Comparison of Radar Signal Processing In Time, Frequency And Mixed Domain

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***Abstract*— This research paper shows the comparison of radar signal processing in different domains. Radar signal processing has great importance in detection of target submerged inside the clutter and noisy environment. Radar receiver receives and enhances the target echoes with noise and clutter. Signal processing suppresses the clutter and noise from the received signals and improves signal to noise ratio and detection of targets. Radar signal processing depends on phase of transmitting pulse, hardware complexity, number of range bins and number of Pulse Repetition Time (PRT). There are three ways to implement radar signal processing. These are Time, Frequency and Mixed domain based processing. The major blocks of radar signal processing are Pulse Compression (PC), Moving Target Indicator (MTI), Window function, Integration – Coherent or Non-Coherent and Constant False Alarm Rate (CFAR). PC improves both range resolution and Signal to Noise Ratio (SNR) whereas other algorithms improve SNR only. Radar signal processing extracts targets from the background noise using above algorithm and passes the target detection information to Radar Data Processor (RDP) for surveillance and tracking. Different processing time is taken in different domain. MatLab is used for simulating, plotting and comparing the results of radar signal processing in different domain.**

Keywords*— *Radar signal processing, Pulse compression, Window function, Moving Target Indicator, FFT, CFAR.

I. Introduction

Radar Signal Processing (RSP) plays significant role in radar system [1]. The major challenges of RSP are to suppress the clutter, noise, external interference, improving SNR and detection of the target in harsh environment [2]. RSP is implemented in different domain based on radar transmitter i.e. Time, Frequency and Mixed domain. Whether Radar is coherent or non-coherent depends on the radar transmitter. Transmitter providing random phase from pulse to pulse is called Non-Coherent radar whereas transmitter providing deterministic phase for pulse to pulse is called Coherent radar. Radar transmits the RF energy in the space through antenna. The block diagram of receiving chain of radar is shown in fig1. Antenna receives reflected RF energy from the target in the space. Receiver (RX) amplifies and down converts target echoes which are corrupted by clutter and noise. RSP suppresses clutter & noise from the received signals and detect the presence of target using various signal processing algorithms. RSP sends this target information to Radar Data Processor (RDP) for predicting new location of target and also sends the same target information to display for visualisation. This paper is focused only on radar signal processing as shown in dashed line of block diagram of receiving chain of Fig1. RSP uses Pulse Compression (PC), Moving Target Indicator (MTI), Window function, Integration, Fast Fourier Transform (FFT), and Constant False Alarm Rate (CFAR) algorithms. Pulse compression technique is used for enhancing range resolution and also improves SNR [3]. Moving target indicator removes the stationary clutter from the received signals [4]. Window function helps in reducing FFT leakage when signals are transformed from time domain to frequency domain [5]. FFT is used for coherent integration and resolving the target with different Doppler bins [6]. CFAR is used for detecting the target in background noise at constant false alarm rate [7]. Coherent radar preserves the phase information of transmitting pulses which are used for finding the Doppler of target. Both amplitude and phase are used in signal processing of coherent radar but only amplitude is used in non-coherent radar. Non coherent signal processing takes only amplitude for processing which improves the SNR $\sqrt{N}$ times for CFAR detection whereas Coherent signal processing uses both amplitude and phase for processing which improves the SNR N times for CFAR detection where N is number of pulses integrated [8]. Coherent signal processing offers Doppler estimation with less interference and signal to noise benefits relative to non-coherent signal processing.

Some radar also uses mixed domain radar signal processing. Mixed domain processing is also coherent type of signal processing in which some parts are implemented in time domain and remaining parts are in frequency domain.

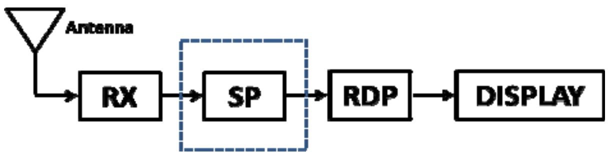

Fig. 1. Block diagram of radar receiving chain

Depending on hardware and algorithm complexity, each domain processing takes different processing time. Probability of detection (P_d) and Probability of False Alarm (P_{FA}) are two major factors for specifying signal processing of radar.

