Performance Analysis of Weighing Functions for Radar Target Detection

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***Abstract*—In high resolution radars, for improvement of range resolution, encoded waveforms like (LFM, NLFM, Phase code etc) are used. For detection of targets as per range resolution of radar, it is essential to address the energy leakage during matched filtering. In this paper, target detection performance of Kaiser, Hanning and Blackman windows for the detection of weak targets entering through the range sidelobes of a strong target is evaluated. It is observed that the performance of Kaiser Window is superior to that of Hanning and Blackman window.**

Keywords—Pulse compression, bandwidth, Linear Frequency Modulation, Phase codes, Non-Linear Frequency Modulation, Range resolution

I. INTRODUCTION

In high resolution radars, for improvement of range resolution, encoded waveforms like LFM, NLFM, Phase code etc are used [1][3]. On receive, using digital pulse compression technique the targets are detected with better range resolution. As part of digital pulse compression technique, matched filtering is done, with FFT based method. Due to the finite range side-lobes of the autocorrelation function of transmitted waveform, energy leakage can happen to the nearby range bins. If the reflections are from a strong target, leakage will be more and will eclipse the detection of weak targets in proximity.

For detection of targets as per range resolution of radar, it is essential to address the energy leakage during matched filtering. Various windowing techniques are used to suppress the energy leakage of matched filtering. The paper studies the effectiveness of Kaiser, Hanning and Blackman windows for addressing the energy leakage and as same time maintaining the detection performance.

II. PULSE COMPRESSION

Pulse compression is a signal processing technique designed to maximize the sensitivity and range resolution of radar systems. The sensitivity of radar depends on the energy transmitted in the radar pulses. This can be expressed in terms of the average transmitted power- that is, the peak power multiplied by the transmitter duty cycle.

Although the peak transmitter power may be as high as several hundred kilowatts, since most radars transmit very short pulses (typically a couple of microseconds long), the average transmitted power may be much less than 1% of this value. Clearly this is not an efficient use of the available transmitter power.

Transmitting longer pulses improves the radar's sensitivity by increasing the average transmitted power. However, simply lengthening the radar pulse has the effect of degrading the range resolution of the radar, since the radio pulse is just spread over a larger distance. A technique is needed for increasing the average power without compromising resolution.

Range resolution is the ability to detect two targets in space that are close to each other. If the transmitted pulse is wide enough to simultaneously dwell on both targets, the returned signal will appear to the radar as single target. The key to solving this problem is the realization that the range resolution of a radar does not necessarily depend on the duration of the transmitted pulse; in fact, it depends on the bandwidth of the pulse. For a simple rectangular pulse, the bandwidth is just 1/T, where T is the pulse duration.

However, by manipulating the amplitude and/or phase within the pulse, its bandwidth can be altered without changing its duration. In other words, the radar resolution can be changed independently of the average transmitted power. This manipulation of the transmitted pulse is known as pulse coding, or in some cases, pulse modulation.

The pulse compression is a practical implementation of a matched-filter system. The coded signal may be represented either as a frequency response $H(\omega)$ or as an impulse time response $h(t)$ of a coding filter. The coded signal is obtained by exciting the coding filter $H(\omega)$ with a unit impulse. The received signal is fed to the matched filter, whose frequency response is the complex conjugate $H^*(\omega)$ of the coding filter. The output of the matched-filter section is the compressed pulse, which is given by the inverse Fourier transform of the product of the signal spectrum $H(\omega)$ and the matched-filter response $H^*(\omega)$.

The pulse compression is a practical implementation of a matched-filter system. A matched filter is a correlation of transmitted waveform coefficients and received waveform signal. Correlation process is equivalent to convolution, if we flip the coefficients of transmitted pulse. Convolution in time domain is equivalent to complex multiplication in frequency domain. To implement the process, Fourier transform of transmitted and received waveform is performed followed by complex multiplication. Output of the complex multiplication is processed using inverse Fourier transform. The output of IFFT (Inverse Fast Fourier Transform) is matched filtered output.

There are three main waveform design techniques which are used in digital pulse compression. These techniques are liner/nonlinear frequency codes, binary phase codes, and poly-phase codes. The pulse compression is based on the autocorrelation function since in the absence of noise; the

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output of the matched filter is proportional to the code autocorrelation. Given the autocorrelation function of a certain code, the main lobe width (compressed pulse width) and the side lobe levels are the two factors that need to be considered in order to evaluate the code's pulse compression characteristics.

