RESEARCH ARTICLE OPEN ACCESS

# Optimization of Digital Signal Processing Techniques for Surveillance RADAR

Sonia Sethi, RanadeepSaha, JyotiSawant
M.E. Student, Thakur College of Engineering & Technology, Mumbai
Manager, Design & Development L&T, Heavy Engineering , Powai, Mumbai
Asst. Professor Thakur College of Engineering & Technology Mumbai,

**ABSTRACT**
Digital Signal Processing techniques for ground surveillance RADAR has been thoroughly investigated and optimized for an improved detection of target. Using the established techniques like Pulse compression, Fast Fourier Transform and Windowing, the present work optimizes the selection of pulse coding techniques, window type and different filters.The work proposes techniques to mitigate inherent problems in RADAR Signal Processing like *Range Side Lobe* and *Clutter*. This paper covers the complete design of digital signal processing building blocks of Pulse Doppler RADAR namely, Modulation, Demodulation, Match Filtering, Range Side Lobe suppression, Doppler Processing and Clutter Reduction.Rejection of land and volume clutter(rain clutter) has been optimized. Related simulation results have been presented.

**Keywords:** Surveillance RADAR, Pulse compression, Range resolution, Peak side lobe level (PSL), Barker Code, FFT, Matched Filter, Clutter, Rain Clutter

## I. INTRODUCTION

RADAR is an acronym of RAdio Detection and Ranging. During the World War II, there was a rapid growth in RADAR technology and systems. RADAR finds applications in many areas such as military, remote sensing, air traffic control, law enforcement and highway safety, aircraft safety and navigation, ship safety and space[1][4]. *Surveillance RADAR* is designed to continuously scan a volume of space to provide initial detection of all targets. Surveillance RADAR is generally used to detect and determine the position of new targets. Ground Surveillance RADAR systems are a type of surface-search RADAR that detect and recognize moving targets including personnel, vehicles, watercraft and low flying, rotary wing aircrafts.In modern days, the signal processing on the received echoes of the RADAR is performed in digital domain. With advent of digital computing and low cost memory storage, signal processing in RADAR,the inherent advantages are like re-configurability, size, cost and accuracy.

The present work aims to optimize the signal processing blocks of surveillance RADAR pertaining to modulation, demodulation, Doppler processing and clutter rejection in digital domain.

Several literatures describes techniques like pulse compression with different coding techniques, pros and cons of different windowing techniques, different filters. In the present work, the optimization hasbeencarried out in totality, end to end of a RADAR signal processing chain, considering a very slow moving target. Both of uplink and downlink chain have been considered. In this paper, different phase coding techniques have been studied for pulse compression.*Range Side-Lobe Reduction* is performed using *windowing*. For the suppression of the stationary clutter, MTI filter and higher order Chebyshev IIR filters are evaluated. The paper also proposes a baseband signal frequency staggering technique to reduce the rain clutter content in the RADAR echoes.

## II. Basic Block Diagram

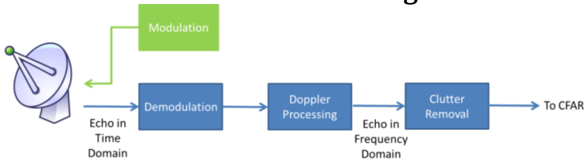


Figure 1 Scope of Paper

The main aim of this paper is to extract the time domain echoes available at the RADAR receiver in presence of clutter and present them in frequency domain. Presenting RADAR echoes in frequency domain helps in identifying the velocity of the targets and differentiating moving targets from dynamic clutter.

The paper deals with four major blocks as shown in figure1above. First block is the transmit signal generation; in this block, pulse compression is required in which the frequency or phase modulation can be used to increase the spectral width of a long pulse and obtain the resolution of short pulse.

High energy transmit signal is required to improve the detection. So, for long range detection application the energy should be high to detect the received echo. This can be attained by either increasing the transmitted power or by increasing the interval time. However, high power transmitters are not cost effective. Simultaneously, increasing the interval also possess some problems as long pulses has poor resolution in the range dimension and the short pulses possess less energy[2]. This paper deals with the proper selection of code for the pulse compression to achieve proper range resolution.

After the modulation, the second block is the demodulation of the received echo. After reception the signal is passed through the properly designed low pass filter. Matched filtering is performed on the filtered echo to compress the received echo. It is performed on the transmit reference signal and the received echo and cross correlation is obtained between them for the detection of the target.

