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Improvement of a Doppler Profile of a Lower Atmospheric Wind Profiler Radar Time Series data Using Signal Processing Techniques

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Abstract

Spectral analysis is a vital problem which occurs in many applications. One of the most important application areas of Digital Signal Processing (DSP) is the power spectral estimation of periodic and random signals. For instance, the task of detecting the periodicity in a time-series can be cast as a spectral analysis problem. This can be interpreted as the problem of estimating the amplitudes and frequencies of superimposed sinusoids buried in noise. Spectral estimation is also relevant in other problems related to radar. The classical approaches to spectral analysis (of uniformly sampled data) include the Fast Fourier Transform (FFT) as well as its variants, which are typically based on smoothing the FFT spectral estimate. The wind profiler data, which are processed in the present work has been obtained from the Lower Atmospheric Wind Profiler (LAWP) radar at National Atmospheric Research Laboratory (NARL), Gadanki, India. The Radar wind profiler is a remote sensing tool for measuring the height profile of wind velocities with high time and high resolutions in all weather conditions. These LAWP radars can measure the wind profiles in the first few kilometers of the atmosphere. The main objective of this work is to denoise the wind profiler data using Peak Pick with Moving Average (PPMA). Improvement of Doppler shift for LAWP data is obtained by using PPMA method and compared with the before denoising signals. The result shows that there is an effectual Doppler after using PDMA method for LAWP signals.

Keywords: Doppler Beam Swinging, Peak Pick with Moving Average, Wind Profiler radar, Signal to Noise Ratio.

INTRODUCTION

The power spectrum of a signal is an average quantity which tells us about the power of various frequencies within that signal [1]. The constraint for power spectrum evaluation arises in a variety of contexts, including the measurement of noise spectra for the blueprint of optimal linear filters, the detection of narrow-band signals in wideband noise and the estimation of parameters of a linear system by using noise excitation. Estimation of the power spectrum in general is the procedure of estimating the power spectral density of a random signal based on a finite number of observations. The more observations, we have, the more accurate will be the estimation of the spectrum. Another important consideration regarding the spectral estimation is that most often the observations of the signal are corrupted by noise.

Following the success with the Jicamarca radar in obtaining strong continuous echoes in the 10-35 km altitude range, many researchers recognized the potential of Very High Frequency (VHF) radars for exploring the clear (neutral) atmosphere and could foresee the value of these radars for studying the dynamics of the middle atmosphere (10-100 km). Advances in radar system technology, primarily in attaining greater system sensitivities at lower VHF, have extended this technique to a ‘clear-air’ capability. The term wind profiling radar or wind profiler is often used to emphasize the operational applications of the clear air radar technique. Generally the Mesosphere-Stratosphere-Troposphere (MST) radars are very high sensitivity and expensive radars, which use very high power and large antenna, operating in the lower VHF band, and used primarily for ‘research’ applications. Wind profiler radars, on the other hand, are relatively less sensitive and low-cost systems, which use less power and smaller antenna, operating at lower and middle Ultra High Frequency (UHF) band, and used for both research and operational applications.

In the early 1980s National Oceanic and Atmospheric Administration (NOAA) developed operational wind profilers, and deployed the Colorado wind-profiling network. Presently the study of wind profilers is known as clear atmopsheric radars and operates typically in the VHF (30 – 300 MHz) and UHF (300 MHz –3GHz) bands. NARL has been operating this wind profiler radar at 1280 MHz with the Doppler Beam Swining Technique (DBS). This wind profiler radar objective is to achieve better range resolution with upper limit average power. Wind profilers have been developed by researchers and commercial groups for applications ranging from atmospheric wind quality studies to climate monitoring. It can compute the absolute Doppler spectrum of atmospheric targets with a time resolution on the order of 1 min. The range resolution of this Doppler radar is about 100m. It is used to study the atmospheric boundary layers. It is important to extend the wind profiler technology on the lower portion of the atmosphere. These profiles are very important for studying meteorological phenomena and for weather forecasting. These wind profiles receive the echoes from the atmosphere in the height range from about 0.1Km to 4-5Km. These wind profiler radars are coherent and very high sensitive. These radars are pulse Doppler Radars and works on the principle of the Doppler effect.

