IMPLEMENTATION OF MATCHED FILTER FOR RADAR RECEIVER ON FPGA

A MASTER'S THESIS

in

Electrical and Electronics Engineering

Atilim University

by

MOHAMED SALEM A. SHFAT

SEPTEMPER 2018

IMPLEMENTATION OF MATCHED FILTER FOR RADAR RECEIVER ON FPGA

A THESIS SUBMITTED TO

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OF

ATILIM UNIVERSITY

BY

MOHAMED SALEM A. SHFAT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

SEPTEMBER 2018

Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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ABSTRACT

IMPLEMENTATION OF MATCHED FILTER FOR RADAR RECEIVER ON FPGA

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Septemper 2018, 68 pages

The underlying thesis scouts about a radar receiver in general and the Matched Filter and the implementation of this filter on the field programmable gate array FPGA. The practical implementation of the radar system is not as simple as its basic concept might seem. The Radar is operated by detection of the echo which is returned from reflecting objects (targets) and radiating the electromagnetic energy.The information about the target is provided by the nature of the echo signal such as position, velocity, and perhaps size. Several sources exist which are able to affect and confuse the quality of the radar these include undesired interference and echo The Matched Filter is a kind of filter helps to separate the reflected signal from the clutters and undesired echoes by increasing the SNR of the received echo in order to give the radar high ability to detect the targets successfully. The FPGA have been chosen as a platform for this work because of its high quality and speed in processing especially in digital systems design. In this work, the Matched filter is implemented on FPGA by using the Verilog language and MATLAB for generating the echo signals. Throughout this study, it was clearly shown that all the selected tools and language are suitable for this practical work.

Keywords: Radar systems and receiver, Matched Filter, FPGA, Verilog HDL.

ÖZ

FPGA üzerinde Radar Alıcı için Eleştirilmiş Filtrenin Uygulaması

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Eylül 2018, 68 sayfa

Bu tez, genel olarak radar alıcısını ve spesifik olarak eşleştirilmiş filtreyi ve bu filtrenin FPGA üzerinde uygulanmasını incelemektedir. Birçok örnekte pratik uygulaması olmamasına rağmen, radarın temel konsepti nispeten basittir. Radar elektromanyetik enerjiyi yaymak ve yansıtıcı nesnelerden (hedeflerden) geri dönen sinyalı tespit ederek çalışır. Eko sinyalinin doğası, konum, hız ve belki de boyut gibi hedef hakkında bilgi sağlar. Radar bilgilerinin kalitesini karıştırabilecek veya azaltabilecek birçok istenmeyen eko ve müdahale kaynakları vardır. Eşleştirilen Filtre, radarın etraftaki hedefleri başarıyla algılayabilmesi için alınan ekoların SNR'sini artırarak yansıyan sinyalin dağınık ve istenmeyen ekolardan ayrılmasına yardımcı olan bir filtredir. FPGA, özellikle dijital sistem tasarımında yüksek kalitesi ve işlem hızı nedeniyle bu çalışma için bir platform olarak seçilmiştir. Bu çalışmada, Eşleştirilmiş filtre, Verilog dili kullanılarak FPGA üzerinde uygulanmaktadır. MATLAB da, tasarımı test etmeye yankı sinyallerini oluşturmak için kullanılmıştır. Bu çalışma boyunca, seçilen bütün araçların ve dilin bu pratik çalışma için uygun olduğu açıkça görülmüştür.

Anahtarkelimeleri: Radar’ın sistemi ve alıcısı, Eşleştirilen Filtre, FPGA, Verilog HDL.

DEDICATION

To My Parents

ACKNOWLEDGMENTS

I sincerely appreciate my supervisor Assist.Prof.Dr. Mehmet Efe Özbek for guiding and helping me through the entire process. I would also like to thank my co-supervisor Prof.Dr. Ali Kara. To my family and friends, I also like to offer sincere thanks to my entire family and allies for the continued support.

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LIST OF SYMBOLS AND ABBREVIATIONS

FPGA - Field Programmable Gate Array

ILA - Integrated Logical Analyzer

IF - Intermediate Frequency

RF - Radio Frequency

SNR - Signal to Noise Ratio

FMCW - Frequency Modulated Continuous Wave

FM - Frequency Modulation

PM - Phase Modulation

FFT - Fast Fourier Transform

IFFT - Inverse Fast Fourier Transform

HDL - Hardware Description Language

IP core - Intellectual Property core

UART - Universal Asynchronous Receiver-Transmitter

ROM - Read Only Memory

RAM - Random Access Memory

LUT - LookUp Table

DSP - Digital Signal Processing

JTAG - Joint Test Action Group

CHAPTER 1

DETECTION OF RADAR SIGNALS IN THE PRESENCE OF NOISE

1.1 Introduction

The two main tasks that radar conducts are detecting the presence of the objects that are reflecting, and the fetching of data from the waveform that is received to acquire the target's information such as velocity, position, and maybe size. The tasks of both detection and information extraction might be performed independently and in either arrange, despite the fact that a radar that is a good recognition gadget is generally a decent radar for removing data, and the other way around. There are a few parts of the issue of identifying radar motions within the sight of noise which will be considered. Noise at last confines the capacity of any radar; this causes the issue of extracting data from the received waveform [1].

A radar system's performance can be evaluated through the following:

- The biggest range that it can detect the presence of a target of a given size.
- How accurately it can give the location of a target in angle and range measurement
- The ability of the radar to differentiate different targets.
- The radar system's ability to discover the target echo if it is surrounded by clutter echoes, jamming signals or interference which unintentionally comes from ally radar transmitters.
- The radar's capability to identify the target's type.
- The radar's maintainability, reliability and availability.

1.2 The Matched Filter in a radar field

The 'Matched Filter' idea was produced simultaneously and autonomously by D.O. North and by Van Vleck and Harvard Radio Research lab) around 1943, 1944, as a piece of engineering endeavors amid WWII to decide the impacts of electromagnetic counter measures or jamming, on radar execution, and furthermore as an assistance make preparations for such jamming. The idea of matched filter is so much a piece of the expert custom that we underestimate its utilization: it is presently 'standard'.

By and large, the motivation reaction of the filter that is coordinated to a specific received signal is a replica of its waveform. The intermediate frequency amplifier (IFA) is an approximation of a matched filter with respect to the received reflected pulse from target. If the reflected echo from the target is a train of N-pulses, substantial improvement in target detectability can be achieved by integrating these pulses. Integration may be in the IF section of the receiver (pre detection) or in the video section (post detection). Higher improvement is obtained in the case of the pre detection integration because the relative phase between pulses is known (coherent integration). In most cases, post detection integration is used because it is less costly and relatively simple in realization.

Increasing radar detectability under clear and jamming environments is one of the important improvement fields of modern radar performance. The realization of matched filters, which maximize the S/N ratio, is one of the main tools to fulfil this task.

A matched filter does not need to protect the wave state of the got echoes. The wave shape is known ahead of time, being pretty much the equivalent as that of the transmitted heartbeat. What is imperative is that the filter delivers the biggest conceivable pinnacle yield because of each reverberate motion, for a given level of commotion. Along these lines it boosts the possibility of perceiving substantial echoes with a threshold detector [4].

The activity of a matched filter is shown by Figure 1.1 Part (a) demonstrates two rectangular echo pulses. To a limited extent (b) they are tainted by irregular clamor. In the event that a limit indicator forms this flag in addition to commotion waveform, obviously incidental high noise waveform are probably going to cause false alarms. Part (c) demonstrates the impact of coordinated filtering. The pinnacle yield because of each signal is currently significantly bigger, contrasted and the noise, and a limit level V_t can be effectively employed [4].

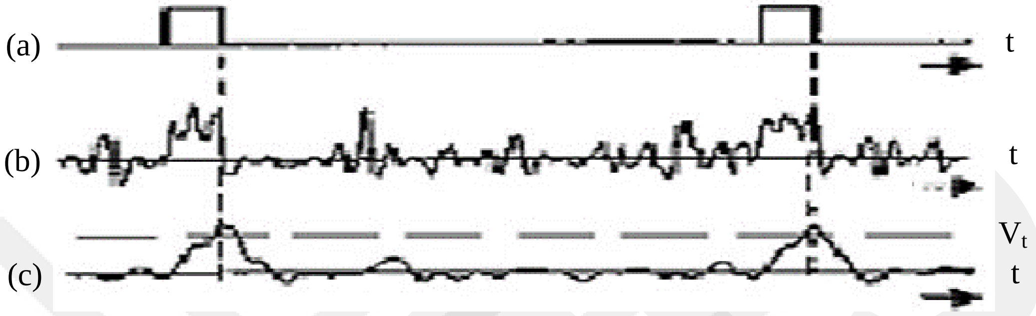


Figure 1.1 Improving signal-to-noise ratio by matched filtering

Note that the matched filter has not safeguarded the signal wave shape. (Truth be told, it gives a triangular type of output pulse if the info pulse is rectangular.) Furthermore, the pinnacle signal yield concurs with the trailing edge of the information pulse. Matched filter recognition hence includes a period defer equivalent to the span of the info signal.

A matched filter is typically characterized as far as its motivation reaction, which dependably appears as a period turned around form of the signal. Along these lines, such a channel is 'coordinated' to a specific signal wave shape and to no other. It will be demonstrated that, when this wave shape is bolstered into the channel, the yield appears as the signal's autocorrelation work. Therefore, a matched filter is regularly alluded to as a kind of correlator. Whatever the type of the signal, the autocorrelation work is symmetrical with a pinnacle an incentive at its inside. It is this pinnacle which we use for edge recognition [4].

To comprehend the task of a matched filter, we have to investigate its activity in the time domain. Figure 1.2 demonstrates a period constrained signal 'pulse' x(t), whose wave shape is thought to be known ahead of time (we require not accept a rectangular pulse, on the grounds that the idea of coordinated separating is flawlessly broad and applies to any type of signal).

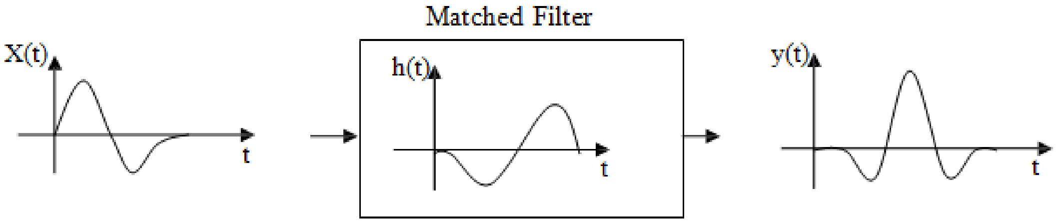


Figure 1.2 The Matched Filter

The signal is passed into a matched filter, impulse response h(t) is, by definition, a period time-reversed rendition of x(t). The impulse response speaks to the reaction to a unit motivation work conveyed at the instant t=0.

Similarly as with some other linear filtering, the yield from the matched filter might be found by convolving x(t) with h(t), giving

$$y(t_0) = \int_{-\infty}^{\infty} x^2(\tau)d\tau \tag{1.1}$$

where τ is an auxiliary time variable. This is essentially a proportion of the aggregate energy in x(t). Hence, the advantages of matched filtering depend just on the info signal's energy not its itemized wave form.

It might likewise be useful to outline the performance of the matched filter in the recurrence space. Similarly as with any straight time-invariant (LTI) framework, its recurrence and motivation reactions form a Fourier change combine. For this situation h(t), is a period turned around rendition of the signal x(t). Time inversion does not influence the extent of the relating otherworldly capacity, just the stage. So the size of the recurrence reaction must be indistinguishable to that of the information signal range. Recurrence parts firmly spoke to in x(t) are unequivocally transmitted; weaker segments, less so. Clamor lying outside the signal's transfer speed is totally dismissed. Along these lines the matched filter streamlines the signal to-commotion proportion.

In functional radar, matched filtering is proficient at middle of the road frequencies. The sifting properties of the IF speaker are hence, preferably, those of the suitable matched filter. For instance, if a radar utilizes customary 'rectangular' beats, the drive reaction of the IF speaker ought to be a sinusoidal swaying at transitional recurrence, of indistinguishable length from a normal resound. In the recurrence area this relates to a thin band-pass normal for sin(x)/x form. Despite the fact that it isn't conceivable to make a channel with unequivocally these qualities, the utilization of an inexact channel prompts little loss of performance.

Before going further, the relation between the S/N ratio and the improvement of radar detectability will be illustrated through the radar equation. In principle radar operates by transmitting a signal in a particular direction and receiving any reflected signals. A reflected signal from an object (usually metal in the case of RF and microwave signals) contains much information about that object. The information that can be extracted is dependent upon the transmitted waveform and signal processing on reception. The received radar power is given by [3]

$$S = \frac{P_t G_t \sigma_t G_r \lambda^2}{(4\pi)^3 R^4} \tag{1.2}$$

where$P_t$is the transmitted power, $G_t$is the gain of the transmitting antenna,σ_t is the radar target cross-section, $G_r$is the gain of the receiving antenna, λ is the radar wavelength, and R is radar target range.

