Sudan University of Science and Technology

College of Graduate Studies

Evaluation OF Phase-Coded Pulse Compression Waveforms in Software Defined Radar

تقويم الإشارة المضغوطة في أنظمة الرادار المعرفة بالبرامج

A thesis Submitted in Partial Fulfillment of the Requirements for the Degree of MSC in Electronics Engineering (communication)

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بسم الله الرحمن الرحيم

"قُلْ إِنَّ صَلاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ الْعَالَمِينَ"

الإنعام:الأية 162

DEDICATION

To who me gave me love, power and faith my parents... to who believes on me my husband...

ACKNOWLEDGEMENT

First, thank ALLAH and thank him for my conciliation to complete this research and I might want to offer my sincerest of thanks towards my undertaking administrator and guide **Dr. Rashid A. Saeed** for his recommendation amid my venture work. He has lastingly urged me to remain concentrated on accomplishing my objective. His perceptions and bits of knowledge helped me to build up the general bearing of the exploration and to push ahead with examination inside and out. He has helped me extraordinarily and been a wellspring of learning.

My special thanks to my husband **Eng. Suhail Badawi Abdelkarim** for the steady motivation and consolation during my exploration.

Last, yet not the least, I might want to recognize the adoration, support and inspiration I got from my parents and hence I dedicate this thesis to my family

ABSTRACT

Pulse compression procedures are utilized as a part of radar systems to profit the advantages of huge range detection In this search in terms of capability of long span pulse and high range determination capacity (resolution capability) of short duration pulse. In this search these procedures (techniques) a long duration pulse is utilized which is either phase or frequency modulated before transmission and received signal is gone through, a matched filter is utilized for pulse compression to accomplish high signal to-noise ratio (SNR). Be that as it may, the matched filter output i.e. autocorrelation function (ACF) of a modulated signal is related with extend sidelobes alongside the mainlobe. These sidelobes are undesirable outputs from the pulse compression filter and may veil a weaker target which is available closer to a more grounded target. Thus, these sidelobes influence the execution of the radar identification system. In this theory, couple of examinations have been made to decrease the range sidelobes utilizing (software defined) techniques in order to enhance the execution of radar detection system . Phase coded signals a long pulse is partitioned into various sub pulse each of which is assigned with a phase esteem. The phase task ought to be with the end goal that ACF of the phase coded signal achieve bring down sidelobes. Poly-phase and Barker codes yield bring down sidelobes. In this work, are proposed to ideally pick the parameters of Poly-phase and Barker codes to accomplish decreased lobes, low peak sidelobe and limit mainlobe width.

المستخلص

تقنيات ضغط النبضة المستخدمة في أنظمة الرادار تمت الاستفادة منها ومن محاسنها في نطاق واسع في هذا البحث من حيث القدرة علي الكشف بنبضات طويلة وفي نفس الوقت أن لها القدرة العالية التي لدى النبضات القصيرة . في هذه البحث عند استخدامنا لتقنيات النبضة طويلة الأمد استخدمت إشارات تم تعديلها أم بالطور أو التردد قبل الإرسال, والإشارة المعدلة التي تم استقبالها مرت عبر مرشح لتجميع الطاقة لنبضة القصيرة . تم استخدام فلتر المتطابقة لتحقيق اعلي نسبة للإشارة مقارنة مع الضجيج ومرشح المطابقة أدي دالة التطابق لإشارة المعدلة. التغطيات الجانبية مقترنا مع إشارة التغطية الرئيسية تكون هي عبارة عن المخرجات غير مرغوب فيهم من مرشح ضغط النبضة قد تؤدي إلي حدوث ضعف في تحديد موقع الهدف من حيث القدرة علي تحديد الهدف قريب أم بعيد . وبالتالي فان هذه التغطيات الجانبية تؤثر على أداء نظام استشعار الرادار.قمنا في هذه الأطروحة, ببعض التحقيقات القليلة لتقليل نطاق تعريف التغطيات الجانبية باستخدام تقنيات تعريف الرادار بالبرامج لتحسين أداء أنظمة الرادارات. إشارات الطور المشفر في مرحلة النبضة الطويلة مقسم الي عدد من النبضات كل منها لديه قيمة للطور . هذه المرحلة مرحلة مهمة وهنا دالة التطابق حققت اقل تغطيات جانبية لإشارات المشفرة مسبقا .في هذا العمل كل من الرموز بلوفيس و باركر تم وضع اقتراح للعناصر أو المعايير الأمثل لتحقيق اقل تغطيات وبالتالي ظهرت التغطيات الجانبية لها اقل قمة و التغطية الرئيسية ظهرت لها قمة اعلي وذروة محدودة وعرض ضيق..

CONTENTS

LIST OF FIGURES

ACRONYMS

ACF - Auto-Correlation Function

ADC - Analogue to Digital Converter

Ae - Antenna area

AWGN- Additive White Gaussian noise

B – bandwidth

CW- Continuous Waveform

DAC- Digital-to-Analogue Converter

FIR - Finite Impulse Response

IF - Intermediate Frequency

JTRS - Joint Tactical Radio System

LFM - Linear Frequency Modulated

NLFM- Non- Linear Frequency Modulated

NATO- North Atlantic Treaty Organization

NP-Output Noise Power

PC - Phase Coded

PC - Pulse Compression

PCR - pulse compression ratio

PCT - Pulse Compression Technique

PRF -Pulse repetition frequency

PSD - power spectral density

PSL - Peak Sidelobe Level

RADAR - Radio Detection And Ranging

RF – radio Frequency

SDR - Software Defined Radio-Radar

SNR - Signal to Noise Ratio

SSR - Signal to Sidelobe Ratio

SP-Signal Power

TB - time-bandwidth

TR- Transreceiver

USDD -US Department of Defense

US –unit states

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

The wireless communications upheaval began with the cell phone toward the start of the 80's and every one of the changes which have prompted the duplicate of portable and wireless communications networks and standards. Wireless communication systems are quickly advancing through the relentless development of the old standards with the new generations. A reaction of this fast development is excess of mobile system standards; each significant nation has its own standards. Along these lines, the software defined radio (SDR) idea is rising as a potential practical solution . SDR is new communication system architecture in the field of wireless communications. It has assumed a noteworthy part in controlling the advancement of communication systems [1].

Software-Defined Radio (SDR) Forum defines SDR technology as "radios that offering software control of a variety of modulation techniques, wide-band or narrow-band operation, communications security functions (such as hopping), and waveform requirements of current & advanced standards over a broad frequency range [1].

The innovation is advanced by the US Department of Defense to supplant number of single protocol radios with a typical stage that could be reprogrammed to guarantee interoperability. In military setting advantages of SDR are self-evident: specially appointed changes scrambling/encryption codes as well as modulation scheme, data rate, channel bandwidth. To develop standards for US government equipment, the Joint Tactical Radio System (JTRS) project has been made. JTRS began in 1997 to supplant roughly 750 000 military transceivers with 250 000 SDR radios. Amid the years, the extent of JTRS has been extended to empower interoperability with the NATO and other " Allied Forces" radio systems [2].

SDR Forum (International organization for promoting development and use of SDR technologies) has made five groups of software-radio classes (tiers). The first group (Tier 0) is Hardware radio. The second (Tier 1) is Software Controlled Radios with just the control functions implemented in software. The third gathering (Tier 2) SDRs, called Reconfigurable SDRs, is most generally utilized today. Fundamentally, software is utilized to control a variety of modulation techniques: wideband or narrowband operation, security capacities and the waveform requirements of current and advancing standards over a frequency range. The fourth group (Tier 3) Ideal Software Radio has the greater part of the capacities of Tier 2 systems. Today it is the most developed sort of SDR that is achievable The last group (Tier 4) - Ultimate Software Radios is characterized by the SDR Forum for comparison purposes as it were [1].

Customarily circulator technique is utilized for confining the transmitting and receiver parts of the transceiver. The disadvantage of this architecture is that the entire RF spectrum is converted by the analogue to digital converter (ADC) making the specifications of this device (bandwidth, dynamic range and sampling rate) unrealizable with today’s technologies. All the principle capacities are done in Software including the RF and IF handling of the signals, trailed by the baseband capacities, for example, modulation /demodulation. In spite of the ideal software radio may currently be impracticable, it ought to be noticed that many Functions in the present handsets and base-stations are actualized as programming code and not as equipment parts. These can be considered as practical programming radios[3].

1.2 SDR FEATURES

Following are the some key features of SDR technology:

- **Reconfigurability**: SDR permits conjunction of numerous software modules implementing diverse standards on a similar system permitting dynamic setup of the system by simply choosing the suitable programming module to run. This dynamic configuration is possible both in handsets as well as infrastructure equipment. The wireless network infrastructure can reconfigure itself to subscriber's handset type or the subscriber's handset can reconfigure itself to network type.

- **Ubiquitous Connectivity**: SDR enable implementation of air interface standards as programming modules and numerous instances of such modules that implement different standards can co-exist in infrastructure equipment and handsets. This helps in investigation global roaming facility
- **Interoperability**: SDR facilitates execution of open design radio systems. End-users can smoothly use innovative third-party applications on their handsets as in a PC system. This enhances the interest and utility of the handsets.

One of the most areas which take advantages from software defined radios is the area of radars systems. Software defined radar is the latest trend in radar development.

1.3 SOFTWARE DEFINED RADAR

RADAR is an acronym of Radio Detection And Ranging. It is a protest discovery system which utilizes electromagnetic waves particularly radio waves to decide the range, elevation, direction or speed of both moving and fixed objects, for example, aircraft ,ships, spacecraft ,guided missiles ,motor vehicles, weather formations, and terrain. The radar dish, or antenna, transmits pulses of radio waves or microwaves which bounce off any object in their path. The object returns a tiny part of the wave's energy to a dish or antenna which is usually located at the same site as the transmitter. The modern uses of radar are highly diverse, including air traffic control, radar astronomy, and aircraft anti-collision systems, antimissile [4].

The fast advances in digital technology made many theoretical capabilities practical with digital signal processing and digital data processing. Radar signal processing is defined as the manipulation of the received signal, represented in digital format, to extract the desired information whilst rejecting unwanted signals. Pulse compression allowed the use of long waveforms to obtain high energy simultaneously achieves the resolution of a short pulse by internal modulation of the long pulse. The resolution is the capacity of radar to recognize targets that are closely spaced together in either range or bearing. The internal modulation may be binary phase coding, Poly-phase coding, frequency modulation, and frequency stepping. There are many points of interest of utilizing pulse compression techniques in the radar field. They include reduction of peak power, relevant reduction of high voltages in radar transmitter, protection against detection by radar detectors, significant improvement of range resolution, relevant reduction in clutter troubles and protection against jamming coming from spread spectrum action [5].