Third block deals with the Doppler processing. After matched filter, all the received echoes are arranged in the sequentially in a 2D matrix.FFT is performed on the samples from multiple transmit pulses. Frequency domain transformation of the echoes enables to extract the velocity of the target in that particular range bin.

Fourth block deals with the clutter filters to remove the stationary and volume clutter. This paper focuses on the rain clutter as an example of volume clutter.

## III. Simulation Details

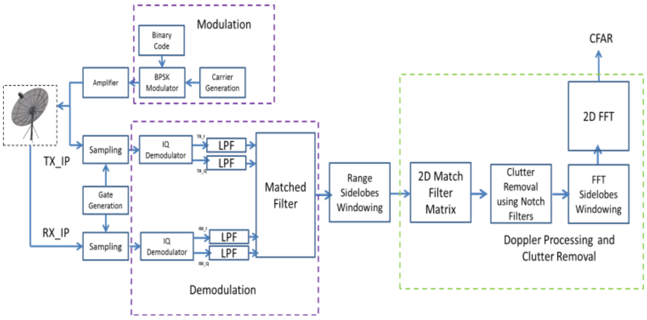


Figure 2 System Block Diagram/ Simulation Details

The simulation work is divided into three main blocks as mentioned in Figure 2:

a) Modulation
b) Demodulation
c) Doppler Processing and Clutter Suppression

Details of simulation studies are described in the following sections.

### 3.1 Modulation:

Modulation is performed in the transmitter. It generates electromagnetic signals, which enables the RADAR to detect target. To achieve good range resolution, frequency or phase modulation can be used. This paper focuses on Binary phase shift keying which is a type of phase modulation.Pulsed RADAR is limited in range resolution by the pulse length and in range sensitivity by the average radiation power. Pulsecompression isused in order to obtain a high range resolution and good detection probability. Pulse compression utilizes long pulsesto obtain high energy and simultaneously achieve the resolution of a short pulse by internal modulation of the long pulse. The range resolution of RADAR depends on the autocorrelation pattern of the coded waveform which is the compressed output of matched filter. The binary sequences having elements as ±1or 0,1have good aperiodic autocorrelation function and are selected for the analysis.

#### *3.1.1 Pulse Compression:*

There are two criteria for the selection of optimal phasecodes:

a) Auto-correlation function of the phase codes should have uniform side-lobes [1].
b) They should have high peak to side lobe ratio (PSLR).

If the selected binary phase code does not have high PSL & uniform side lobes then the weak target will be masked under side lobes of strong target and thereby goes undetected.

Three types of binary codes are compared in this paper for pulse compression. The three codes compared are Linear Recursive Sequences or Shift-Register Codes, Pseudorandom codes and Barker codes. The limitation with the pseudorandom codes is in the dynamic range offered which is bounded by the length of the transmitted sequence. The detection of echoes becomes difficult in some cases where large attenuation values can be confused with noise. The problem with complementary codes is that the two codes have to be transmitted on two separate pulses, detected separately, and then subtracted[3]. Although higher length of linear sequence code or complimentary codes will yield better PSL unlike barker codes they do not possess uniform side lobes. So, out of these three codes, barker codes of length 13 have been selected for pulse compression. Figure 3 and Figure 4 shows the simulation result for 13 bit barker codeautocorrelation function.

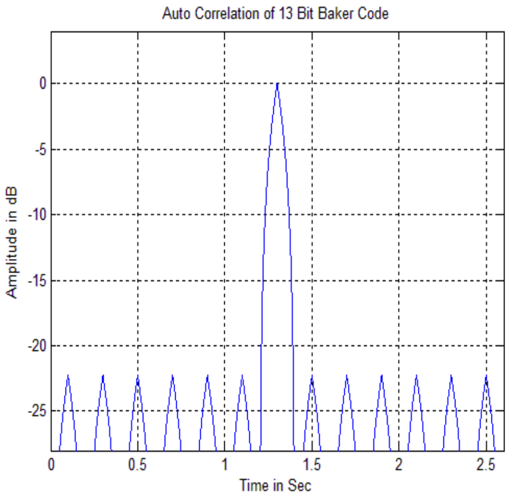


Figure 3 Simulation Results of Autocorrelation Function of 13 Bit Barker Code.

