Ground Clutter Mitigation and Design of Moving Target Indication Filters with Non-Uniform Pulse Repetition Intervals

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Certificate

This is to certify that the thesis entitled, "*Ground Clutter Mitigation and Design of Moving Target Indication Filters with Non-Uniform Pulse Repetition Intervals* " and submitted by Ajay Raj T: 14EC204, Ankita Singh: 14EC208, Sheethal Jadhav: 14EC222 in partial fulfillment of the requirements of RENS EC332 embodies the work done by them under my supervision.

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Contents

1 Introduction 2

2 Moving Target Indication Radar 4

2.1 Background 4

2.2 MTI Filtering 5

2.2.1 Delay Line Cancellers 5

2.2.2 FIR Type MTI Filters 5

2.2.3 Recursive MTI Filters 6

2.3 Blind Speed Problem 6

3 Non Uniform MTI Filter Design 7

3.1 Least Square Design 8

3.2 Convex Design 9

3.3 Min-Max Design 9

4 Simulation Results 11

5 Conclusion 15

5.0.1 Future Work 15

6 Bibliography 16

1. Introduction

Detection of moving targets in strong clutter has been one of the most important tasks of the radar systems throughout the history. Through the evolution of radar systems a number of techniques and methods are developed in order to increase the target detection capability of the radar systems in strong clutter. One of the basic methods is the usage of Moving Target Indication (MTI) signal processor. As the name implies, it is used to indicate the presence of moving targets in heavy clutter by discriminating the component of the return echo due to moving targets from stationary background.

First MTI designs were based on the analog delay line cancellers, which are used for cancelling stationary clutter by subtracting the successive returns in order to improve the detection of the target component.With the introduction of digital systems, digital filters are developed and improvements in performance have been attained.

Design of the MTI processor is mainly based on the design of filter structure for clutter attenuation. For stationary clutter attenuation, simple highpass filters provide sufficient attenuation, whereas higher order filters can be required to sufficiently attenuate clutter with significant Doppler spread. Digital implementation of the MTI signal processor filter has a periodic characteristic due to uniform sampling with constant pulse repetition frequency (PRF). Because of the periodic nature, the moving targets having Doppler frequencies which are integer multiples of PRF are cancelled by the MTI filter along with the background clutter. Therefore, these moving targets are not seen by the radar. Velocities that correspond to the undetected frequencies are called blind speeds. There are different approaches for the solution of this problem in the literature. One of them is staggering the interpulse durations, that is the usage of different interpulse periods instead of a single one .

The usage of staggered interpulse durations improves the blind speed performance in MTI radars. It should be noted that the improvement in blind speed comes at almost no additional computational cost. An important disadvantage of non-uniform sampling is the passband ripples which are much larger in comparison to uniform PRI systems. Due to these ripples, the fluctuations of signal power at the MTI filter output may degrade the detection performance for particular Doppler frequencies. Therefore, it is important to design MTI filters by considering the detection probability and performance of the radar system for the specific Doppler frequencies.

In the present work, we study three widely adopted FIR filter design techniques, the least square, convex and min-max filter design. The systematic design of each approach is described. A number of performance measures are defined and comparison between different filters is given for the various scenarios. Obtained results indicate that it is possible to design non uniform filters according to different cutoff frequencies and clutter attenuation values. One can optimize the filter response by defining the clutter attenuation, cutoff frequency and interested Doppler frequency band and selecting a suitable weight factor.

2. Moving Target Indication Radar

2.1 Background

It is difficult to distinguish a moving target in the presence of ground-clutter or sea-clutter environment due to strong clutter echos. Detection of moving targets in these conditions is performed using Moving Target Indication (MTI) radar. The MTI radar is a type of pulse radar that uses the non-zero Doppler shift of moving targets for their detection by cancelling the stationary background clutter.

There are different types of MTI Radars classified according to operation modes, environments and used signal processing algorithms. Coherent MTI Radar is the type in which a moving target is detected as a result of pulse-to-pulse change in echo phase relative to the phase of a coherent reference oscillator.In other words, it is a system that uses the phase difference resulting from Doppler effect to separate the moving targets from stationary background clutter.

Another type of MTI radar that uses the clutter echo as the reference signal to discriminate the Doppler-shifted information of target echo is known as Non-Coherent MTI or externally Coherent MTI. This type of MTI is simpler than coherent MTI; but it requires the presence of clutter for detecting the moving targets.