II. THEORY

Radar signal processing uses various algorithms for detecting the presence of target. These algorithms are PC, MTI, Window function, Integration - Non-Coherent or Coherent, and CFAR. These algorithms are selected in radar depending upon hardware resources, phase and amplitude of received signals and processing domain. Pulse compression is commonly used in all domains because it enhances range resolution as well as SNR. Remaining algorithms are used for improving SNR and suppressing noise & clutter from received signal. Non coherent radar uses time domain processing because transmitter does not preserve phase of each pulse whereas Coherent radar uses frequency domain because phase of each pulse is preserved by transmitter. Some radars use mixed domain because some parts of frequency domain are easy to implement in time domain. Performance of Mixed and Frequency domain is same. The radar signal processing in different domain is explained one by one:

A. Time Domain

Time domain processing is the simplest form of signal processing for Non-coherent radar. It is easy to implement on hardware because it depends on signal amplitude only. Hence time domain processing is also called non-coherent signal processing. The processing chain of time domain is shown in fig 2.

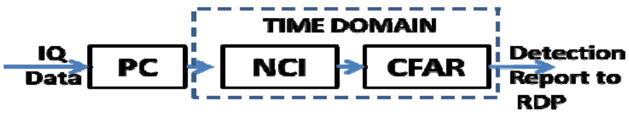

Fig. 2 Time domain radar signal processing chain

PC, Non-Coherent Integration, and CFAR algorithms are implemented in time domain. Digital IQ data are fed to pulse compression. Non-Coherent Integration is done on absolute value of PC data by integrating number of pulses. Non-Coherent Integration in Time domain ($NCIT_j$) of each bin is calculated by equation 1.

$$NCIT_j = \sum_{i=1}^{N} abs\left(s_{ij} \otimes m_i\right) - - - - (1)$$

Where S_{ij} is i x j input matrix, i is number of pulse, j is number of range bins, m_i is pulse canceller coefficient, N is total number of pulses.

After integration, Cell Average CFAR (CACFAR) is done on background noise with adaptive threshold in time domain. Adaptive threshold multiplication factor for non-coherent processing depends upon P_{FA}, $P_{d,}$ number of pulses and MTI stage. Based on CFAR output, it is decided that target is present or not present in the background noise. If target is present, RSP declares only target position and strength in report.

B. Frequency Domain

Frequency domain radar signal processing is complex and time consuming because it takes lot of hardware resources and computation. All algorithms are implemented in frequency domain except PC. Time domain PC output is converted into frequency domain using FFT. MTI and windowing is done on FFT output using multiplication and convolution. The frequency domain radar signal processing chain is shown in fig 3.

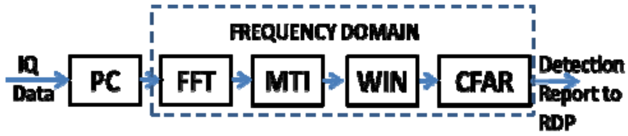

Fig. 3 Frequency domain radar signal processing chain

MTI followed by Window function and Window function followed by MTI give the same performance. Therefore, Window function and MTI can be interchanged during processing. FFT takes lot of memory and computation. Coherent integration in Frequency domain (CIF_j) of each bin is calculated by equation 2.

$$CIF_j = abs\left(\left(S_{ij} \times M_i\right) \otimes W_i\right)\right) - - - (2)$$

Where S_{ij} is the FFT s_{ij} , M_i is the FFT of m_i ,W_i is the FFT of w_i ,N is the total number of pulses, i is the number of pulse , j is the number of range bins, m_i is mti coefficient , w_i is window function coefficient.

