The Effect of Shape Parameter “α” in Dolph-Chebyshev Window on the SNR Improvement of MST RADAR Signals

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Abstract
In this paper, the effect of window shape parameter “α” in Dolph-Chebyshev Window on the SNR values of MST Radar returns has been investigated. Six sets of multibeam observations of the lower atmosphere made by the Indian Mesosphere-Stratosphere-Troposphere (MST) RADAR are used for the result analysis. Prior to the Fourier Transform, the in-phase and quadrature components of the Radar echo samples are weighted with the Dolph-Chebyshev Window Function. It is observed that the Dolph-Chebyshev Window can be used with the window shape parameter “α” corresponding to the minimum of sidelobe attenuation of 50dB to taper the Radar data for spectral analysis. From the results, it may be noted that there is an effect of side lobe reduction in the improvement of SNR of noisy data. The results also shows that, the improvement of SNR of noisy data due to the effect of side lobe reduction and demands for the design of optimal windows.

Keywords
Dolph-Chebyshev Window Function, DFT, FFT, SNR, Spectral Analysis.

I. Introduction
Harmonic analysis with the Discrete Fourier Transform (DFT) plays a central role in Radar Signal Processing. The significance of using data weighting windows with the DFT [1-3] plays an important role in resolving the frequency components of the signal buried under the noise. Since the use of an inappropriate window can lead to corruption of the principal spectral parameters, hence it is instructive to consider the criteria by which the choice of data weighting window to be used is made [4]. This paper presents the effects of “α” in the Dolph-Chebyshev Window [5-6] on the SNR of Radar returns and proposed an optimum value of “α” with which data may be weighed using Dolph-Chebyshev Window Function.

II. The Data Weighting Windows
There are many types of data weighting windows, which are used to select finite number of samples of impulse response. Data Windows are the time-domain weighting functions that are used to reduce Gibb’s oscillations resulting from the truncation of Fourier Series [7]. Their roots date back over one-hundred years to Fejer’s averaging technique for a truncated Fourier Series and they are employed in a variety of traditional signal processing applications including power spectral estimation, beam forming, and digital filter design. Windows have been employed to aid in the classification of cosmic data [8-9] and to improve the reliability of weather prediction models [10].

It is well known [1-3] that the application of Fast Fourier Transform (FFT) to a finite length data gives rise to leakage and picket fence effects. Weighting the data with suitable windows can reduce these effects. However the use of the data windows other than the rectangular window affects the bias, variance and frequency resolution of the spectral estimates [2-3]. In general, variance of the estimate increases with the use of a window. An estimate is to be consistent if the bias and the variance both tend to zero as the number of observations is increased. 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 are used to weight time series of the in-phase and quadrature phase components of the Radar return samples prior to applying the DFT. The observed Doppler spectra therefore represent convolutions of the Fourier Transforms of the original signals with those of the data weighting windows projected onto the discrete frequencies [1].

III. Spectral Leakage
For signal frequencies, observed through the rectangular window, which do not correspond exactly to one of the sampling frequencies, the pattern is shifted such that non-zero values are projected onto all sampling frequencies. This phenomenon of spreading signal power from the nominal frequency across the entire width of the observed spectrum is known as spectral leakage [1, 11-12]. The effect of data windowing on the SNR improvement of MST Radar signals has been reported in the literature [13-19]. By properly selecting the shape parameters of the adjustable windows, it is made possible to achieve the SNR improvement with the Optimum shape parameters [14-19].

In literature many windows have been proposed [1, 20-24]. They are known as suboptimal solutions, and the best window is depending on the applications. Windows can be categorized as fixed or adjustable [25]. Fixed windows have only one independent parameter, namely, the window length which controls the mainlobe width. Adjustable windows have two or more independent parameters, namely, the window length, as in fixed windows, and one or more additional parameters that can control other window characteristics [1, 21-22, 26-27].

The Kaiser and Saramaki windows [20-21] have two parameters and achieve close approximations to discrete prolate functions that have maximum energy concentration in the main lobe.

With adjusting their two independent parameters, namely the window length and the shape parameter, it can be controlled the spectral parameters of main lobe width and ripple ratio for various applications. Kaiser window has a better sidelobe roll-off characteristic than the other well known adjustable window Saramaki [25], which are special cases of Ultraspherical Window [24], but obtaining a window which performs higher sidelobe roll-off characteristics for the same main lobe width than Kaiser window will be useful.