MTI Radars used in airborne applications named as Airborne MTI or AMTI. Operation principle of this type is similar to the Coherent MTI; however, compensation for the moving radar platform is necessary. The Doppler shift of the received echos change depending on the relative motion of the moving radar platform and target.

Adaptive MTI Radar is another type of MTI radar that adapts itself to the clutter. According to change in clutter characteristics, the coefficients of the MTI filter are changed on time basis. Adaptation to the clutter can be achieved by different estimation techniques for clutter covariance matrix.

2.2 MTI Filtering

Different types of MTI filters are developed and have been used through the radar history. These filters are designed according to hardware specifications and the operation constraints of the radar system. A typical MTI filter has a highpass filter characteristics that is designed for rejecting zero or small Doppler frequencies and passing higher frequencies corresponding to the moving targets. MTI filters can be classified in three main categories as follows.

2.2.1 Delay Line Cancellers

The delay line canceller is an analog technique used in the first MTI signal processor design. The operation is based on subtracting two consecutive radar returns.

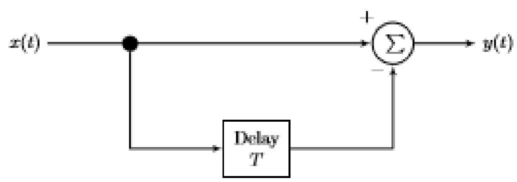

Figure 2.1: Filter Structure of the Single Delay Line Canceller.

Time domain difference equation of the single delay line canceller with pulse repetition interval (PRI) T is given as

$$y(t) = x(t) - x(t - T) \tag{2.1}$$

Single delay line canceller rejects the stationary clutter which has zero Doppler shift. When the clutter has spread in the spectrum, then the performance of the single delay line canceller decreases and the clutter residue resides at the filter output, especially at small Doppler frequencies. When slow moving targets are present, then the detection performance of these targets are affected by the clutter residue.

2.2.2 FIR Type MTI Filters

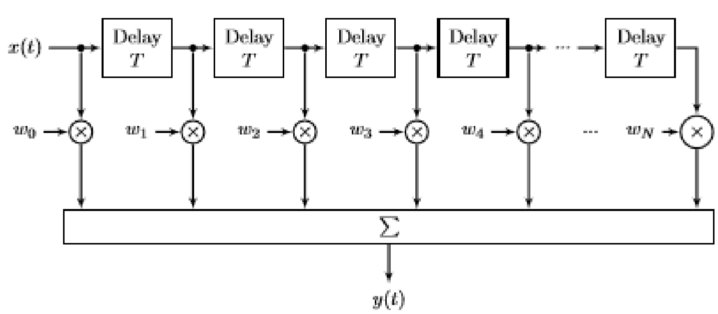

Figure 2.2: General Structure of a Uniform FIR Filter

Finite-Impulse-Response (FIR) filters can be used for MTI processing if the filter weights are chosen in order to obtain a high pass filter characteristics.One of the simplest and widely used uniform FIR type MTI filter is the Binomial MTI filter whose coefficients are formed by binomial numbers. This method corresponds to the cascade of single delay line cancellers.

2.2.3 Recursive MTI Filters

Recursive filters are also used as an MTI signal processor. They are utilized to shape the stopband response. Recursive filters have the feedback coefficients and feedforward coefficients.Using recursive filters, stopband of the filter can be shaped more easily due to additional degrees of freedom that comes from feedback coefficients. However, these filters have poor transient response. This type of filters can be designed using classical z-transform theory and pole-zero analysis. Z-domain transfer function of a recursive filter is

$$H(z) = \frac{\beta_0 + \beta_1 z^{-1} + \beta_2 z^{-2} + \ldots + \beta_M z^{-M}}{1 + \alpha_1 z^{-1} + \alpha_2 z^{-1} + \ldots + \alpha_N z^{-N}}$$

2.3 Blind Speed Problem

One of the main disadvantages of the usage of uniform interpulse duration in digital MTI filters is that moving targets with Doppler frequencies that are integer multiples of the PRF will be canceled together with clutter because of periodic sampling of Doppler frequency. The nulls that result from the periodic sampling characteristics of the system are given by:

$$f_d = \frac{n}{PRI} = nxPRF \tag{2.2}$$

The speeds correspond to these undetected Doppler frequencies are named as blind speeds. Operation with a lower center frequencies results in a decrease in range and angle resolutions of the radar. Lower frequency band is used in civil applications. Therefore, lowering the frequency is not a desirable choice for many of radar systems. Increasing the pulse repetition frequency decreases the unambiguous range and causes range ambiguities. Usage of more than one PRF's increases first blind speed of the radar system whereas multiple-time-around clutter echoes will fold into different ranges. Operating the radar at more than one frequency causes stress on transmitter and is not desirable within the usual frequency bands allocated.

