PREFACE

Wavelet transform has many recent applications in variety of fields in science and technology. The applications are wide ranging including signal and image processing, denoising, data compression and adaptive signal processing. The ability to provide time frequency localization of non-stationary signals, multi resolution analysis and the flexibility in the choice of basis functions make the wavelet based techniques very versatile and powerful tool for signal processing. However the application of wavelet transforms for radar signal processing has hitherto been rather limited. This thesis aims to use wavelet transform based signal processing to improve the range and accuracy of atmospheric radar data.

Mesosphere-Stratosphere-Troposphere (MST) radar is used to measure wind velocities, temperature pressure and humidity of an atmosphere. The target in this case, unlike radars used to detect objects such as aircrafts etc., is soft target i.e. variation in the air refractive index due to the variations in the air pressure. MST Radar is high power coherent pulse Doppler radar operating typically around 50 - 200 MHz. When RF pulse is fired into the atmosphere, small part of its energy is scattered and reflected back due to the variation in radio refractive index of neutral atmosphere. Therefore MST radar signal is extremely weak. It is estimated that the signal strength drops typically by about 2 dB per km and the signal is obscured by the noise beyond a range when the SNR drops below -10 dB despite considerable improvements in radar design and transmitted power. The range up to which discernable signal can be observed in MST radar data is limited to typically 12-14 km, when only standard signal averaging and filtering techniques are used. So far different averaging techniques, such as consensus average and median estimator, were employed to improve SNR. Certain adaptive techniques were proposed to trace the signals from noisy data at higher ranges (up to 16-22 km). Similarly higher order spectral estimation technique was used to account for non-Gaussian nature of the Doppler echoes. All these methods have yielded reliable detection of the Doppler echoes to a maximum range of about 22 km under favorable conditions. The work reported here deals with application of discrete time wavelet transform for denoising and analysis of MST radar data with a view to increasing the height coverage and improve the accuracy of the parameters extracted from the spectra. The Experimental data used in this work was
collected using the MST radar facility at the National Atmospheric research laboratory at Gadanki, India (13.5°N, 79°E).

Wavelet transform is a mathematical technique that can be used to split a signal into different frequency bands with a time resolution matched to its frequency scale, thus providing excellent time and frequency representation. Further the basis function in Wavelet transform is not completely fixed as in the case of other transforms such as Fourier and Laplace Transform etc. Thus the form of the basis function can be chosen, of course while satisfying the requirements of a basis function of wavelet, in such a fashion that it resembles the functional form of the signal of interest. Then it provides a sparse representation of the signal, wherein the entire energy in the signal is with in few wavelet coefficients, providing good signal to noise separation. Therefore the first phase of the work reported in this thesis pertains to designing a basis function suitable for the MST radar clear-air echo.

As the spectrum of the MST radar clear-air Doppler echo is predominantly of Gaussian in nature in the off-vertical direction, it was assumed that the wavelet basis function is a shifted Gaussian in frequency domain. A wavelet function should exhibit normalization, orthogonality properties and it should have one zero at $\pi$ in the frequency response. It should be ensured that the chosen wavelet basic function and the corresponding MRA filter coefficients should satisfy these properties. The corresponding MRA filter coefficients in this work were calculated by rewriting the low pass filter coefficients in terms of trigonometric functions of Sine and Cosine represented by parametric angles, such that the above conditions are satisfied. Then these parametric angle values were obtained by LEVENBERG-MARQUARDT optimization method. It was found that eight filter coefficients represent chosen wavelet. Then high pass filter coefficients were calculated using the recursion relation between low pass and high pass filter coefficients. Frequency response of these filter coefficients were found to be as desired i.e. say, as in the case of a standard wavelet like Daubechies wavelet (db10). The ability of this wavelet to reconstruct MST radar signal perfectly with minimal artifacts is verified in the following way. Towards this first an MST radar signal was decomposed using this wavelet and then reconstructed back by performing inverse wavelet transform and it was found that the signal is reconstructed without any observable artifacts. The analysis of the MST radar data performed using this wavelet, as described below, provided better results viz. compared to next best standard wavelet Daubechies (db10).
First it is necessary to find out the required levels of decomposition for the designed wavelet for MST radar data before applying denoising technique and it was found that three-level wavelet decomposition is sufficient in the present case. Then proper thresholding method and threshold values were selected in order to get best level of denoising. Different standard threshold selection techniques such as Adaptive threshold, Universal threshold, a Heuristic threshold and Minimax (minimum of maximum) threshold selection method were examined and hard and soft thresholding techniques were considered. These techniques were tested by denoising both reasonably strong and reasonably weak signals. After extensive study it is found that Adaptive threshold selection technique provides suitable thresholds for both strong and weak signals, the threshold values are slightly adjusted manually in order to have single set of thresholds for all the ranges. It was found that hard thresholding method is suitable for MST radar data. This denoising technique was applied on all range bins of experimental MST radar profile. This procedure is first applied on simulated data as Doppler echo position is known in that case. The Doppler echo in these simulated spectra was chosen to have Gaussian distribution with width typical of observed Doppler echoes, with a chosen shift and unit peak value for the lowest range bin. Random Gaussian noise was added to this spectrum to obtain a noisy signal by using standard noise generator. Then the data for higher range bins were generated by reducing the Doppler echo strength by 2 dB per every kilometer keeping the noise power constant as in the case of a realistic MST radar data. Different experimental situations were simulated by generating the profiles for different seed values of the noise generator. Wavelet based denoising technique is applied on these profiles to verify denoising performance.