The input signal to the receiver is very weak and requires a strong amplification in order to be used. In addition to the signal, there is the thermal noise, N, which isgiven by

$$N = kTFB_n \tag{1.3}$$

where k is the Boltzmann constant, B_n is the receiver noise bandwidth, F is the receiver noise figure and T is the noise temperature.

Therefore, in the radar receiver output, there will not be only the useful signal but also noise. A threshold level is selected such that the presence of target is assumed if the receiver output exceeds this level. There is a risk of considering some noise spikes as targets (false alarm) or to lose weak signal in noise (miss detection).

In practice, the presence of the target will easily be detected if its echo signal is strong compared to noise. According to the signal-to-noise ratio S/N and the selected threshold level, the probability of detecting the true signal P_d and the probability of false alarm P_{fa} [5] are determined. Since the noise power is proportional to the receiver bandwidth, it might be thought that the best way of reducing noise is to narrow the receiver bandwidth as much as possible.

According to filter theory, the maximum S/N ratio is obtained when the filter is ideally matched to receive the signals during the on-target time. This requires that the filter bandwidth must be the reciprocal of pulse width δ [5], that is

$$B_n = \frac{1}{\delta} \tag{1.4}$$

Thus

$$\frac{S}{N} = \frac{S\delta}{kTF} = \frac{E}{kTF} = \frac{E}{N_0} \tag{1.5}$$

where$E$ the energy of the radar signal reflected by the target towards the receiver and$N_0$is the noise power density of the receiver per unit bandwidth.

If only one radar pulse of power $P_t$and length δ is transmitted, the product givesthe radiated energy $P_t\delta$, and the received energy is given by

$$E = \frac{P_t\delta_t G_t\sigma_t G_r\lambda^2}{(4\pi)^3R^4} \tag{1.6}$$

Assuming that a matched filter is used, one obtains

$$\frac{S}{N} = \frac{P_tG_t\sigma_tG_r\lambda^2}{(4\pi)^3kTFB_nR^4} \tag{1.7}$$

Rearranging (1.7), then

$$R^4 = \frac{P_tG_t\sigma_tG_r\lambda^2}{(4\pi)^3kTFB_n\, {}^{S}\!/_{N}} \tag{1.8}$$

Using a matched filter ensures that the signal-to-noise ratio capable of giving the required detection and false alarm probabilities will be smaller.

In the real situation, more than one pulse is reflected from the target. Considering that $W_a$is the antenna rotation rate, then the target will be illuminated for a time T_{ot}, which is given by

$$T_{ot} = {}^{\theta_B}/_{W_a} \tag{1.9}$$

where θ_B is the antenna beam width. The number of pulses (N_i) received during the on-target time is given by

$$N_i = F_r T_{ot} \tag{1.10}$$

where F_r isthe pulse repetition frequency. The energy corresponding to these pulses will be $N_i P_t \delta$. Generally, the integration is not perfect and the integration loss L_i has to be considered. Taking into account the remaining sources of losses ratherthan the integration loss [1], the general free space range equation for pulsed radar may be written as

$$R^4 = \frac{N_i P_t G_t \sigma_t G_r \lambda^2}{(4\pi)^3 kTFB_n \frac{S}{N} \, L_i L_m L_x L_{tx} L_{rx} L_b} \tag{1.11}$$

where L_i is the integration loss, L_{tx} is the transmission loss in the signal path between the transmitter and the antenna, L_{rx} is the receiver loss in the received signal path between the antenna and the receiver, L_b is the beam shape loss which accounts for the fact that the target is not illuminated with a constant gain during the on-target time, L_m is the matched filter loss which accounts for the fact that the receiver is not an ideal matched filter and L_x is the loss due to the type of signal processing.

From the earlier discussions of signal detectability and the corresponding radar range equations, it was emphasized that the S/N ratio should be maximized. The receiver transfer characteristic, which achieves this end for white noise, is called matched filter [6].

1.3 Literature review of the theory and applications of detection of the radar echoes in the presence of noise

Paper [7] by Marcum was first issued as a classified report. In this classic, Marcum applies the now-well-known work of Rice [8] on steady-state signals in noise to evaluate in considerable detail the statistical detection of a target by pulsed radar. As an aid in this evaluation, the paper presents extensive graphical data for determining the probability of detection of a target at any range (normalized with respect to an ‘idealized’ range), given the values of three parameters:

- The time taken to detect the target.
- The average time interval between false alarms.
- The number of pulses integrated.

In the paper by Marcum [7] it is assumed that the target can be modelled as a non-fluctuating point reflector during the entire time when it is illuminated by the transmitted signal. However, in general the radar cross section of a target is a statistical variable, which is recognized by Marcum himself. The radar cross section, denoted by σ, is defined by [5]

$$\sigma = \frac{Power\ reflected\ toward\ antenna\ per\ unit\ solid\ angle}{Incident\ power\ density/4\pi}$$

Swerling in his classic paper [9] extends some of Marcum's results (mainly the computation of probability of detection versus normalized range curves) to four kinds of radar-cross-section fluctuations. The four fluctuation models of target considered by Swerling are based on the use of two different probability density functions for the radar cross section, in conjunction with two extreme forms of correlation. The four fluctuation models are commonly referred to as Swerling I, II, III, and IV. Note that in the case of Swerling I, the model is exponentially distributed in terms of the radar cross section or scattered power; this is equivalent to a Rayleigh distribution in terms of the scattered or received voltage.

Paper [10] by Kanter is concerned with analysing the performance of a pulsed radar receiver with a scanning antenna, which is influenced by the following factors:

The received pulses are amplitude-modulated by the two-way gain pattern of the antenna, assuming that the same antenna is used for both transmission and reception.

The received signal may contain a clutter component produced by reflections from fixed targets (such as buildings, mountains, etc.) or slowly moving targets (such as trees, fields of grass, etc.). The echo from such undesired targets experiences zero or a small Doppler frequency shift. On the other hand, the echo from a moving target (such as an aircraft) experiences a larger Doppler frequency shift, determined by the radial velocity of the target. A technique that is widely employed in practice to separate the target from clutter involves the use of a 'moving target indicator (MTI)' filter connected to the video output in the receiver [5]. Delay-line cancellers provide a method of realizing the MTI filtering action. Post detection integration.

To evaluate the effects of antenna gain pattern, clutter, and Post detection integration on receiver performance, the customary practice has been to assume them to be mutually independent, so that their combined effect can be obtained by adding their individual contributions, considered one at a time. Kanter [10] describes a procedure for finding the exact probability density function at the integrator output by including the effect of these factors simultaneously. This, in turn, enables the evaluation of receiver performance by calculating the probability of false alarm and probability of detection.

Paper [11] by Siebert presents a unified philosophical treatment of three basic issues in the design of search radar systems limited by additive white Gaussian noise:

- The reliability of detecting target echoes.
- The accuracy with which target parameters (for example, range delay and Doppler frequency shift) can be estimated.
- The extent to which such estimates can be made without ambiguity.

In discussing these issues, Siebert makes extensive use of the classic work of Woodward and Davies, reproduced in paper [12].

Paper [13] by Birdsall presents a unified treatment of the detection of a signal known exactly or a signal known except for phase. The paper introduces the useful concept of a ‘receiver operating characteristic’ for assessing the performance of a receiver. In such a characteristic, the probability of detection is plotted against the probability of false alarm for varying signal-to-noise ratio.

Paper [14-15] by Kelly et al., which is in two parts, develops a unified and complete mathematical treatment of detecting and extracting information from a signal in the presence of additive Gaussian noise. This paper, and that of Peterson et al., have one basic feature in common, namely, they both treat the radar receiver as a decision-making device. In this respect, the viewpoint adopted in both papers differs from that of Woodward and Davies, who treat with the radar receiver as a device to present useful information to a human observer. Thus, whereas Woodward and Davies in papers [12, 16] use Shannon's information theory in their analysis of the radar reception problem, Birdsall in paper [13] and Kelly et al in paper [14-15] adopt the philosophy of hypothesis testing. In the detection of a known signal in noise, which corresponds to a simple binary hypothesis testing, this theory results in a 'likelihood ratio test'. The likelihood ratio is defined by (using the terminology of Peterson et al)

$$I(x) = \frac{f_{SN}(x)}{f_N(x)} \tag{1.12}$$

where$f_{SN}(x)$is the probability density function of the n-dimensional sample vector x, given that the received signal consists of signal plus noise (designated as hypothesis H_1), while$f_N(x)$is the probability density function of$x$, given that the received signal consists of noise alone (designated as hypothesisH_0). Note that regardless of the dimensionality of x, the likelihood ratio$I(x)$ is a one-dimensional random variable. The decision-making process involves comparing$I(x)$ with some thresholdη as shown by

$$I(x) < H_1\ \eta \text{ or } > H_0 \tag{1.13}$$

This relation states that if the thresholdη is exceeded, the receiver decides in favour of H_1(i.e., signal is present); otherwise, it decides in favour of H_0 (i.e., no signal ispresent).

Various researchers investigated detection applications within the radar's field. They adopted different methods such as:

In paper [17] by Difranco and Kaiteris, the performance of electronically scanned radar systems is evaluated in clear and in barrage jamming environment. It is shown that the figure of merit for search radar in a heavy jamming environment is the average power side-lobe gain product; where side-lobe gain is defined as the inverse of the average side-lobe level. The figure of merit for a track system in a heavy jamming is the average power antenna gain side-lobe gain product.

Moustafa [18] introduced a design and implementation of a digital single pulse IF matched filter and a digital IF matched filter. The design in this thesis is based on the impulse invariance method. This process may be realized recursively and non-recursively. The implementation is based on the non-recursive one.

Bhattacharya and Mahapatra [19] described a formula of combatingrandom delay-Doppler clutter. Utilization of the ambiguity function of the signal can solve the problem. To match the clutter rejection ability, a similar filter receiver is assumed followed by the optimization of the transmitted signal parameters. The signal set chosen is the family of frequency-coded constant amplitude pulse bursts, and a criterion function is derived in terms of the frequencies of individual sub pulses. The suggested formula maximizes the detection potentials of the radar for every cluster distribution within the delay-Doppler plane of the radar.

In paper [20] by Schurmann, matched filters dependent on exact wake-signature models were connected to carry imaging radar-B engineered gap radar pictures and delivered top SNR estimations of 17-21 dB, exhibiting that wake signatures can be effectively abused for ship recognition. A battery (roughly 100) of filters can decide the ship heading to inside a few degrees.

ShixueCai and Deubes [21] proposed that a coordinated filter is utilized for picture edge recognition to augment the yield signal-to- noise of an edge administrator. The creators accept stochastic models for edge, foundation, and noise, characterize the recurrence exchange capacity of matched filters, and accomplish ideal edge location in the recurrence space. They propose two new administrators in the spatial space for perceiving edges in two-dimensional pictures. The first, called the normal distinction filter, joins the yields of two band-pass filters at two symmetrical introductions. The second edge administrator, called the middle contrast filter, is a change of the normal distinction filter.

1.4 Evaluation of matched filter design

The Matched Filter is a network whose frequency response function maximizes the output peak signal to mean noise ratio, this noise is Additive White Gaussian Noise (AWGN) with zero mean and variance $N_0/2$.

To avoid the growth of size, complexity, high cost and low reliability of analog techniques, it is also designed using a WDF approach, which has a big advantage compared to other digital filters based on bilinear transformations. It preserves the properties of analog filters in both the pass-band and the stop-band.

The introduced design of a SPMF in this thesis has the following properties:

- It has a good approximation of $sin(x)/x$frequency response.
- It is designed and implemented at the RF band unlike any conventional approximate IF matched filter.

CHAPTER 2

RADAR SYSTEMS THEORY AND FIELD PROGRAMMABLE GATE ARRAY “FPGA”

2.1 Theory of Radar

Radar stands for Radio detection and ranging. It consists of an electromagnetic system which helps to detect and locate the bodies present at a much higher distances. It can help to see the objects and this seeing is completely independent of the night, fog, smoke and other things which hinder the normal vision. There is a particular range of objects the radar can deal with convenience. A radar can also measure the instantaneous speed of an object which is moving away or towards the observatory station in a simple way.

There are many factors which place radar above normal vision and one of them is, with radar, the object can be seen at a much higher distance than the normal vision. The ability of the Radar to see and detect the object is not affected by the condition of light or the obstacles which come in its way. There are many factors in which Radar is inferior to normal eye. The picture which is provided by the Radar has poor quality. Even the most advanced Radar equipment which is currently available only provides the gross outlines of a large object. For instance, a normal eye can see the entire ship and fine details can be observed regarding the ship which is not possible with Radar.

2.1.1 Working of Radar

The operation of the radar is initiated by the generation of the radio waves from a transmitter. The radio wave must have noticeable amount of energy after being reflection from the object which is to be measured. The transmitter must be powerful. The wave after being reflection from the object is received by the receiver which most probably is located at the same position as that of transmitter for convenience. The echoes which are absorbed by the receiver help us to determine the properties of the object or they help us to make a picture of the object. There are many types of signals which the transmitter can send. The signals can be frequency modulated, c-w signals and signals modulated by the other techniques.