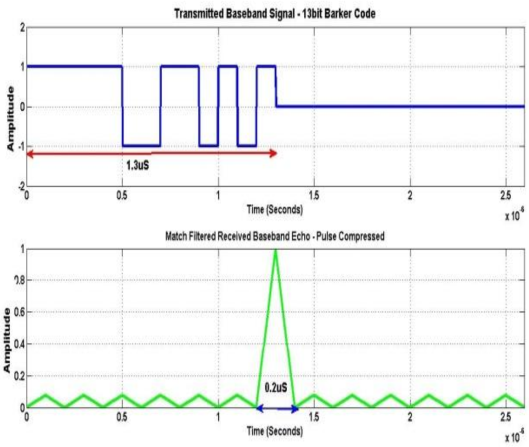


Figure 4Compressed Output of 13 bit Barker Code

### *3.1.2 Modulation Technique*

Technique of phase-coded modulation used here is binary phase shift keying (BPSK) with the phase "0" of the if sine wave represented for bit "1" and phase "π" represented for bit "0". The carrier is modulated with Barker Code using BPSK modulation scheme. Figure5 shows the simulation results obtained for BPSK modulation with barker code.

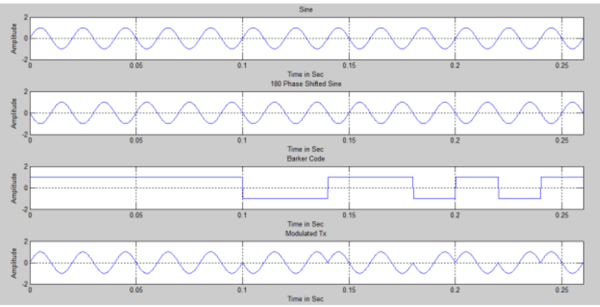

Figure 5 Modulation Scheme Simulation Results

### 3.2 Demodulation

The IQ demodulation stage is most commonly digitally implemented as an in-phase and quadrature mixing operation. The mixing operation involves digital multiplications by sine and cosine as shown below in figure 6.

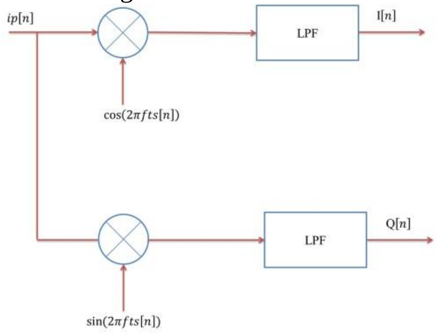


Figure 6 Demodulation at Receiver

Figure7 shows the simulation results obtained at Demodulator side.

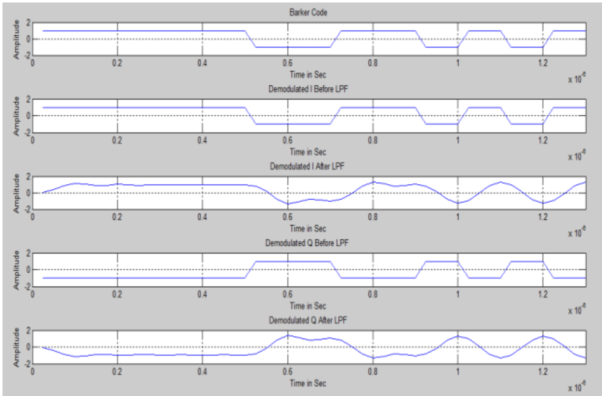

Figure 7 Simulation Results at Demodulator

### *3.2.1 Low Pass Filter*

A 4th Order Type 1 Chebyshev filter is designed as of low pass filter.These are analog or digital filters having a steeper roll -off than Butterworth filters. However, they have more pass band ripple (type I) or stop band ripple (type II) which does not affect system performance when limited to lower magnitude of for example 0.1dB.

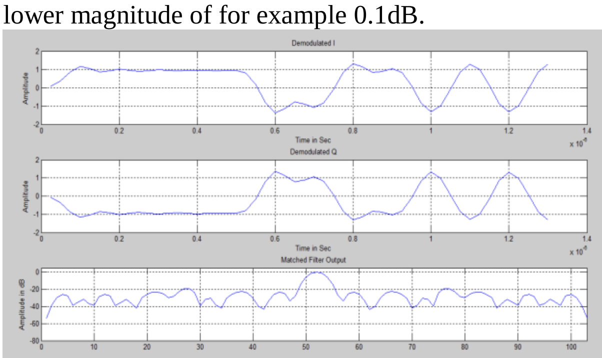

Figure 8 Demodulation using LPF.