Adaptive tracking methods were employed earlier to track the MST radar signals in the higher range bins, where the signal strength becomes comparable or even less than the noise level based on the knowledge of the position and other details of the Doppler echoes at lower bins. An adaptive tracking method is developed in this work on the same lines of one of the earlier methods with suitable modifications. This method works based on SNR, permissible wind shear and Doppler velocity window (DVW). An SNR threshold is chosen (after several trails) to be 15 dB below the SNR of the highest range bin. The tracking started from the first bin whose highest peak was selected as Doppler echo as in almost all cases the Doppler echo is quite prominent and easily detectable in several smaller range bins. From the next bin onwards, the Doppler peak in a range bin (say \( i^{th} \) bin) is chosen in the following way. First a Doppler window (DVW) was fixed
based on the position of the detected Doppler echo of the previous (i-1) bin. Doppler velocity window limits are set at ±10% of the coherent integration filter band width on either side of the mean Doppler shift of the previous range bin since the signal is not to expect to change by more than 10% of the coherent filter bandwidth from one range bin to the next. Then five most prominent peaks are chosen within this window as candidate signals. Starting from the peak having highest total power, the peak satisfying the SNR criterion was chosen as the Doppler echo. If none of the peaks satisfy the SNR criterion, the strongest peak which falls within the permissible wind shear is chosen as Doppler echo. The wind shear threshold was selected based on earlier two range bins. The wind shear threshold for present bin (say i\textsuperscript{th} bin) is set by adding the full width of the Doppler velocity peak in present bin to the difference in mean Doppler velocity between present bin (say i\textsuperscript{th} bin) and previous bin (i-1). The wind shear threshold set for present bin is used for next range bin to identify prominent peak.

If no Doppler echo was detected based on the above two criteria in a given range bin that bin was skipped and DVW and wind shear threshold for the next bin were computed from the earlier bins. This adaptive tracking method had improved ability to detect the Doppler echoes at higher ranges. This adaptive tracking algorithm combined with wavelet denoising using the wavelets designed here was used in this work for the processing of the MST radar data as described below.

The methodology developed in this work, for the wavelet denoising of the MST radar data was first tested using the simulated data, generated as described the above, as the details of the signal are known in simulated data. Different types of variations in the Doppler shifts were considered. The analysis of the data using the procedure as described the above resulted in an increase in the range, on the average, by about 60%. That is, when the data were denoised using the wavelet designed in this work and the Doppler echo was tracked using the adaptive tracking method described the above, the range up to which the signal was correctly detected was typically about 60% higher compared to tracking the raw data itself. Further if the denoising is performed using the next best suited wavelet, \textit{viz.}, Daubechies wavelet and then the same adaptive tracking method was applied, the improvement in the range compared to raw signal was only about 30%. This clearly demonstrates the suitability of the designed wavelet to the clear air echo signals of the MST radar.

Then the efficacy of this methodology in improving the range was verified using the experimental data. The data was collected using the MST radar facility at Gadanki,
India (13.5°N, 79°E). The data from the beams in all four directions (making angle of 10°
with the vertical beam) were collected, denoised using the currently designed wavelet and
tracked using the adaptive tracking method described the above. The correctness of the
detected Doppler echoes using this method was ascertained by comparing the North and
South beams, as the profiles of the Doppler echoes in these two directions should show
mirror symmetry within the normal ranges. The results show that the detected echoes
show mirror symmetry to much higher ranges when they were denoised using the
designed wavelets compared to the Daubechies wavelet or the raw data. Similar results
were obtained when East and West beams were compared. There seems to be the
consistent result on a large collection of the data giving about 80% improvement in the
range compared to the raw data. That is, while the standard wavelet (db10) based
denoising improves the ability to detect Doppler echoes reliably by about 40%
(improvement in the range), employing the wavelet designed in this work provides almost
80% improvement.