III. CONSTANT FALSE ALARM RATE

This algorithm is to maintain the false alarm rate. Cell Averaging CFAR or Greatest of CFAR etc can be used to maintain the false alarm rate. These algorithms are also used to avoid clutter (which is the unwanted targets).

IV. WINDOWING FUNCTIONS

There are several different types of windowing functions that can applied in radar applications depending on the signal. To understand how a given window function affects the frequency spectrum, it is required to understand more about the frequency characteristics of windowing functions. An actual plot of a window shows that the frequency characteristic of a window is a continuous spectrum with a main lobe and several side lobes. The main lobe is centered at each frequency component of the time-domain signal, and the side lobes approach zero. The height of the side lobes indicates the affect the windowing function has on frequencies around main lobes. The sidelobe response of a strong sinusoidal signal can overpower the main lobe response of a nearby weak sinusoidal signal. Typically, lower sidelobes reduces the leakage in the measured FFT (Fast Fourier Transform) output, but increases the bandwidth of the major lobe. The sidelobe roll-off rate is the asymptotic decay rate of the side lobe peaks. By increasing the sidelobe roll-off rate, spectral leakage can be reduced [3] [9].

Selecting a window function is not a simple task for radar application. Each window function has its own characteristics and suitability for different applications. To choose a window function, it is required to estimate the frequency content of the signal.

- ❖ If the signal contains strong interfering frequency components distant from the frequency of interest, choose a smoothing window with a high sidelobe roll-off rate.
- ❖ If the signal contains strong interfering signals near the frequency of interest, choose a window function with a low maximum sidelobe level.
- ❖ If the frequency of interest contains two or more signals very near to each other, spectral resolution is important. In this case, it is best to choose a smoothing window with a very narrow main lobe.
- ❖ If the amplitude accuracy of a single frequency component is more important than the exact location of the component in a given frequency bin, choose a window with a wide main lobe.
- ❖ If the signal spectrum is rather flat or broadband in frequency content, use the uniform window, or no window.
- ❖ In general, the Hanning (Hann) window is satisfactory in 95 percent of cases. It has good frequency resolution and reduced spectral leakage. If you do not know the nature of the signal but you want to apply a smoothing window, start with the Hann window [6] [9].

Even window function is not used, the signal is convolved with a rectangular-shaped window of uniform height, by the nature of taking a snapshot in time of the input signal and working with a discrete signal. This convolution has a sine function characteristic spectrum. For this reason, no window is often called the uniform or rectangular window because there is still a windowing effect.

V. PROPERTIES OF WINDOWING FUNCTIONS

Kaiser Window

The formula for generating Kaiser Window [4] [13] [16] coefficients is given by

$$w[n] = \frac{I_0\left[\beta\sqrt{1-\left(\frac{2n-1}{N}-1\right)^2}\right]}{I_0[\beta]},\ 0 \le n \le N \qquad (1)$$

where β is the parameter to control the side lobe level. I_0 is the zeroth-order modified Bessel function of the first kind. β = 0 will result in a rectangular window.

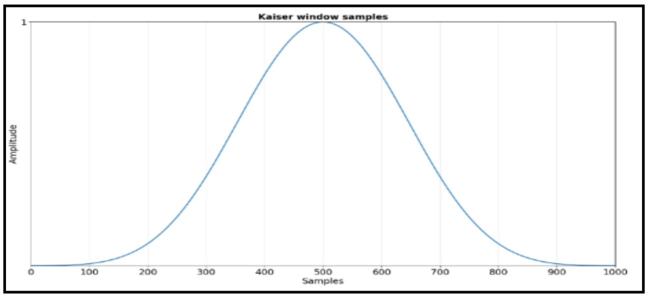

Fig 1 : Kaiser Window Coefficients

The windowinf functions samples are generated for 1000 points for analysis.