*3.2.2 Matched Filter*

The output of the Low Pass Filter block is then given to the matched filter block. Matched filter is a linear network that maximizes the output peak-signal-to-noise (power) ratio of a RADAR receiver. It maximizes the detectability of a target. Its output is computed from the cross-correlation between the RADAR received signal and a delayed replica of the transmitted waveform.

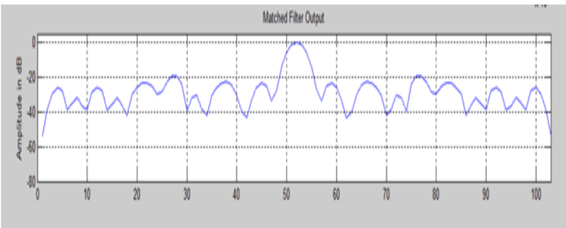


Figure 9 Matched Filter Output

*3.2.3 Range Sidelobes Reduction*

The barker codes are used as they give a uniform sidelobes. Peak to sidelobe ratio needs to be maximized for detecting weak targets so that they are not masked by the stronger nearby target. Most of the RADAR applications, the required PSLR ratio is atleast 30dB whereas the barker codes give -22.3 dB.In [5] biphase codes with their optimum sidelobe suppression filter with optimum lengths and minimum multipliers are considered and low sidelobe levels of 35dB to 40dB is achieved by K means clustering technique. This paper utilizes windowing technique to increase the PSLR and to reduce range sidelobes. The window shapes the output of the matched filter such that side-lobes are further attenuated. Total 17 windows areapplied and compared. On the basis of the results obtained, it can be concluded that a Gaussian Window with 1/σ = 30 yield the highest PSLR of -70.08 dB. Figure 10 shows the matched filter output without and with windowing.

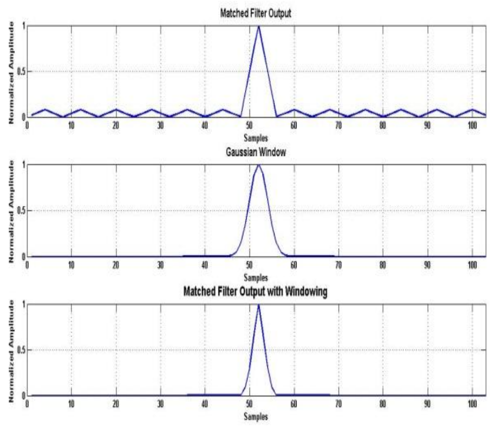


Figure 10 Matched Filter Output with and without Windowing

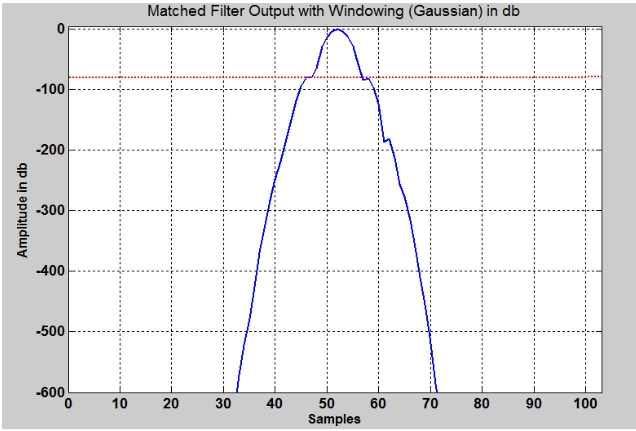


Figure 11 Matched Filter Output with Windowing in dB

**3.3 Doppler Processing and Clutter Suppression**

The matched filter output is arranged into 2D matrix. The received signal in time domain is translated into frequency domain using FFT. Atarget is detected in the range dimension (fast time samples). This gives the range bin to analyse RADAR echoes in the slow-time dimension. FFT is performed on the slow-time samples corresponding to the specified range bin in the 2D matrix. Peaks are obtained in the magnitude spectrum at Doppler frequency and range corresponding to the target. Frequency axis is scaled to velocity axis so that velocity of the target can be directly read from the FFT plot.