LOWER ATMOSPHERIC WIND PROFILER RADAR

Lower Atmospheric Wind Profiler (LAWP) Radars are expansively used for obtaining the wind information in all weather environments. These radars have the capability for probing the atmosphere, wind profiling. These radars are also called Doppler radars. Doppler radars can be used for meteorological research. Wind profilers are expected to have a growing impact upon weather forecasting, atmospheric research environmental pollution monitoring, climate, air traffic control and many more. It is therefore important that the wind measurements of these radars are both accurate and reliable. The minimum height limitation arises from various factors like receiver overload due to strong clutter and internal reflections in large antenna arrays, the inherent inability of large antenna operating in this frequency range to form well-defined beams in the first few kilometers above the array and the limitation of bandwidth at these frequencies. The operating frequency band of LAWP radar is 900-1400 MHz. These radars are popular for measuring the wind vector by making use of variations in amplitude and frequency of radio waves which are transmitted from a radar system. The features of high spatial resolution and fast system recovery time require operation at frequencies near 1000 MHz.

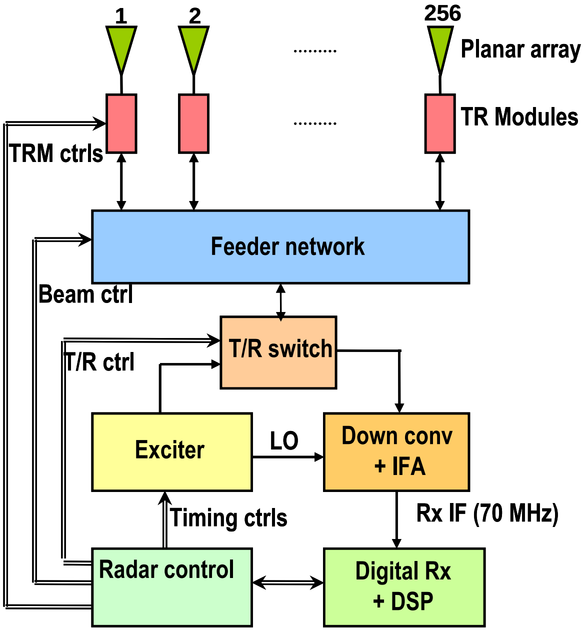

Figure 1: Block diagram of LAWP Radar

The specifications of the LAWP radar system are shown in Table 1.

Table 1: LAWP radar system Specifications.

S.No.	LAWP Radar system Specifications
1.	Operating frequency is 1280 MHz
2.	Wind profiling Technique is Doppler Beam Swinging.
3.	Minimum height range is 100m
4.	Maximum height range is about 3-6 km in clear air and up to 12 km during precipitation
5.	Type of Antenna is Active patch array 16 x 16 (2.8m x 2.8m)
6.	Type of Tx/Rx is Solid-state TR modules (256)
7.	Pulse length range is 0.25μs to 8 μs
8.	System recovery time is < 0.5μs

The pioneering work in making these radar wind profilers practical was accomplished in 1980s by Aeronomy Laboratory (AL) at NOAA. Initial UHF wind profilers were configured either with dish antenna or passive microstrip patch arrays or coaxial collinear antenna arrays for simplicity and commercial viability. LAWP radar being extensively used for atmospheric research and operational meteorology and has applications beyond wind profiling. These data can be used to estimate the Noise Levels and Doppler shifts [2]. They provide almost hysterically measurement of wind over a range of altitudes and detailed information on vertical profile and wind variations. Zenith beams provide for direct measurement of vertical motions. In addition to the wind and wind variability, the Doppler wind profiler provides quantity of signal strength and Doppler width.

DOPPLER BEAM SWINGING TECHNIQUE

These wind profilers use either Spaced Antenna (SA) technique or Doppler Beam Swinging (DBS) technique to measure the atmospheric wind velocities. To derive the components of the wind vector, these systems operate with DBS technique with three fixed beams in Vertical, East-West, and North- South directions. The SA technique employs a single vertical beam but receives the echo with multiple receivers.

Most commonly used technique for finding wind velocities is the Doppler Beam Swinging technique and the radial velocity measurements are made at each specified height along each beam. Spaced Antenna technique measures the temporal and spatial variation of field pattern of radar signals which are partially reflected or scattered from refractive index irregularities in the atmosphere. The antenna is pointed perpendicular to the horizontal plane and the spectral or complex autocorrelation analysis yields an estimate of the vertical velocity.