Hanning Window

The following formula generates Hanning window [12] samples:

$$w[n] = 0.5\left(1-\cos\left(\frac{2\pi n}{N}\right)\right), 0 \le n \le N-1 \qquad (2)$$

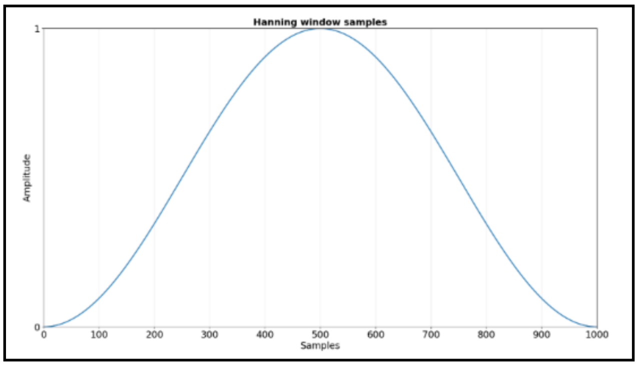

Fig 2: Hanning Window Coefficients

Blackman Window

The formula for Blackman window [14] is

$$w[n] = 0.42 - 0.5\cos\left(\frac{2\pi n}{N}\right) + 0.08\cos\left(\frac{4\pi n}{N}\right) \qquad (3)$$

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Blackman window was designed to give minimal leakage possible on side lobes.

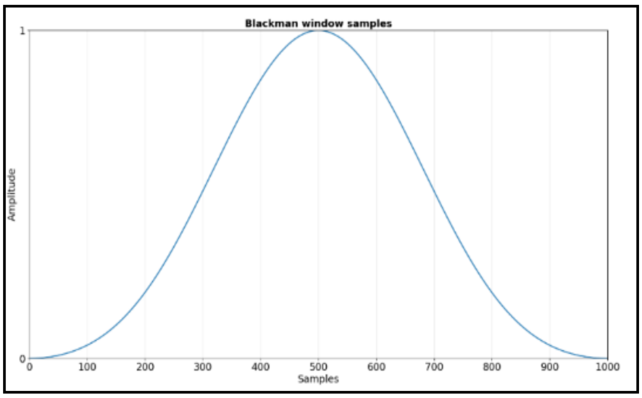

Fig 3 : Blackman Window Coefficients

The Blackman window is similar to Hanning window. The resulting spectrum has a wide peak, but good side lobe compression. There are two main types of this window. The 4-term Blackman is a good general-purpose window, having side lobe rejection in the high 90s dB and a moderately wide main lobe. The 7-term Blackman window function has all the dynamic range you should ever need, but it comes with a wide main lobe.

VI. SIMULATION AND RESULTS

To evaluate the performance of windowing techniques, two targets are generated within a Pulse Repetition Time (PRT): a target at 10 km distance and another at 13 km distance whose amplitude is 0.01 times that of first target. The specifications used for the simulation is,

- PRT : 1 ms [Max. Range = 150 km]
- Pulse width T : 100 µs
- Beamwidth : 5 deg
- Chirp bandwidth B : 5 MHz
- Sampling rate Fs : 10 MHz
- *Target 1 parameters*
  Range : 10Km
  Velocity : 50 m/s
  Target RCS : 100 m^2
- *Target 2 parameters*
  Range : 13 Km
  Velocity : 50 m/s
  Target RCS : 1 m^2

Figure 4 to 7 shows the matched filter simulation output using various windowing techniques.