In pulse compression technique, the transmitted signal is frequency or phase Modulated and the received signal is processed using a specific filter called "matched filter". In this form of pulse compression, a long pulse of duration T is divided into N sub pulses each of width τ. The phase of each sub-pulse is chosen to be either 0 or π radians. A matched filter is a linear network that maximizes the output peak-signal to noise ratio of a radar receiver which in turn maximizes the detectability of a target. In 1950-60, the practical realization of radars using pulse compression has taken place. At the starting, the realization of matched filters was difficult using traverse filters because of lack of delay line with enough bandwidth. Later matched filters have been realized by using dispersive networks made with lumped-constant filters. In recent years, instead of matched filters, many advanced filters are in use. The binary choice of 0 or π phase for each sub-pulse may be made at random [4][5].

However, some random selections may be better suited than others for radar application. One criterion for the selection of a good “random” phase-coded waveform is that its autocorrelation function should have equal time side-lobes. Barker codes have called perfect codes because the highest side lobe is only one code element amplitude high. However, the largest pulse compression ratio that can be obtained with barker code is only 13 [5].

The codes that use any harmonically related phases on certain fundamental phase increments are called Poly-phase codes. Frank proposed a Poly-phase code called as Frank code which is more Doppler tolerant and has lower side-lobes than binary codes. Krestschmer and Lewis have presented the variants of Frank code. P1 code which is derived from step frequency, Bolter matrix derived P2 code and linear frequency derived P3 and P4 codes. The significant advantage of P1 and P2 codes over the Frank code and the P4 code over P3 is that they are tolerant to receiver band limitations [6].

1.4PROBLEM STATEMENT

The pulse compression in radar has significant applications in the current years. For better pulse compression, peak signal to sidelobe ratio should be as high as possible so that the unwanted clutter gets suppressed and should be very tolerant under Doppler shift conditions. Many pulse compression techniques have come into existence including SDR networks. Substantial effort has been made to suppress the sidelobes of the different waveforms using software defined radar

- For Phase coded (PC) waveforms the amplitude weighing strategies are utilized at the receiver to suppress sidelobes. The objectives in the environment are definitely not always stationary. If the target is in motion, the reflected waveform is Doppler shifted version of the transmitted waveform. When this Doppler shifted waveforms are passed through the weighted receiver matched filter the PSR degrades. Under such situations it is required to improve the PSR.

1.5 OBJECTIVES OF THE THESIS

The primary goal of present research work is to propose proficient pulse compression techniques for various radar signals. The different destinations might be recorded as:

- To create pulse compression Phase coded (PC) codes having lower peak sidelobes.

- To select proper parameters Phase coded pulse prepare to accomplish reduced grating lobes, low peak sidelobe level and narrow mainlobe width.
- Analyzing the Phase coded (PC) signal considering the time bandwidth product, Doppler Effect and affect the matched filter (ACF).

1.6 METHODOLOGY

In this thesis the codes that used related phases on certain fundamental phase increments are called Poly-phase codes like Frank and p4 codes, from binary codes proposed Barker code. at Poly-phase codes which is more Doppler tolerant and has lower side-lobes than binary codes. By use MATLAB program make simulations to phase coded waveforms in virtual SDR radar.

1.7 THESIS OUTLINES

The structure of this Master Thesis is organized as follows:

Chapter 1: This chapter outlines the motivation and scope of the work.

Chapter 2: The concept of pulse compression in radar. LFM and NLFM Radar Waveforms. Matched filter. the Radar Ambiguity Function in detail .

Chapter 3: The concept of Barker codes and all Poly-phase codes are described in detail.

Chapter 4: The main codes to be tested and the main differences between them are described, in order to evaluate the performance of these codes.

Chapter 5: The main ideas presented in the thesis are collected and summarized in this chapter.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Radar is an electromagnetic system used to recognize and find the protest by transmitting the electromagnetic signals and accepting the echoes from the items inside its scope. The echoes are utilized to extricate the data about the objective, for example, range, angular position, speed and other recognizing characteristics [4]. The reflected signal from the radar not only indicates the presence of a target, but also compares the received echo signal with the transmitted signal, so that various information can be extracted regarding the target. Nowadays, Radars are commonly used in Air Traffic Control System. It requires a good presence of target location and good target resolution. Good range resolution can be achieved with a shorter pulse. But on the other hand, shorter pulses require more peak power. The shorter the pulse gets, more energy is required to pack the pulse by increasing the peak power.

Introduction of high peak power makes the design of transmitters and receivers difficult since the components used in the entire system must be able to withstand the peak power. In order to overcome this problem, convert the short duration pulse into a longer pulse. Increasing the length of the pulse results in reduction in the peak power of it, but it reduces range resolution To preserve the range resolution, modulation is to be incorporated to increase the bandwidth of the long pulse (transmitting pulse). This used technique is called the Pulse Compression Technique (PCT) and is used widely in Radar applications where high peak power is undesirable [7].

2.2RADAR PARAMETERS

Pulse width (τ): The transmission time of the pulse (usually measured in microseconds).Also called the pulse duration.

Pulse repetition frequency (PRF): The number of pulses transmitted in a given time (usually measured in pulses per second).

Peak power (P_t): The maximum power of the pulse (measured in Watts).

Wavelength (λ): The wavelength of the radio wave transmitted by the radar. For weather radars this is in the microwave region (wavelengths of 3 to 10 cm are common).

Beam width (θ): The angular width of the radar beam.

Antenna area (A_e): The area of the antenna aperture. For a given beam width, as the wavelength increases a larger antenna area is required. Thus, a radar operating at a wavelength of 10-cm radar will have a larger antenna than one operating at 3-cm.

Antenna gain (G): The ratio of the radiance in the beam (L) versus the isotropic radiance (L_0) [8].

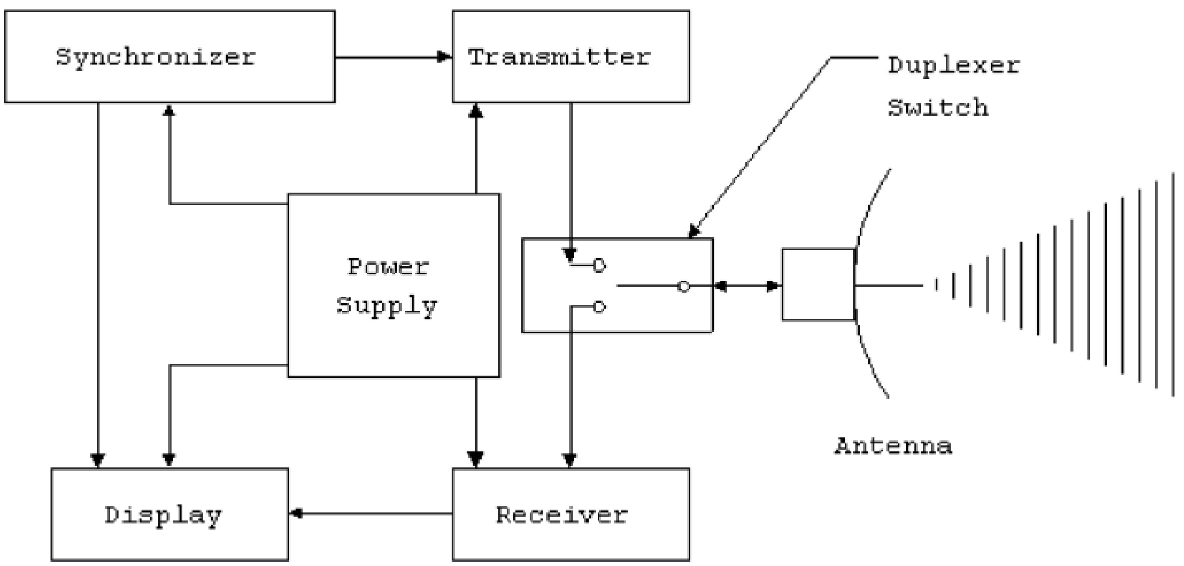

Figure 2.1: illustrate of simple radar

Most of the modern radar systems employ a pulsed waveform which gives extend data precisely. The essential favorable position of pulsed radar is that the transmitter and receiver can have a similar antenna because of throbbing nature of the waveform. A pulsed waveform is appeared in *Figure 2.2*, The unambiguous range R_u that can be measured by this waveform as described in is

$$R_u = cT_r/2 \qquad (2.1)$$

Where: **c** is the speed of light. T_p is the pulsed term and T_r is the pulse repetition time.

Two vital elements to be considered for radar waveform configuration are range resolution and most extreme range detection. Range resolution is the capacity of the radar to isolate firmly divided targets and it is identified with the pulse width of the waveform. The smaller the pulse width the better is the range resolution. Be that as it may, if the pulse width is diminished, the amount of energy in the pulse is diminished and henceforth most extreme range detection gets lessened. To defeat this issue pulse compression techniques are used in the radar systems [4][9].

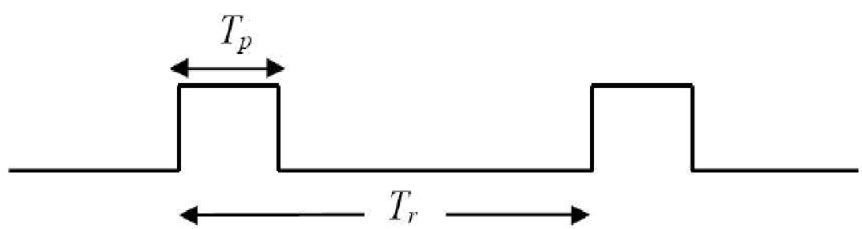

Figure 2.2: Pulsed radar waveform

2.3 PULSE COMPRESSION

The greatest detection range relies on the quality of the received echo. To get high quality reflected echo the transmitted pulse ought to have more energy for long distance transmission since it gets lessened over the span of transmission. The energy content in the pulse is corresponding to the duration and in addition the peak power of the pulse. The result of peak power and duration of the pulse gives a gauge of the energy of the signal. A low peak power pulse with long duration provides the same energy as achieved in case of high peak power and short duration pulse. Shorter duration pulses achieve better range resolution. The range resolution $\mathbf{r_{res}}$ is expressed as:

$$\mathbf{r_{res} = c/\ 2B} \qquad (2.2)$$

where **B** is the bandwidth of the pulse.