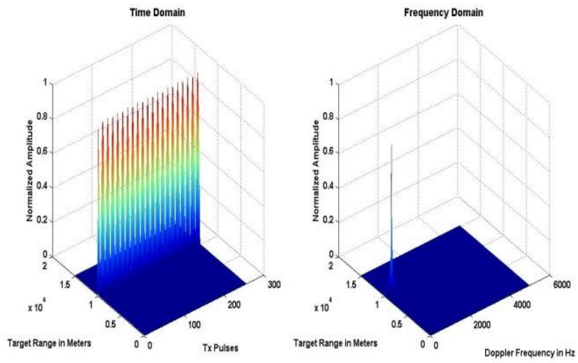


Figure 12 Doppler Processing

Figure12 above shows the Doppler processing performed on the matched filter output.

*3.3.1 FFT Sidelobe Reduction*

Taking the FFT of the 2D matrix also results in processing errors because of that signals output spreads from one bin to into other bins.This is called spectral leakage,which degrades the outputand due to this the strong interfering signals masks the weaker target echoes. Therefore, this paper focuses on the widowing technique to reduce leakage errors. Comparitive analysis of 17 different types of windows have been performed in order to identify the window which minimizes the spectral leakage. In order to identify the best performing window, the amplitude of sidelobes at the corner frequencies of a fixed bandwidth 195-351 Hz around the center doppler frequency of 266.67 Hz were measured for all 17 windows. Simulation results indicated Chebyshev window has the least sidelobes of -43dB amongst all the windows.

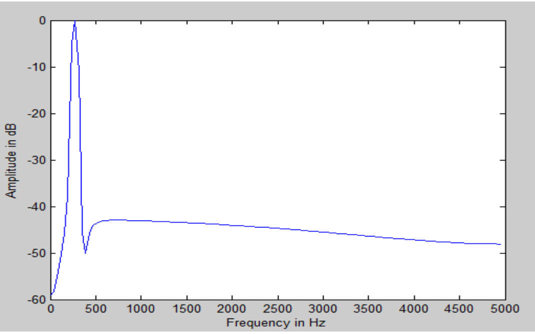


Figure 13FFT Windowing with Chebyshev Window

3.3.2 **Clutter Suppression**

Clutter means unwanted echoes from the natural environment. These unwanted echoes "clutter" the RADAR and the wanted target detection is difficult. Clutter includes echo returns from land, sea, weather (particularly rain), birds, and insects. Echoes from land or sea are examples of surface clutter. Echoes from rain and chaff are examples of volume clutter[1][4].

This paper focuses on thestationary that island clutter and rain as one of the volume clutter.

3.3.2.1**Stationary Clutter Reduction**

A Band Stop IIR filter, with transfer function shown in equation below, is implemented in this paper to remove stationary clutter. Although IIR filter introduces phase distortion, however, it has narrower transition band thereby protecting low velocity targets from unintentional attenuation occurring in linear phase FIR filters with wider transition bands.

$$H_{stationary\ clutter\ filter}(z) = \frac{0.7-4.17z^{-1}+10.42z^{-2}-13.89z^{-3}+10.42z^{-4}-4.17z^{-5}+0.7z^{-6}}{1-5.72z^{-1}+13.66z^{-2}-17.43z^{-3}+12.54z^{-4}-4.82z^{-5}+0.77z^{-6}} \quad (1)$$

