Signal Processing of Lower Atmospheric Wind Profiler using Different Windowing Techniques

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ABSTRACT: *Lower Atmospheric Wind Profiler, also called as atmospheric radar, most suitable remote sensing instrument, used to provide continuous high resolution wind measurements in the lower atmosphere. Signal processing of this atmospheric radar is necessary to estimate the wind profiler moments and signal to noise ratio. The signals, which are processed in the present work, have been obtained from the Lower Atmospheric Wind Profiler (LAWP) at National Atmospheric Research Laboratory, Gadanki, India. In this paper we implement different windowing conditions, to reduce noise from the received data. This paper is based on comparing the signal to noise ratio obtained by the application of different windows to the received time series data. Signal processing of experimental data is performed MATLAB code developed and graphs were plotted.*

Keywords: *Clutter, LAWP, Moments, Signal to noise ratio, Window.*

I. INTRODUCTION

Observations of wind velocity profiles are very important for studying meteorological phenomena and for weather forecasting. Radar Wind Profiler (RWP) is a Coherent-Pulse- Doppler-Radar, is used for observing the height profiles of the three components of the wind velocity vector, with high time and height resolutions without influence of weather conditions [1].

The L-band Lower Atmospheric Wind Profiler (LAWP) is used for conducting research in the lower atmosphere [4]. National Atmospheric Research Laboratory (NARL) at Gadanki (13.47°N, 79.18°E) near Tirupati, India has been operating this 1280 MHz, atmospheric radar for studying structure and dynamics of the lower atmosphere. These radars employ bi-phase coding (pulse compression) with complementary codes, to achieve better range resolution with maximum average power (height coverage). These radars receive the echoes from the atmosphere in the height range from about 200m to 4-5Km, in clear air, which are very weak and contaminated with clutter. These radars are sensitive to hydrometer and are useful to study precipitation/ convection phenomena [1].

II. PRICIPAL OF OPERATION

Wind profiling radars depend upon the scattering of electromagnetic energy by turbulent irregularities in the refractive index of the air. The refractive index of air is a measure of the speed at which electromagnetic waves propagate through the atmosphere[1,6].A spatial variation in this refractive index encountered by a propagating electromagnetic (radio wave) causes a minute amount of the energy to be scattered (or dispersed) in all directions. A fraction of this scattered energy returned to the radar site is received and analyzed [4].

The atmosphere is in a constant state of agitation, which produces irregular, small scale variations in the temperature and moisture over relatively short distances, causing refractive index variation in the lower atmosphere. As the refractive index irregularities are carried by the wind, they prove to be good tracers of wind [1].

Radar wind profiler derives information on the dynamic atmosphere behaviour by making use of variations in amplitude and frequency of radio waves which are transmitted from radar system, backscattered by the atmospheric refractive index irregularities and received by the radar system again. Radar wind profilers use either Doppler beam swinging (DBS) technique or spaced antenna (SA) technique for measuring the atmospheric winds.

Present work uses DBS technique for measuring the atmospheric winds [1].

2.1 Doppler Beam Swinging technique

It is the most commonly used technique for wind velocity measurements. One antenna beam is pointed toward zenith, and two beams are pointed at oblique angles in the range 10-20^{o} off-zenith with orthogonal azimuths (three-beam system). The oblique beams provide a measurement of the horizontal velocity and the vertical beam provides a direct measurement of the vertical velocity. Radial velocity measurements are made at each specified height along each beam [6]. For each height, the radial velocities measured from three beams are used to derive the east-west (zonal), north-south (meridional), and vertical components of the wind[1].

III. SIGNAL PROCESSING STEPS

In this section we present signal & data processing algorithm, used for extraction of wind profiler moments, signal to noise ratio and wind vector.