For unmodulated pulse the time duration is conversely corresponding to the data transfer capacity(bandwidth). In the event that the data transfer capacity is high, at that point the term of the pulse is short and henceforth this offers a superior range resolution. For all intents and purposes, the pulse duration can't be lessened uncertainly. As per Fourier theory a signal with bandwidth B can't have duration shorter than 1/B i.e. its time-bandwidth (TB) product can't be less than unity. A very short pulse requires high peak power to get adequate energy for large distance transmission. However, to handle high peak power the radar equipment become heavier, bigger and hence cost of this system increases. In this way peak power of the pulse is always limited by the transmitter [10]. A pulse having low peak power and longer duration is required at the transmitter for long range detection. At the yield of the receiver, the pulse ought to have short width and high peak power to show signs of improvement go range resolution. *Figure 2.3* shows two pulses having same energy with various pulse width and peak power. To get the benefits of bigger range discovery capacity of long pulse and better range resolution capacity of short pulse, pulse compression techniques are utilized as a part of radar systems. The range resolution relies upon the bandwidth of a pulse but not necessarily on the duration of the pulse. Some modulation techniques, for example, frequency and phase modulation are utilized to build the data transfer capacity of a long duration pulse to get high range resolution having limited peak power. In pulse compression technique a pulse having long duration and low peak power is modulated either in frequency or phase before transmission and the received signal is passed through a filter to accumulate the energy in a short pulse [5]. The pulse compression ratio (PCR) is defined as

$$\mathbf{PCR}=\frac{\mathbf{W\ BC}}{\mathbf{W\ AC}} \qquad (2.3)$$

Where:

W_{BC}: width before compression

W_{AC}: width after compression

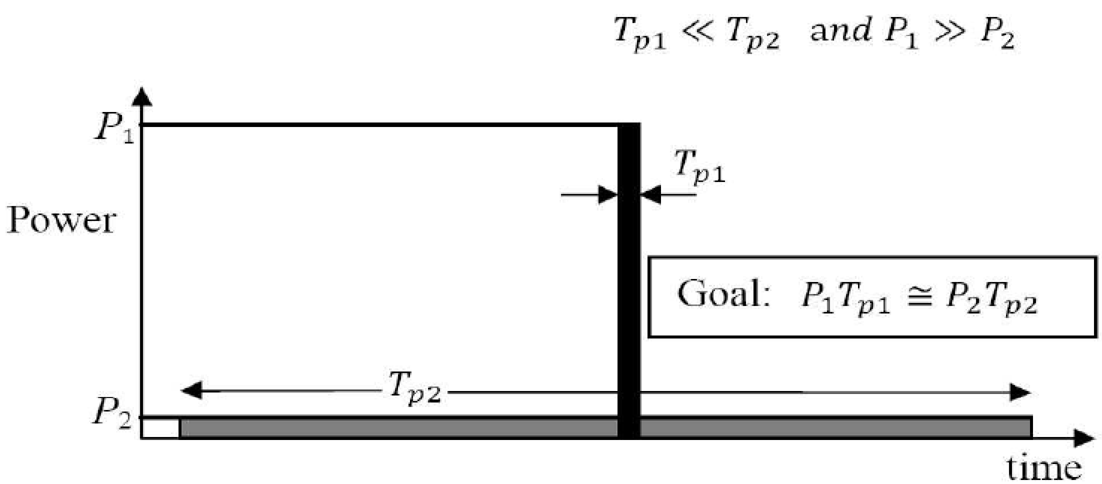

Figure 2.3: Transmitter and receiver signals

Pulse compression assumes a noteworthy part in radar systems in accomplishing great signal quality and high resolution. The great signal quality is accomplished by long duration pulses, which decreases the peak power. Transmitting longer pulse increases the sensitivity of radar system by increasing the average transmitted power. But the longer pulse deteriorates the range resolution of the radar. For restricted target order, range resolution should be high enough which is obtained by narrow pulses. Consequently as a bargain, pulse compression technique is employed in which a long duration pulse is either frequency or phase modulated to increase the bandwidth. This long duration modulated pulse is compressed at the receiver utilizing matched filter. In pulse compression technique a long coded pulse is transmitted and the received echo is processed to obtain a relatively narrow pulse. The signal to side lobe ratio performance, noise performance and Doppler tolerance performance must be considered as major aspects for a pulse compression technique In view of these considerations many pulse compression techniques have been advanced [11].

The square outline of a pulse compression radar system is appeared in *Figure 2.4.* The transmitted pulse is either frequency or phase modulated to expand the bandwidth. Transreceiver (TR) is a changing unit utilizes the same antenna as transmitter and receiver. The pulse compression filter is usually a matched filter whose frequency response matches with the spectrum of the transmitted waveform. The filter plays out a relationship between's the transmitted and the received pulses. The received pulses with similar characteristics to the transmitted pulses are picked up by the matched filter whereas other received signals are comparatively ignored by the receiver [4][11].

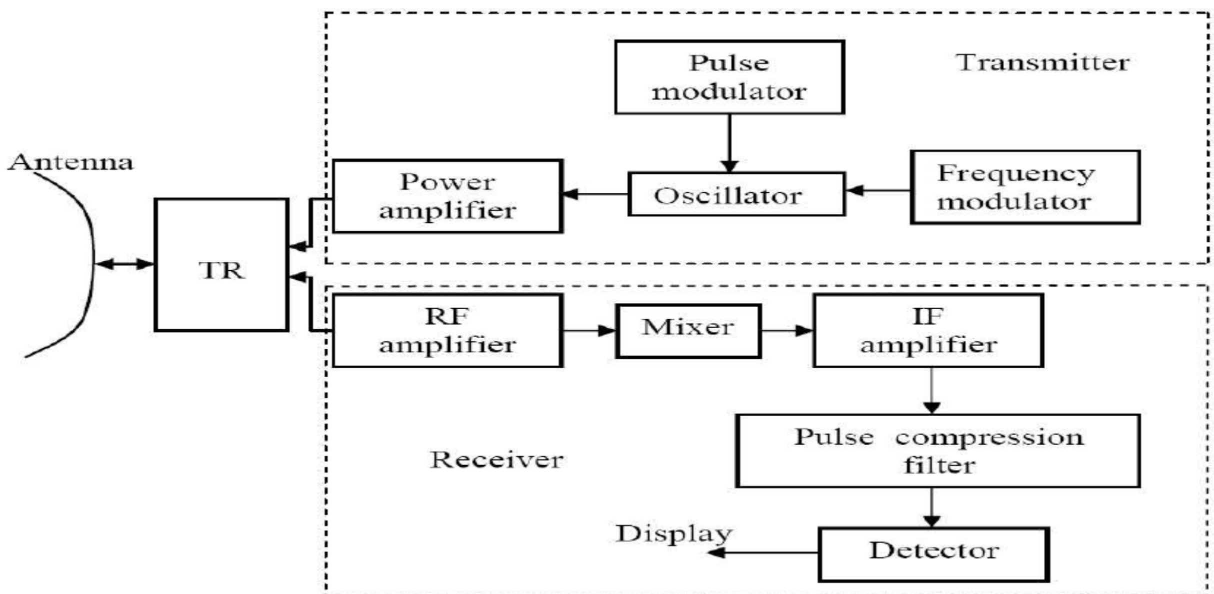

Figure 2.4: Block diagram of a pulse compression radar system

2.4 RADAR SIGNALS

In radar system a specific waveform is first decided for a given application and it is utilized to plan the ideal recognition system. The waveform ought to give slightest measure of uncertainty or ambiguity when the reflected signal is utilized to remove the data about the range, the speed and the quantity of genuine targets exhibit in the earth. The diverse types of signals those are generally utilized as a part of radar systems are talked about in sequel [12].

2.5 LFM AND NLFM RADAR WAVEFORMS

In the radar literature, LFM is known to be easily generated by a variety of technology and has a superior performance in pulse compression, Pulse compression is used to increase the range resolution and signal to noise ratio (SNR). To transmit a long pulse that has a bandwidth corresponding to a short pulse, pulse compression technique is required. Despite the above advantages, LFM carries few limitations which cannot be ignored. A compressed LFM signal produces a first side lobe at a level of -13 dB to the peak of the main lobe at the receiver. But for this compression, the output SNR may get reduced typically by 1 to 2 dB. A single dB of SNR lost is equal to 25 % decrease in transmitter power [13]. Few more important corns of the LFM waveform are given below:

- Low signal to noise ratio (SNR).
- LFM always require a weighting function for pulse compression.
- Range resolution is not very good.

Due to this scientists concluded with use of a new waveform called non- linear frequency modulated (NLFM) waveform. NLFM waveform does not require any weighting function, they have inbuilt one. More over their range resolution in very good and their pulse shape is very much Doppler tolerant [13].

2.5.1 LINEAR FREQUENCY MODULATED WAVEFORM

LFM waveform commonly known as linear chirps are the most commonly used waveform in radar systems as it can be easily generated, have good range resolution and more Doppler tolerant than NLFM.

Linear Frequency Modulation is used in radar systems frequently to achieve wide-operating bandwidths. A linear FM chirp has a linear time frequency description as its frequency varies linearly over the pulse duration of the signal. In case of LFM frequency increases (up chirp) or decreases (down chirp) linearly with time [13].

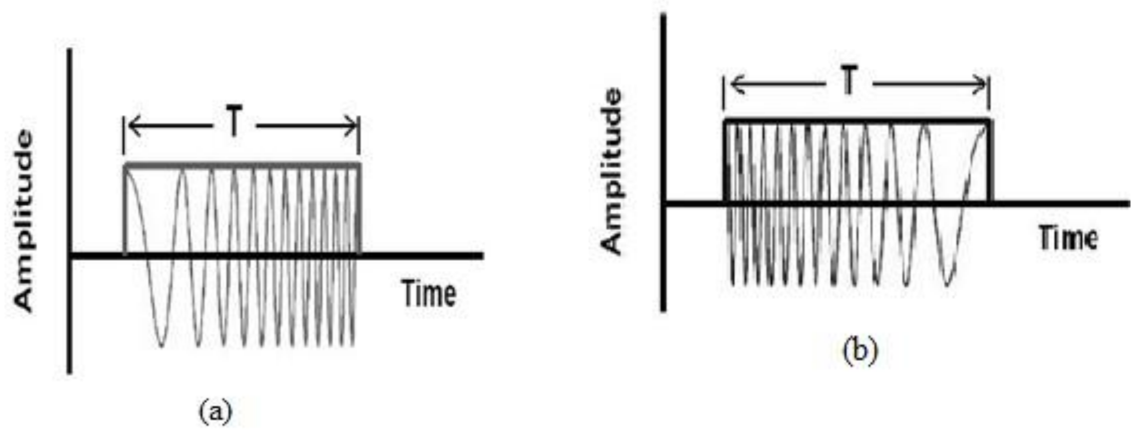

Figure 2.5 (a) Increasing Frequency (Up chirp) Figure2.6 (b) Decreasing Frequency (Down chirp)

The Following figure shows the time frequency characteristics of the signal. Fig 2.7 depicts the frequency versus time characteristics of a linear FM chirp.