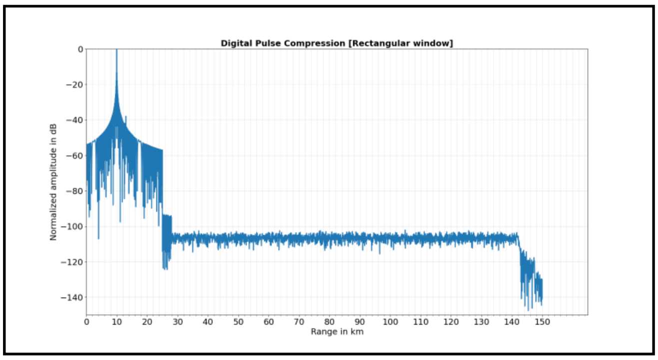

Fig 4 : Digital pulse compression output with Rectangular window

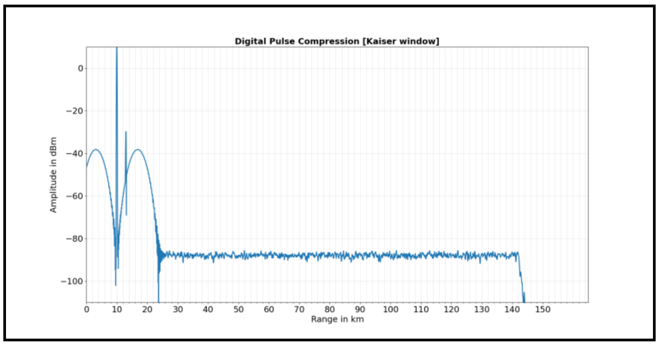

Fig 5: Digital pulse compression output with Kaiser window

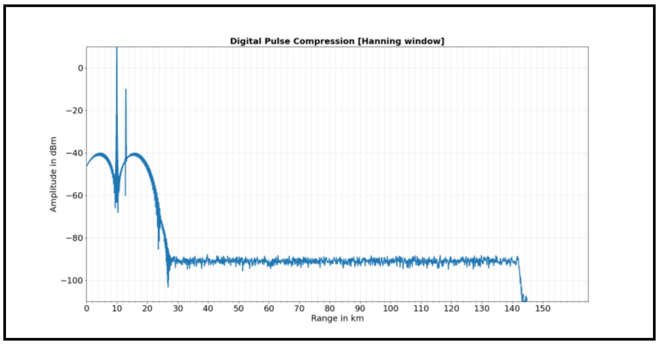

Fig 6: Digital pulse compression output with Hanning window

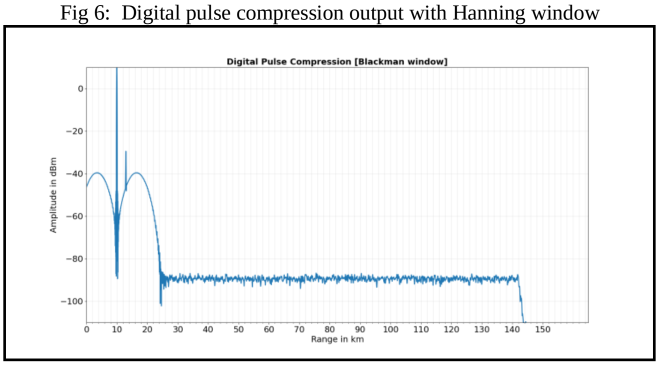

Fig 7 : Digital pulse compression output with Blackman window

Cell averaging constant false alarm rate (CACFAR) detection is used in this simulation.

- $P_{fa} = 1e^{-6}$
- No of training cells : 16
- No of guard cells : 4

Figures 8 to 11 show CACFAR outputs using various windowing techniques.

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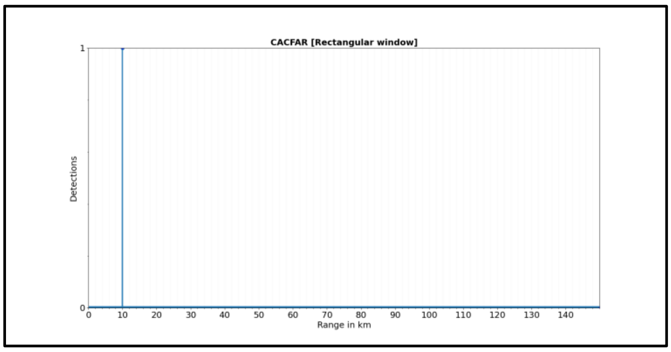