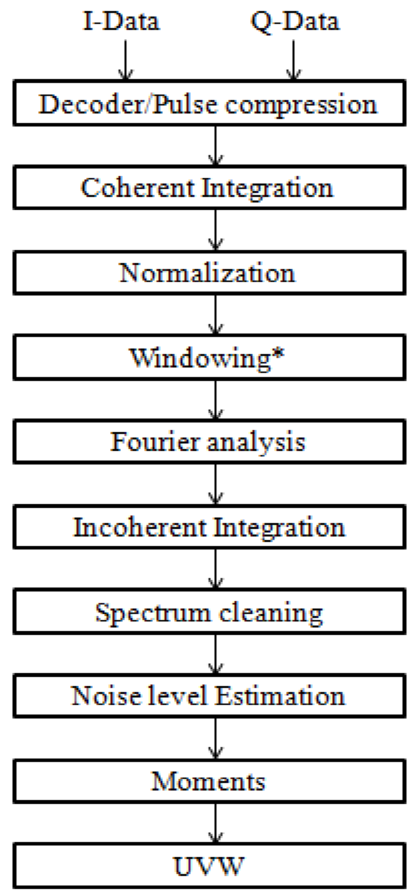

Fig.1. Signal Processing Steps of LAWP Radar

3.1 Decoder/ pulse compression

Best range resolution is obtained with short pulse, but the height coverage will be minimum due to low average transmit power. Decreasing the inter-pulse-period (IPP) compromises the unambiguous maximum range obtained [2] On the other hand, using long pulse increases the height coverage but the range resolution degrades. To have maximum height coverage and best range resolution simultaneously, we use a technique called Pulse compression. It is a technique of transmitting a long pulse and compressing the same upon reception. It allows more of the transmitter average power capacity to be used without sacrificing range resolution.

In the time domain a pulse can be compressed via phase coding, especially binary phase coding. A long pulse is divided into 'n' number of small segments, each and each segment is phase coded on transmission. Upon reception, the signal is decoded with reference to transmit code which results in compression of the pulse by a factor ‘n’. The decoding operation involves cross correlating the incoming data with the replica of the transmitted data[4].

3.2 Coherent Integration

It is a digital box-car low pass filtering process. Here the complex digital data samples are coherently integrated for a predefined number of pulses which lead to an a reduction in the volume of the data to be processed and an improvement in the SNR. Signal to noise ratio is increased by a factor of number of pulses integrated, because the wide band noise is filtered out. It also improves delectability of echoes with low signal to noise ratio[2].

3.3 Normalization

Normalized is done by applying a scaling factor corresponding to the operation performed on the input data. It is necessary to avoid data overflow resulting in any succeeding operations performed on it. The Normalization has following components.

- Sampling resolution of ADC.
- Scaling due to pulse compression in decoder
- Scaling due to coherent integration
- Scaling due to number of FFT points.

if Δv - ADC bit resolution (10/16384),
w - Pulse width in microsecond,
M - Number of IPP integrated
M - Integrated time /inter pulse period,
N - Number of FFT points

Then the normalization factor is given by

$$s = \frac{\Delta v}{w * M * N}$$

The complex time series {Ii , Q_i where i = 0, . . ,N-1} at the output of the signal processor is scaled as

$$\tilde{I}_i = s * I_i , \quad \tilde{Q}_i = s * Q_i$$

3.4 Windowing

Windowing is a technique used to shape the time portion of the data, to minimize edge effects that result in spectral leakage and picket fence effect in the FFT spectrum. To reduce these affects, in time domain the signal is multiplied by a finite weighting sequence called, window [7]. Windows are the time domain data functions that are used to reduce Gibb’s oscillation resulting from the abrupt truncation of Fourier series [6]. However the use of the data windows other than the rectangular window affects the bias, variance and frequency resolution of the spectral estimates. An estimate is said to be consistent if the bias and the variance both tend to zero.

Spectral leakage can be reduced by applying a window that has lower side lobes in frequency domain compared to rectangular window [7]. Thus, the problem associated with the spectral estimation of a finite length data by the FFT techniques is the problem of establishing efficient data windows or data smoothing schemes. Data windows applied to the LAWP radar signals in present work are given below.