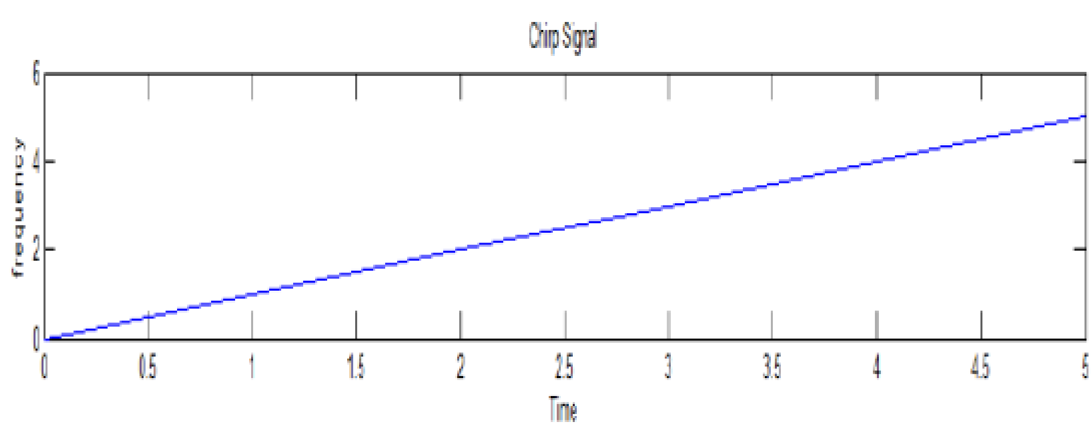

Figure 2.7 Time vs. frequency plot of linear FM chirp

Complex exponential version of the LFM chirp waveform is given as:

$$\mathbf{S\ (t) = exp\ (j\phi\ (t))} \qquad \textbf{(2.4)}$$

Where **ϕ (t)** is the instantaneous phase given by the equation as below where is the instantaneous phase given by the equation as below

$$\mathbf{\phi\ (t) = 2Л\ (f_0 + kt^2)} \qquad \textbf{(2.5)}$$

The instantaneous frequency as a linear function of time is expressed

$$\boldsymbol{f_i = 1/2\pi(\frac{d\phi}{dt})} \qquad \textbf{(2.6)}$$

$$\boldsymbol{f_i = f_0 + kt} \qquad \textbf{\textit{(2.7)}}$$

Where k is the slope.

f_o is the fundamental frequency.

LFM waveforms can reduce side lobe level by -13dB by applying various methods but at the cost of reduced SNR. Therefore to overcome this we opt for a new waveform NLFM which can do the same with good SNR and low cost. In the next section NLFM waveform is thoroughly described.

2.5.2 NON LINEAR FREQUENCY MODULATED (NLFM) WAVEFORM

NLFM is considered to be capable of achieving fine resolution, good SNR, low cost and high-quality interference mitigation. NLFM is having superior detection rate characteristics and is more precise in range determination than LFM. In case of NLFM, it is observed that the time frequency characteristic is non-linear in nature [13]. Figure 2.8 show that:

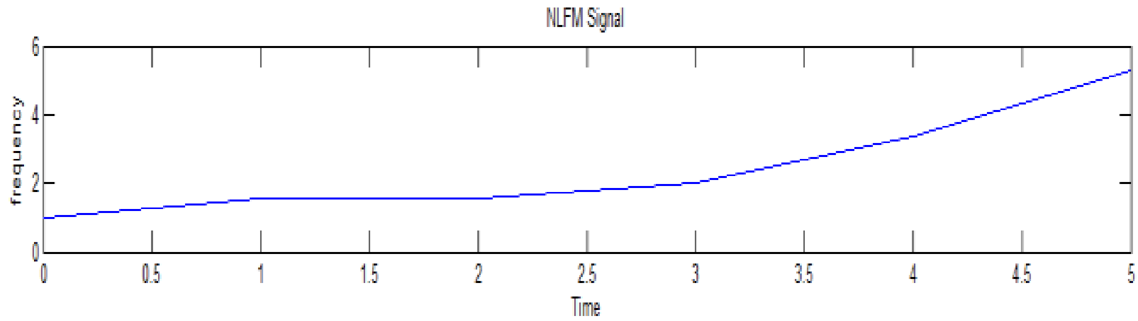

Figure 2.8: Time vs. frequency plot of linear FM chirp

The complex exponential of NLFM waveform is given by

$$\mathbf{S\ (t) = exp\ (j\phi\ (t))} \qquad \textbf{(2.8)}$$

Here in this case, the instantaneous frequency f_i is given as:

$$f_i = f_0 + kt + \cos(t) \qquad \textbf{(2.9)}$$

Where f_0 is the fundamental frequency

t is the instantaneous time

K is the slope

Non linear frequency modulation waveform does not require weighting function as they have an in built weighting function. NLFM is a waveform which cannot be easily generated.

2.6 MATCHED FILTER

In radar applications the reflected Pulse compression is utilized to decide the nearness of the objective. The reflected signal is undermined with Additive White Gaussian noise (AWGN). The probability of detection depends upon the signal-to-noise ratio (SNR) rather than the exact shape of the signal received. Consequently it is required to maximize the SNR rather than preserving the shape of the signal. A filter that maximizes the output SNR is called matched filter. A channel that expands the yield SNR is called coordinated channel. A matched filter is a linear network that maximizes the output peak-signal to noise (power) ratio of a radar receiver which in turn maximizes the delectability of a target. It is obtained by correlating a known signal, or a template, with an unknown signal to detect the presence of the template in the unknown signal [14][15].

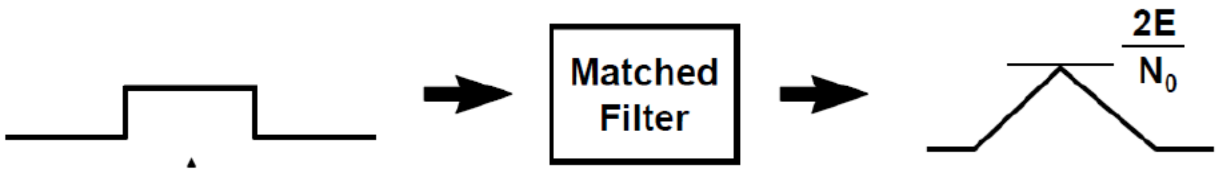

Figure 2.9: Matched Filter response

An input signal s(t) along with AWGN is given as input to the matched filter as shown in *Figure 2.9* . Let $N_0/2$ be the two sided power spectral density (PSD) of AWGN. It is required to find out the impulse response h(t) or the frequency response H(f) (Fourier transform of h(t)) that yields maximum SNR at a predetermined delay t_0. In other words, h(t) or H(f) is determined to maximize the output SNR which is given by

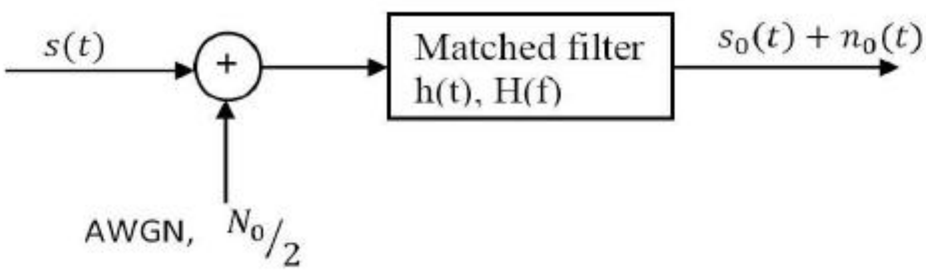

Figure 2.10: Block diagram of matched filter

2.6.1 MATCHED FILTER BASICS

The signal power to noise power is given by

$$(SP/NP)_{out} = |s_0(t_0)|^2 / n_0^2(t) \qquad \textbf{(2.10)}$$

SP-Signal Power, NP-Output Noise Power, $s_0(t_0)$-value of signal at $t=t_0$, $|n_0^2(t)|$-mean square value of noise

This is equivalent to convolving the unknown signal with a conjugated time-reversed version of the template. It is the optimal linear filter for maximizing the signal to noise ratio (SNR) in the presence of additive stochastic noise. It has a frequency response function which is proportional to the complex conjugate of the signal spectrum [15].

$$H(f) = G_a S^*(f) \exp(-j2\pi f t_m) \qquad \textbf{(2.11)}$$

Where G_a is a constant, t_m is the time at which the output of the matched filter is a maximum (generally equal to the duration of the signal), and S*(f) is the complex conjugate of the spectrum of the (received) input signal s(t), found from the Fourier transform of the received signal s(t) such that

$$S(f) = \int_{-\infty}^{\infty} s(t) \exp(-j2\pi f t)\, dt \qquad \textbf{(2.12)}$$

A matched filter for a transmitting a rectangular shaped pulse is usually characterized by a bandwidth B approximately the reciprocal of the pulse with τ or Bτ ≈ 1. The output of a matched filter receiver is the cross-correlation between the received waveform and a replica of the transmitted waveform Instead of matched filter, an N-tap adaptive filter is used, by taking input as 13-bit barker code [1 1 1 1 1 -1 -1 1 1 -1 1 -1 1] and desired output as [12zeros 1 12zeros], and weights are trained using different adaptive filtering algorithms [10].

2.7 THE RADAR AMBIGUITY FUNCTION

In pulsed radar , an ambiguity function is a two-dimensional function of time delay and Doppler frequency $\chi(\tau, f)$ showing the distortion of a returned pulse due to the receiver matched filter (commonly, but not exclusively, used in pulse compression radar) due to the Doppler shift of the return from a moving target. The ambiguity function is determined by the properties of the pulse and the matched filter, and not any particular target scenario. Many definitions of the ambiguity function exist; Some are restricted to narrowband signals and others are suitable to describe the propagation delay and Doppler relationship of wideband signals. Often the definition of the ambiguity function is given as the magnitude squared of other definitions (Weiss). For a given complex baseband pulse s(t), the narrowband ambiguity function is given by

$$\chi(\tau, f) = \int_{-\infty}^{\infty} s(t)s*(t-\tau)e^{i2\pi ft}\,dt \qquad \textbf{(2.13)}$$

where $*$ denotes the complex conjugate and i is the imaginary unit. Note that for zero Doppler shift (f=0) this reduces to the autocorrelation of s(t) . A more concise way of representing the ambiguity function consists of examining the one-dimensional zero-delay and zero-Doppler "cuts"; that is, $\chi(0, f)$ and $\chi(\tau, 0)$, respectively. The matched filter output as a function of a time (the signal one would observe in a radar system) is a Doppler cut, with constant frequency given by the target's Doppler shift $\chi(\tau, f_D)$.