Widely used solution to blind speed problem in MTI filters is the usage of non-uniform (staggered) PRI. With this method the first blind speed is increased with respect to a uniform PRI MTI system. Two main staggering approaches utilized generally: pulse to pulse and block to block staggering.

3. Non Uniform MTI Filter Design

Non-uniform sampling and filtering have been frequently used in several applications in the processing of acoustic, image and radio frequency signals. The studies mostly focus on decreasing the total sampling time, reconstruction of the non-uniformly sampled signals, and improving the system performance.

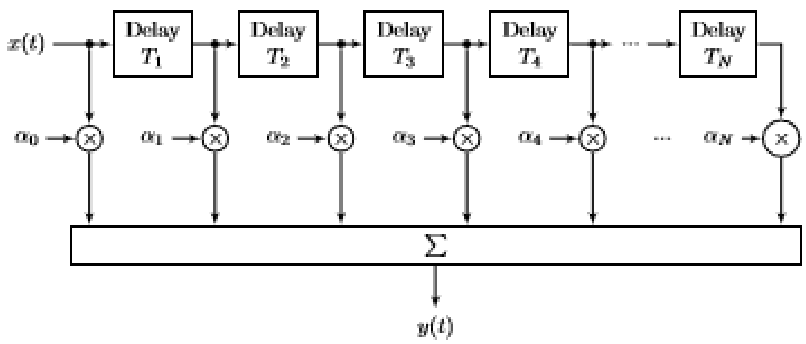

Figure 3.1: Non-uniform FIR Filter Structure

Design of staggered PRI MTI filter mainly relies on defining the frequency domain constraints and finding the optimal values for the interpulse periods Ti and filter coefficients αi. The adjustments of these parameters are done by considering the ideal MTI filter response.

Possible objectives of the MTI filter design can be listed as follows;

- All targets in the velocity interval of interest be equally detectable
- Clutter at the output of the filter be minimum
- Required MTI improvement factor for the clutter attenuation be satisfied
- The deepest null in the passband should not be excessive

- Passband ripple should be minimized and kept uniform

3.1 Least Square Design

The approach depends on minimizing the error between the desired filter and the designed filter. The standard cost function for a least square sense designed filter is given by where

$$J_{cost} = \int_0^{f_d} |H_d(f) - H_{ls}(f)|^2 df$$

H_d(f) and H_{ls}(f) indicates the frequency responses of the desired and least square sense designed filter respectively. H_d(f) is the ideal highpass filter whose frequency domain definition is given by

$$H_d(f) = \begin{cases} 0 : 0 < f < f_c \\ 1 : f_c < f < f_p \end{cases}$$

Here f_c is the cut off frequency used for adjusting the notch of the filter according to attenuation bandwidth and f_p is the bound for passband interval of Doppler frequency.

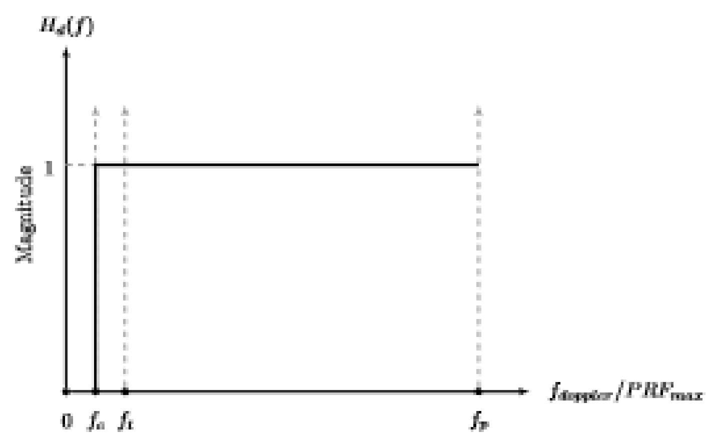

Figure 3.2: Desired high pass filter

For non-uniform MTI filter, least square minimization problem can be stated as

$$\begin{aligned} &\textbf{minimize} \quad ||H_d(f) - H_{ls}(f, \alpha_i)|| \\ &\textbf{subject to} \sum_{i=0}^{N-1} \alpha_i = 0, \quad x \in \Re \end{aligned}$$