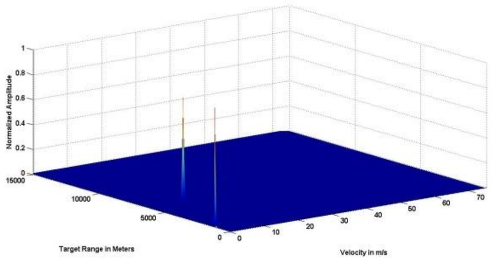


Figure 14 Stationary Clutter Removal -No Filter

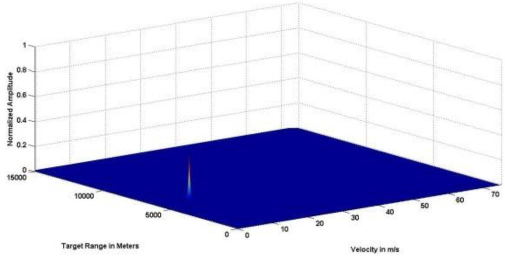


Figure 15 Stationary Clutter Removal Using MTI Filter

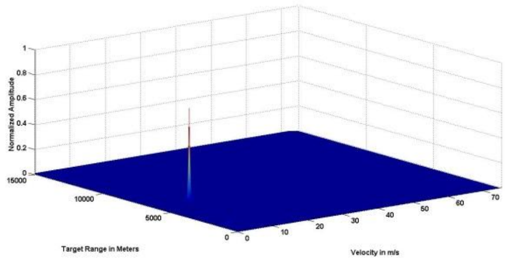


Figure16 Stationary Clutter Removal Using IIR Notch Filter

Figure 14 demonstrates a scenario where a stationary target (velocity = 0m/s) is present at a distance of 1000m and slow moving target (velocity = 10m/s) at a distance of 6000m. Figure15 shows that using an MTI filter, the stationary target is filtered out however, at the same time the slow moving target is attenuated due to wider stop band of MTI filter .Fiure16 shows that using an IIR type DC Notch filter, the stationary target is filtered out without attenuating slow moving target as it has a narrow stop band.

**3.3.2.2 Rain Clutter Reduction**

This paper proposes a preventive technique to limit rain as the volume clutter and a rain clutter filtering technique.

a) Rain Clutter Preventive Technique – Baseband Signal Frequency Staggering

This technique proposes to increase the barker code frequency. It can be seen that lower the value of τ, where τ is the bit interval of modulating binary code, smaller is the resolution volume.

$$\frac{S}{C} = \frac{\sigma_t * L}{(\pi/4)\theta_e\theta_a(c\tau/2)\sum\sigma R^2} \quad (2)$$

Where $\sigma_t$ = RCS of the Target, c = speed of light, τ = Bit Interval i.e. Time interval between each barker codes, R= Range in m, $\theta_e$ – Elevation in Radians, $\theta_a$ – Azimuth in Radians, ∑σ = Backscatter Coefficient and $L$ are the processing losses appropriate to rain backscatter case.

Under the situation where the target and clutter cannot be differentiated, the bit rate can be increased momentarily i.e. baseband frequency is staggered to a higher frequency, thereby reducing the clutter content and thus enabling detection of the target. Once the rain clutter is reduced, the barker code bit rate can be restored to its original value.

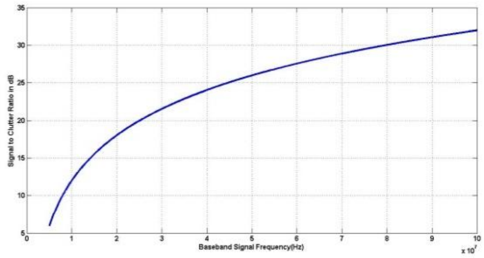


Figure 17SCR vs Baseband Signal Frequency, Azimuth = 30 Degree, Elevation = 1.65 Degree, Rainfall rate = 16 mm/hr, Target RCS = 3m$^2$, Loss = 30dB

Figure 17 shows the simulation results plotted between SCR and Baseband Signal Frequency. It is evident from the plot and Table 1 that increased baseband frequency improves the signal to clutter ratio.

Table 1Baseband Signal Frequency vs SCR

| **Baseband Signal Frequency (MHz)** | **Signal to Clutter Ratio (dB)** |
|---|---|
| 5 | 5.968 |
| 10 | 11.99 |
| 40 | 24.03 |
| 80 | 30.05 |

