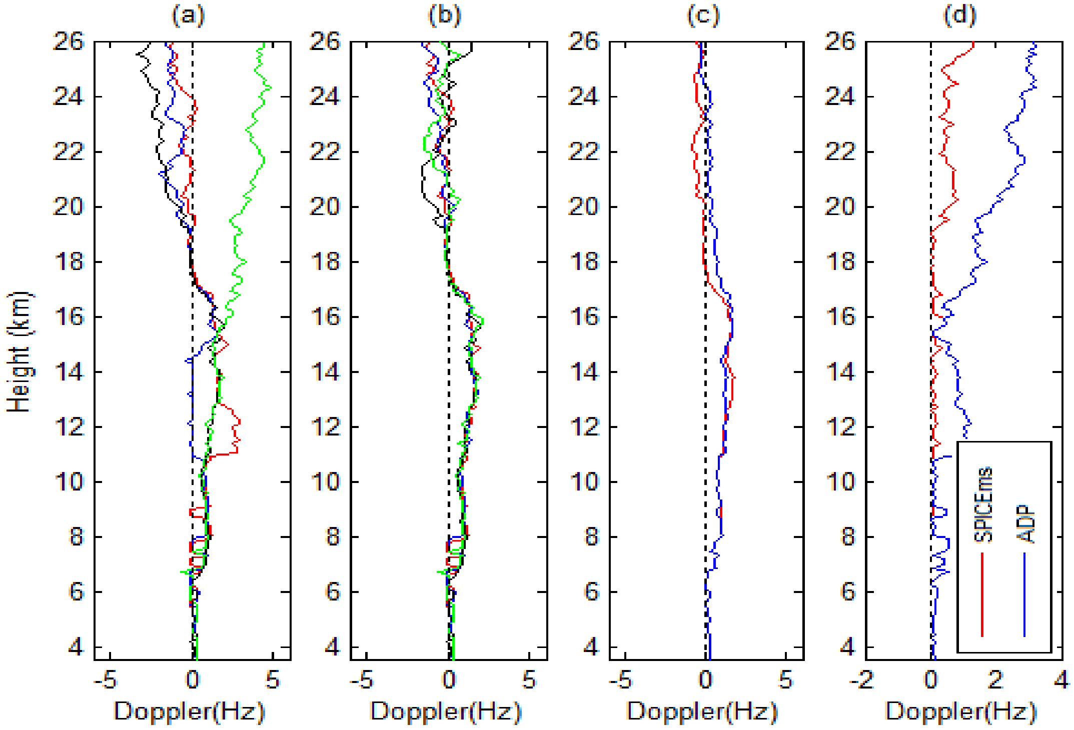

Fig.3. Doppler height profiles for 4 scans of the east beam (a) ADP and (b) SPICE$_{ms}$. (c) Mean Doppler height profile of the east beam. (d) Standard deviation for the east beam for Feb 9, 2015.