CACFAR is done on absolute value of FFT data for each pulse. CFAR is repeated N times in frequency domain as compared to time domain. Adaptive threshold multiplying factor of coherent processing depends upon size of range bin window and probability of false alarm (P_{FA}). If target is present, RSP declares target position, strength and filter number. Filter number gives the speed of target.

C. Mixed Domain

It is intermediate type of radar signal processing. First half of the processing is done in time domain whereas remaining half is done in frequency domain. It is only mathematical processing where multiplication in time domain is equivalent to convolution in frequency domain and vice versa [9].

Fig. 4 Mixed domain radar signal processing chain

Input signals come from receiver in time domain. PC, MTI and window function are implemented in time domain as shown in left side of Fig. 4 by dashed line. MTI is done by convolution on PC output data while window function is done by modulation on MTI output. Window function is used for reducing the FFT spill over. Coherent Integration and CFAR are implemented in frequency domain as shown in right side of Fig. 4 by dashed line. FFT is done on window function data containing both amplitude and phase. That is why Mixed based signal processing is also called coherent signal processing. Coherent Integration in Mixed domain (CIM_j) of each bin is calculated by equation 3.

$$CIM_j = abs\left(FFT\left(\left(s_{ij} \otimes m_i\right) \times w_i\right)\right) - - - (3)$$

where s_{ij} is i x j matrix of PC output, m_i is MTI pulse canceller coefficient, w_i is the window function coefficient, N is total number of pulse, i is number of pulse, j is number of range bin.

After Integration, magnitude data are fed to CACFAR algorithm. CFAR output gives target detection information which is sent to RDP for further processing.

III. Design simulation

For comparing different type of radar signal processing, the following parameters are taken as input for simulation:

Waveform = Linear Frequency Modulation
Pulse width = 10 µs,
Bandwidth = 5 MHz,
Simulated Target = Doppler Fr/2, range 15 km, +12 dB noise
Simulated Target = Doppler Fr/8, range 15 km, -18 dB noise
Range bin = 1024
Number of pulse = 32
P_d = 0.9
P_{fa} = 10^{-6}

Matlab software is used for simulating and comparing the result of different type of radar signal processing [10]. 1K range bins and 32 PRTs are used for target simulation. Fr/2 and Fr/8 Doppler's are injected in target. Input data of 1 K range bins and 32 PRTs are generated in time domain using above parameter with +12 dB and -18 dB target strength. Same simulating data is fed to different type of radar signal processing algorithms. Mixed domain processing is only mathematical transformation of frequency domain processing. Multiplication in time domain is equivalent to convolution in frequency domain and vice versa. This property is used for implementing the mixed domain processing as shown in equation 4.

$$F((d \otimes m) \times w) = (F(d) \times F(m)) \otimes F(w) - - - (4)$$

Where d is the input data, m is the pulse canceller coefficient, w is the window function coefficient, F ( ) is FFT, ⊗ is convolution and x is multiplication.

Hamming and Hanning window functions are used for reducing FFT leakage. Hamming gives -43 dB side lobe with -6dB side lobe fall off whereas Hanning gives -35 dB side lobe with -12 dB side lobe fall off. 3 pulse canceller coefficients are used in moving target indicator. Window function is not used in time domain because there is no of FFT spill over. But window function is used in mixed domain and frequency domain. MTI data is multiplied with window function coefficient in mixed domain whereas FFT data is convoluted with window function coefficient in frequency domain.

+12 dB target signal is simulated above the noise floor at the input of pulse compression. LFM has 5 MHz bandwidth and 50 coefficients for correlation. Input data are correlated with stored LFM coefficient in pulse compression. Pulse compression output is fed to different type of radar signal processing for comparing the result. Mixed and frequency domain processing is almost same but only implementation is different. MTI is common in all domains for removing stationary clutter. CFAR is done for 10^{-6} false alarm rate and 32 range bins window. Adaptive threshold is calculated for detecting the target in background noise. Different multiplication factor is used for coherent and non-coherent CFAR. Same thing is repeated for Fr/8 Doppler target

IV. RESULTS

Using simulation parameter, single target of Fr/2 Doppler is simulated at 15 Km with +12 dB signals strength above the noise floor as shown in Fig 5.