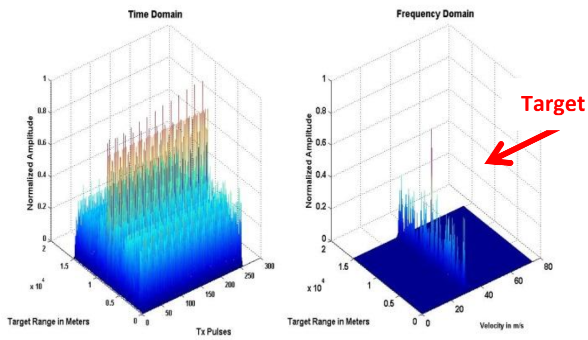


Figure 18 Simulation of Target with Rain Clutter, Barker Code Frequency = 5MHz

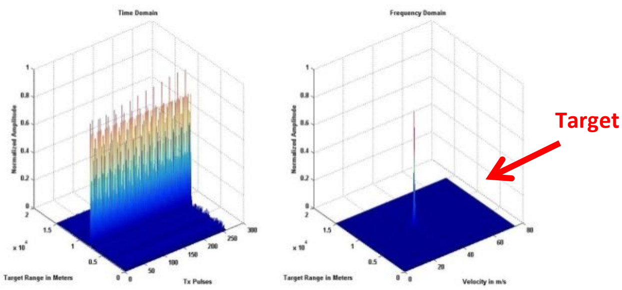


Figure 19 Simulation of Target with Rain Clutter, Barker Code Frequency = 40MHz

From the simulation results in Figure18 and 19, it is evident that increasing the baseband signal frequency reduces the content of clutter thereby making it easy to detect the target which was otherwise masked by the rain clutter.From the table1 we can state that proposed clutter removal technique helps in improving Signal to Clutter ratio by 24 dB when baseband signal frequency is increased from 5MHz to 80MHz as compared to the technique proposed in [5] which improves SCR by 20dB. The proposed technique can further improve SCR if the baseband signal frequency is further increased.

b) Rain Clutter Reduction – Using Notch Filter

Second technique proposed in this paper is an adaptive notch filter whose notch frequency can remove rain clutter. The notch frequency of the filter keeps adapting to the wind information obtained from an anemometer like device. The required attenuation of the filter can be calculated using equation (2).

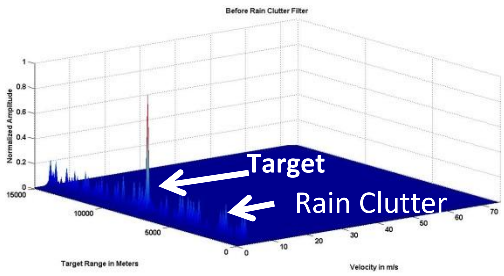


Figure 20 Simulation of Clutter Removal using Notch Filter –After Filtering

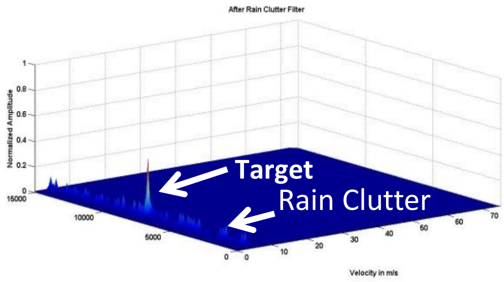


Figure 21Simulation of Clutter Removal using Notch Filter –After Filtering

Figure 20 and Figure 21 shows the simulation results obtained without and with notch filter. The transfer function of 2$^{nd}$ Order Butterworth IIR type notch filter is given in equation (3).Thus, the Rain clutter is reduced with the notch filter.

$$H_{Rainclutterfilter}(z) = \frac{0.993 - 1.9589z^{-1} + 0.993z^{-2}}{1 - 1.9589z^{-1} + 0.9867z^{-2}} \qquad (3)$$

If wind velocity is different from target velocity, the improvement in SCR is equal to the absolute value of the stop band attenuation of the notch filter. For example, if stop band attenuation is -13dB then the SCR is improved by 13dB.

## IV. Conclusion

This paper presents simulation of signal processing block of Surveillance Radar. Design of demodulation LPF, stationary clutter IIR type DC notch filter and notch filter to reduce rain clutter, are presented in this paper.

In this paper "windowing" technique is used to remove range side-lobes. Simulation results suggest that Gaussian window helps to achieve PSLR of 70.08dB.This is an improvement over PSLR of 40 dB achieved in [5].

The proposed stationary clutter IIR type DC notch filter helps in filtering stationary clutter without attenuating echoes from slow moving targets.

A volume clutter preventive technique has been proposed which increases the baseband signal frequency to reduce the size of clutter cell and thereby reducing the amount of clutter entering the received echoes. Simulation results indicate an increase in baseband frequency from 5MHz to 80MHz helps in boosting Signal-to-Clutter ratio (SCR) by ~ (approximately)24dB as compared to the technique proposed in [6] which improves SCR by 20dB.

Furthermore, if the wind velocity is different from target velocity then the notch filter for rain clutter improves SCR by the amount of absolute value of stop band attenuation. For example, if stop band attenuation is -13dB then the SCR is improved by 13dB.

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