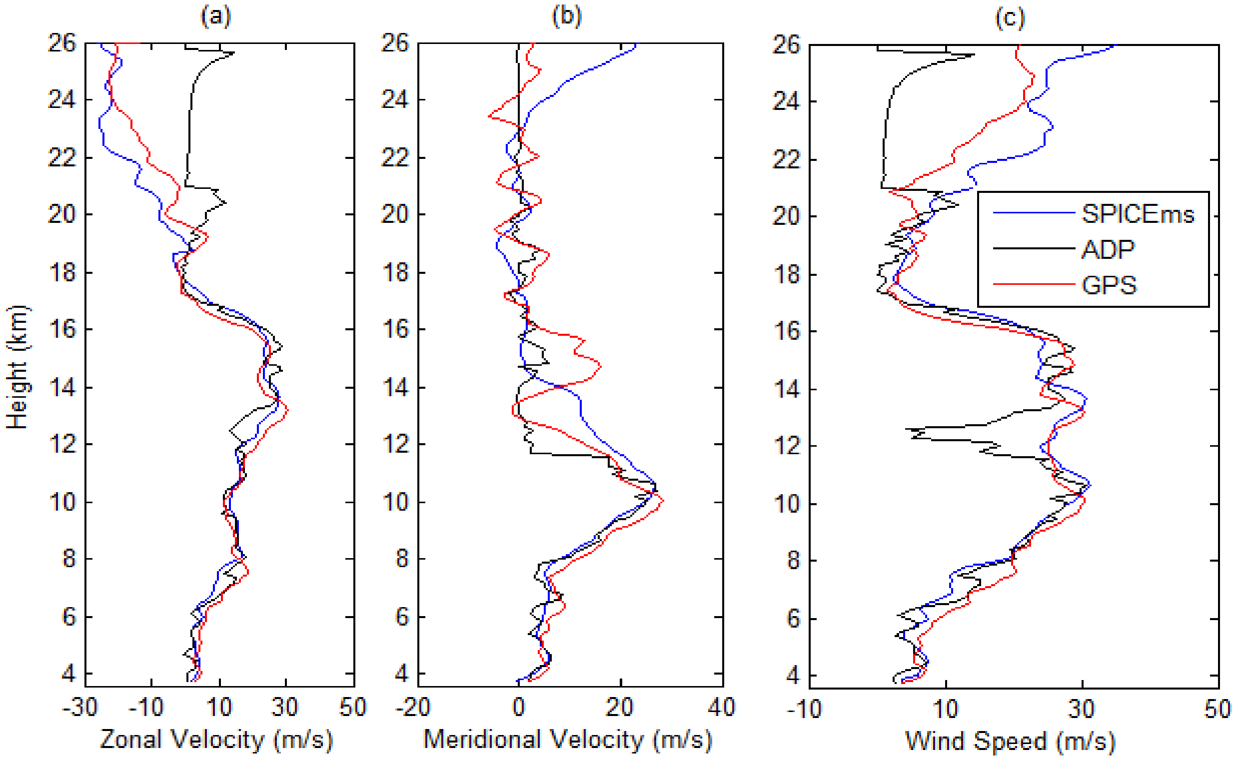

Fig.4. Comparison of Zonal, Meridional and Wind velocities for the data collected on Feb 09, 2015 using SPICE$_{MS}$, ADP and GPS radiosonde.

The Doppler height profiles for 4 scans of the east beam obtained using ADP and best SPICE$_{ms}$ are shown in fig. 3(a) and (b) respectively. The mean Doppler height profiles estimated using SPICE$_{ms}$ and ADP are compared in fig. 3(c), and similarly, the standard deviations are compared in fig. 3(d). Until the height of 20 km, the standard deviation for SPICE$_{ms}$ lies very close to the zero line, whereas that of ADP shows the a clear deviation from zero line. The zonal U , meridional V and wind speed W components obtained from the ADP, GPS and SPICE$_{MS}$ are shown in Fig.4. From figure 4, it can be observed that, the wind speed estimated using SPICE$_{MS}$ is able to follow the GPS values, while the wind speed obtained using the ADP is observed to deviate from those obtained by GPS data. Furthermore, the performance comparison of SPICEms, PALG and MWT with an existing method, ADP is depicted in fig.5.