As it can be deduced that radar can work in situations like rain, fog and darkness. The object located at large amount of distances can also be observed where normal human eye is almost useless. Another important prospect is the fact that it can also measure the distance to the object. A radar consists of the following parts.

1) Receiving antenna.
2) Transmitting antenna.
3) Receiver.

The electromagnetic radiations are emitted by the transmitter and some part of these electromagnetic waves is transmitted back by the object. These reflected electromagnetic waves are received by the receiving antenna and then feed it to the receiver. The receiver then uses the energy and information contained in the e=wave received by the receiver and try to extract the location of the object, presence of the object, relative velocity and all other required information and data. The wave which is transmitted by the radar consists of the shape of rectangular pulses which are very narrow. These pulses are in the form of a train, and this is known as radar waveform. It must be kept in mind that there can be other type of waveforms too and it is not necessary to use these waves each time.

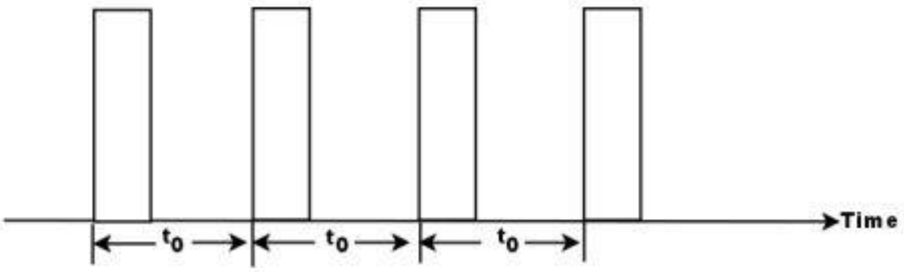


Figure 2.1 Typical Radar waveform

The figure 2.1 shows that after every $t_0$seconds, an electromagnetic pulse with a certain amount of energy is transmitted. The frequency of transmission, which is number of pulses per second is defined by the following formula

$$f_p = \frac{1}{t_0} \tag{2.1}$$

For instance, if electromagnetic wave is sent after 0.10 seconds then frequency of transmission is given by

$$f_p = \frac{1}{t_0} = \frac{1}{0.10} = 10\ Hz \tag{2.2}$$

If a pulse with a certain energy is sent at a given interval of time, it moves towards the target with a speed of c meters/second, strikes the target and then reflects and moves back with the same speed. The receiving antenna receives the reflected wave and the time T_R is measured which is the time between sending of the wave and it's receiving after being reflected back by the target. The distance to the target is given by the following formula

$$R = \frac{cT_R}{2} \tag{2.3}$$

The distance$R$ is in meters and c is normally considered to be the speed of light and its value is given by

$$c = 3 \times 10^8 \frac{m}{s} \tag{2.4}$$

The above derivation assumes that there is only one wave which is transmitted and received but in general there is a train of waves which is sent. In figure 2.2 the first one is transmitted by the transmitter and received before the second wave is transmitted so there will be no ambiguity as it will be clear that the first wave received is the reflection of the wave sent.

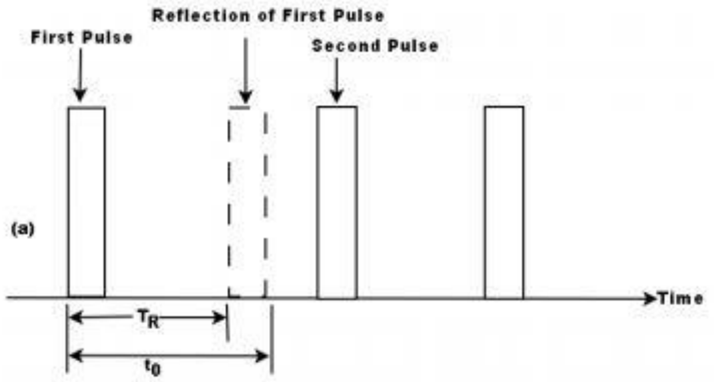


Figure 2.2 No Ambiguity

However, in the figure 2.3, it can be seen that the first wave is received after the second wave is transmitted so it will become difficult to identify whether the wave received is the reflection of the first wave or second wave.

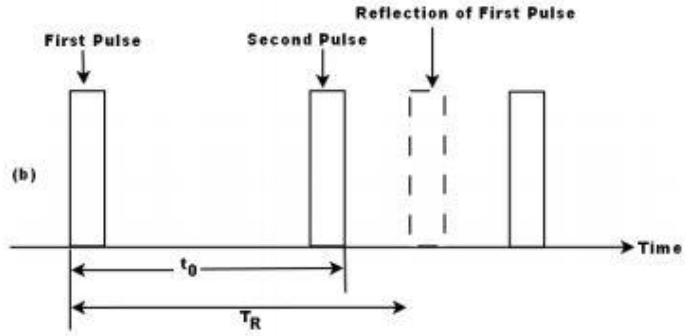


Figure 2.3 Ambiguity is present

So, in this way ambiguity occurs and some additional information is required by the radar to determine. This ambiguity does not occur if

$$T_R < t_0 \tag{2.5}$$

In the above case, the reflected wave is received before the transmission of the second wave. So, the maximum distance which does not introduce any ambiguity in the system is denoted by R_{unamb} and is given by the following relation

$$R_{unamb} = \frac{c}{2f_p} \tag{2.6}$$

It is known as maximum unambiguous range of radar.

2.2 Radar Receiver

As it is already seen that the pulse reflected by the object is taken by the receiver antenna and is fed to the receiver. There is a sufficient decrease in the amplitude of the pulse, so the firsts step is the amplification of the weak echoes, reflected by the object. After amplifying, the envelope of the pulse is detected. The pulse is amplified and then it is fed to the indicator.

The receivers which are normally employed have the capability to receive weak echoes and amplify them by a factor of 30 million. It is not easy to amplify the radar frequencies, so a superheterodyne receiver is used which changes the radar frequency to an intermediate frequency so that it can be amplified.

2.2.1 Requirements for Radar receivers:

The ideal receiver should have the following properties.

1) The amplification of the pulse should not introduce any noise or distortion.
2) Bandwidth characteristics should increase the probability of detection of the signal.
3) Dynamic range should be large enough so that it can deal with large clutter signals.
4) Interfering signals should be rejected so that the required information is properly dealt and information is optimally detected.

2.2.2 Minimum detectable signal:

There is another important aspect associated with the receiver and it is, the minimum amount of power which can be received by the receiver as this factor helps in the determination of the maximum range performance of the radar. MDS has got a sensitivity level of around 10^{-13} watts for radars.

Based on requirements, a receiver is designed for a particular sensitivity value. If a designer designs a receiver with more sensitivity level than required, it would decrease the bandwidth of the system and in this way the receiver will be able to process the signals which are not required. If the sensitivity is set at higher power levels, the number of false alarms will be small which are going to be processed and along with this, the probability of the detection of the good signal, containing lower noise value will decrease.

2.2.3 Bandwidth

Another most important factor is the noise of the receivers as the receiver adds a certain amount of noise in each signal present at its input and the radar receiver has no exceptions. Even if the receiver is designed with proper care and keeping all the factors which will reduce the noise into consideration, the noise is introduced due to the thermal motion of the electrons in the resistive components of the receivers and it cannot be reduced. The amount of noise introduced due to thermal motion is directly proportional to the bandwidth of receiver. Therefore, in order to reduce this noise, the bandwidth of the receiver must be reduced. But as the bandwidth decreases, the receiver fails to amplify and process the reflected signals. So, there must be a trade-off.

In normal practice, the bandwidth of the receiver is taken as the reciprocal of the duration of the pulse. For instance, if a pulse has 1 micro second duration then the bandwidth of the receiver must be around 1 Mhz.

2.2.4 Superheterodyne receiver

The received RF or radio frequency signals must be transformed into video signal so that the required information can be extracted from the echoes. This conversion is achieved with the help of Superheterodyne receiver and the important components of the receiver are provided below in figure 2.4.

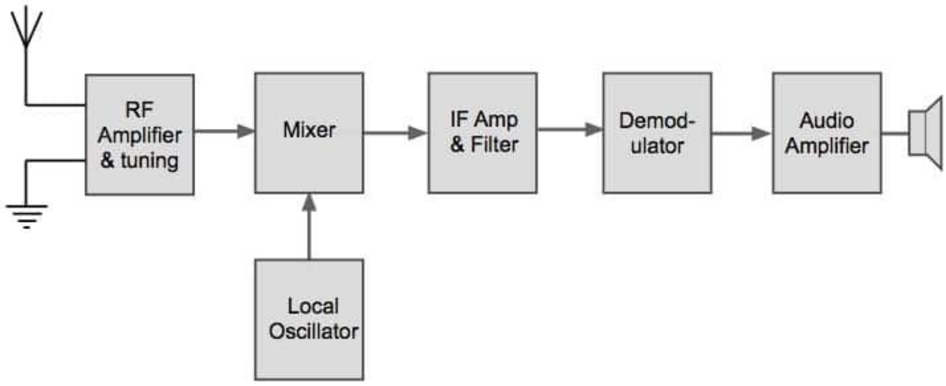


Figure 2.4Block diagram of a Superheterodyne receiver

The Superheterodyne receiver helps to reduce the RF frequency into a lower IF frequency which makes it easier to process. In the next step this IF frequency is going to be amplified and demodulated which in return will provide u with the video signal.

The figure 2-4 shows the block diagram of Superheterodyne receiver. The reflected wave comes in after being received by the antenna and it is fed to the filter. The filter provides us with the frequencies required for our desired frequency band. After filter stage, there comes a mixer stage. The filter has also got the input from the local oscillator. These two signals, one which is coming from the filter while the other one is coming from a local oscillator, beat together, which in return produces the required IF signal through the process of heterodyning. There is a fixed frequency difference between the RF signal and the local oscillator and this frequency difference is known as IF. This IF-carrier is then fed to IF amplifier which then feeds it to the detector.The detector output consists of the video component of the input signals.

2.2.4.1 Image frequency filter

Ahead of the converter or mixer stage as it can be observed in figure (2.4), there comes a low noise RF amplifier stage which helps in the reduction of the unwanted signals from RF and helps in the addition of the sensitivity of the receiver. Image frequencies are removed by selecting appropriate borders of the bandwidth of the amplifier.

Some of the older radar receivers do not employ any of such low noise RF filters and they feed the RF signal directly to the mixer stage and this can lead to many disadvantages.

2.2.4.2 Mixer stage

The mixer stage helps to get the IF frequency from RF wave. For achieving that purpose, the mixer also receives input from local oscillator. Then heterodyning process takes place and IF frequency is achieved.

$$f_{IF} = f_{rx} - f_{local} \tag{2.7}$$

$$f_{IF} = f_{local} = f_{rx} \tag{2.8}$$

For instance, if the required intermediate frequency is 60 MHz, then the local oscillator will track its frequency to be more than 60 MHz than that of the incoming signal. For instance, if a receiver is tuned to receive signal with frequency of 1030 MHz and if the local oscillator is tuned to frequency 1090 Mhz. Both the received and local signals are going to be mixed and the frequency obtained as a result of mixing is going to be difference of both frequencies which is 60 Mhz. This IF frequency is then going to be magnified in the IF stages and later sent to the detector stage.

2.2.4.3 IF filter

This filter must be able to generate the required intermediate frequency from the mixer frequencies generated in the mixer stage. It consists of bandpass filter which can be one or more in number.

The band pass filter employed has narrow bandwidth as the energy of the signal must not be affected.

2.2.4.4 IF amplifier

The bandpass and gain of the signal can be amplified. The signal which is converted to IF signal, it is amplified by employing several IF amplifiers stages. IF amplifier stages are responsible for the gain of the receiver signal. The bandwidth of the IF stages determine the bandwidth of the receiver. The gain of the IF stages must be variable so that a constant output signal can be achieved for different amplitude inputs.

2.2.4.5 Detector

The detector is employed to serve the purpose of conversion of IF pulses into video pulses. The simplest is the diode detector which is given in the figure 2.5 below.

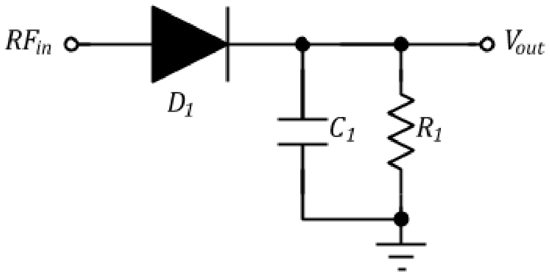


Figure 2.5 Simple detector circuit

2.3 FMCW Radar

FMCW radar is also known as frequency modulated continuous wave. It is a special type of radar sensor which like a continuous wave radar emits continuous transmission power. However, it is different to Continuous wave radar in a way that it can change its operational frequency at the time of measurement which means that the transmitted signal is modulated in phase or frequency. Run time measurements are only possible when the operating frequencies can be changed during measurements.