The radar ambiguity function represents the output of the matched filter, and it describes the interference caused by range and/or Doppler of a target when compared to a reference target of equal RCS. The ambiguity function evaluated at $(\tau,f_d)=(0,0)$ The radar ambiguity function is normally used by radar designers as a means of studying different waveforms. It can provide insight about how different radar waveforms may be suitable for the various radar applications. It is also used to determine the range and Doppler resolutions for a specific radar waveform [8].

2.8 PHASE CODED PULSE COMPRESSION

In this form of pulse compression, a long pulse of duration **T** is divided into **N** sub-pulses each of width **τ**. An increase in bandwidth is achieved by changing the phase of each sub-pulse. The phase of each sub-pulse is chosen to be either **0 or π** radians. The output of the matched filter will be a spike of width **τ** with an amplitude **N** times greater than that of long pulse. The pulse compression ratio is $N = T/\tau \approx BT$, where $B \approx 1/\tau$ = bandwidth. The output waveform extends a distance T to either side of the peak response, or central spike. The portions of the output waveform other than the spike are called time side-lobes [16].

2.8.1 BARKER CODES

The binary choice of 0 or π phase for each sub-pulse may be made at random. However, some random selections may be better suited than others for radar application. One measure for the determination of a decent “random” phase-coded waveform is that its autocorrelation function should have equal time side-lobes. The binary phase-coded sequence of 0, π values that result in equal side-lobes after passes through the matched filter is known as a Barker code [16].

2.9 POLYPHASE CODES

The codes that utilization any harmonically related phases in view of a specific principal phase increment are called Poly-phase codes. Poly-phase codes show better Doppler tolerance for broad range-Doppler coverage than do the bi-phase codes, and they display moderately great side-lobe characteristics[6].

Poly-phase compression codes have been derived from step approximation to linear frequency modulation waveforms (Frank, P1, P2) and linear frequency modulation waveforms (P3, P4). These codes are inferred by separating the waveform into sub-codes of equivalent duration, and utilizing phase an incentive for each sub-code that best matches the general phase direction of the fundamental waveform. In this area the poly-phase codes in particular Frank, P1, P2, P3, P4 codes and their properties are portrayed [6][7].

2.9.1 FRANK CODE

The Frank code is derived from a step approximation to a linear frequency modulation waveform using N frequency steps and N samples per frequency . Hence the length of Frank code is N^2. The Frank coded waveform consists of a constant amplitude signal whose carrier frequency is modulated by the phases of the Frank code.[6]

The phase of the i_{th} code element in the j_{th} row of code group is computed as

$$\varphi_{i,j} = \left(\frac{2\pi}{N}\right)(i-1)(j-1) \qquad \textbf{(2.14)}$$

Where i and j ranges from 1 to N.

2.9.2 P1 CODE

The P1 code is also generated using a step approximation to a linear frequency modulation waveform. In this code, M frequency steps and M samples per frequency are obtained from the waveform using a double sideband detection with the local oscillator at band center .The length of the resulting code or compression ratio is N_c=M x M .If i is the number of the sample in a given frequency and j is the number of the frequency, the phase of the i^{th} sample of the j^{th} frequency component can be expressed as below

$$\varphi_{i,j}=-\pi/M[M-(2j-1)][(j-1)M+(i-1)] \qquad \textbf{(2.15)}$$

Where i =1,2,3.M, j=1,2,3…M and M=1,2,3… For the P1 code

the $\boldsymbol{PSL}=20log10(1/M\pi)$

2.9.3 P2 CODE

For the P2 code M even, the phase increments within each phase group is the same as the P1 code, except that the starting phases are different .The P2 code also has a length or compression ratio of N_c=M*M .The P2 code is given by

$$\varphi_{i,j}=-\pi/2M[2i-1-M][2j-1-M] \qquad \textbf{(2.16)}$$

where i=1,2,3… M and j=1,2,3…M and where M=2,4,6…

The requirement for M to be even in this code stems from. the desire for low autocorrelation side lobes. For the P2 code,

the $\boldsymbol{PSL}=20log10(1M\pi)$ is same as P1 code.

2.9.4 P3 CODE

The P3 code is conceptually derived by converting a linear frequency modulation waveform to base band, by synchronous oscillator on one end of the frequency sweep (single side band detection) and sampling the I and Q at Nyquist rate. The phase of the i^{th} sample of the P3 code is given by

$$\varphi_i = -\pi/N_c(i-1)^2 \qquad \textbf{(2.17)}$$

Where i=1,2,…, N_c and N_c is the compression ratio.

2.9.5 P4 CODE

In the generation of P3 code if the local oscillator frequency is offset in the I and Q detectors, resulting in coherent double side band detection, it results in P4 code. The P4 code consists of the discrete phases of the linear chirp waveform taken at specific time interval, and exhibits the same range Doppler coupling associated with the chirp waveform. The phase sequence of a P4 signal is described by

$$\varphi_i = -[\pi(i-1)^2/Nc] - \pi(i-1) \qquad \textbf{(2.18)}$$

where i =1 to N_c and N_c is the pulse compression ratio.

CHAPTER THREE

METHODOLOGY

3.1 PHASE CODED WAVEFORMS

This chapter is about the different poly phase codes and their properties. First the Barker code are discussed followed by the discussion poly phase codes contain Frank, P4 codes. For each code, the phase characteristics, autocorrelation properties and Doppler properties are examined.

3.2 SEQUENCE POLYPHASE CODES

The codes that use any harmonically related phases on certain fundamental phase increments are called poly phase codes . Well know poly phase codes with better Doppler tolerant and low range side lobes are Frank and P4 codes. The significant advantage of the Frank code and the P4 code they are tolerant to receiver band limitations. In this thesis Barker, Frank and P4 codes is used for simulation purpose and the phase sequence of these codes was mentioned in chapter two.

3.3BLOCK DIAGRAM OF THE GENERAL SDR SYSTEM

This research aims to illustrate the ease of applying these codes (barker ,frank ,p4) using computer and this is the role of SDR which I will do is analyze these codes.

The entire system block diagram is given above in Figure 3.1. The phase code given at the input is undergone expansion by modulation to increase the range resolution and it is transmitted all these processes are done within SDR exciter . The reflected signal from the radar not only indicates the presence of a target, but also compares the received echo signal with the transmitted signal in RF front end , so that various information's can be extracted regarding the target.

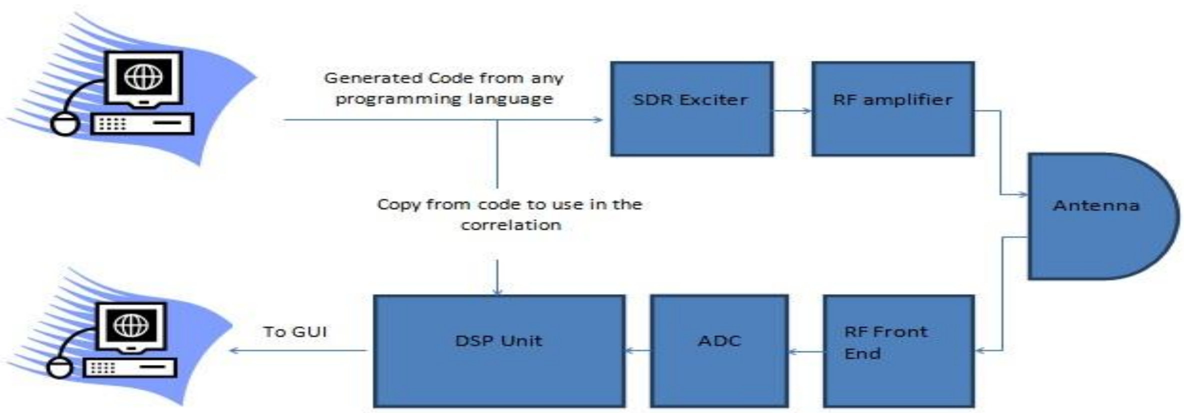

Figure 3.1: Block diagram of the general SDR system

3.4FLOW CHART OF PHASE CODED METHODOLOGY

The method followed in this research for phase coded pulse compression in software defined radar involves mainly two steps, first of all generation of phase coded waveform followed by Matched Filtering. The flow chart which describes the whole work is shown in figure 3.2 :

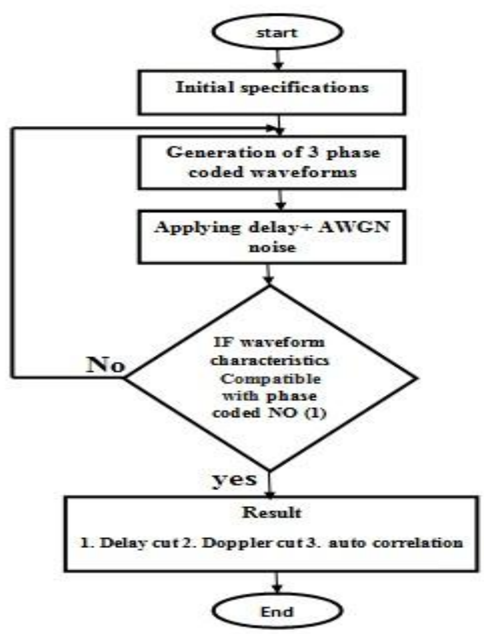

Figure 3.2: Flow chart of the phase coded methodology

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

4. SIMULATION RESULTS AND DISCUSSION

The Importance of this chapter comes from it is name! In this chapter the theoretical characteristic of the phase codes which was discuss in the previous chapters will be testes and implemented in trusted computer aid simulation tool.

As mentioned previously the aim from this thesis is to make a clear view and decision of how the using of software defined concepts we make the implementation of these codes much easier and then to decide which one of tested codes has better results regarding to the test parameter.