- Rectangular Window
- Hanning window
- Blackman window
- Kaiser window

3.4.1 Rectangular Window

The window used to achieve simple truncation of the ideal infinite length impulse response is called a rectangular window. The rectangular Window function is defined as

$$f(t) = 1 \qquad |t| \leq \tau$$
$$= 0 \qquad Elsewhere$$

And its Fourier transform is given by

$$F(\omega) = \frac{2\sin(\omega\tau)}{\omega}$$

Where τ represents the ne sided duration of the window. The oscillatory behaviour exists in the Fourier transform of the rectangular window because the impulse response is infinitely long and not absolutely summable, thus the filter becomes unstable and the rectangular window has an abrupt transition to zero. So, the frequency response of a rectangular window has a narrow main lobe width centred at zero [2].

3.4.2Hanning Window

The Hanning window is sometimes called as Hann window. The Hanning window function is defined by

$$f(t) = 0.54 + 0.46\cos(\pi t/\tau), \qquad |t| \le \tau$$
$$= 0 \qquad \text{Elsewhere}$$

And its Fourier transform is given by

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

3.4.3 Blackman Window

The Blackman window function is defined as

$$f(t) = 0.42 + 0.5\cos(\pi t/\tau) + 0.25\cos(2\pi t/\tau) \quad |t| \le \tau$$
$$= 0 \qquad \text{Elsewhere}$$

and its Fourier transform is given by

$$F(\omega) = \frac{0.84\sin(\omega\tau)}{\omega} + 0.5\left[\frac{\sin(\omega+\pi/\tau)\tau}{(\omega+\pi/\tau)} + \frac{\sin(\omega-\pi/\tau)\tau}{(\omega-\pi/\tau)\tau}\right] + 0.08\left[\frac{\sin(\omega+2\pi/\tau)\tau}{(\omega+2\pi/\tau)} + \frac{\sin(\omega-2\pi/\tau)\tau}{(\omega-2\pi/\tau)\tau}\right]$$

Blackman window reduces the side lobe level at the cost of increasing its transition width. For a window function to be optimum, the transition width of the side lobe should be small.

3.4.4 Kaiser Window

The Kaiser window is superior to the other windows, because for the given specifications its transition width is always small. It provides flexibility to the designers to select the side lobe level and the length of the window. By varying the parameter α desired side lobe level and main lobe peak can be achieved. Further the main lobe width can be varied by varying the length of the window. It has a attractive property that the side lobe level can be varied continuously from the low value in Blackman window to the high value in the rectangular window [7]. The Kaiser Window function in discrete time domain is defined as

$$w_k(n) = \begin{cases} \dfrac{I_o\left(\alpha\sqrt{1-\left(\frac{2n}{N-1}\right)^2}\right)}{I_o(\alpha)}, & |n| \le \frac{N-1}{2} \\ 0, & otherwise \end{cases}$$

Where α is the shape parameter of the window, N is the length of the window and I0(x) is the modified Bessel function of the first kind of order zero.

The important parameters should be considered while using a window are the mainlobe width, leakage factor and side lobe attenuation Leakage factor is the ratio of power in the sidelobes to the total window power. Relative sidelobe attenuation is the difference in height from the mainlobe peak to the highest sidelobe peak. Mainlobe width (-3dB) is the width of the mainlobe at 3 dB below the mainlobe peak. For a window the mainlobe Width should be narrow and the relative side lobe amplitude should be small[5].

Comparison between the main lobe width, leakage factor and side lobe attenuation of the above used windows are shown below for N=256, where N=No. of FFT Samples.