3.2 Convex Design

In convex filter design, staggered MTI filter design formulated as a convex optimization problem. A convex optimization problem can be stated as

$$\begin{aligned} &\text{minimize} \quad f_0(x) \\ &\text{subject to} \quad f_i(x) \le b_i, i = 1, \ldots, m \end{aligned}$$

where the functions $f_{[}0]$,...,$f_{[}m]$ are convex.

Convex design of non-uniform MTI filter starts with the formulation of design constraints as a convex optimization problem. Design constraints are based upon same approach as in least square sense design which is the minimization of the passband error and maximization of the stopband attenuation. Similar to the least square design, the passband ripple and the stopband attenuation goals are linked with the weight factor W. Using the stated constraints, the optimization problem of the convex design can be stated as follows

$$\begin{aligned} &\text{minimize} \quad \delta \\ &\text{subject to} \quad |H(f,\alpha_i)| \le \delta, \quad f \in [0, f_c], \quad \alpha_i \in \mathbf{R}, \quad i \in \mathbf{N_0} \\ &\qquad\qquad\quad |H(f,\alpha_i) - 1| \le W\delta, \quad f \in [f_t, f_d], \quad \alpha_i \in \mathbf{R}, \quad i \in \mathbf{N_0} \\ &\qquad\qquad\quad \sum_{i=0}^{N-1} \alpha_i = 0, \quad \alpha \in \mathbf{R} \end{aligned}$$

The optimization variables are the filter weights αi's, N is the filter order,$f_{[}t]$, $f_{[}d]$ is the lower and upper bound of normalized passband frequency respectively and $f_{[}c]$ is the upper bound of normalized stopband frequency. It must be noted that weight factor W affects the passband ripple directly, different from the least square design. In the least square design, the weight factor affects the clutter attenuation.

The convex optimization problem solved by using CVX library, which is a MATLAB package developed for implementation of disciplined convex programming problems. It is possible to solve constrained minimization and maximization problems using CVX library.

3.3 Min-Max Design

The min-max filter design aims to select the filter coefficients to minimize the maximum deviation from the desired response in the passband. This method is different than the two previous methods. The earlier methods have a single optima which is the global one while this one has many local maximas. Therefore, this method requires a good initial filter coefficient set for a satisfactory performance. It is therefore necessary to experiment with different initial filter weights to determine the parameters that satisfy the required specifications. From the constraints perspective, this filter design also based on the minimization of the maximum passband ripple and maximization of the stopband attenuation. The optimization problem of the min-max design can be stated as follows

$$\begin{aligned} &\textbf{minimize} && \delta \\ &\textbf{subject to} && |H_{mm}(f,\alpha_i)| \leq \delta, \;\; f \in [0, f_c], \;\; \alpha_i \in \mathbf{R}, \;\; i \in \mathbf{N_0} \\ & && |1 - |H_{mm}(f,\alpha_i)|| \leq W\delta, \;\; f \in [f_t, f_p], \;\; \alpha_i \in \mathbf{R}, \;\; i \in \mathbf{N_0} \\ & && \sum_{n=0}^{N-1} \alpha_n = 0, \;\; \alpha \in \mathbf{R} \end{aligned}$$

Here H$_{[}mm$](f,αi) is the frequency response of the min-max filter and the variable δ shows the maximum deviation from the desired characteristics (for W = 1). The goal in this design is to minimize the maximum deviation from the desired highpass characteristic. The first and second constraints enforce the magnitude deviation be smaller than δ (for W = 1) in the designated bands. The third constraint guarantees that the min-max design has a null at DC frequency.

Different from the LS design, there is no closed form mathematical relation from which the optimal min-max filter coefficients can be retrieved. The optimization has to be done numerically. The numerical implementation of the optimization problem requires the discretization of frequency band into a dense set of frequency points.Similar to the convex design, a weight factor W is introduced to establish a trade-off between clutter attenuation and passband ripple objectives. It should also be noted that the min-max problem examined here is focused on minimizing the maximum deviation of the magnitude response from the desired response.