4.1 KEY FEATURES

- High-level language for numerical computation, visualization, and application development
- Interactive environment for iterative exploration, design, and problem solving
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, numerical integration, and solving ordinary differential equations
- Built-in graphics for visualizing data and tools for creating custom plots
- Development tools for improving code quality and maintainability and maximizing performance
- Tools for building applications with custom graphical interfaces
- Functions for integrating MATLAB based algorithms with external applications and languages such as C, Java, .NET, and Microsoft® Excel®

Sample rate

Specify the sample rate, in hertz, as a positive scalar. The value of this parameter must satisfy these constraints:

- The ratio of Sample rate to Pulse repetition frequency must be an integer scalar or row vector of integers.

- The product of Sample rate and Chip width must be an integer.

Phase code

Specify the phase code type to use in phase modulation.

Chip width (s)

Specify the duration, in seconds, of each chip in a phase-coded waveform as a positive scalar.

The value of this parameter must satisfy these constraints:

- The product of Chip width, Number of chips, and Pulse repetition frequency must be less than or equal to one.
- The product of Sample rate and Chip width must be an integer.

Number of chips

Specify the number of chips in a qphase-coded waveform as a positive integer. The product of the Chip width, Number of chips, and Pulse repetition frequency parameters must be less than or equal to one.

The next graph shows additional constraints on the number of chips for different code types.

4.2 STEPS OF THE SIMULATION

Three codes were chosen to be simulated and analyzed in these theses:

1. Barker Code.
2. Frank Code.
3. P4 Codes.

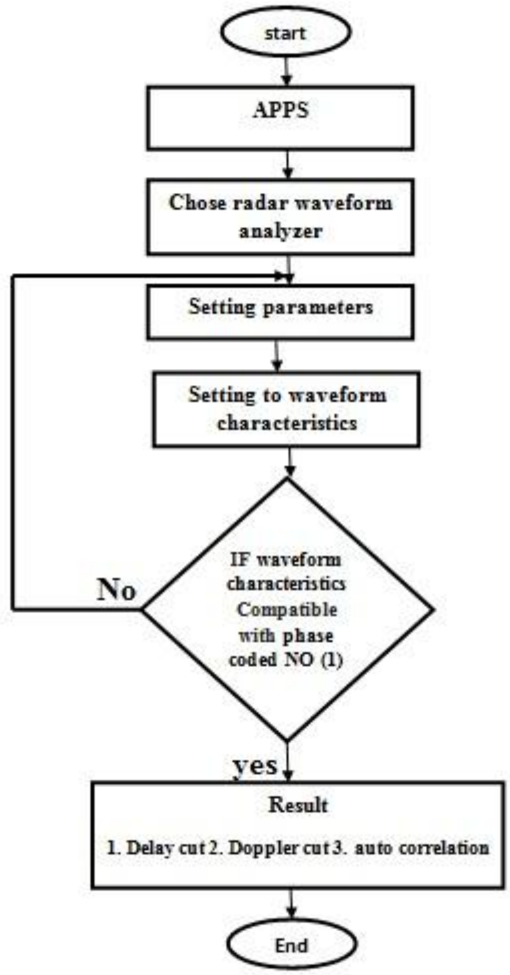

Figure 4 : flow chart steps to phase coded in matlab

This test criteria is:

- implantation and drawing of each code with the following characteristics:

  Range resolution: 150m

  Doppler frequency resolution: 2 kHz

  Minimum Range: 150m

  Maximum range: 15 km

  Minimum Doppler: 5 kHz

  Time bandwidth product: 0.1

  Duty Cycle: 1%

- Analyzing the studied codes by using the ambiguity function:

  In a radar system, the choice of a radar waveform plays an important role in enabling the system to separate two closely located targets, in either range or speed. Therefore, it is often necessary to examine a waveform and understand its resolution and ambiguity in both range and speed domains. In radar, the range is measured using the delay and the speed is measured using the Doppler shift. Thus, the range and the speed are used interchangeably with the delay and the Doppler [25].

  Usually in modern radar system the ambiguity function represents the output of matched filter thus it is perfect to use it in the analyzing deferent codes waveforms.

- phase-coded waveforms, among which the popularly used ones are Barker codes, Frank codes. In a phase-coded waveform, a pulse is divided into multiple subpulses, often referred to as chips, and each chip is modulated with a given phase. All phase-coded waveforms have good autocorrelation properties which make them good candidates for pulse compression. Thus, if a phase-coded waveform is adopted, it could lower the probability of interception as the energy is spread into chips. At the receiver, a properly configured matched filter could suppress the noise and achieve good range resolution.
- Perform the autocorrelation function for each one of the selected codes.

4.3 BARKER CODE RESULTS

One family of binary phase codes that produce compressed waveforms with constant side lobe levels equal to unity is the Barker code .*Figure 4.1* illustrates this concept for a Barker code of length five; by using the older mentioned parameters for the Barker code the following figure shows the implanted code:

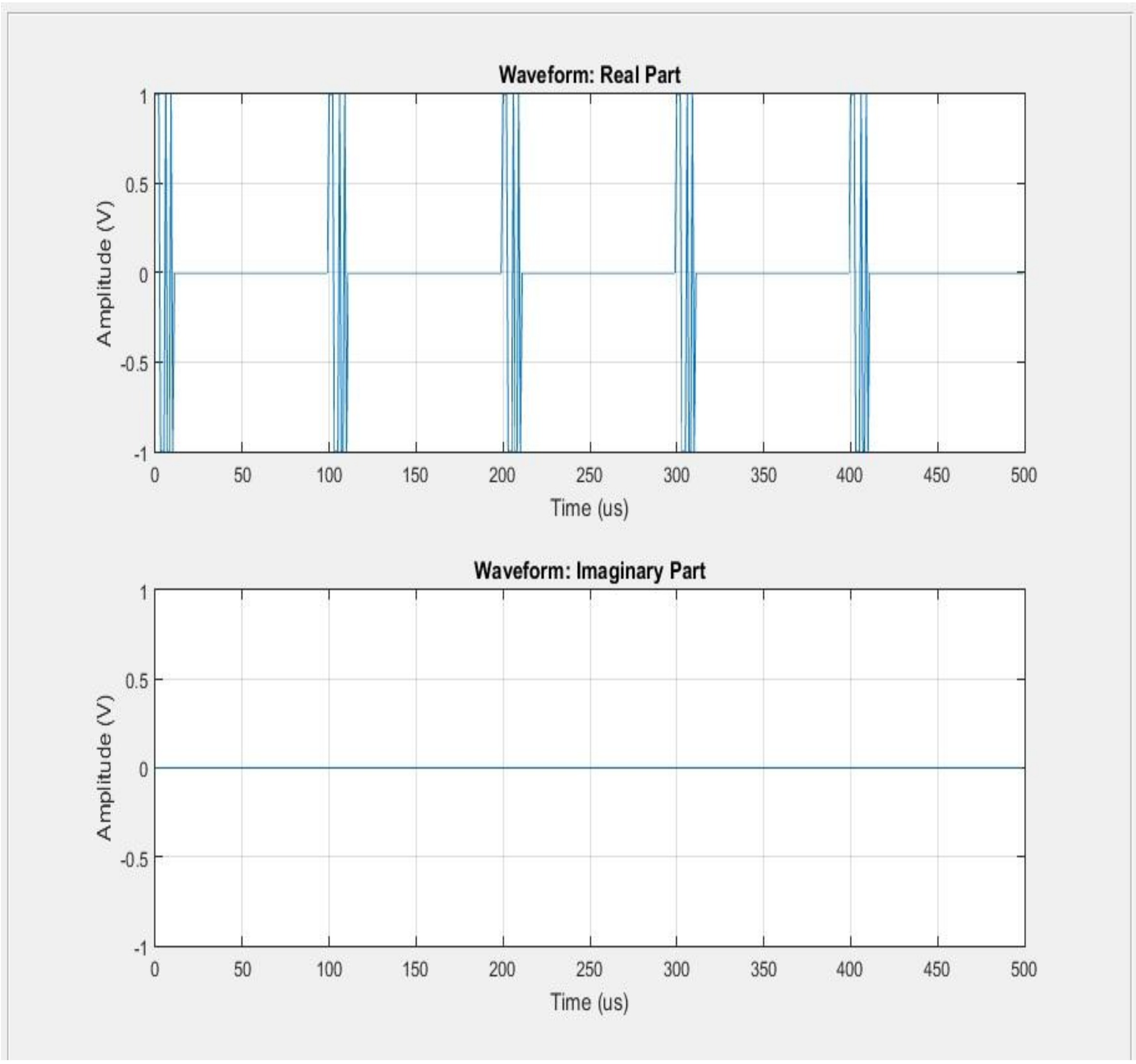

Figure 4.1: the waveform (real, imaginary) part of five element Barker code

Delay Cut:

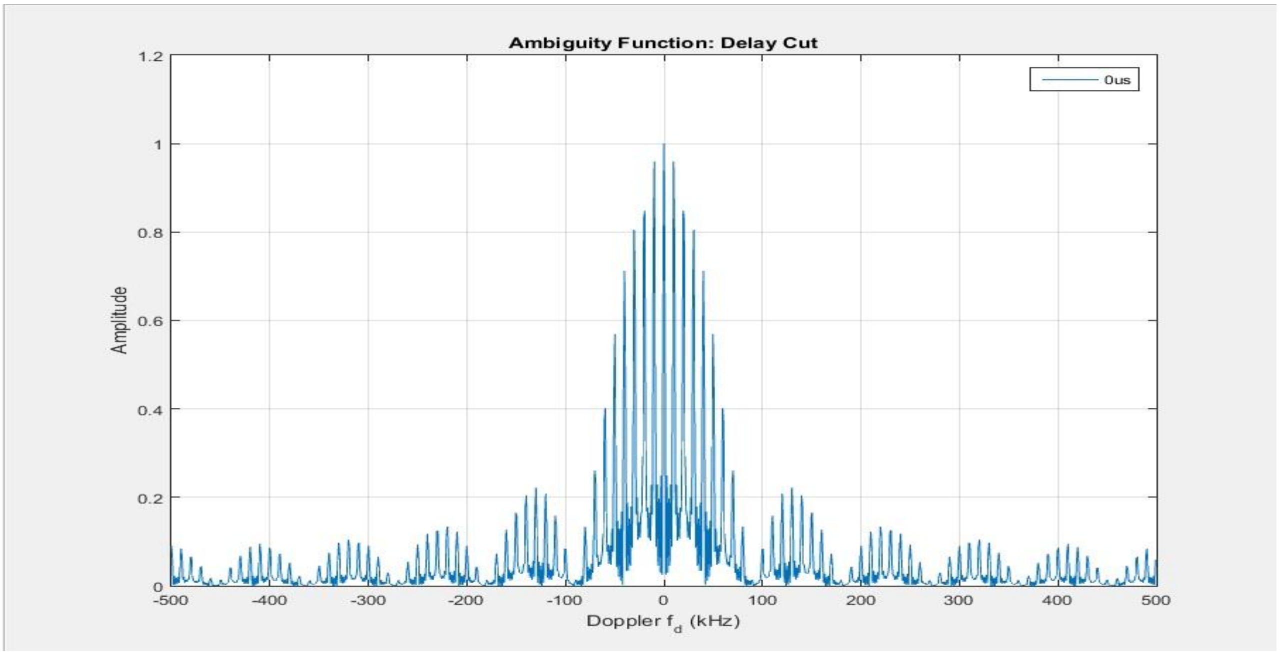

Figure 4.2: Zero delay cut corresponding to Fig. 4.1

From the figure, one can see that the zero Delay cut of a Barker code's ambiguity function has an interesting property. All its sidelobes have the differ height of the mainlobe