Fig 8 : Target detections with Rectangular window

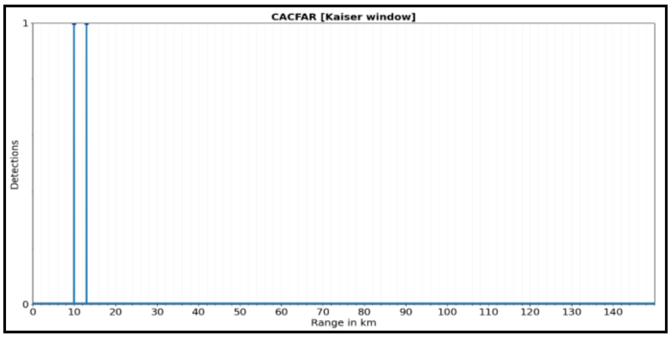

Fig 9 : Target detections with Kaiser window

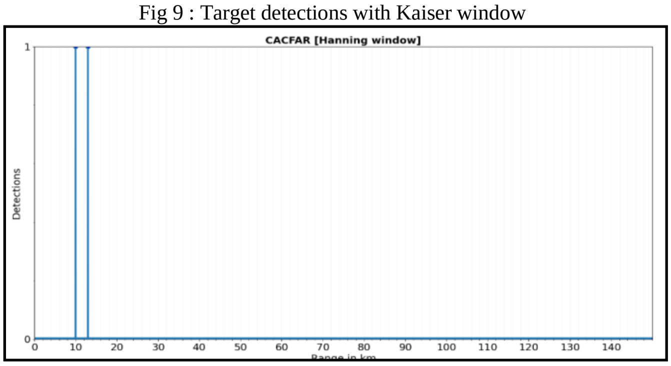

Fig 10 : Target detections with Hanning window

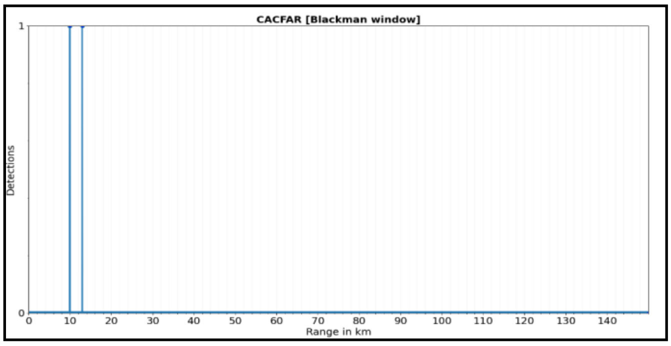

Fig 11 : Target detections with Blackman window

Probability of Detection and SNR Calculation

Denote the range bin at which the single pulse SNR is unity (0 dB) as R_0, and refer to it as the reference range bin. Then, for a specific radar, the single pulse SNR at R_0 is defined by the radar equation and is given by,

$$(\mathrm{SNR})_{R_0} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 B F L R_0^4} = 1 \quad (4)$$

The single pulse SNR at any range R is,

$$\mathrm{SNR} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 B F L R^4} \quad (5)$$

Dividing Eq.(5) by Eq.(4) yields,

$$\frac{(\mathrm{SNR})_{R_0}}{\mathrm{SNR}} = \left(\frac{R_0}{R}\right)^4 \quad (6)$$

Therefore, if the range R_o is known then the SNR at any other range is,

$$(\mathrm{SNR})_{\mathrm{dB}} = 40\log\left(\frac{R_0}{R}\right) \quad (7)$$

The SNR is calculated for each range bin with the radar parameters shown above and listed below table. Table 1 shows a comparative analysis of peak levels of second target compare to peak level of first target with respect to the placement of second target over the span of range.

Detection of Second target at range (m)	Kaiser (β = 4)	Hanning	Blackman
11000	-80	-80	-80
11500	-79	-78	-79
12000	-79	-78	-79
12500	-79	-77	-78
13000	-79	-78	-79
13500	-78	-77	-77
14000	-78	-77	-77
14500	-76	-75	-75
15000	-84	-84	-84

Table 1: Comparison of Target SNR with windowing functions

Table 2 shows the CACFAR detections of second target over the span of rage for different windows techniques.

Detection of Second target at range (m)	Kaiser (β = 4)	Blackman	Hanning
11000	1	1	1
11500	1	1	1
12000	1	1	1
12500	1	1	1
13000	1	1	0
13500	1	1	0
14000	1	0	0
14500	1	0	0
15000	0	0	0

Table 2: Comparison of Target detections windowing functions

It can be observed from the table given above that Kaiser window performs better than Hanning and Blackman windows for the detection of weak targets appearing on the side lobe portion of strong targets.

VII. CONCLUSION

In high resolution radars, for improvement of range resolution, encoded waveforms like LFM, NLFM, Phase codes, etc. are used. For detection of small targets which are close to bigger targets as per range resolution of radar, it is essential to address the energy leakage during matched filtering. Various windowing techniques viz., Kaiser, Blackman and Hanning windows are studied for the suppression of the energy leakage of matched filtering. To evaluate the performance of windowing functions, a strong target and a weak target is considered for analysis. It was observed from the simulation that Kaiser Window performs better for the detection of weaker targets emerging through the side lobe portion of strong target.

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