Simple continuous wave radar system carries a disadvantage which is, they cannot measure the range properly because it does not have timing mark which is necessary in the measurement of the time taken between the transmission and receiving of the signal and this time helps in the measurement of the range.

In these radars a signal is transmitted which has an increase or decrease in the frequency periodically. After receiving the echo signal, the change in frequency has got a delayΔt, the basic characteristics of FMCW radars are given below.

1) It has got the ability of the measurement of small ranges.
2) The radars have the ability to measure the velocity and target range simultaneously.
3) The range measurements have great accuracy.
4) The signal is processed after mixing at a very low frequency range which simplifies the realization of the circuits which process the signal.

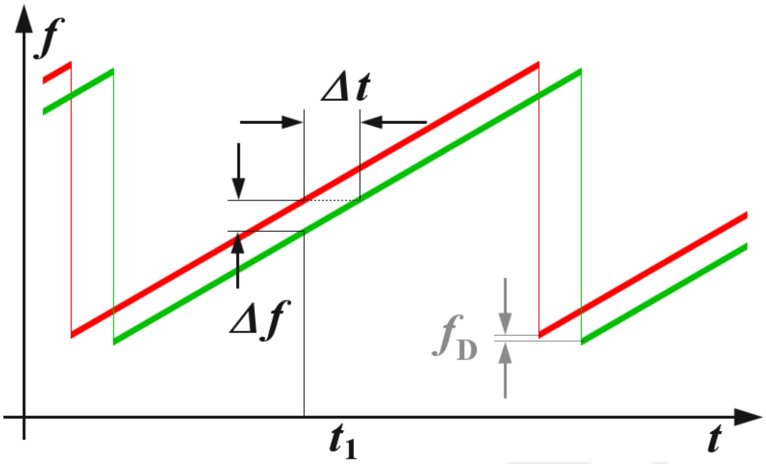


Figure 2.6 Ranging with an FMCW radar

2.3.1 Principle of measurement

The way in which FMCW Radars measures is given by

1) The distance is measured by the comparison of the received signal's frequency with a reference which most of the times is transmitted signal.
2) The transmitted waveform's duration is higher than the time required receiving time.

The distance$R$ can be measured with the help of the following relation

$$R = c_0 \frac{|\Delta t|}{2} = \frac{c_0 |\Delta f|}{2\left(\frac{df}{dt}\right)} \tag{2.9}$$

where

c_0	Speed of light
Δt	Delay time (s)
Δf	Measured frequency difference
R	Distance between antenna and reflecting object
$\frac{df}{dt}$	Frequency shift per unit of time

Table1 Parameters of the range equation

If the change in the frequency is linear when observed over a wide range, then the range can easily be measured by simple comparison. The difference in frequency Δf is directly proportional to the range.

2.3.2 Modulation pattern

There are several modulation patterns which can be employed for the measurement purpose.

- **Sawtooth modulation:** This modulation technique is employed when range is relatively longer along with negligible effect of Doppler frequency.
- **Triangularmodulation**: This technique assists in separation of frequency difference of Doppler frequency.
- **Stepped modulation**: For interferometric measurements, stepped modulation technique is used.
- **Sinusoidal modulation:** These modulation techniques have been used in the past.

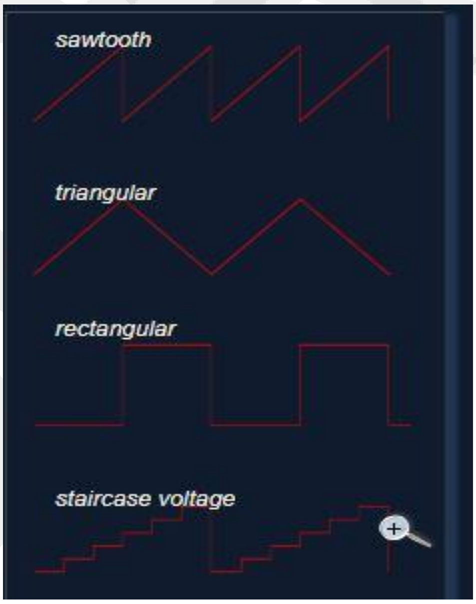


Figure 0.7 FMCW modulation techniques

2.4 Pulse compression

Pulse compression is a technique or term which can be described as a wave shaping process. This process is required when a propagating waveform is disturbed or modified because of the network properties which represent the transmission line.

In this method, the pulse is modulated internally in either frequency or phase, and in those targets can also be resolved which have overlapping returns and this is known as intra pulse compression. The idea of the pulse compression originated with the desire of amplifying the transmitted pulses. In this method, the high energy of the pulse with long width is combined along with the high resolution of the short pulse. The method is described with the help of the following figure 2.8.

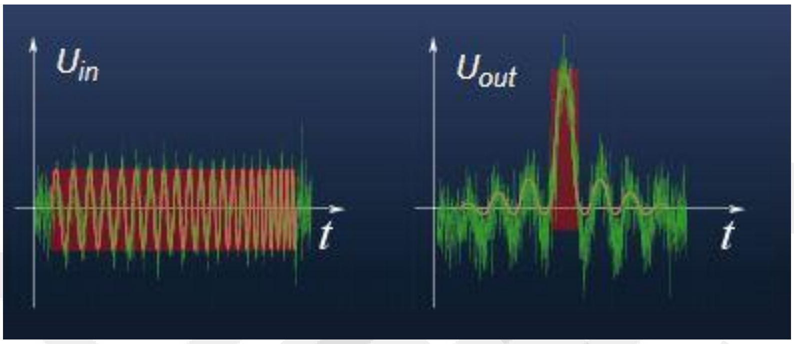


Figure 0.8 Input and output of the pulse compression

The older type of the pulse radars require high power to achieve for getting the required range. Also, there is another condition by which the transmission pulse should be as small as possible because range resolution is affected by this parameter. These radars should be capable of generating and radiating the required transmit power in micro or Nano seconds. For this purpose, powerful transmitter and modulator vacuum tubes are used.

When solid state technology is employed, high power transmitters have not been produced such as high-power pulses. This is because they have limited dielectric strength and their working temperature range is also limited. Therefore, in such radar transmitters, for transferring the wave with high amount of energy, longer duration of the pulse is required. So, to improve the radar pulse resolution, the pulse needs to be modulated internally. The frequency is unique in each part of the pulse due to which the echoes can be separated completely and combined into a small output pulse. The returned signal or the echo signal is compressed in special filters in its duration. Due to which this process is known as pulse compression.

2.4.1 Types of Modulation

The types can be

1) FM modulation
2) PM modulation.

In FM modulation which is also known as frequency modulation, there are three more types which are given below.

- Linear.
- Non-linear.
- Time frequency coded waveform.

2.4.2 Pulse compression with linear FM waveform:

In this method, the pulse which is going to be transmitted has got linear FM waveform. In this method wiring is kept simple. It also carries one disadvantage which is that, jamming signals can be generated easily. The following block diagram will explain the things in more detail.

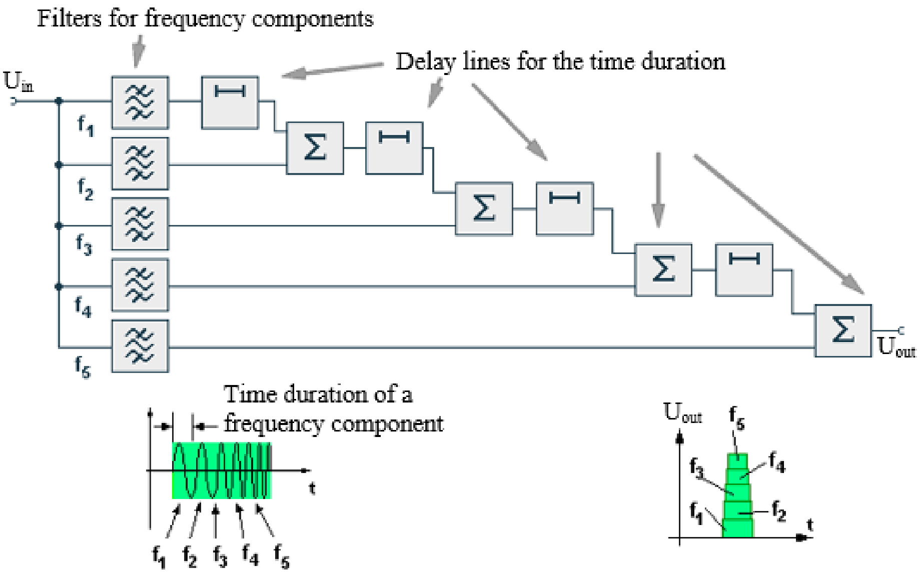


Figure 0.9 Block diagram for the method

The compression filters present has simply got dispersive delay lines which contain a delay and this delay is a linear function of the frequency.

2.5 Matched filter

A matched filter is an optimal solution for improving the signal to noise ratio. These filters are mostly employed in the signal detection. They correlate a known signal with an unknown signal to detect the presence of known signal in the unknown signal.

In case of radars, there is a problem which is, both the received signals and the template are unknown signals. Many reflected signals (echo) are changed due to the Doppler effect to a much extent. They are altered by such a huge amount that it becomes completely different f the transmitted signal and it is no longer reflection of the signal which is sent by the transmitter. The reflected signal can be integrated with the different Doppler frequencies.

The pulse compression circuit is the perfect example of the matches filter and this is already explained in the topic 2.4. It is necessary that both the transmitted and received signals must be same in shape. But if echo signal is superimposed by the Doppler frequencies then this filter is not effective. In that case all frequencies are going to be shifted in a certain direction and either the lowest or the highest frequency is not included in the signal processing. Modern radar systems can deal with this effect.A probable solution can be these frequencies are not necessary for signal processing. So that even a target character is going to be produced when any of the two frequencies is not present. Another solution can be in which the filter will deal with the additional frequencies. Improves system will take into account each Doppler frequency separately so a large number of filters are going to be connected in parallel. The diagram is shown in figure 2.10.

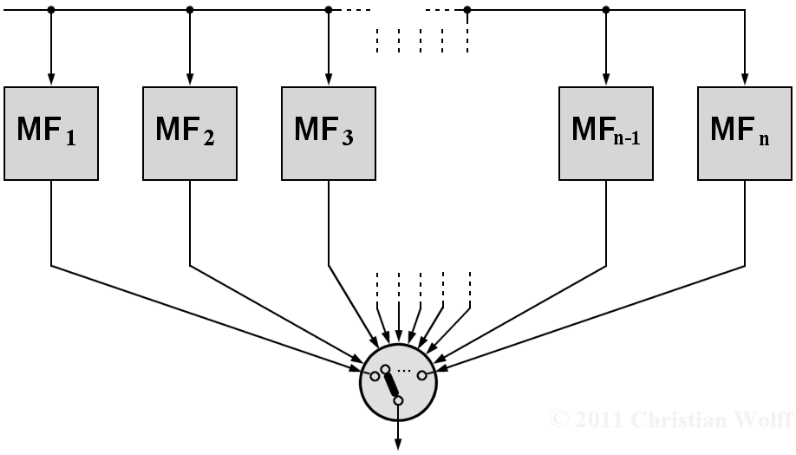


Figure 0.10 Parallel circuitry of large number of filters

2.6 FPGA

FPGA stands for functional programmable gate arrays. This is a device which is mostly employed in digital electronic circuits or logic circuits. They consist of programmable logics and are made up of semiconductor devices. They can be programmed with the help of Verilog. The programmable logic components can consist of anything like gates, memory elements, blocks of memories etc.

2.6.1 FPGA working

The great advantage which FPGA carries is that chip can be re-programmed again and again as required and is completely programmable. In other words, it can be called as a large digital circuit which can be configured as required according to the design. If a circuit board is being manufactured and it contains FPGA as its part, then it is programmed in the manufacturing process, but it can be re-programmed again.

As it is already discussed that they contain many advantages but there are certain disadvantages which are associated with them. They are slow than other devices like microcontrollers or another equivalent IC’s. Along with this, they are more expensive than other IC’s.

FPGA’s are used in many applications. However, keeping in view their cost, they are not used in high volume cheap products. They find its applications in places where complex logic circuitry is required. They include applications in large areas from equipment for imaging and video to circuitry for military applications as well as in electronic circuits.

2.6.2 FPGA internals

The internal structure of the FPGA consists of two basic elements.

1) Common Logic blocks array.
2) Routing channels.

The logic block which constitute the FPGA can be implemented in many ways. The way in which it can be implemented depends upon the manufacturer. The variations occur in the number of inputs and outputs, the complexity of the logic blocks in terms of the circuitry and the number of switches or transistors used. These directly affect the area which is covered on the chip and as the area increases the size of the silicon which is used also increases.

The FPGA internal routing system consists of the electrical wires which are interconnected through electrically configurable switches. With the help of this, different points on the chip can be linked together which means the connection of the different common logic blocks.

