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Improved Temperature Profiles for Atmospheric Radar Signal Using Dual-Tree Complex Wavelet Transform

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ABSTRACT
Atmospheric temperature profiles play a very important role in the study of atmospheric stability and turbulence structures. The temperature profile for Troposphere and lower Stratosphere are derived from backscattered signal of Indian MST radar located at Gadanki (13.5^0N, 79.2^0E), using vertical wind observations. The altitude profiles of Brunt-Vaisala (BV) frequency are obtained from the derived spectra of vertical wind. The temperature profiles are then obtained from BV frequencies following Revathy et al. This method leads to poor temperature profiles under unstable atmospheric conditions and large horizontal winds due to low Signal to Noise Ratio (SNR). Better temperature profiles even at severe weather conditions with low SNR can be obtained by priori application of denoising technique. In the present paper, Dual tree Complex Wavelet Transform (DTCWT) is implemented, and is used as denoising technique. DTCWT provides a high degree of shift-invariance and better phase information compared to other complex wavelet transforms.

The MST Radar data is first denoised with DTCWT and then the temperature profiles are derived using the above mentioned technique of identifying BV frequencies. The derived temperature profiles are compared with the profiles of original MST data without denoising and radiosonde flight data at radar site during the observations, for validation. A good improvement in the profiles is obtained due to improvement in SNR using DTCWT.
Keywords- Back Scattered Signal, Dual Tree Complex Wavelet Transform,MST Radar, Shift invariance, Vertical temperature profile.

I. INTRODUCTION

Atmospheric Radar Signal processing is a field of signal processing where there is a lot of scope for development of new and efficient tools for spectrum cleaning, detection and estimation of desired parameters. The echoes received from MST region are very weak and buried in noise, hence denoising methods are necessary [1]. These methods result in enhancement of signal to noise Ratio (SNR) in order to have improvement in detection ability [2].

Fast Fourier Transform (FFT) is an important tool for analysis and processing of many natural signals. But it is limited to stationary and linear signals. ShortTime Fourier Transform (STFT) deals with non-stationary signals but with a trade-off between time and frequency resolutions. Continuous Wavelet Transform is an alternative approach to STFT which overcomes resolution problem by changing the width of window during the computation of transform. As far as, the reconstruction of the signal is concerned, this transform provides highly redundant information, which requires significant amount of computation time and resources.

Discrete Wavelet Transform (DWT) on the other hand, is considerably easier to implement, when compared to Continuous Wavelet Transform and provides sufficient information both for analysis and synthesis of original
signal with a significant reduction in computation time. Standard DWT is implemented through a simple filter bank structure and allows Multi Resolution Analysis (MRA). These advantages popularized DWT in many signal processing applications like Denoising, Spectrum Cleaning, Evaluation of desired parameters etc. The three main disadvantages associated with DWT are lack of shift invariance, lack of symmetry of mother wavelets and poor directional selectivity.

These disadvantages are diminished by the use of complex wavelet transform [3] like Analytic Wavelet Transform (AWT) and Dual Tree Complex Wavelet Transform [4]-[6].

In this paper, DTCWT with soft thresholding technique is implemented and applied to backscattered radar signal. The results are compared with DWT in terms of SNR.

The temperature profiles of atmosphere plays a very important role in the studies of atmospheric stability and turbulence structures. The temperature profiles, in the present paper are derived using the method of Revathy et al., by identifying Brunt-Vaisala frequency from the spectra of vertical wind velocity [7], [8]. The data of MST radar, Gadanki collected in vertical mode is first subjected to DWT and DTCWT to have improvement in SNR.Then the temperature profiles using the above method are derived and compared with Radiosonde flight data for validation.

II. MST RADAR SYSTEM AND DATA BASE

The Indian Mesosphere-Stratosphere-Troposphere (MST) radar at Gadanki (13.47^0N, 79.2^0E) is a high power, highly sensitive, pulse coded and coherent VHF phased array radar operating at 53 MHz with a peak power aperture of $3X10^{10}wm^2$ and average power aperture of 7X108 wm^2. The vertical resolution is 150m. The backscatter signals provided by MST Radar is used for experiments in lower atmosphere, i.e., from an altitude of 3.75km to altitudes ranging from 25 to 31 km. Radar records data for each range gate and the resolution of sample vary based on experimental specification. Radar echoes are recorded in 6 beam directions, viz. East, West, Zenith-x, Zenith-y, North and South directions. These data are complex innature and hence the method adopted is complex signal analysis. Only sample data in vertical mode (Zenith-x or Zenith-y) is used for analysis to demonstrate DTCWT and derive Temperature profiles. The Radiosonde observations, at Gadanki are used to validate the temperature profile obtained from MST radar data.