The Atmospheric Radar returns considered to be composed of a quasi-monotonic (atmospheric) signal superimposed on a background of white noise. As might be expected, since the signal does not correspond exactly to one of the sampling frequencies, the forms of the signal portions of the spectra follow those of the envelopes of the side lobe maxima. Spectral leakage from the signal therefore exceeds noise level, evaluated by the method of...
Hildebrand and Sekhon [28], and a corresponding underestimate of signal-to-noise ratio.

In this paper, the improvement of SNR of MST Radar signals is investigated based on the shape parameter “α” of Dolph-Chebyshev Window Function [5-6]. The main advantage of this window is to reduce the computational cost when compared with the Kaiser Window. Also they provide higher side lobe roll-off ratio than Kaiser Window which is useful in the improvement in SNR of MST Radar signals.

IV. Dolph-Chebyshev Window

The optimality criterion addressed by the Dolph-Chebyshev window is that its Fourier Transform exhibits the narrowest main-lobe width for a specified side-lobe level. The Fourier Transform of the window is a mapping of the Nth order algebraic Chebyshev polynomial to the Nth order trigonometric Chebyshev polynomial by the relationship $T_n(X)=\cos(N\beta)$. The Dolph-Chebyshev Window is constructed in the frequency domain by taking uniformly spaced samples of the window with Discrete Fourier Transform (DFT)

$$W(k) = (-1)^k \frac{\cos(N\cos^{-1}(\beta \cos(\pi k/N)))}{\cosh(N\cosh^{-1}(\beta))}, 0 \leq k \leq N-1$$

Where,

$$\beta = \cos\left(\frac{1}{N} \cosh^{-1}(\alpha)\right)$$

and

$$\alpha = \text{Length of the sidelobe attenuation.}$$

Discrete time domain Dolph-Chebyshev Window function can be written as

$$w(n) = \sum_{k=-\infty}^{\infty} W(k) e^{j2\pi nk/N}$$

The Fourier Transform of this window exhibits uniform or constant side-lobes levels (inherited from the Chebyshev polynomial) and it contains impulses in its time domain series. These impulses are located at the window boundaries. Fig. 1 and fig. 2, indicate the time and frequency description of a Dolph-Chebyshev Window. The Chebyshev or equal ripple behavior of the Dolph-Chebyshev Window can be obtained iteratively by the Remez (or the Equal-Ripple or Parks-McClellan) Filter design routine. For comparison, Figure.1 presents a window designed as a narrow-band filter with 40 dB side-lobes and fig. 2, are 80 dB side-lobes.

Windows (and filters) with constant side-lobe levels, while optimal in the sense of equal ripple approximation, are suboptimal in terms of their integrated side-lobe levels. The window (or filter) is used in spectral analysis to reduce signal bandwidth and then sample rate. The reduction in sample rate causes aliasing. The spectral content in the side-lobes (the out-of-band energy) folds back to the in-band interval and becomes in-band interference. A measure of this unexpected interference is integrated by side-lobes, for a given main-lobe width, is greater when the side-lobes are equal-ripple.

From systems point of view, the window (or filter) should exhibit 6 dB per octave rate of falloff of side-lobe levels. Faster rates of falloff actually increase integrated side-lobe levels due to an accompanying increase in close-in side-lobes as the remote side-lobes are depressed (while holding main-lobe width and window length fixed). To obtain the corresponding window time samples $w(n)$, we simply perform the DFT on the samples $W(k)$ and then scale for unity peak amplitude. The parameter “α” represents the logarithm of the ratio of main-lobe level to sidelobe level. Thus a value of “α” equal to 3 represents side-lobes 3 decades down from the main lobe, or side-lobes 40 dB below the main lobe. The variation of SNR is considered as a function of side lobe attenuation (“α”) in dB.

In contrast to the other windows, the Dolph-Chebyshev window has two parameters: the length of the sequence N and a shape parameter “α”. As the length of the window is fixed to 512 data points in case of MST Radar data used, the shape parameter “α” can be varied. As the parameter increases the side lobe level of the frequency response decreases. In this paper, the SNR variation of MST radar data as a function of side lobe attenuation has been investigated.