2.6.3 Designing with FPGA

The function of the FPGA is designed with the help of software programming. The design process on FPGA is started by user providing a hardware description Language or a schematic. Common hardware description languages include Verilog, VHDL. The next task on the FPGA design is the generation of the netlist for the FPGA family used. The netlist is then fitted on the FPGA architecture with the help of a process known as “place and route”.Finally, the FPGA is programmed, and design is placed on FPGA.

2.6.3.1 Verilog

Verilog is a hardware description language which means it can document the electronic and digital circuits. Verilog is employed for verification through simulation, for testing purposes and for timing analysis. Logic synthesis is another important application.This language helps the designers to design at various levels of abstraction. Mostly Verilog is the most widely used hardware description language and over 50,000 active designers employ this hardware description language. A digital system can be described by this language. The digital system can be a microprocessor or a simple flip flop. The simple flip flop is given by:

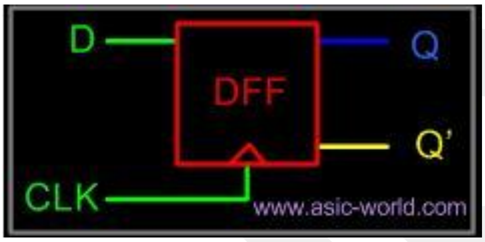


Figure 0.11 A simple D flip flop

With the help of Verilog, the D flip flop can be designed as

```
// D flip-flop Code
module d_ff (d, clk, q, q_bar);
input d,clk;
output q, q_bar;
wire d,clk;
reg q, q_bar;

always @ (posedgeclk)
begin
q <= d;
q_bar<=! d;
end

endmodule
```

The Verilog HDL language has been chosen to be used in this thesis because it’s easier than VHDL and can be learned in a shorter time. Also it’s suitable for the small and medium projects.

2.6.4 FPGA testing and debugging

As the circuitry can be complex so rigorous testing should be done on the FPGA design. The stage needs to be done at each stage of the development process. The testing includes timing analysis, simulation and many other methodologies.

When the design is completely validated then a binary file is generated which helps to configure the FPGA. After that there are several ways to debug the design on the FPGA, one is to use the debugging cores like ChipScope or ILA IP Core, which already exists in the programming software, and this way is more favourite to be used in common, and it’s the used way to debug the results in this thesis. The other ways can be done by sending the data through the serial port of the FPGA to a host PC using UART and read it over there, or to record it in an SD card then display it on a software in the PC.

CHAPTER 3

HARDWARE IMPLEMENTATION OF MATCHED FILTER USING FIELD PROGRAMMABLE GATE ARRAY (FPGA)

3.1 What is a FPGA?

FPGA is an integrated circuit which has numerous indistinguishable Configurable Logic Blocks (CLBs) which may be modified to do distinctive arithmetic or Logic functions. These respective squares are connected through a framework of programmable switches and wires. Figure 3.1 demonstrates the inner architecture of FPGA.

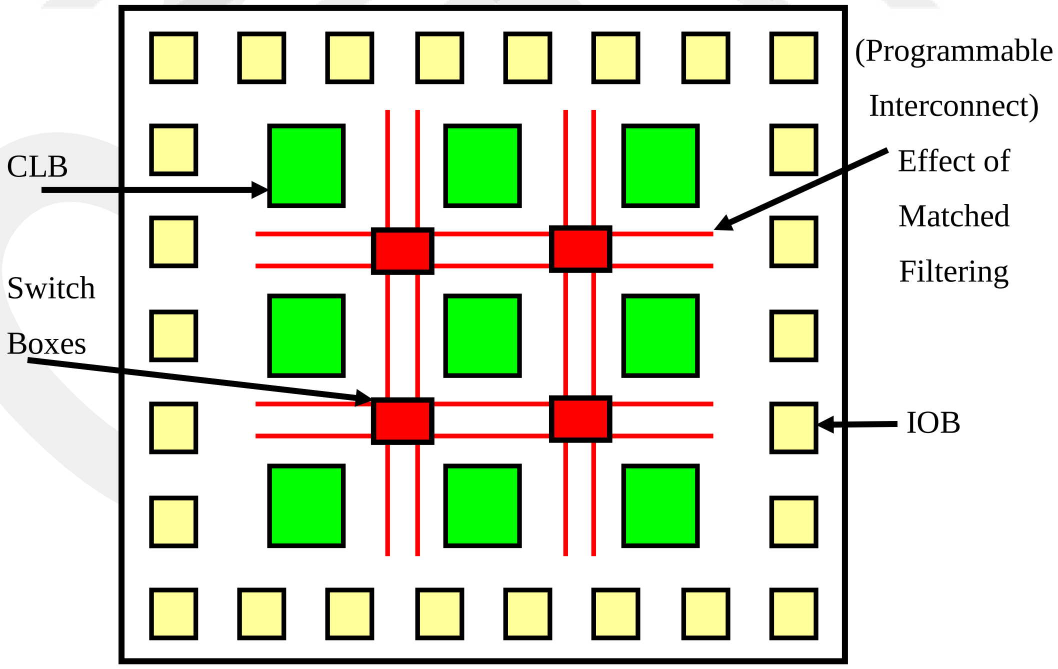


Figure 0.1 Internal structure of FPGA

Field Programmable implies that the FPGA's function is characterized by a client's program as opposed to by the producer of the device. A client's outline is actualized by indicating the straightforward logical function for each CLB and specifically shutting the switches in the interconnect matrix. Complex plans are made by consolidating these fundamental squares to make the coveted circuit.

Contingent upon the specific FPGA device, the outlined program is either scorched in for all time or is stacked from an outer memory each time the device is fuelled up.

Using an external memory has the following advantages:

- Reprogramming the settings of the Read Only Memory (ROM) can fix bugs.
- One can force the FPGA to reset “in system “to give it the ability to perform diverse tasks as found necessary.

Diverse manufacturers have diverse designs for their FPGA devices, but fundamentally they share a similar fundamental idea FPGA mainly consists of three parts: interconnection matrix, the I/O cells and the logic cells. These parts will be explained briefly in the following section [29].

3.1.1 The Logic Cells

Logic cells, or Configurable Logic Blocks (CLBs), are blocks of reason that can be organized to give the user’s needed logic performance. Logic cells have multiplexers, logic function generator sand flip-flops that are typically applied as lookup tables (LUTs). Each LUT has a group of inputs and outputs. Several LUTs may be utilized to produce a single complex functionality. In given FPGAs, Random Access Memories (RAMs) and ROMs are accessible to the designer. Memory devices are severally implemented in LUTs in the logic cells, although other devices have separate cells to implement them. The existence of flip-flops inside the logic cells makes FPGA ideal for pipelined designs.

3.1.2 The I/O Cells

These cells offer the interfacing of the internal logic and the external device package pins. Every I/O cell is connected to an external package pin and could be set for bi-directional signals, output, or input. several applications need the outputs and inputs to be registered, so the I/O cells frequently have flip-flops in them.

3.1.3 The Interconnect Matrix

I/O cell sand the logic cells are linked together with a routing matrix. This matrix offers a way of joining cells to each other. Diverse vendors have varying methods of offering routing.

3.1 Producing an FPGA Design

The design with FPGA involves different steps these steps are illustrated in figure3-2and it includes the design entry either by HDL coding or by schematic capture, then the function simulation to make sure that the design is performing the required function correctly, the next step would be the logic union. The logic synthesizer takes the incorporated source and delivers a computerized logic identical for it.

When the logic has been combined, the fitting programming needs to play out a place-and-route. This procedure takes all the integrated logic and connects it inside the FPGA.

After place and route, the outline must be re-mimicked with the new planning parameters delivered by the genuine design. In the event that everything has gone well, the new reproduction results will concur with the anticipated outcomes. Something else, if the issues experienced are noteworthy, at least one segments of the FPGA may should be overhauled.

When the place-and-route has occurred, a design record is produced for the objective gadget. Since most FPGAs at present utilized are SRAM based, they must be customized or designed on catalyst. There are various methods for playing out this progression yet the most well-known is to utilize a sequential programming ROM. This ROM has an interior location counter and for the gadget programming, it gives the required signs and information to the FPGA.FPGAs are regularly programmed by means of their JTAG (Joint Test Action Group) port.

Testing the programmed device means to verify that it works as expected. This is done by applying input signals to the device and checking the corresponding outputs.

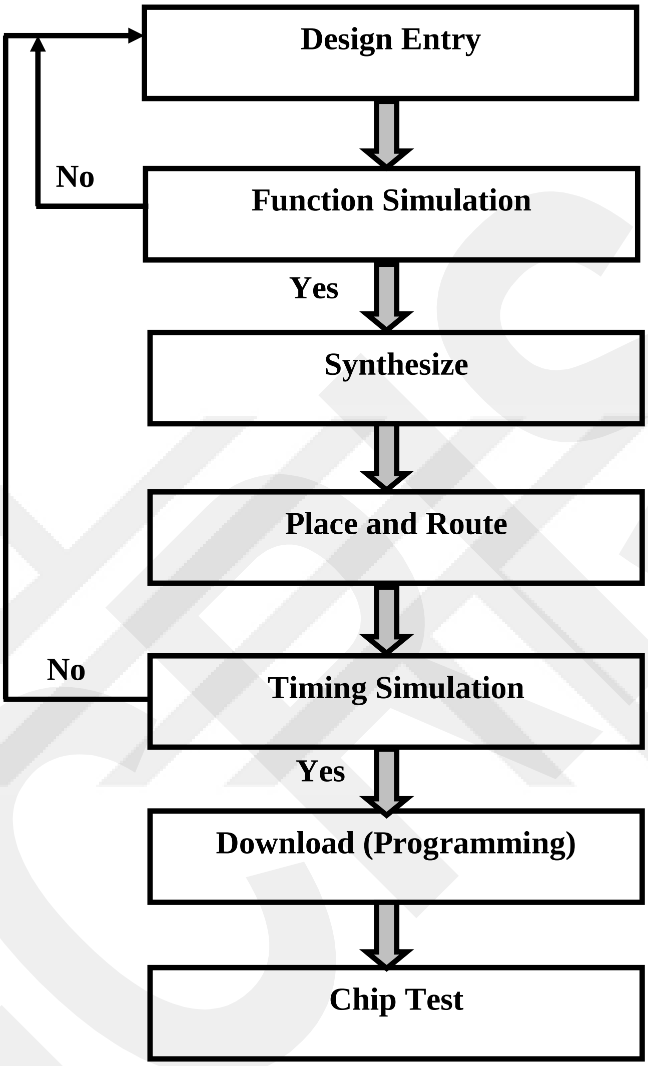


Figure 0.2 FPGA design flow

3.2 The Used FPGA Kit

Different companies produce different development kits to be used for prototype designing, downloading, and testing. In the present work, the ARTIX-7 Arty board is used. This kit was introduced by Xilinx, a pioneer company in the world of Programmable Logic Devices (PLDs)[32].The Spartan-3 kit consists of a two main parts; software and hardware.

The software development tool used is Vivado 2017.1

The hardware part is the ARTY board this board includes is based on the Artix-7 FPGA chip in a thin Ball Grid Array package.

The Arty Board has the following features:

- Xilinx Artix-35T FPGA:
  - 33,280 logic cells in 5200 slices (each slice contains four 6-input LUTs and 8 flip-flops);
  - 1,800 Kbits of fast block RAM;
  - Five clock management tiles, each with a phase-locked loop (PLL);
  - 90 DSP slices;
  - Internal clock speeds exceeding 450MHz;
  - On-chip analog-to-digital converter (XADC).
  - Programmable over JTAG and Quad-SPI Flash
- System Features:
  - 256MB DDR3L with a 16-bit bus @ 667MHz
  - 16MB Quad-SPI Flash
  - USB-JTAG Programming circuitry (USB Micro cable required, NOT INCLUDED).
  - Powered from USB or any 7V-15V source
- System Connectivity:
  - 10/100 Mbps Ethernet
  - USB-UART Bridge
- Interaction and Sensory Devices
  - 4 Switches
  - 4 Buttons
  - 1 Reset Button
  - 4 LEDs
  - 4 RGB LEDs
- Expansion Connectors:
  - 4 Pmod connectors
  - Arduino/chip KIT Shield connector

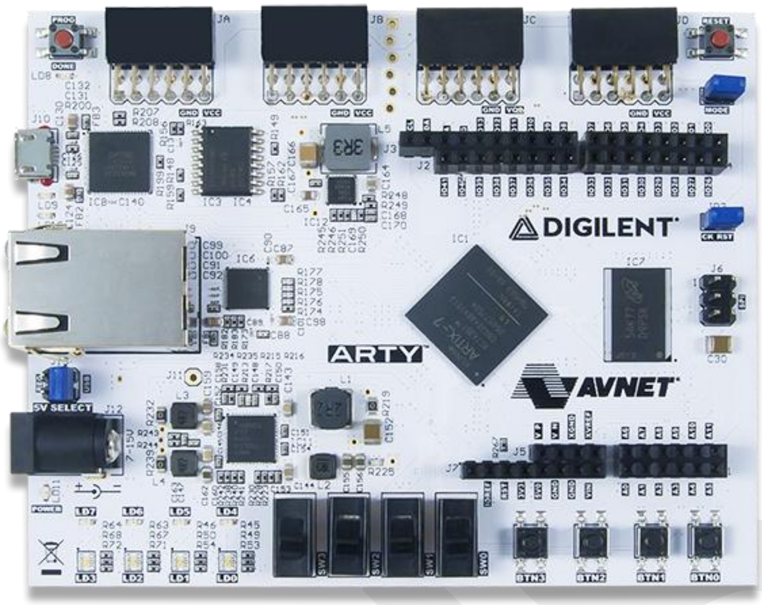


Figure 0.3 Arty board

3.3 Software Packages

The software packages used includes a specific IDE tool for building the complete design on Xilinx FPGA, and a simulation software to verify the functionality of the design before performing the hardware implementation.