Min-max design requires more computation compared to the previous least square and convex design methods. Initial filter coefficients and the weight factor must be selected appropriately in order to obtain the required response in terms of stopband attenuation and the passband ripple. The taken approach for the min-max design of non-uniform MTI filter requires two phases. First, the weight factor is determined according to the required stopband attenuation by using the binomial coefficients as the initial filter coefficients. After the weight factor selection, different initial conditions for specified number of iterations are tried and the coefficients that give the minimum deviation in the passband are selected.

4. Simulation Results

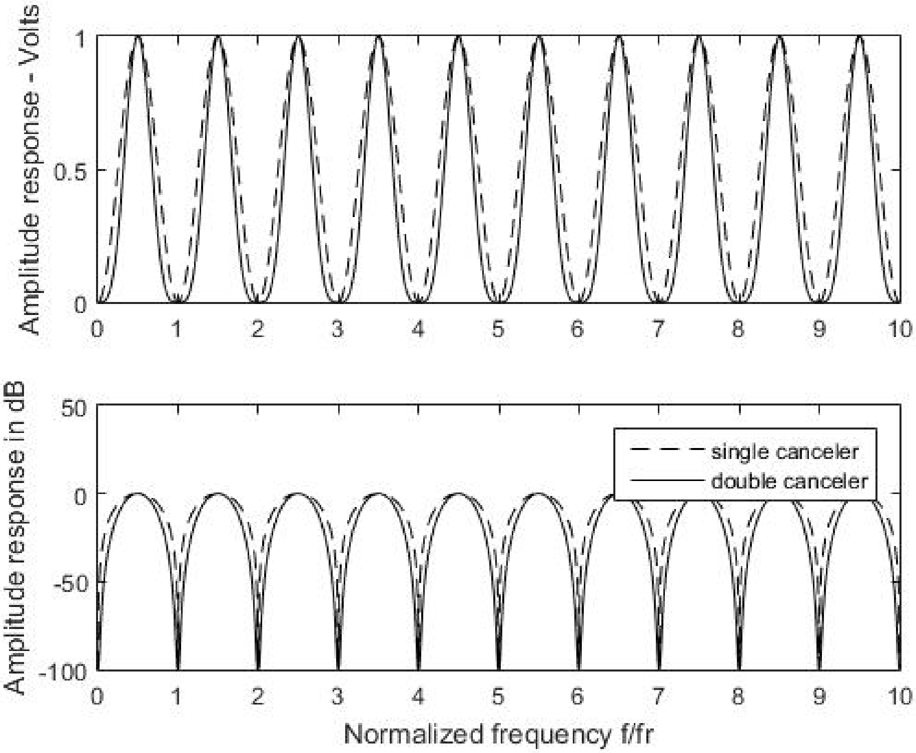

Figure 4.1: Cancellers

Figure 4.2: Fast time samples of uniform prf

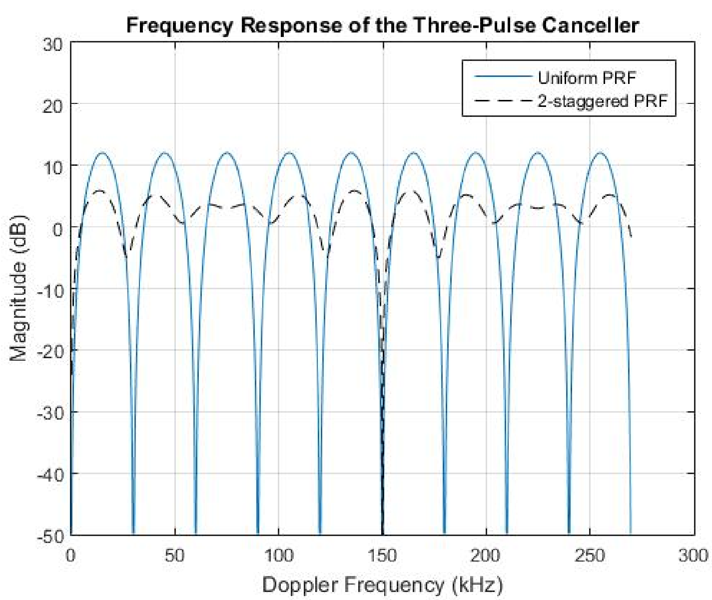

Figure 4.3: Frequency response of 3 pulse canceller

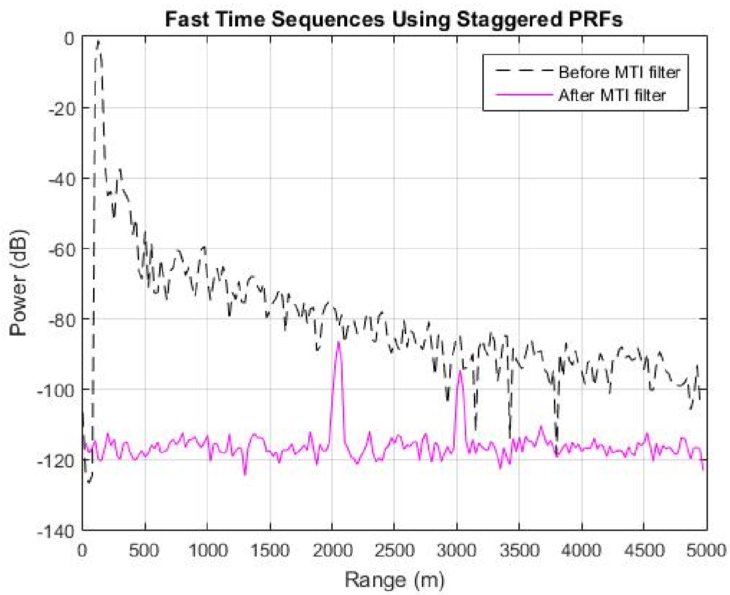

Figure 4.4: Fast time samples of staggered prf

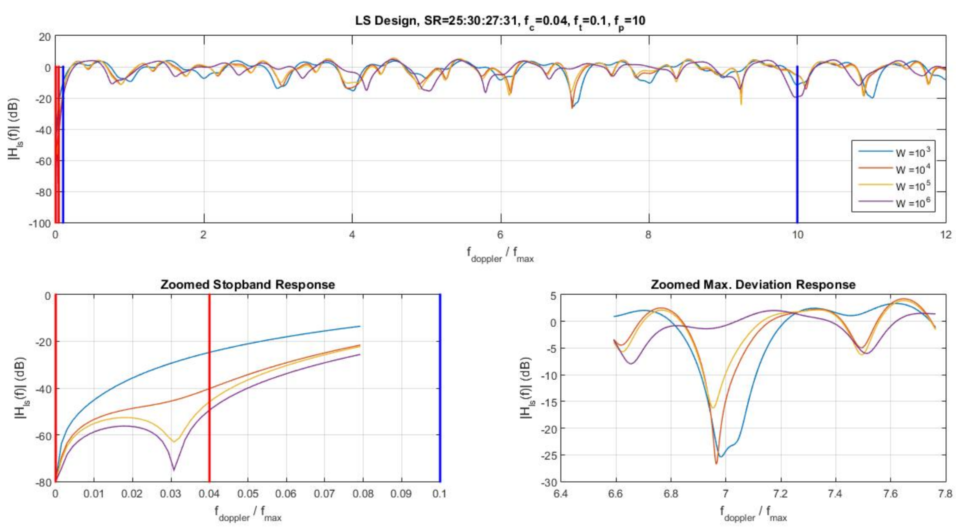

Figure 4.5: Least Square Design