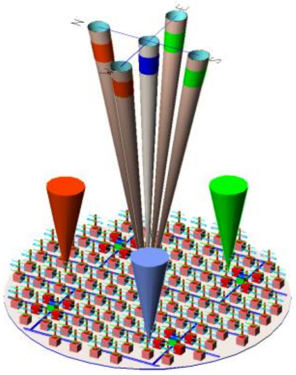

Figure 2: Antenna Configuration for Doppler Beam Swinging Technique

The wind profiler is operated in a selected sequence of beam directions. Comparison of the received echo with the transmitted pulse permits the determination of the Doppler frequency. The beam pointing sequence is repeated for every 1-5 min. For each height, the radial velocities measured from the three beams are used to derive the east-west (zonal), north-south (meridional), and vertical components of the wind, U, V and W respectively. The profiler beams are generally pointed to high elevation angles to ensure the sampling volumes to be relatively close to each other

If the beams are oriented to the east at zenith angle θ_1 (beam 1), to the north at zenith angle θ_2 (beam 2) and to the vertical θ_3 (beam 3), the radial velocities along these three beams are

$$\begin{aligned} V_{R1} &= U\,Sin(\theta_1) + WCos(\theta_1) \\ V_{R2} &= U\,Sin(\theta_2) + WCos(\theta_2) \\ V_{R3} &= W \end{aligned} \qquad (1)$$

Normally V_{R1} and V_{R2} will be the same, about 150. From these three equations, the U, V and W are computed, as V_{R1}, V_{R2}, and V_{R3} are measured and θ_1 and θ_2 are known.

DATA PROCESSING

The time series complex data $\{(I_i, Q_i), i = 0, 1. . . N_{FFT} - 1\}$ is subjected to FFT to obtain the complex Doppler spectrum $\{(X_i, Y_i), i = 0. . . N_{FFT} - 1\}$ of the received echoes. I_i and Q_i are the in-phase and quadrature components in time series data, X_i and Y_i are the real and imaginary components of the complex Doppler spectral data, and N_{FFT} is the number of time series FFT points. The echo signals, which are in time series contains the I channel and Q channel and these signals are decoded and then send to Coherent Intergration as input. The steps involved in lower atmospheric wind profiler radar data processing are Coherent Integration, Normalizaton, Peak Pick with Moving Average, Fourier analysis, incoherent integration, spectrum cleaning etc. The main reason for applying phase coding (pulse compression) is to operate with a maximum average power at a given range resolution and unambiguous range. Because of the long coherence in time for UHF or VHF radar echoes, complementary codes are appropriate for this application. Radar wind profilers, by virtue of being coherent in nature, obtain amplitude and phase information of the echo signals.

Coherent Integration is a low pass filtering process achieved by combining the complex digital data samples for a particular number of pulses. The main advantage of coherent integration is that it reduces the data rate and it improves the detectability of echoes with low signal to noise ratio (SNR). The ground clutter components can be reduced by subtracting in each range gate from the quadrature components of the short term signal time series, which are used to calculate the spectrum. Doppler spectrum, even after removing the clutter, exhibits uncertainties due to noise level fluctuation across the Doppler window. Often, it is difficult to derive the moments from the spectrum without some kind of smoothening. The original Doppler spectrum contaminated by the DC and clutter.Clutter removed spectrum is associated with the noise fluctuations. When the noise fluctuations become comparable to the signal level, then identification of the desired atmospheric signal peak will be difficult. A process called peak pick with moving average is performed to remove the noise fluctuations from the spectrum. Incoherent integration is then performed, if necessary, where several succeeding spectra are averaged to improve signal detectability and this can also be removed the noise in the Doppler spectrum.

WINDOWING

After detrending, the time series data are subjected to either rectangular or Hamming windowing. The complex time series data, after windowing is converted into the Doppler power spectrum by applying complex Fast Fourier Transform (FFT) and computing the power spectrum. Incoherent integration is then performed, if necessary, where several successive spectra are averaged to improve the detectability. Alternatively, clutter can also be removed in the frequency domain, by taking out a significant number of points on both sides of the zero Doppler and replacing these points by the value obtained by averaging the two points. The number of points to be replaced is dynamic for each rangebin. Thus, the difficulty related to the spectral estimation of radar data by the FFT techniques is the problem of establishing efficient data windows. Data processing supports the selection of Rectangular, Hanning and Hamming window before the FFT computation. The steps in the radar data processing are shown in figure 3.