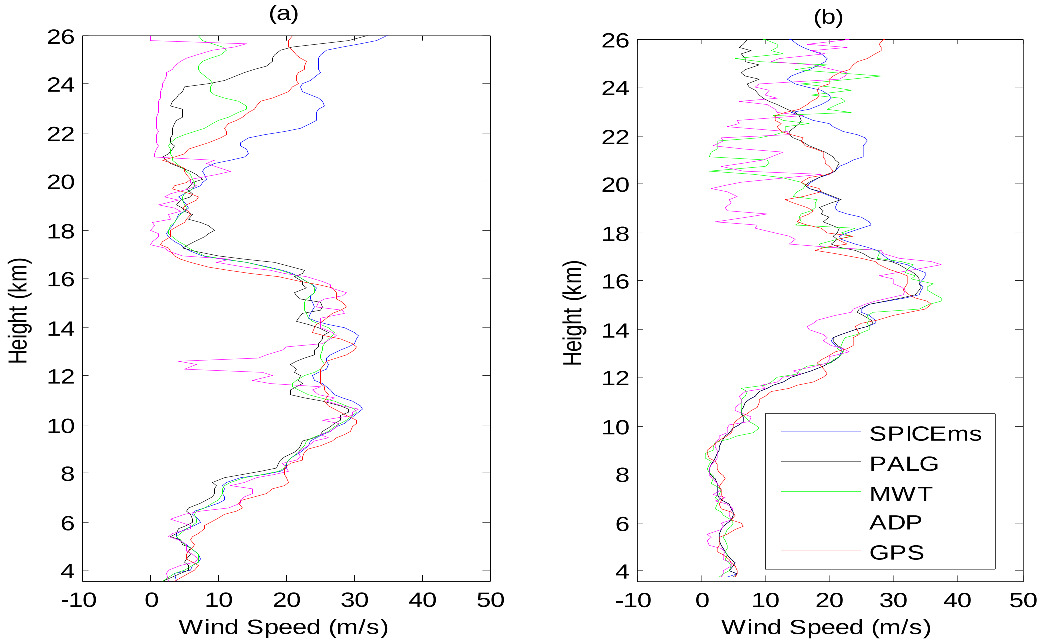

Fig.5. Comparison of wind speed using SPICE$_{ms}$, MDWT, IPCA, ADP and GPS for radar data collected on Feb 9, 2015.

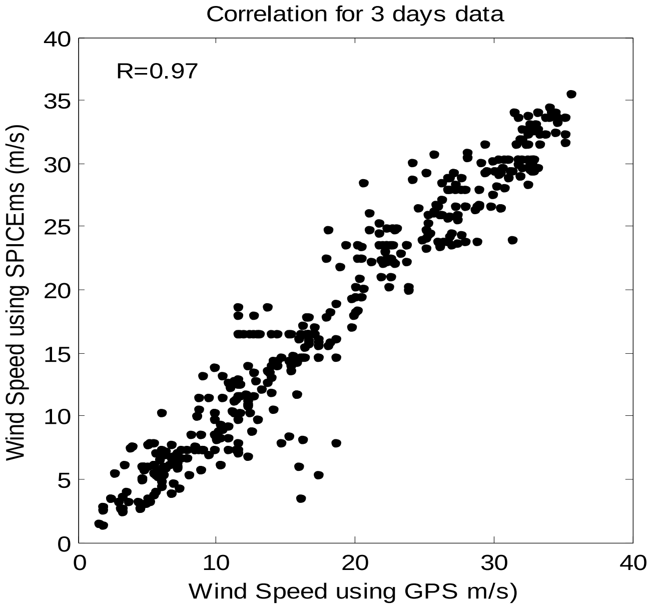

Fig.6. Correlation between the GPS and the SPICE$_{MS}$ for the data received on Feb 09, 2015.

Fig.6 shows the correlation analysis plot for the radar data received on Feb 09, 2015. The correlation factor obtained using the proposed algorithm (SPICE$_{MS}$) is 0.97 and the high correlation coefficient indicating that SPICE$_{MS}$ is performing better than the rest of the methods.

4. Conclusion

In this paper, the three spectral estimation algorithms are presented and applied to the MST radar data. The proposed algorithms achieved a significant enhancement in SNR at higher altitudes and they have shown the reduction in deviation of mean Doppler profiles and standard deviation when compared to the existing method, ADP. The correlation between wind speeds calculated using GPS and ADP, MWT, PALG and SPICE$_{MS}$ have been calculated for the three days radar data collected in the month of February 9 to 11, 2015, which attained a correlation factor of 0.87, 0.93, 0.95, and 0.97 respectively. Multi-snapshot semi-parametric iterative covariance based estimation algorithm named SPICE$_{MS}$ has given better performance than the other methods.

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