Table.1. Comparison of Window Parameters

	Mainlobe Width (-3dB)	Side lobe Attenuation (dB)	Leakage Factor (%)
Rectangular	0.0068359	-13.3	9.15
Hanning	0.010742	-31.5	0.05
Blackman	0.012695	-58.1	0
Kaiser(α=20)	0.018555	-155	0

From the above comparison, we can observe that Kaiser Window has the narrow mainlobe width and less side lobe amplitude.

3.5 Fourier Analysis

FFT is applied to complex time series {(I_i, Q_i), i = 0,1, . . . ,N-1} to obtain complex frequency domain spectrum { (X_i, Y_i), i = 0, ... , N-1}.

$$X_i + Y_i = \frac{1}{N}\sum_{k=0}^{N-1}(I_k + jQ_k) \quad \exp(-2\pi ik/N)$$

Power spectrum is calculated from the complex spectrum as

$$P_i = X_i^2 + Y_i^2, \quad i = 0,1,......., N-1$$

3.6 Incoherent Integration

Doppler spectra's are usually incoherently averaged for all range gates during some dwell time to make it easier to discriminate the signal from the noise. It is the process of averaging predefined number of Doppler spectra [2].

$$P_i = \frac{1}{m}\sum_{k=1}^{m} P_{ik} \qquad i = 0,\cdots\cdots\cdots N-1$$

Where, 'm' is the number of spectra's integrated. The term 'incoherent' is used because the phase information is no longer used at this point.

3.7 Spectrum cleaning & Noise level Estimation

Due to various reasons the radar echoes may get corrupted by ground clutter, system bias, interference, image formation etc. [8].The data is to be cleaned from these problems before going for analysis.

$$p_{\frac{N}{2}} = \frac{p_{\frac{N}{2}+1} + p_{\frac{N}{2}-1}}{2}$$

Where N/2 corresponds to the zero frequency. This is also can be removed in time series by taking out the bias in I and Q channel and then perform the Fourier analysis.

3.8 Moments

The extraction of Zeroth, first and second moments is the key reason for doing all the signal processing and there by finding out the various atmospheric and turbulence parameters in the region of radar sounding [3]. The moments are computed as Zeroth moment or total power in the Doppler spectrum is given by

$$M_0 = \sum_{i=m}^{n} \tilde{P}_i ,$$

First Moment or mean Doppler in Hz is given by

$$M_1 = \frac{1}{M_0}\sum_{i=m}^{n} \tilde{P}_i f_i$$

Where f_i is given by $f_i = \dfrac{(i - N/2)}{(IPP * n * N)}$

Second Moment represents the variance, a measure of dispersion from central frequency, and it is given by

$$M_2 = \frac{1}{M_0}\sum_{i=m}^{n} \tilde{P}_i (f_i - M_1)^2$$

Using the spectral moments, the signal to noise ratio and Doppler width are estimated as follows

$$Signal\ to\ Noise\ Ratio\ (SNR) = 10\log\left[\frac{M_0}{(N*L)}\right] \quad dB$$

$$Doppler\ width\ (full) = 2\sqrt{M_2} \quad Hz$$

3.9 UVW Computation

The prime objective of atmospheric radar is to obtain the vector wind velocity. Velocity measured by radar with the Doppler technique is a line of sight velocity, which is the projection of velocity vector in the radial direction.[1,9] The Doppler Beam Swinging (DBS) method uses a minimum of three radar beam orientations (Vertical, East-West, and North-South) to derive the three components of the wind vector (Vertical, Zonal and Meridional) .

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[2].

$$\text{Height, } H = \frac{c * t_R * \cos\theta}{\sin\theta} \text{ meters}$$

$$\text{Velocity, } V = \frac{c * f_D}{2 * f_c} \text{ m/sec}$$

Where
c - velocity of light in free space,
f_D- Doppler frequency,
f_C- Carrier frequency,
λ - Carrier wavelength
θ - Beam tilt angle,
t_R - Range time delay.