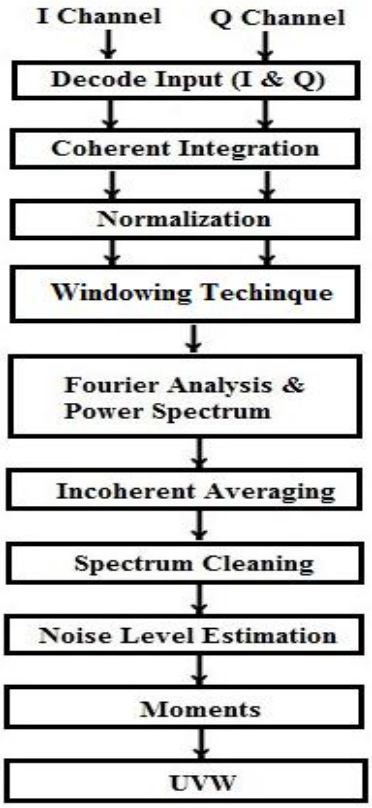

Figure 3: Steps for the Radar data processing using Windowing Technique

The radar data in time series are in the form of the complex signal.

$$I(t) = A\,Cos(2\pi f_c t + \varphi_k) \qquad (2)$$

$$Q(t) = A\,Sin(2\pi f_c t + \varphi_k) \qquad (3)$$

$$S_{rec}(t) = A\,e^{j(2\pi f_c t + \varphi_k)} = I + jQ \qquad (4)$$

Where I(t) is the In-Phase and Q(t) is the Quadrature-Phase signals.

$S_{rec}(t)$ is the Complex signal and φ_k is the Phase.

Windowing is a process of forming a finite length sequence from an infinite length sequence by multiplying an infinite length sequence with a window. There are different types of windows. In this, Hamming window is used to denoise the radar data and the expression the Hamming window is given by

$$\begin{aligned} f(t) &= 0.54 + 0.46\cos(\pi t/\tau), && |t| \le \tau \\ &= 0, && elsewhere \end{aligned} \qquad (5)$$

$$F(w) = 1.08\frac{\sin(w\tau)}{w} + 0.46\left[\frac{\sin(w+\pi/\tau)}{w+\pi/\tau} + \frac{\sin(w-\pi/\tau)}{w-\pi/\tau}\right] \qquad (6)$$

Peak Pick with Moving Average Algorithm

An algorithm called peak pick with moving average algorithm is implemented to identify the correct peak in every range. It may be noted that the Doppler frequency of the signal peaks changes slowly from one rangebin to the next. For the Lower Atmospheric Wind Profiler Radar data, the total number of rangebins is 40. This property is exploited by the successive peak pick with moving average algorithm in finding the correct peak from the multiple peaks in a given data [6]. This algorithm finds the position of the peak across consecutive rangebins. The algorithm starts from the lowest rangebin and progresses upward to the maximum rangebin. This ensures that the strong clear air peaks in the lower ranges are identified before the weaker clear air peaks are to be found, giving the algorithm a much better tracking the clear-air peak into the higher ranges.

To identify and analyze the peaks or spikes in a given time series data, this algorithm is very important and this can be used in many applications like bioinformatic, signal processing, image processing. To reduce the effect of noise, it is compulsory that the confined signal to noise ratio should be over a certain threshold. Thresholding can be used to find the local maxima for signal portions which exceeds the threshold level. With this technique, effective Doppler shifts can be obtained. Peak detection technique is one of the methods for reducing the probability of false detection. The advantage of this algorithm is better height coverage and effective Doppler shift.

Computing the threshold automatically by adapting it to the noise levels in the time-series as

$$Threshold = (max + abs\_avg)/2 + K * deviation \qquad (7)$$

Where max is the maximum value in the time-series, abs_avg is the average of the absolute values in the time series, K is the influence factor of the deviation, $deviation$ is the difference between an observed value and the expected value of a variable and abs_dev is the mean absolute deviation.

$$abs\_avg = \frac{\sum_{i=1}^{N} |P_i|}{N} \quad (8)$$

$$deviation = \frac{\sum_{i=1}^{N} |P_i - avg|}{N} \quad (9)$$

If the deviation is very low, the threshold will nearly be in the middle of maximum value and the average value.