The design IDE is responsible for creating the design codes, block diagrams and IP cores and writing test benches, and the simulation software is used for performing all required functional and timing simulations based on the written test benches.

3.4.1 Vivado 2017.1

The Vivado 2017.1 design suite is used for developing the hardware design and implementing it on the Arty board. The Vivado offers different design sources including HDL coding, Block diagram and IP-core generation, other sources such as soft-processors and hard-processors can be used using the Vivado.

3.4 Design and implementation of the Matched Filter using FPGA

This section includes a detailed description of the hardware implementation of the Matched filter on the Arty Board. The selection and configuration of the IP cores also shall.

3.5.1 Introduction

A digital filter can be realized either in time domain or in frequency domain. In case when the filter coefficients are more than 128 the filter cannot be implemented in hardware due to the large number of the multiply add operations required. In this case filtering in frequency domain is more practical.

The following block diagram shows the design used in the implementation of the Matched filter in frequency domain, the input signal is converted to frequency domain using FFT, then it is multiplied by the FFT of the stored replica of the transmitted signal.

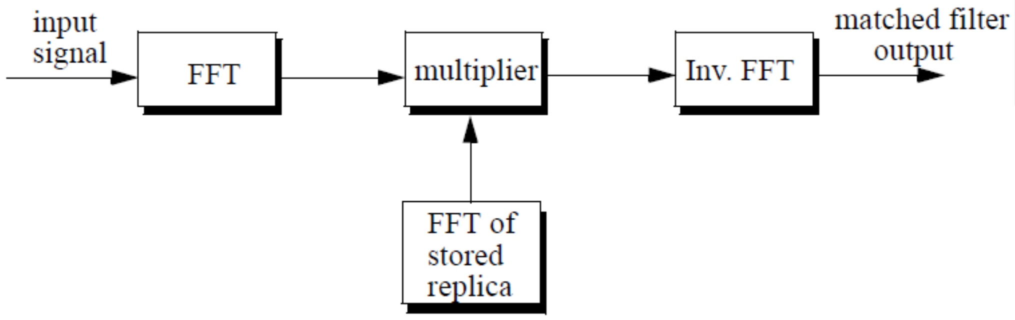
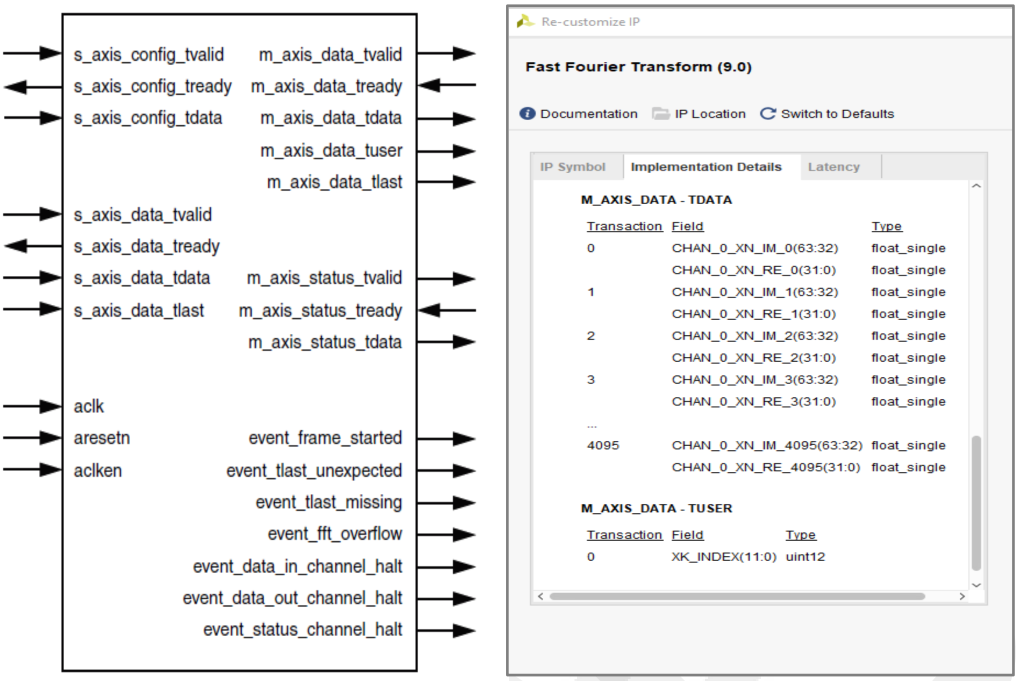


Figure 3.4 Matched Filter block diagram

3.5.2 FFT and Filter Design

The Xilinx IP (intellectual property) core V9.0 for FFT is used to realize the fast convolution. This core computes an N-point forward FFT or inverse FFT (IFFT) where N can be $2^m, m = 3, 4, 5, \ldots, 16$.The input data is a serial vector of N complex values represented as b_x bits two’s complement numbers (b_x bits for each of the real and imaginary components of the data sample such thatb_x =8, 12, 16, 20, 24). Similarly, the phase factors (FFT weights) can be 8, 12, 16, 20, or 24 bits wide.

The N elements output serial vector is represented using by-bits for each of the real and imaginary components of the output data (by depends on b_x).Input data is presented in natural order, and the output data can be in either natural or bit/digit reversed order. Figure 3.5shows a functional block of the used FFT core.



Fast Fourier Transform (9.0)

M_AXIS_DATA - TDATA

Transaction	Field	Type
0	CHAN_0_XN_IM_0(63:32)	float_single
	CHAN_0_XN_RE_0(31:0)	float_single
1	CHAN_0_XN_IM_1(63:32)	float_single
	CHAN_0_XN_RE_1(31:0)	float_single
2	CHAN_0_XN_IM_2(63:32)	float_single
	CHAN_0_XN_RE_2(31:0)	float_single
3	CHAN_0_XN_IM_3(63:32)	float_single
	CHAN_0_XN_RE_3(31:0)	float_single
...		
4095	CHAN_0_XN_IM_4095(63:32)	float_single
	CHAN_0_XN_RE_4095(31:0)	float_single

M_AXIS_DATA - TUSER

Transaction	Field	Type
0	XK_INDEX(11:0)	uint12

Figure 3.5 FFT IP core v 9.0

The input signal of the FFT core which was generated previously on MATLAB is a floating point format signal which means it has 32 bits width and that’s what the FFT IP core requires as an input, the output of the FFT core is classified into real and imaginary components, the first 32 bits (from 0 to the 31^{th} bit) of the FFT output (m_axis_data_tdata) represents the real component of the output signal while the last 16 bit (From 32 to 64^{th} bit) represents the imaginary component as it’s shown in the figure above.

The Radar system has a Tr of 4 us and the sampling frequency is 100 MHZ, therefore the FFT length chosen is 4096 points. In order to save resources Radix-2 lite architecture was chosen for implementing the FFT.

The Matched filter is a filter whose coefficients are the replica of the transmitted signal, therefore a replica from the generated wave is padded with zeros to represent the 4096 point coefficients of the filter.

The FFT for the filter coefficients was calculated using MATLAB then stored in 2 ROMs(real coefficients and imaginary coefficients) to be multiplied by the results of the FFT, this multiplication is complex multiplication performed using adder subtractor and 4 multipliers, it calculates the product as follow:

Assume the FFT output= $R1 + jI1$

And the ROM output= $R2 + jI2$

The product is calculated as follow:

$$(R1R2 - I1I2) + j(R1I2 + R2I1)(3.1)$$

All the Multipliers, Adders and subtractor are generated using IP cores then these IP cores are instantiated in a complex multiplier top Verilog file. The complex multiplier connects the IP cores as shown in figure 3.6.

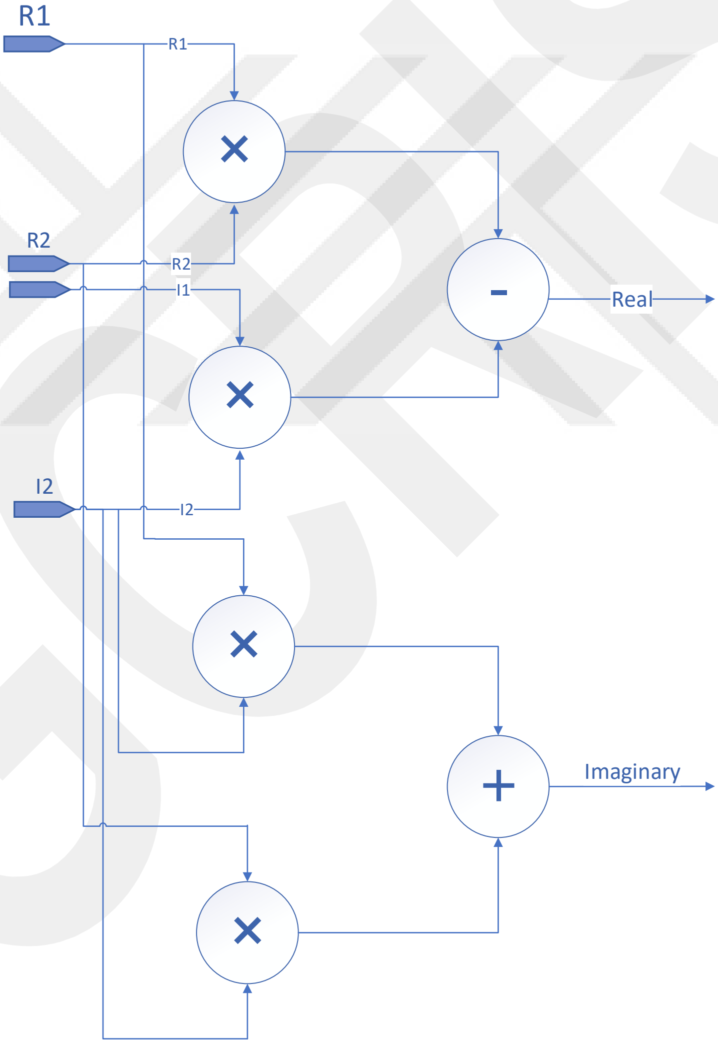


Figure 0.6 Complex Multiplier

The result of the complex multiplier is then applied to IFFT to return the signal back to time domain.

3.6 Testing and verification

In order to test the Filter, the wave form generator output is connected directly to the Filter input, the waveform itself is a block memory storing the digital values representing the waveform. This digital values can be used to represent also the waveform + noise in order to test the matched filter performance.

The output of the Matched filter is connected to integrated logic analyzer ILA IP core, this IP core can be instantiated and connected inside FPGA design to capture a predefined amount of data inside the FPGA and send it to PC through the JTAG port. The ILA IP core is shown in Figure 3.7 [39].

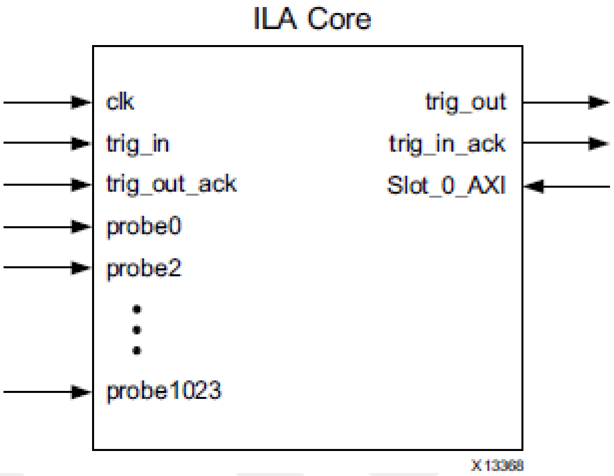


Figure 3.7 ILA debugging core

In order to test the filter and prove that is working sufficiently, the filter has been tested with several scenarios and with different input signals. It was tested with normal echo signal with noise and without, with a delayed echo signal with noise and without, with 2 echoes in the same signal with noise and without. Also, to verify that this filter is working well an only-noise signal has been applied to the filter as an input. Each test has done on the FPGA is being done on MATLAB too to compare the results and approve that the Matched Filter is working well. All the testingscenarios and their results are discussed and shown below.

3.6.1 Echo signal without noise

In the first test a normal echo signal without any noise or delay is used to test the Matched Filter to verify the matched filter operation known as pulse compression.

Figure 3.8.1 shows the input pulse on the first axis and the compressed pulse (matched filter output) on the second axis.