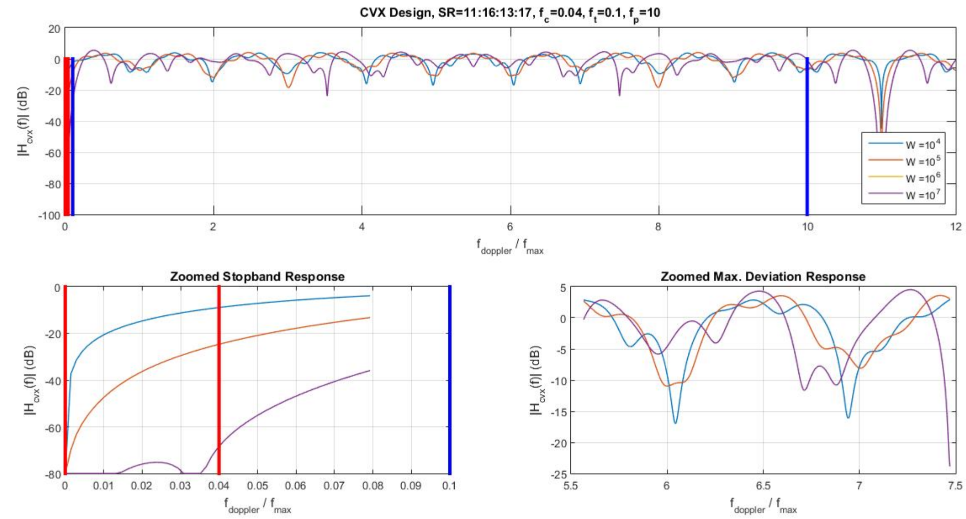

Figure 4.6: Convex Design

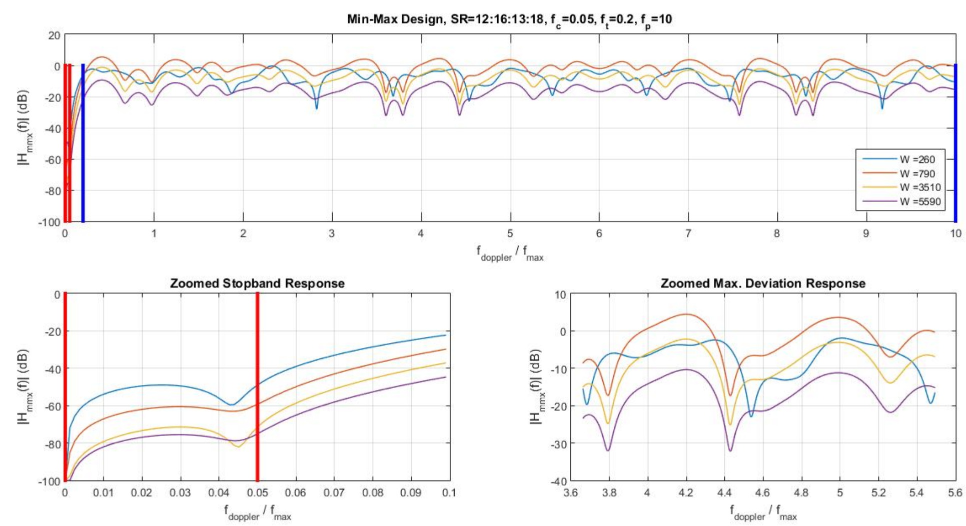

Figure 4.7: Min-Max Design

5. Conclusion

In this work, we apply classical filter design frameworks to the staggered PRI MTI filter and present the results with comparisons. The goal of the MTI filter design is providing maximum clutter attenuation in stopband and minimum ripple in passband. The presented design techniques are based upon these goals. The weighted least square, convex and minmax techniques are utilized to design filters with non-uniform sampling. It has been shown that with a proper selection of the weight parameter, a good compromise between clutter attenuation and flat passband response can be attained.

Two additional approaches are considered in order to increase the signal-to-clutter ratio improvement. First approach implements the modified min-max design by considering the optimum filter's improvement factor. Second approach focuses on the implementation of the designed filters as multiple filters that have time varying coefficients.

Obtained results throughout the thesis work illustrate the effectiveness of the design techniques. Most of the time, required constraints can be achieved with the designs and better responses are obtained generally for different performance measures as compared to the designs in the literature.

5.0.1 Future Work

We will plan to widen the MTI filter design into pulse-Doppler radars by changing the highpass filtering characteristics into bandpass characteristics and design filters for the staggered pulse Doppler Radars. In addition, these type of bandpass filtering can be implemented in nonuniform Airborne MTI Radars.

By improving run time of the algorithms, it is possible to implement staggered MTI filters in an adaptive manner with the estimation of the clutter covariance matrix. Since the designs present flexible solutions to different cutoff frequency and velocity band requirements.

6. Bibliography

1. Mark A. Richards, Fundamentals of Radar Signal Processing
2. Mehmet Ispir, A thesis on design of MTI filters
3. Bassem R Mahafza, Radar signal analysis and processing using Matlab
4. Mark A. Richards, Principles of Modern Radar-Basic Principles
5. radartutorial.mu