These studies show that, this method of denoising the MST radar data using
wavelet analysis not only improves the range over which the Doppler echoes are reliably
detected, it also improves the accuracy of the parameters derived from such data. This is
demonstrated by collecting 10 sets of the MST radar data with a time span of about half
an hour on a day when the weather was steady. It was assumed that the weather
conditions, such as wind velocities and directions did not change within this short period.
The data was denoised using the designed wavelet and Doppler echoes were detected
using the adaptive tracking method described the above for each of these sets of the data.
The first three moments \(m_0, m_1\) and \(m_2\) of the Doppler echoes of each range in each of
these profiles were computed for those detected echoes. Now the data for a given range
in all the sets were averaged and corresponding standard deviations were computed.
These results were compared with the raw data. The results show that, the denoising
using the designed wavelet not only improves the ranges, but also the standard deviations
in the computed physical parameters improve substantially even in the lower ranges. The
results also show that the accuracy of the derived parameters improve due to this analysis
even in ranges where other methods can also detect the Doppler echo. This aspect was
further verified by considering simulated data where the expected values of all the
parameters are known. Several simulated profiles (about 10) correspond to different seed
values of the noise generator are considered. These sets have different noise values
though echo positions and other parameters remain the same. This situation is equivalent to several sets of experimental data collected in a short span under steady weather conditions. The first three moments corresponding to the Doppler power spectra \((m_0, m_1\) and \(m_2\)) were computed for some chosen ranges by using the adaptive tracking method described the above and standard deviations of these parameters over all the sets of data (about 10) were computed. Similar computations were performed after denoising these signals using the designed wavelet. It was again observed that the wavelet based denoising technique, besides increasing the detectable range, improves the accuracy of estimated parameters even at lower altitudes where correct Doppler echo were detected even otherwise.

The work embodied in this thesis is divided into nine chapters. Brief, chapter-wise details are presented below.

Chapter 1 presents an introduction to and theoretical background of wavelet transforms. It also deals with typical applications of wavelet transforms in different areas.

Chapter 2 details some of the background of MST radar necessary for understanding the remainder of this document. It includes an introduction to MST radar data, information this data contains and applications of MST radar. SNR issues in MST radar signal processing, present detection capabilities need for improvement are discussed. An adaptive tracking method of identifying signals in a noisy background is presented here. This chapter also provides technical details of the MST radar facility using which the experimental data reported in this thesis were collected.

Chapter 3 presents the details of the wavelet designing methodologies and denoising techniques. First part of this chapter deals with criteria for selection of wavelet for an application, design aspects and reviews existing wavelet designing methods, where as second part introduces the denoising technique based on wavelet thresholding. It also introduces the threshold selection rules such as Adaptive, Universal, Heuristic and Minimax threshold selection rules and thresholding methods (hard and soft).

Chapter 4 presents the details of wavelet designed for MST radar clear-air-echoes in this work. It starts with criteria for selection of wavelet for an application. Wavelet designing methodology, suitable to MST radar, adopted in this work is presented. Then procedure based on which MRA filter coefficients were computed is described. The results of different tests on this designed wavelet are also presented in this chapter.

Chapter 5 provides the details of development of suitable denoising methodology for the MST radar data. It starts with determining required wavelet decomposition level,
threshold levels and thresholding method to MST radar data. The results of this denoising technique based on these threshold levels on different signals and its ability to improve SNR and detectability of weak signals are also reported in this chapter.

Chapter 6 describes the adaptive tracking algorithm developed in this work and the results of verification of the same on the simulated data.

Chapter 7 deals with results of the analysis of the simulated data using the methods developed above. The results on the simulated data generated using different Doppler shift variations and different noise profiles are summarized. Comparisons with the standard wavelets are also presented.

Chapter 8 deals with results of the analysis of the experimental data using this designed wavelet. The results of the analysis on a large number of experimental data collected under different circumstances and the details of the improvement achieved both in the range of reliable detection of Doppler echoes as well as in the accuracies of the derived parameters are provided in detail.

Chapter 9 presents overall conclusions based on the investigations carried out in this work and possible extensions of this work.