III. DUAL TREE COMPLEX WAVELET TRANSFORM

To overcome the disadvantages of DWT, Kingsbury[5] implemented dual-tree wavelet transform with excellent directionality, reduced shift sensitivity and explicit phase information. To achieve approximate shift invariance with real DWT, the sampling rate is doubled at each level of tree. Figure 1 shows the tree. To make this possible, the samples must be evenly spaced. The sampling rates in tree aof Fig.1 can be doubled by eliminating the down-sampling by 2 after the level 1 filters, H_{0a} and H_{1a}.

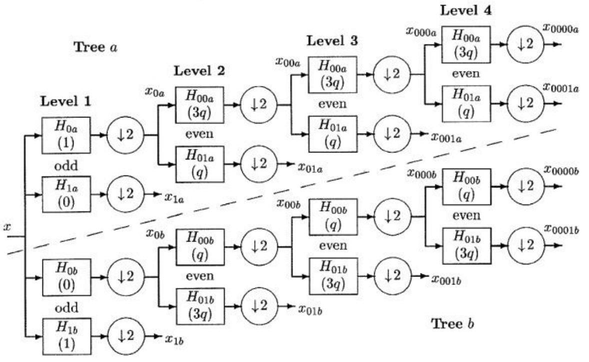

Fig.1 Q-Shift version of the DT CWT

This is equivalent to two parallel fully-decimated trees aand b, provided that the delays of H_{0b} and H_{1b} are one sample offset from H_{0a} and H_{1a}. This offset ensures the pickup of opposite samples in both trees. To get uniform intervals between samples from the two trees below level 1, the filters in one tree must provide delays that are half a sample different (at the filter input rate) from those in the other tree. This statement is also supported by Selesnick [6].

It consists of a pair of filter banks that simultaneously operate on the input signal and provide two-level wavelet decomposition. The filters are designed in such a way that the sub band signals in one filter bank can be interpreted as the real part of a complex wavelet transform and sub band signals of other filter bank can be interpreted as imaginary part i.e., the wavelets associated with the filter banks form Hilbert pair.

The limitation with this implementation is that it is two times expansive because for an N-point signal it gives 2N DWT coefficients, which require more storage space than the input signal. Hence it is redundant.

3.1 Problems of Odd-even length filter

Dual Tree DWT is also complex DWT. In each sub band, one tree produces the real part and the other the imaginary part of the Complex wavelet coefficient and so the filters in the two trees cannot be identical. The first implementation proposed had the constraint of linear phase, and to accomplish this, the implementation required odd-length filters in one tree and even-length filters in the other. Greater symmetry between the two trees occurs if each tree uses odd and even filters alternately from level, but this is not essential.

The problems with the odd/even filter approach to achieve this delay are

- The sub-sampling structure is not symmetrical.
- The two trees have slightly different frequency responses.
- The filter sets must be bi-orthogonal because they are linear phase.

These drawbacks have been overcome with a more recent form of the dual tree known as a Q-shift dual tree.

3.2Q-Shift filters

Two sets of filters are used, the filters at level 1 and the filters at all higher levels. The filters beyond level 1 have even length but are no longer strictly linear phase. Instead they are designed to have a group delay of approximately ¼sample(q).The required delay difference of ½ sample (2q) is then achieved by using the time reverse of the tree a filters in tree b, So that, the delay of tree-b filters become 3q.

The filter coefficients are no longer symmetric hence it is possible to design the Perfect Reconstruction (PR) filters that are orthonormal, so that the synthesis filters are just the time reverse of the equivalent analysis filters in both trees. Hence all filters beyond level 1 are derived from the same orthonormal prototype set. There are a number of choices of possible filter combinations. The key to design filters for Q-shift version of DTCWT is based on selection of a good even length low pass filter with a delay of ¼ sample which also satisfies the standard orthonormal PR condition of 2-band filter bank. The Q-shift transform retains the good shift invariance and directionality properties while also improving the sampling structure.

IV. METHODOLOGY FOR ESTIMATING TEMPERATURE

With MST radar at Gadanki, backscatter signals in the vertical direction are generally obtained from ~3.75 km to altitudes ranging from ~25 to 31 km in the stratosphere. The observations have been carried out on 18 December 2013 with the antenna beam pointing in vertical direction. To obtain Doppler spectra, data of I and Q channels are subjected to FFT. From the first moment (mean Doppler frequency) of each of the Doppler spectra, the vertical wind velocity is derived. These time series of vertical wind velocity are subjected to FFT to obtain the spectra [9]. Spectral peak corresponding to the BV frequency is identified from these spectra using the following criteria.