When K= 0.5, Then the Threshold equation can be rewritten as

$$Threshold = \frac{\max}{2} + abs\_avg \quad (10)$$

Where

$$abs\_avg = \frac{\sum_{i=1}^{N} |P_i|}{N} \quad (11)$$

The Threshold can be calculated based on the above equations.

The ground clutter can be removed from the wind profiler data by applying the thresholding. First the peak value can be identified in each and every range bin and stored these peak values in an array.

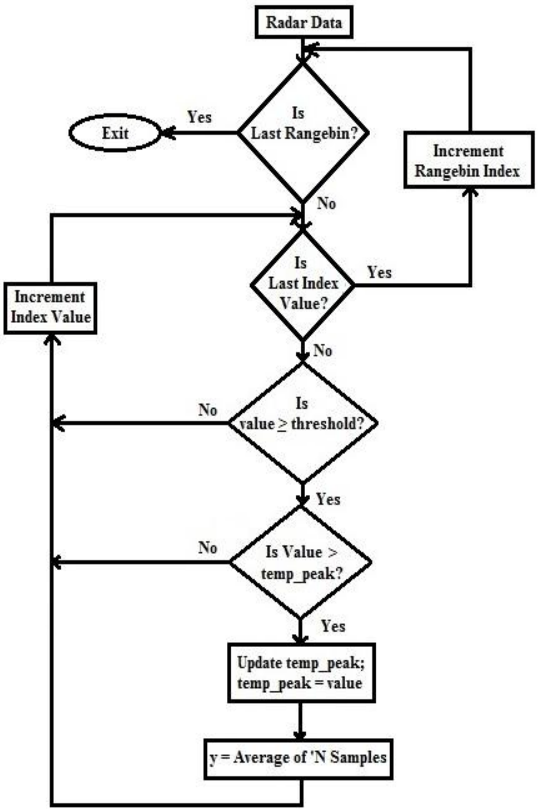

Figure 4: Flow diagram of the Peak Pick with Moving Average Technique

To improve the Smoothness of the signal for the time series data and to improve the estimation of the Noise Level in Doppler Spectra Teter H. Hildebrand and R.S. Sekhon proposed a new method called Moving Average Method and Noise Thresholding Method in 1974 [3].

This method is used for smoothing the radar signals and filters the unwanted noisy components from the radar data and is the most common filter in Digital Signal Processing. It takes 'N' samples of input at a time and calculate the average of those N samples (N=4) and produces a single output point and repeats the same procedure until the radar data gets completed [7]. As the length of the filter increases then the smoothness of the signal gets increases.

$$y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i] \quad (12)$$

Where

$x[i]$ - Input signal

$y[i]$ - Output signal

M - Number of points used in the moving average.

RESULTS

Improvement of Doppler shift of LAWP data on 31st May 2014 in North direction denoising using Windowing and Peak Pick with Moving Average method are shown in figure 4 and figure 5 respectively. The comparison of Signal to Noise ratios in North directions and the wind velocities in East-West (U), North-South (V) and Zenith (W) directions are shown in figure 6 and figure 7 respectively.