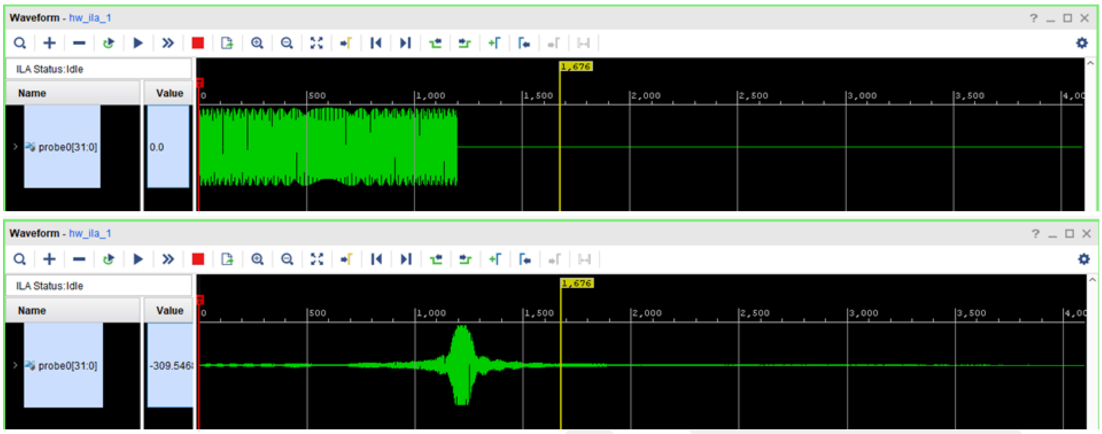


Figure 3.8.1 Signal without noise on FPGA

The figure 3.8.2 shows the same test results but on MATLAB, and it clearly looks the results of the FPGA and MATLAB are identical.

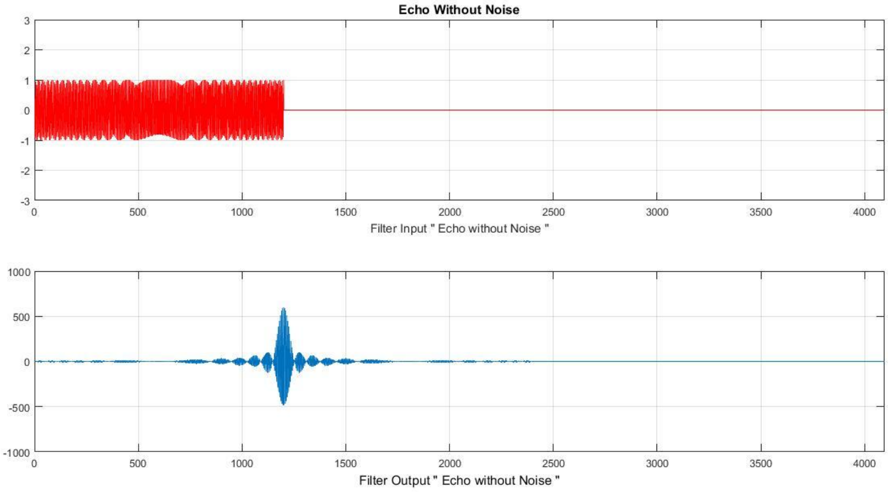


Figure 3.8.2 Signal without noise on MATLAB

3.6.2 Echo signal with noise

In order to verify that the matched filter increase signal to noise ratio, the input pulse is replaced with and input pulse + noise at a noise level of 0 dBm (signal power = noise power), in figure 3.9.1 it is shown that the input pulse on the first axis is completely immersed in noise and the filter output on the second axis can still show the compressed pulse.

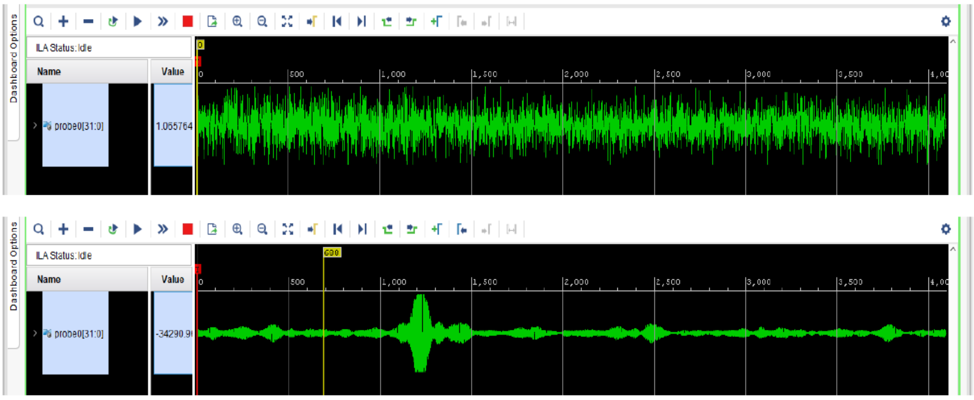


Figure 3.9.1 Signal with noise on FPGA

Figure 3.9.2 shows the output of the filter on MATLAB when the input is noisy echo signal.

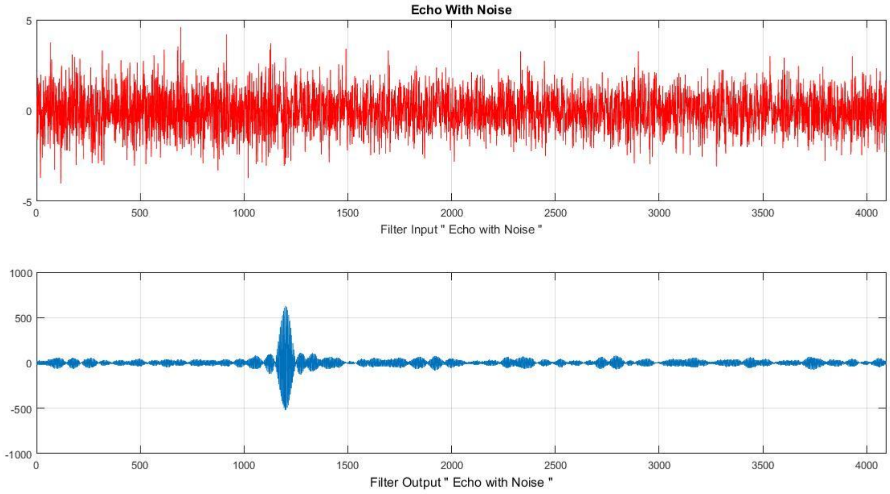


Figure 3.9.2 Signal with noise on MATLAB

3.6.3 Echo signal with delay

Now, a new test scenario is going to be done, the Matched Filter will be tested by inserting an echo input signal without noise, but with delay, because this delay is being useful to give information about how much the target is far from the radar. Figure 3.10.1 contains both the input and the output of the Matched Filter on FPGA.

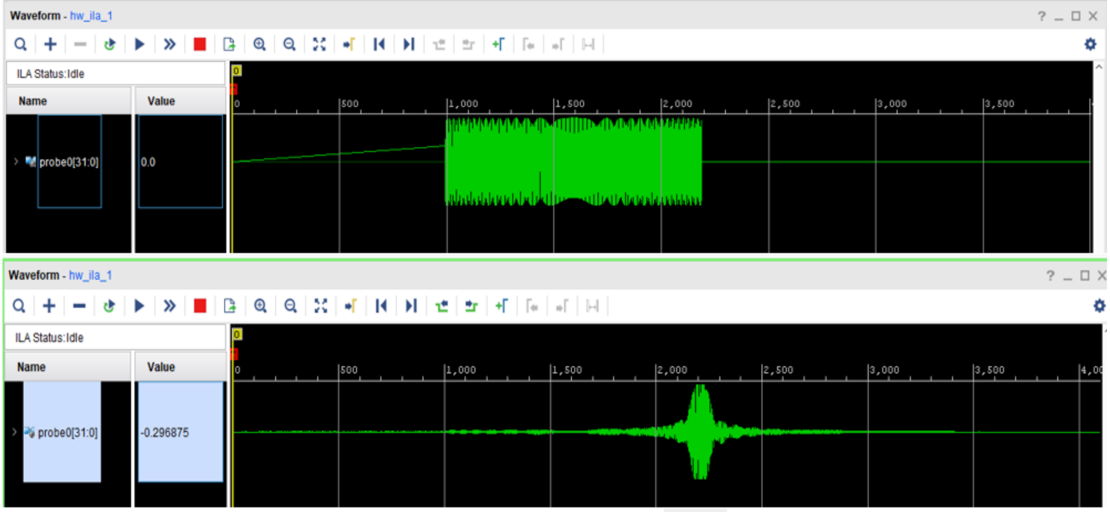


Figure 3.10.1 9Echo signal with delay on FPGA

As shown above, this signal will be applied to the Matched Filter on MATLAB, the result is shown in figure 3.10.2 below.

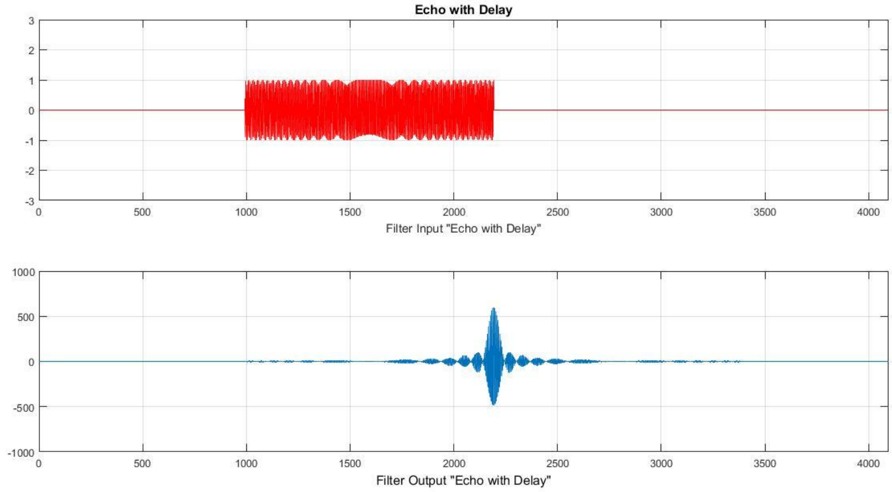


Figure 3.10.2 Echo signal with delay on MATLAB

3.6.4 Echo signal with delay and noise

Now, and as was done in the previous tests, a noise will be the added to the delayed echo signal to verify the performance of the filter with this scenario, the signal is applied to the filter on the FPGA and figure 3.11.1 shows the both input signal and result.

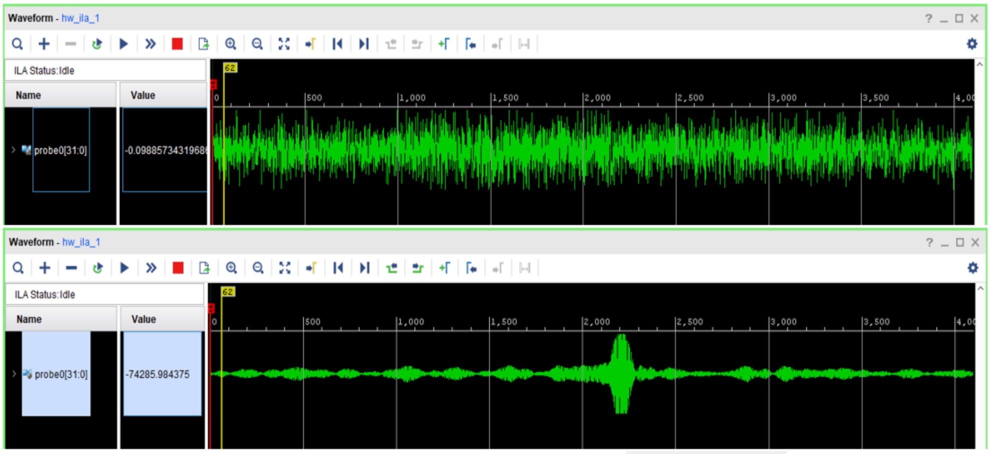


Figure 3.11.1 Echo signal with delay and noise on FPGA

After applying the signal to the filter on FPGA, it has been applied to the filter on MATLAB as well and the result can be seen in figure 3.11.2 below.