- Of the prominent spectral peaks, the required spectral peak, which corresponds to B-V frequency,is one with highest peak frequency
- The spectra on the high frequency side (of the peak) should show a steep decrease followed by no significant peaks.

The series of spectral peaks thus identified gives the required BV frequencies as a function of altitude, in the range 3.6 to 29.1 km.

Using the methodology of Revathy et al. (1996), the temperature profile from measured Brunt-Vaisala frequencies are obtained, from the relation:

$$N^2 = \frac{g}{T}\left[\frac{dT}{dz} + \Gamma\right] \tag{1}$$

Where,

N is the Brunt-vaisala frequency in rad /sec

g is the acceleration due to gravity

z is the altitude and

Γ is the adiabatic lapse rate

On solving equation (1) for T :

$$T\left(z^*\right) = \frac{1}{I\left(z^*\right)}\left[I\left(z_0\right)T_0 - \Gamma\int_{z_0}^{z^*} I\left(z\right)dz\right] \tag{2}$$

Where $$I(z) = \exp\left[-\int \frac{N^2}{g}dz\right] \tag{3}$$

$T\left(z^*\right)$ is the temperature at height z^* and T_0 is the reference temperature taken from radiosonde temperature profile at a reference height z_0

V. RESULTS AND DISCUSSIONS

The DTCWT implemented in this paper requires less computation as the redundancy is minimized by the use of simple separable filters.

The data of 18 December 2013 over a span of one hour is collected and is sufficient for the computation of SNR and retrieval of temperature profiles.The noise in the backscattered signal which may be due to disturbed atmospheric condition, i.e., events such as convection, precipitation is reduced.

SNR is computed and the height profiles of SNR are plotted for the original (noisy) signal, denoised signal using DWT, and DTCWT. These profiles are shown in Fig.2.

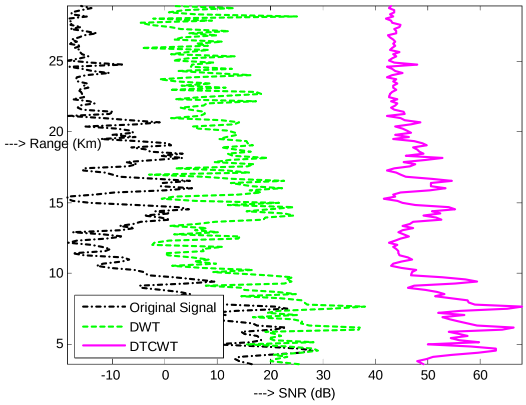

Fig.2 SNR Comparison in Zenith-x direction

After denoising the back scattered atmospheric signal using DTCWT for the above data, the temperature profiles are derived. These profiles are compared with the temperature profiles of original signalbefore denoising and after denoising using DTCWT, in order to show the improvement.The temperature profiles from Radiosondeflight dataof same time is also plotted for validation. The profiles are shown in the Fig. 3.

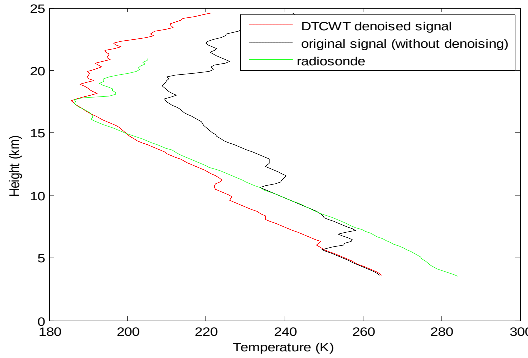

Fig.3 Temperature Profiles

The temperature profiles of denoised signal using DTCWT seem to be more close to radiosonde data than the temperature profiles of original signal.

The discrepancy in the profiles between Radar derived and radiosondemeasured data is either due to disturbed atmospheric conditions or dueto the fact that the temperature measured by radiosonde is point observation, whereas radar derived temperature is an integrated profileover a period of time. This discrepancy is expected and depending onweather conditions, it varies from radar by 2-3k and is reasonable.

The results show that the proposed method of DTCWT has better discriminability than DWT and has the potentiality to improve SNR, which paves a way to retrieve better temperature profiles.

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