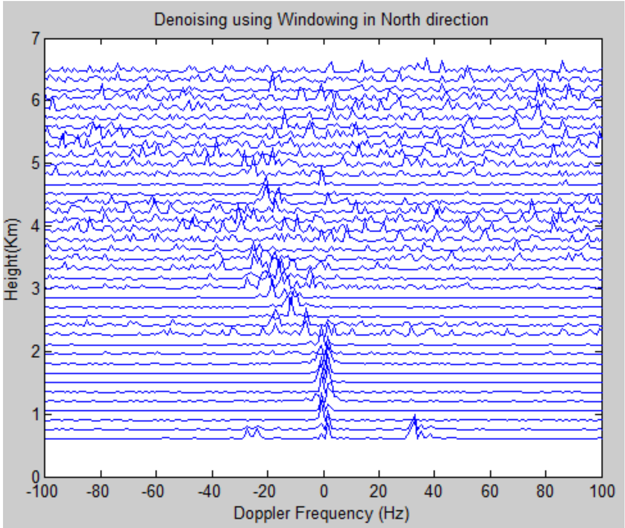

Figure 4: Denoising using Windowing in North direction

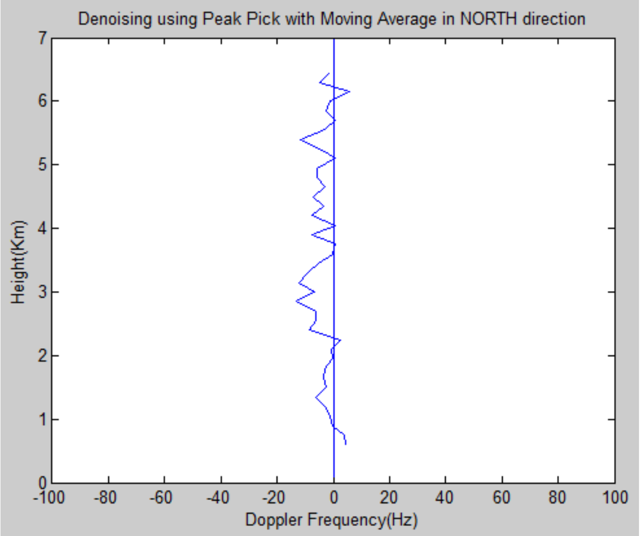

Figure 5: Denoising using Peak Pick with Moving Average method.

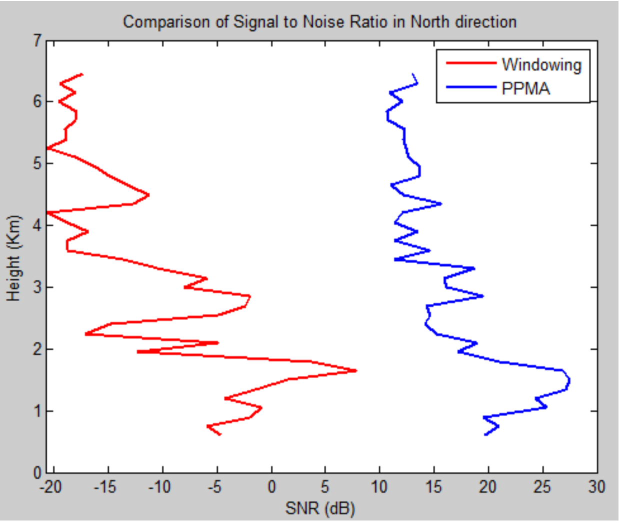

Figure 6: Comparison of Signal to Noise Ratios in North direction

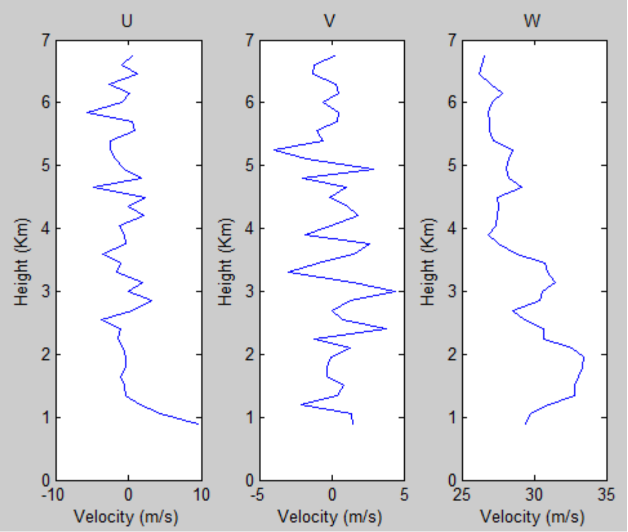

Figure 7: Wind Velocities in UVW directions

CONCLUSIONS

A Peak Pick with Moving Average method has been proposed to estimate the Doppler spectrum. This newly proposed method has been compared successfully with the windowing method. The proposed method provides clear Doppler spectrum and also suppresses the spikes generated due to noise in the spectrum compared to the before denoising signals to a greater extent at higher altitudes. Nearly 19.0626dB SNR improvement in North direction is observed using the Peak Pick with Moving Average (PPMA) method compared to the conventional windowing method. Hence it is concluded that the Peak Pick with Moving Average method can be more proficient for the parameter extraction of the real time radar data and can be suggested an alternative for the windowing method.

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