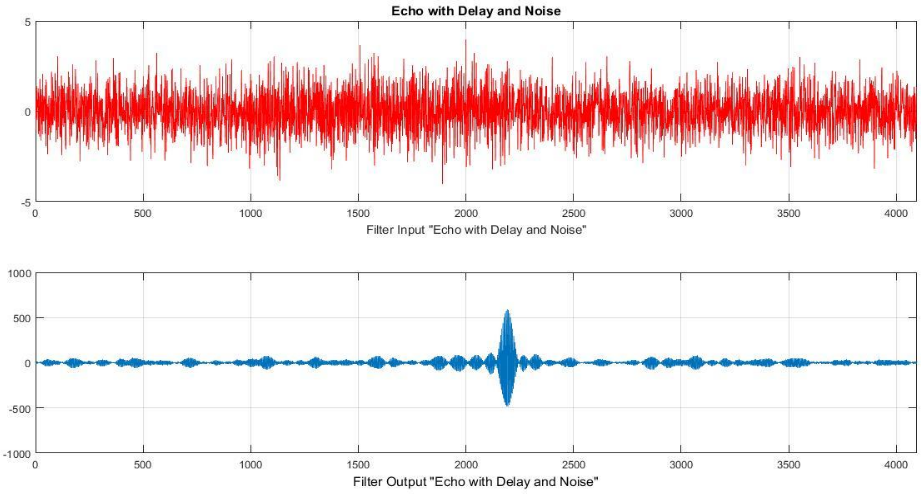


Figure 3.11.2 Echo signal with delay and noise on MATLAB

3.6.5 Two echo signals with delay

After testing the filter with single echo signal with noise and without and with delay and without, it's seen that the filter should be tested with a signal carries 2 echoes, which means it's the reflection of two targets in the radar range, the 2 echoes has been generated to be close to each other so it can be understood that the targets are close to each other too. The signal is applied to the designed Matched Filter on the FPGA and the result is as seen on figure 3.12.1 from ILA debugging core.

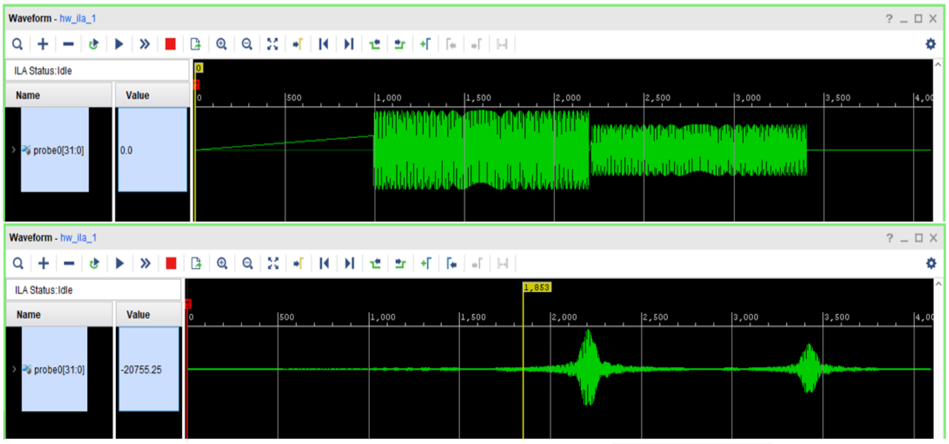


Figure 3.12.1 Two echo signals with delay on FPGA

The same signal's result is shown in figure 3.12.2 below after being applied to the filter on MATLAB.

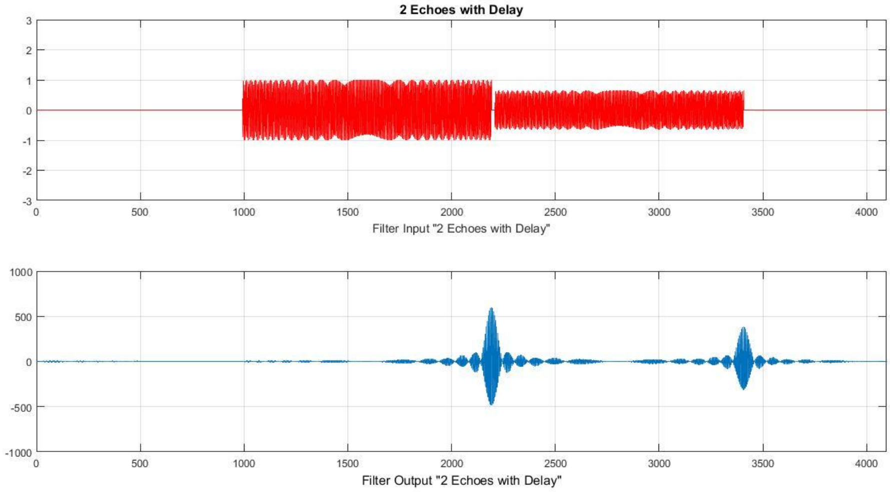


Figure 3.12.2 Two echo signals with delay on MATLAB

3.6.6 Two echo signals with delay and noise

After doing the previous test with a signal which carries to echoes without noise, the filter in this part shall be tested with the same signal added with a white noise. The Matched Filter on FPGA gives a result as shown in figure 3.13.1 after applying the noisy signal as an input to it.

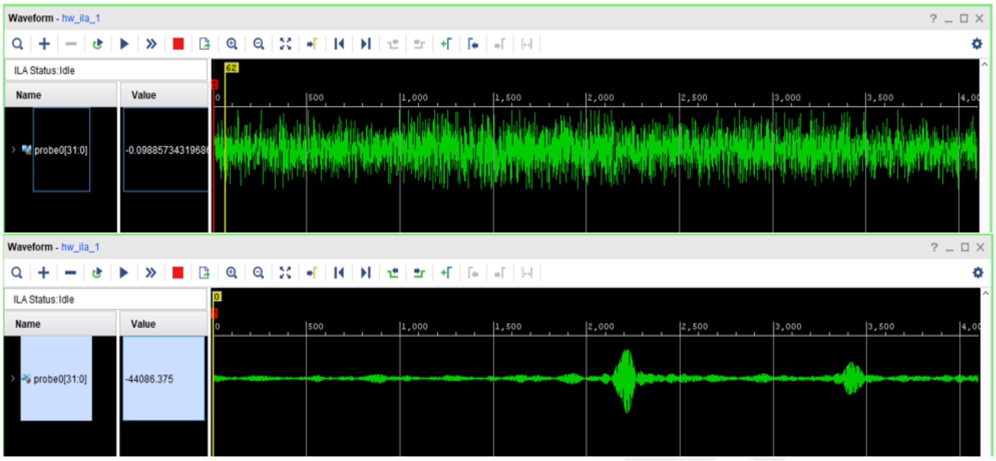


Figure 3.13.1 Two echo signals with delay and noise on FPGA

The figure 3.13.2 below shows the results of the same signal after being applied to the filter on the MATLAB, and as mentioned before it is done to verify that the results of the filter on the FPGA is correct.

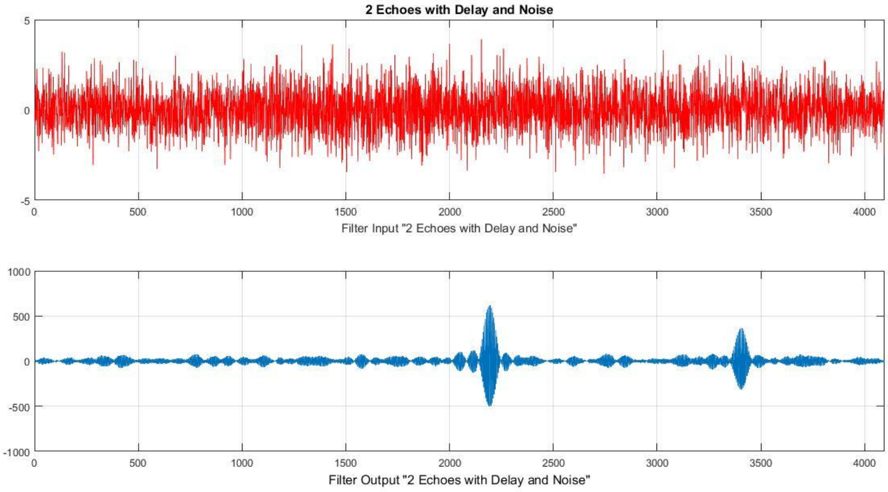


Figure 3.13.2 Two echo signals with delay and noise on MATLAB

3.6.7 Only white noise signal

Finally the filter is tested using noise only to verify that it doesn’t generate peaks with noise as shown in figure 3.14.1.

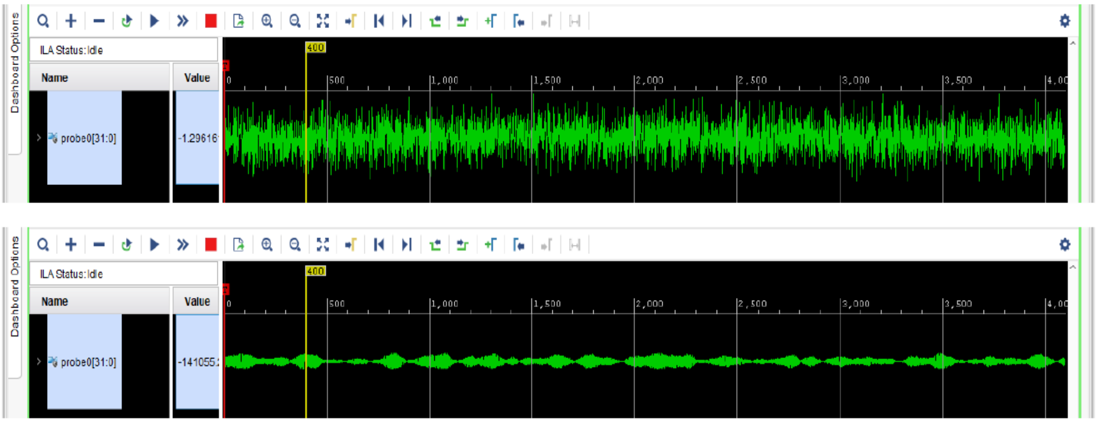


Figure 3.14.1 Only white noise signal on FPGA

The noise will be used with the filter on MATLAB too so it can be ensured that the filter is working sufficiently. Figure 3.14.2 shows the result of this test.

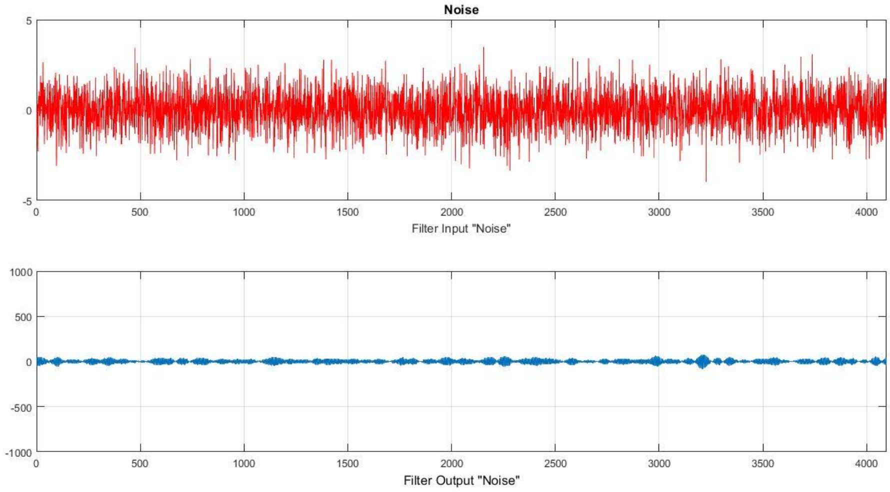


Figure 3.14.2 Only white noise signal on MATLAB

From the all tests' results that have been shown and discussed above, and the comparison that made between FPGA's and MATLAB's results, it can be said that the design is working very well without any problems.

3.7 Device Utilization Summary

After the design of the filter on the FPGA board is completed and successfully worked and tested, the usage summary of the logic cells and parts on the FPGA is shown in the table 3.1 below.

Logic Utilization	**Used**	**Available**	**Usage %**
Number of Slice LUTs	5005	15795	24.06%
Number of fully used LUT – FF pairs	9213	32367	22.15%
Number of Block RAM – BRAM	47	3	94%
Number of DSP slices	20	70	22.22%

Table 2 Utilization Summary

Chapter 4

CONCLUSION

4.1 Conclusion

The main purpose that this thesis has been done for is to study the radar receiver system in general and the matched filter in particular, and study the field programmable gate array and how the digital system could be designed using it, and then to implement it on the FPGA with the Verilog HDL language, generate a radar FM signals from MATLAB and insert it to the designed filter on FPGA in order to test its performance of work, and later verify the results by using the ILA debugging core which already exists on the Vivado software to make sure that the design is working well without a troubles.

While doing this research and this thesis, it was obviously that the designed matched filter was working sufficiently to give the radar the high probability to detect the received signal by increasing its Signal-to-Noise ratio, which has been done by using the both of FFT and the complex multiplier method. The only problem that was in front during the work is that the used FPGA card was not sufficient to hold a bigger signals or to do a further work while the 98% of the memory and resources has been used already in the design so there was no way to use the UART to make a communication between PC and FPGA and to use the MATLAB for debugging, that was solved by storing the signal in COE file and initialize the memory of the FPGA with this signal, and instead of MATLAB the ILA tool was used successfully. So it can be concluded that the design is working effectively as desired and the unexpected problems that happened during the study could be solved.

4.2 Future work

To further this work in future there are some conditions which starts with getting with a more professional FPGA card to try more wide work on FMCW radar receiver and try to design a signal processing system for it in order to get as much information as possible such as the distance and speed of the goal.

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