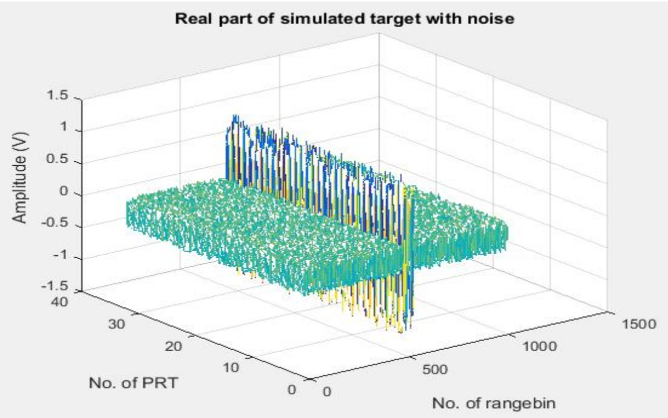

Fig. 5 Real part of simulated +12 dB Fr/2 simulated target data

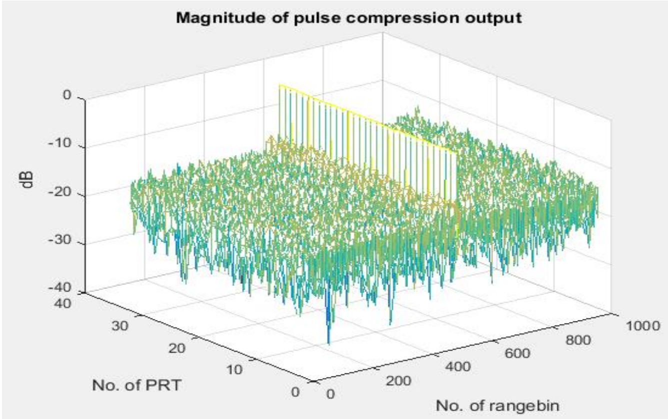

Fig.6 Pulse compression of +12 dB Fr/2 simulated target

Pulse compression is done on above simulated data. The magnitude output of PC is shown in fig 6. Radar signal processing in three domains is done on same PC output. Mixed and Frequency domain gives same performance. So Time and Frequency domain radar signal processing results are compared. Processed data is normalized for CFAR .The compared results are shown in fig.7. Due to pulse compression, range side lobe appears in both the side of target. Threshold level for target declaration is different for NCI and CI. Therefore, NCI declared three targets (blue colour) as compared to red colour dynamic threshold whereas CI declared one target (green colour) as compared to cyan colour dynamic threshold.