After computing the radial velocity for different beam positions, the absolute velocity (UVW) can be calculated. To compute the UVW, at least three non-coplanar beam radial velocity data is required. 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

$$\varepsilon^2 = (V_x \cos\theta_x + V_y \cos\theta_y + V_z \cos\theta_z - V_{D\,i})^2$$

where $V_{D\,i} = f_{D\,i} * \lambda/2$ and i represents the beam number. To satisfy the minimum residual $\partial\varepsilon^2 / \delta V_k = 0$, k corresponding to X,Y, and Z leads to

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} \sum_i \cos^2\theta_{Xi} & \sum_i \cos\theta_{Xi}\cos\theta_{Yi} & \sum_i \cos\theta_{Xi}\cos\theta_{Zi} \\ \sum_i \cos\theta_{Xi}\cos\theta_{Yi} & \sum_i \cos^2\theta_{Yi} & \sum_i \cos\theta_{Yi}\cos\theta_{Zi} \\ \sum_i \cos\theta_{Xi}\cos\theta_{Zi} & \sum_i \cos\theta_{Yi}\cos\theta_{Zi} & \sum_i \cos^2\theta_{Zi} \end{bmatrix}^{-1} * \begin{bmatrix} V_{Di}\cos\theta_{Xi} \\ V_{Di}\cos\theta_{Yi} \\ V_{Di}\cos\theta_{Zi} \end{bmatrix}$$

On solving the above equation, we can derive V_x, V_Y, and Vz, which corresponds to U (Zonal), V (Meridional), W (vertical) components of wind velocity.

IV. EXPERIMENTAL RESULTS

The Figure below shows the signal to noise ratio plot for each beam. SNR of all heights up to 5 km has been plotted with SNR in *x*-axis and height in *y*-axis. We can observe that, in the lower height, the SNR was strong and for Kaiser window has better SNR compared to all other windows.

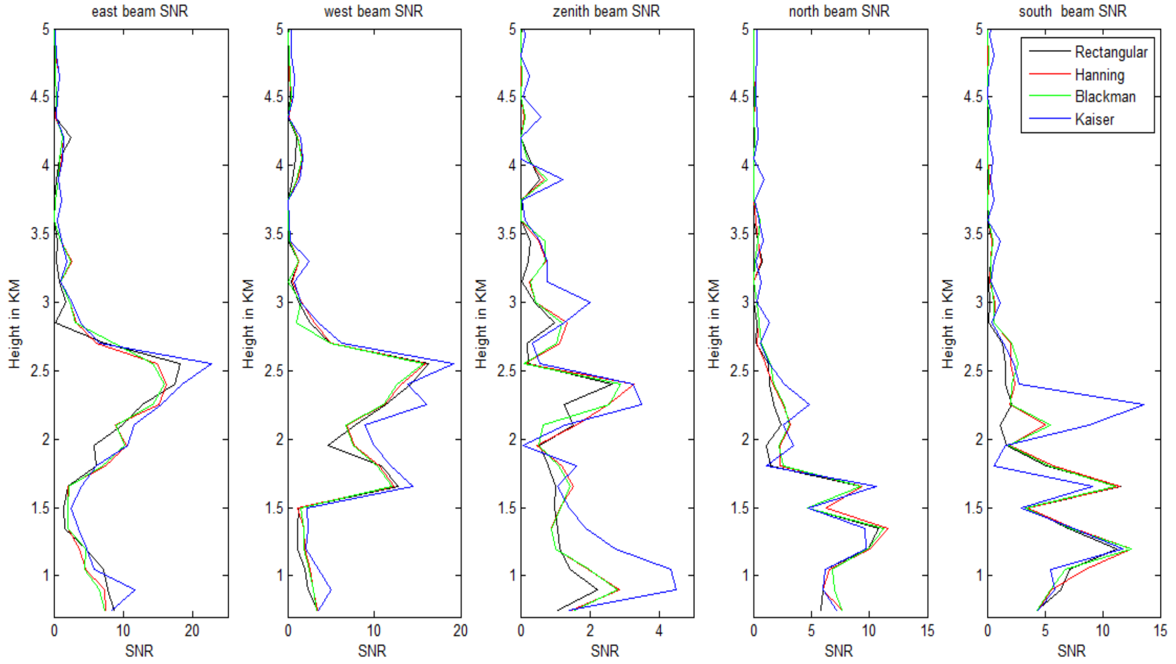

Fig 2: SNR Plots for East, West, Zenith, North, south Beams for different windows.