V. Dolph-Chebyshev Window Applied to Atmospheric RADAR Signals

The specifications of the data selected given in Table 1. The SNR analysis is performed on MST Radar data corresponds to the lower stratosphere [29-30] obtained from the NARL, Gadanki, India. The Radar was operated in Zenith X, Zenith Y, North, South, West and East with an angle of 10° from the vertical direction. The data obtained from the six directions are used to carry on the analysis. Computation using Dolph-Chebyshev window is done to study of the effect of “α” on the SNR of the Radar returns. Data corresponds to lower stratosphere (up to 30 Km)-MST RADAR, Gadanki, India

| No. of Range Bins | : 150 |
| No. of FFT points | : 512 |
| No. of Coherent Integrations | : 64 |
| No. of Incoherent Integrations | : 1 |
| Inter Pulse Period | : 1000µsec |
| Pulse Width | : 16µsec |
| Beam | : 10° |
Table 1: Specifications of MST RADAR

<table>
<thead>
<tr>
<th>Period of Observation</th>
<th>2008-2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Width</td>
<td>16 μs</td>
</tr>
<tr>
<td>Range resolution</td>
<td>150 m</td>
</tr>
<tr>
<td>Inter Pulse Period</td>
<td>1000 μs</td>
</tr>
<tr>
<td>No of Beams</td>
<td>6 no.</td>
</tr>
<tr>
<td>No of FFT points</td>
<td>512</td>
</tr>
<tr>
<td>No of incoherent integrations</td>
<td>1</td>
</tr>
<tr>
<td>Maximum Doppler Frequency</td>
<td>3.9 Hz</td>
</tr>
<tr>
<td>Maximum Doppler Velocity</td>
<td>10.94 m/s</td>
</tr>
<tr>
<td>Frequency resolution</td>
<td>0.061 Hz</td>
</tr>
<tr>
<td>Velocity resolution</td>
<td>0.176 m/s</td>
</tr>
</tbody>
</table>

E₁₀y : East West polarization with off-zenith angle of 10°
W₁₀y : East West polarization with off-zenith angle of 10°
N₁₀x : North South polarization with off-zenith angle of 10°
S₁₀x : North South polarization with off-zenith angle of 10°

VI. Algorithm
The implementation scheme to compute mean SNR verses variation in shape parameter “α” is presented.
(a). Compute the Cosine Hyperbolic Window with the specified “α”
(b). Taper the Radar data with the window weights specified in (a).
(c). Perform the Fourier analysis of the above tapered data [28-30].
(d). Compute the SNR using the procedure [27-28]
(e). Compute the Mean Value Below Zero SNR’S (MVBZ)
(f). Compute the Mean Value Above Zero SNR’S (MVAZ)
(g). Update the value of “α” and repeat the steps (b)-(f).

VII. Results and Discussion
The SNR computation discussed above for the six sets of Radar data is carried on and presented in figs. 4(a)-(f). In the case of East beam, SNR’S (MVBZ) for the entire 150 bins taken into account, increases with the sidelobe attenuation factor “α”. But in the case of West, North and South beams there is no appreciable change observed. In the case of Zenith-X and Zenith-Y beams, MVBZ increases with the sidelobe attenuation of 20-30dB and decreases beyond 30dB. This may be attributed to the fact that the generation mechanism of the zenith beams is different. On the other hand in all the six-sets of data, the Mean Value of the Above Zero SNR’S (MVAZ) increases with sidelobe attenuation “α”. It attains a steady value when “α” is in between 60-70dB.
For the middle 50bins and the uppermost 50 bins the increase in MVBZ values is almost 3dB-9dB, when sidelobe attenuation “α” reaches a value around 50dB-60dB. Further slight improvement is also seen when “α” is increased beyond 60dB. This result is important since the back-scattered signal from the middle and uppermost bins is very weak and improvement in SNR demands for the design of windows with good sidelobe behavior for spectral estimation.

Noting the above observations, it is concluded that the Dolph-Chebyshev window can be used with window shape parameter “α” corresponding to the minimum of sidelobe attenuation of 50dB to taper the data for spectral analysis. The results also suggest that there is an effect of side lobe reduction in the improvement of SNR of noisy data and the design of optimal windows.

VIII. Graphs
SNR Variation of East beam, West beam, North beam, South beam, Zenith-X beam and Zenith-Y beam as shown in fig. 3(a) – 3(f).
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References


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