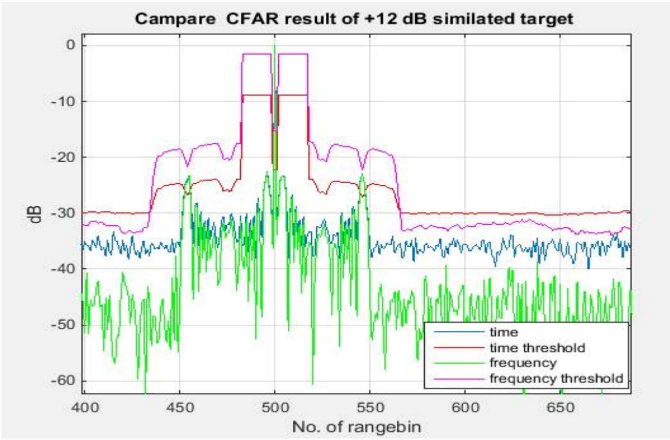

Fig.7 Compare CFAR result of +12 dB Fr/2 simulated target

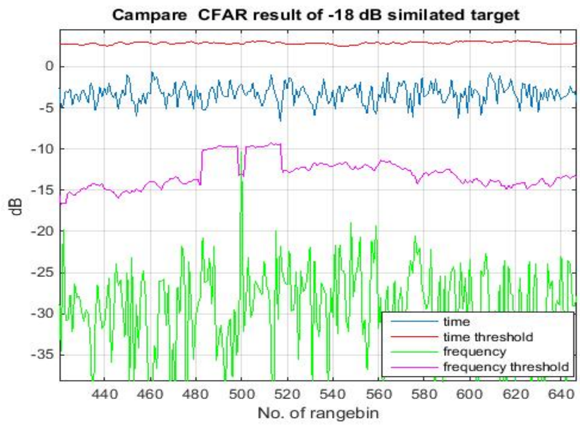

Fig.8 Compare CFAR result of -18 dB Fr/8 Doppler simulated target

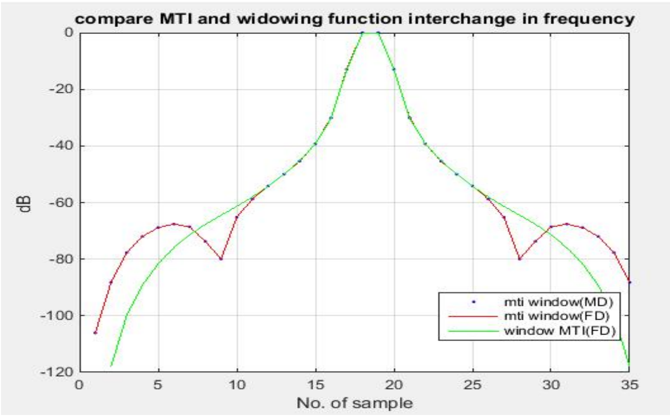

Fig.9 Compare MTI and window function interchange in frequency domain

Same thing is repeated for Fr/8 Doppler target with -18 dB signals strength at 15 km. Red colour shows domain dynamic threshold of time domain whereas green colour shows dynamic threshold of mixed and frequency domain. NCI(Blue colour) does not cross red colour threshold level whereas CI (green colour) crosses at one place. Therefore NCI declared no target but CI declared one target as shown in Fig 8. NCI processing detected +12 dB target signal but missed -18 dB target signal whereas CI processing detected both the target signal. Mixed domain gave same result of Frequency domain.

MTI and window function can be interchanged in frequency domain during processing. This is possible only circular convolution property of DFT. MTI and window function of mixed domain is compared with interchanged MTI and window function in Frequency Domain as show in Fig 9. Dotted curve shows FFT of MTI and window function in Mixed domain, Red line showed FFT of MTI and window function in Frequency domain and green line showed FFT of window function and MTI in Frequency domain. Table I shows the comparison between different types of radar signal processing.

TABLE I. COMPARISON OF RADAR SIGNAL PROCESSING

Domain	*Time*	*Mixed*	*Frequency*
PC	YES	YES	YES
MTI	YES	YES	YES
Window function	-	YES	YES
FFT	-	YES	YES
CFAR	TIME	FREQUENCY	FREQUENCY
MTI & Window function interchange	-	No	YES
Number of samples during processing	VARYING	VARYING	SAME
Matlab Simulation time	0.026327s	0.112884s	0.140019s
SNR Improvements for CFAR	$\sqrt{N}$	N	N

V. Conclusions

This simulation gives the comparison of radar signal processing in different domains. Time domain signal processing is easy to implement but gives poor performance whereas Frequency domain is complex and gives better performance. Frequency and Mixed show same response but differ in implementation. Modulation and convolution property of DFT help in implementing mixed domain processing. MTI and window function can be interchanged in Frequency domain with the help of circular convolution. Coherent processing takes lot of resources, computation and processing time as compared to non-coherent processing. Size of data matrix during process is same in Frequency domain but different in Time and Mixed domain. Mixed domain takes the simplicity of Time domain and reduces the complexity of Frequency domain. Therefore, Mixed domain is the efficient way to implement radar signal processing.

VI. ACKNOWLEDGMENT

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BIOGRAPHY

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