The figures below shows zonal, meridional and vertical velocities obtained from DBS technique for different windows and for each height. Velocities all heights up to 6 km has been plotted with velocity in *x*-axis and height in *y*-axis.

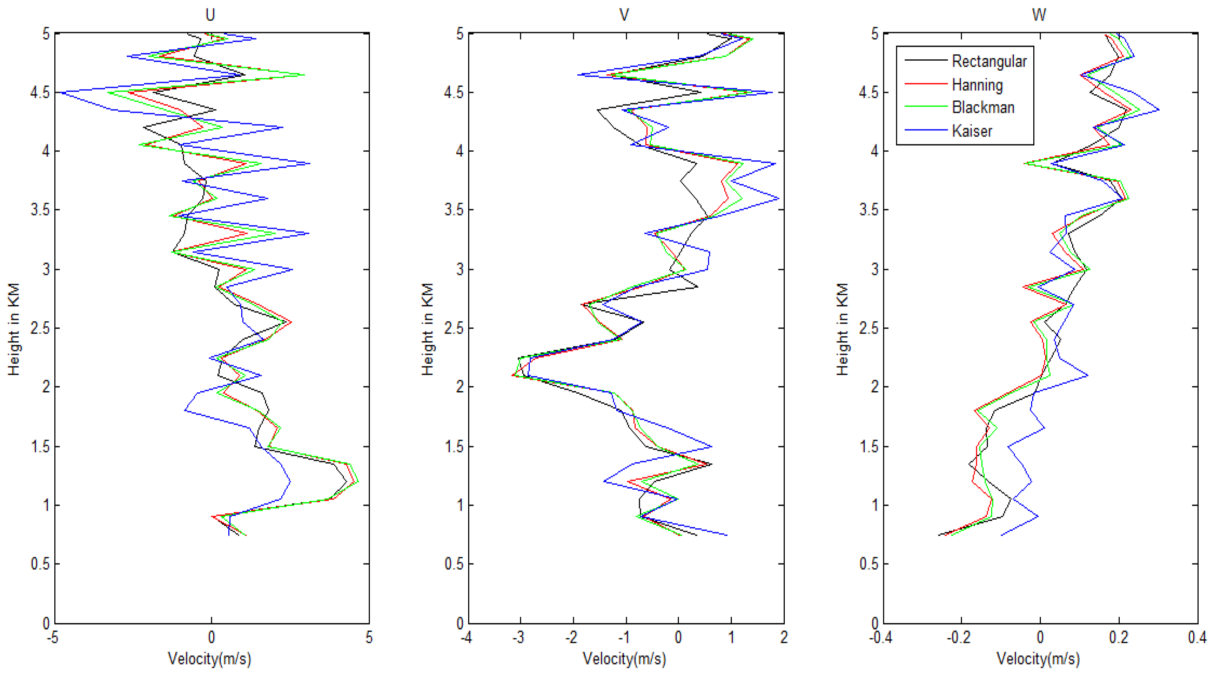

Fig. 3 .Zonal, Meridional & Vertical Velocities for different windows

V. CONCLUSION

This paper describes the need and importance of signal processing techniques using Windowing in radar. In this paper, rectangular, Hanning, Blackman & Kaiser windows are analyzed and the results are compared with each other. Kaiser window is demonstrated to be effective in reducing the noise embedded in the radar echoes. So, Kaiser Window is effective in providing better signal to noise ratio and side lobe suppression.

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