Doppler Cut:

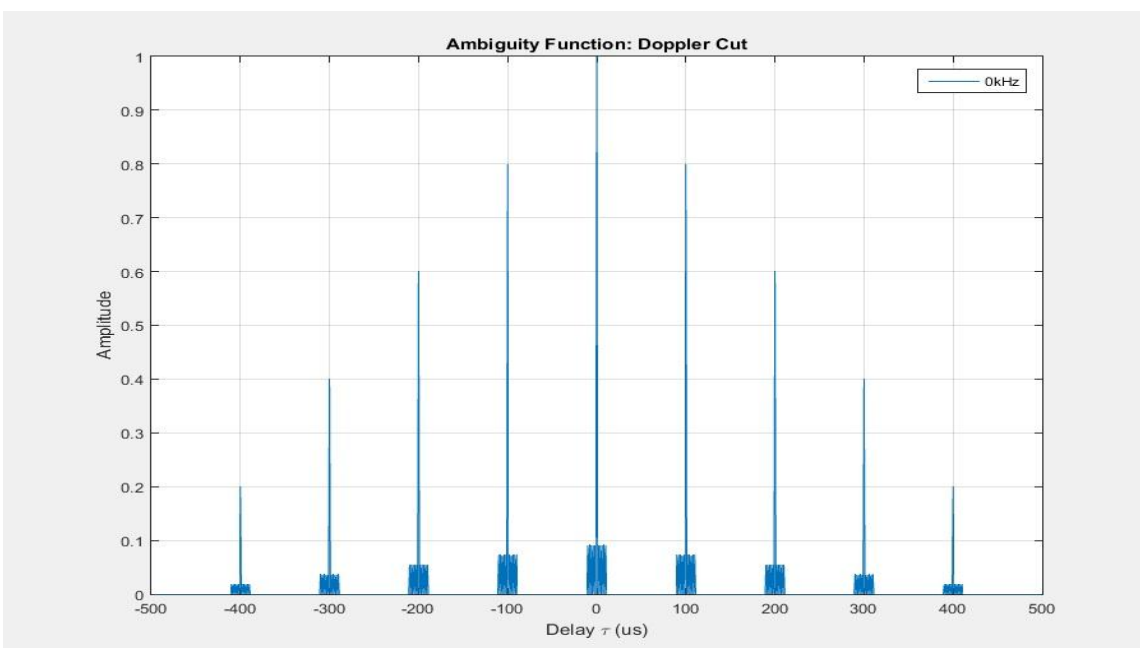

Figure 4.3: Zero Doppler cut corresponding to Fig. 4.1

From the figure, one can see that the zero Doppler cut of a Barker code's ambiguity function has an interesting property. All its sidelobes have the same height and are exactly 1/7 of the mainlobe. In fact, a length-N Barker code can provide a peak-to-peak suppression of N, which helps distinguish closely located targets in range. This is the most important property of the Barker code. The range resolution is approximately 10 microseconds, the same as the chip width.

Autocorrelation function (ACF) :

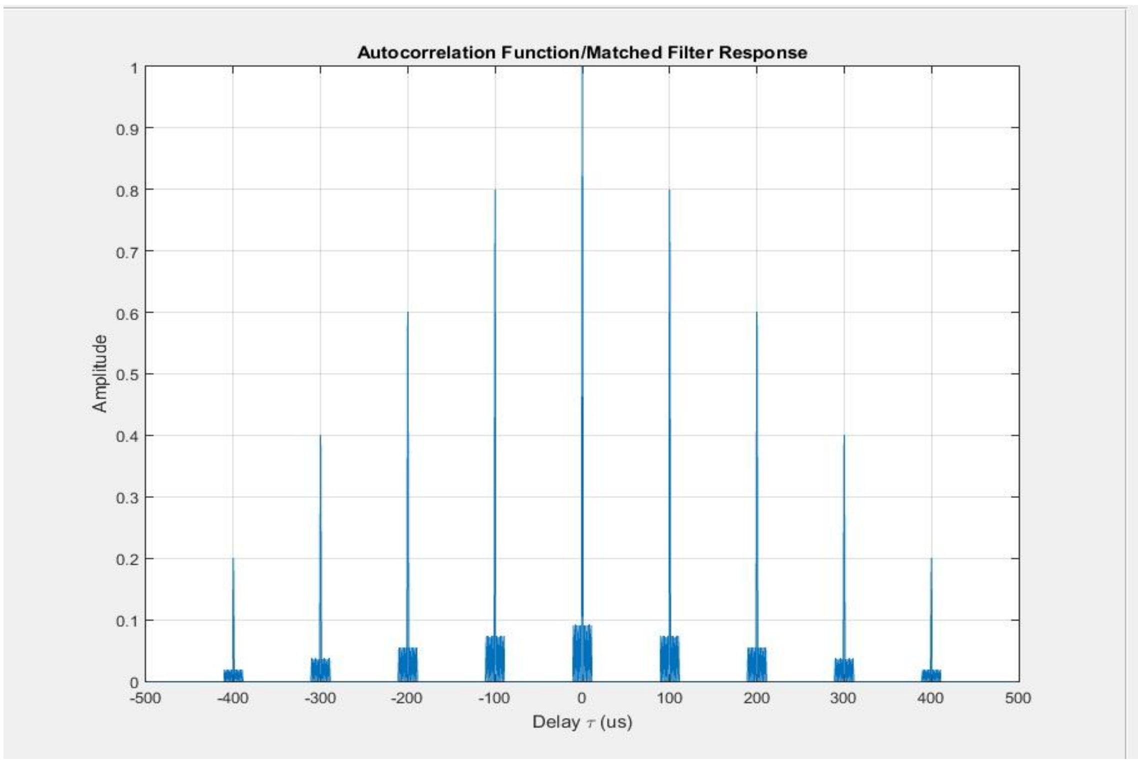

Figure 4.4: Autocorrelation function (ACF) plot corresponding to Fig. 4.1

Meanwhile, Figure 4.2, figure 4.3and Figure 4.4 give the corresponding distance ambiguity function diagram (**Delay Cut**), speed ambiguity function diagram (**Doppler cut**) and Autocorrelation function (**ACF**),We can see that this code could get high main lobe and low side-lobe . The Barker code length is 5. The side lobe level is -13.97 dB.

4.4 FRANK CODE RESULTS

The Frank code was the first code to give an accelerating phase using digital components *Figure 4.5* illustrates this concept for a Frank code of length five. By using the older mentioned parameters for the Frank code the following figure shows the implanted code:

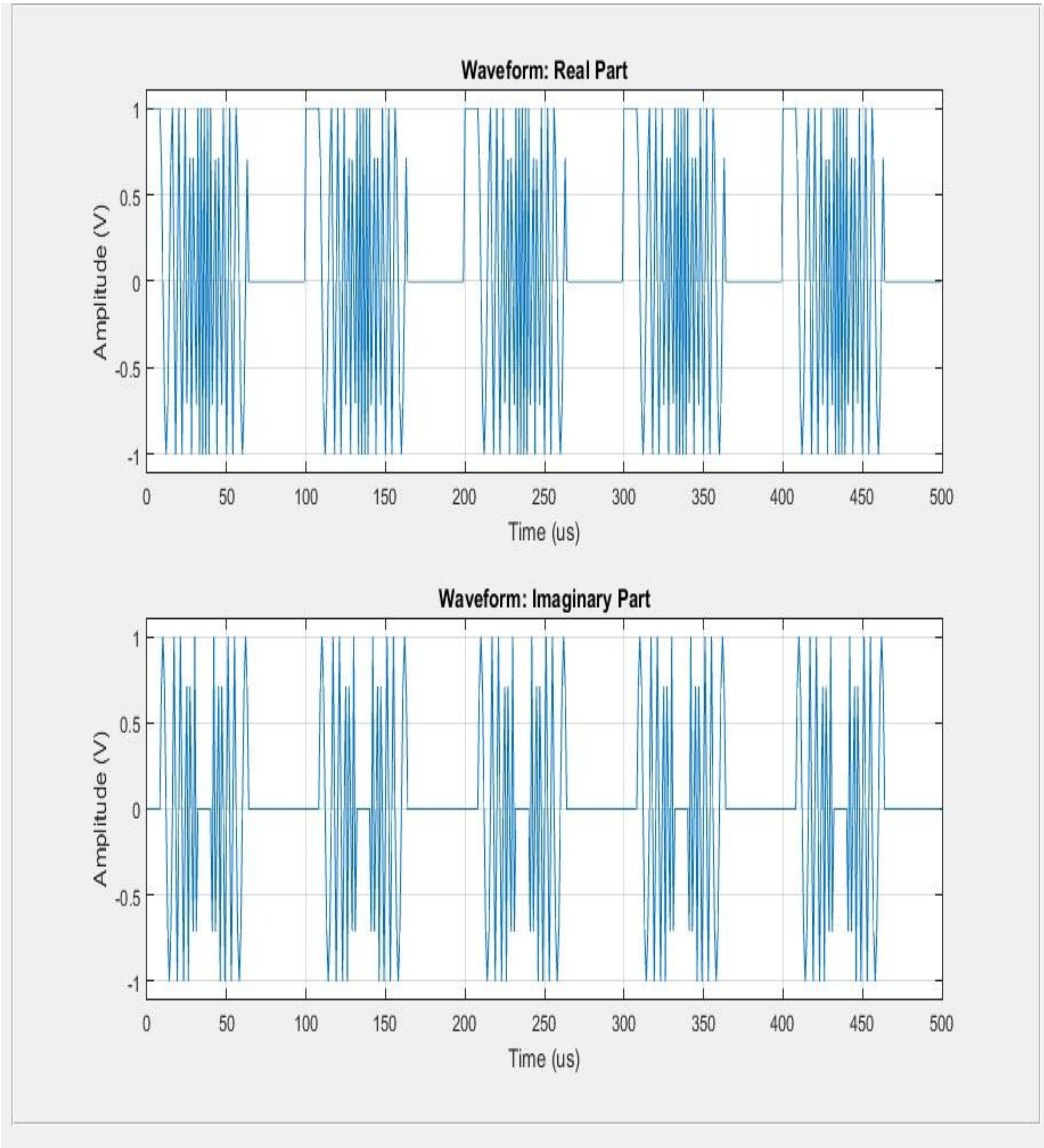

Figure 4.5: the waveform (real, imaginary) part of five element frank code

Delay Cut:

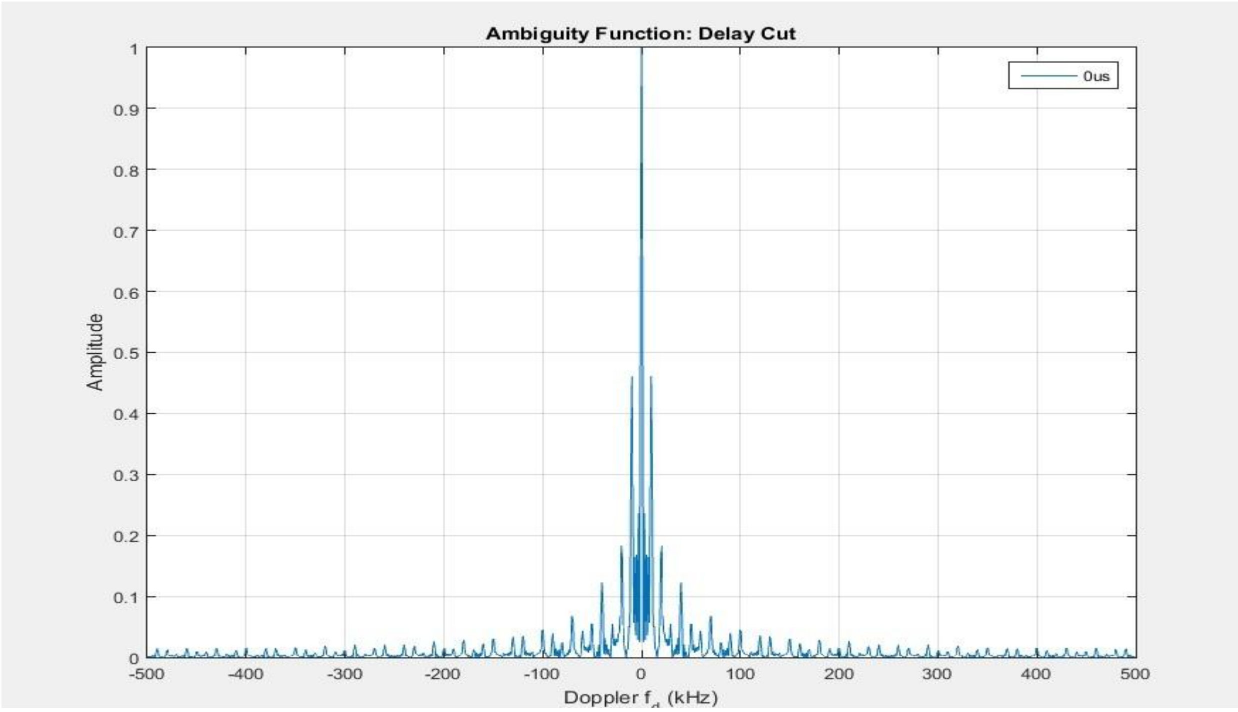

Figure 4.6: Zero delay cut corresponding to Fig. 4.5.

Doppler Cut:

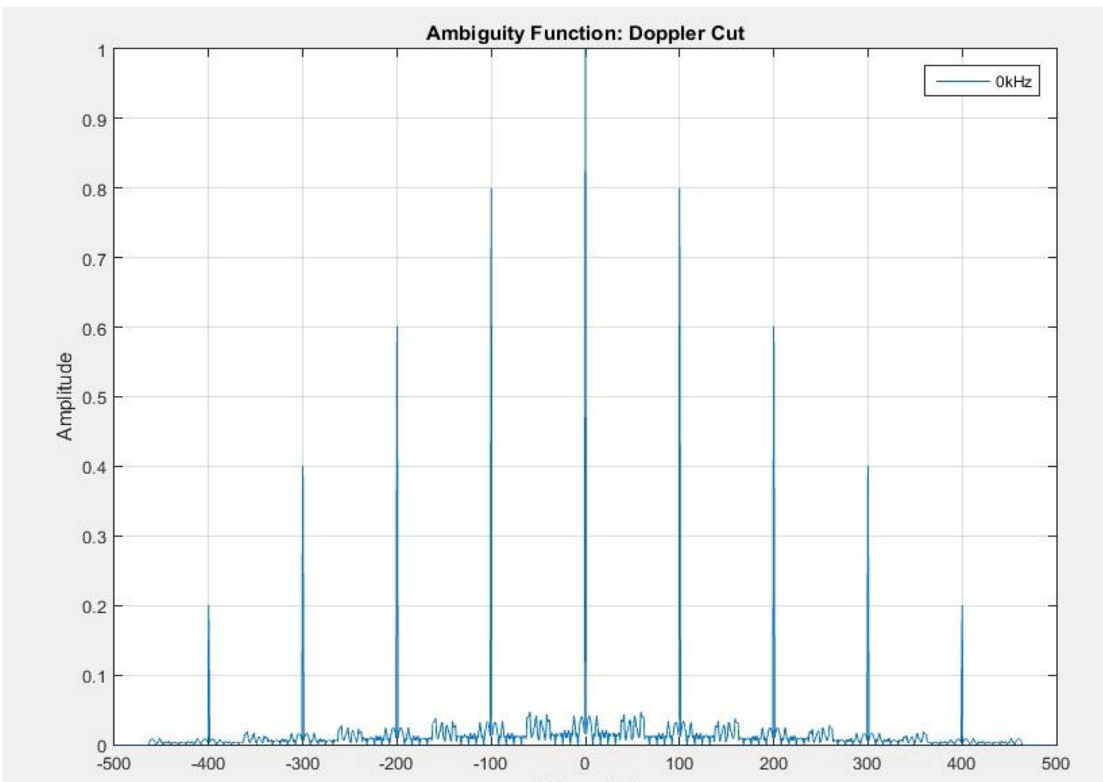

Figure 4.7: Zero Doppler cut corresponding to Fig. 4.5.

From these figures, one can make the following observations:

- The first null in Doppler is still at 1 kHz, so it has the same Doppler resolution as the 5-pulse frank pulse train. The sidelobes in the Doppler domain still present as in the frank pulse train case.
- The first null in delay is still at 1 microseconds, so the range resolution is preserved. Notice that because each subpulse is similar , the sidelobes in the range domain disappear.

Autocorrelation function ACF:

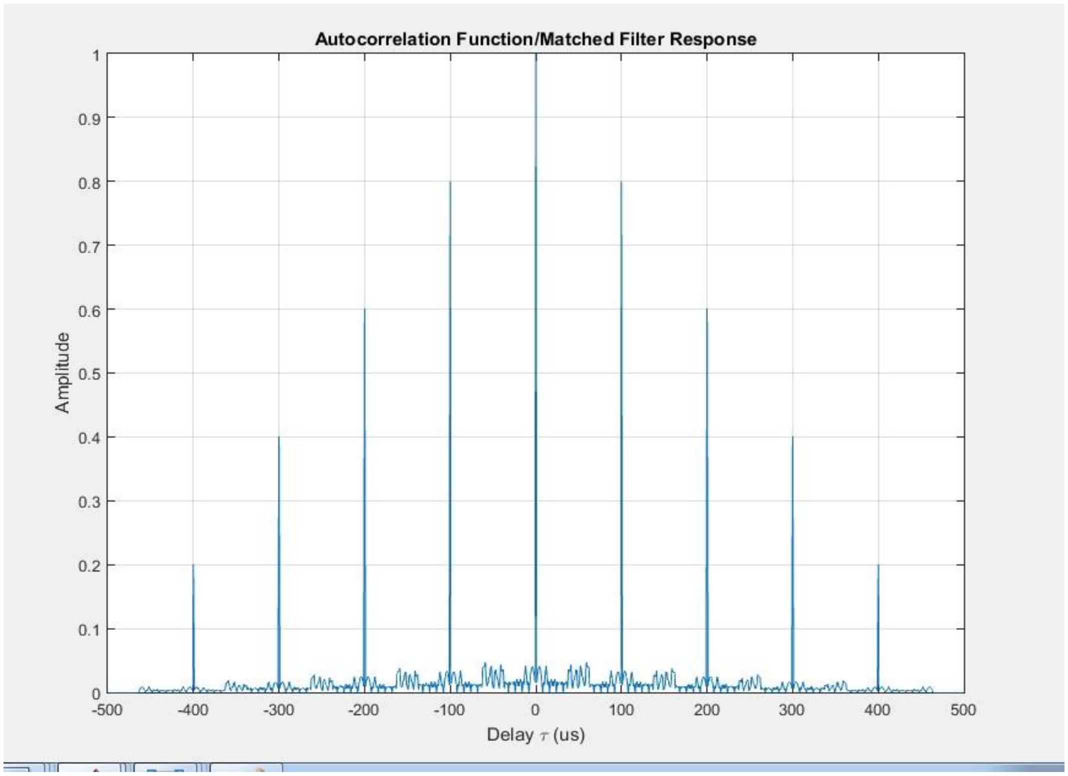

Figure 4.8: Autocorrelation function (ACF) plot corresponding to Fig.4.5.

Through, Figure 4.6, figure 4.7 and Figure 4.8 give the corresponding distance ambiguity function diagram (**Delay Cut**), speed ambiguity function diagram (**Doppler cut**) and Autocorrelation function (**ACF**), We can see that this code could get high and narrow main lobe and flat distance side-lobe .the autocorrelation function of Frank code degrades at much slower rate than that for Barker code, however the peak shifts in position rapidly and a range error occurs due to this shift. The frank code length is 5. The peak side lobe level is -23.9 dB.

4.5 P4 CODE RESULTS

P4 code is derived from conceptual coherent double sideband detection of a linear frequency modulation waveform *Figure4.9* illustrates this concept for a P4 code of length five. By using the older mentioned parameters for the P4 code the following figure shows the implanted code:

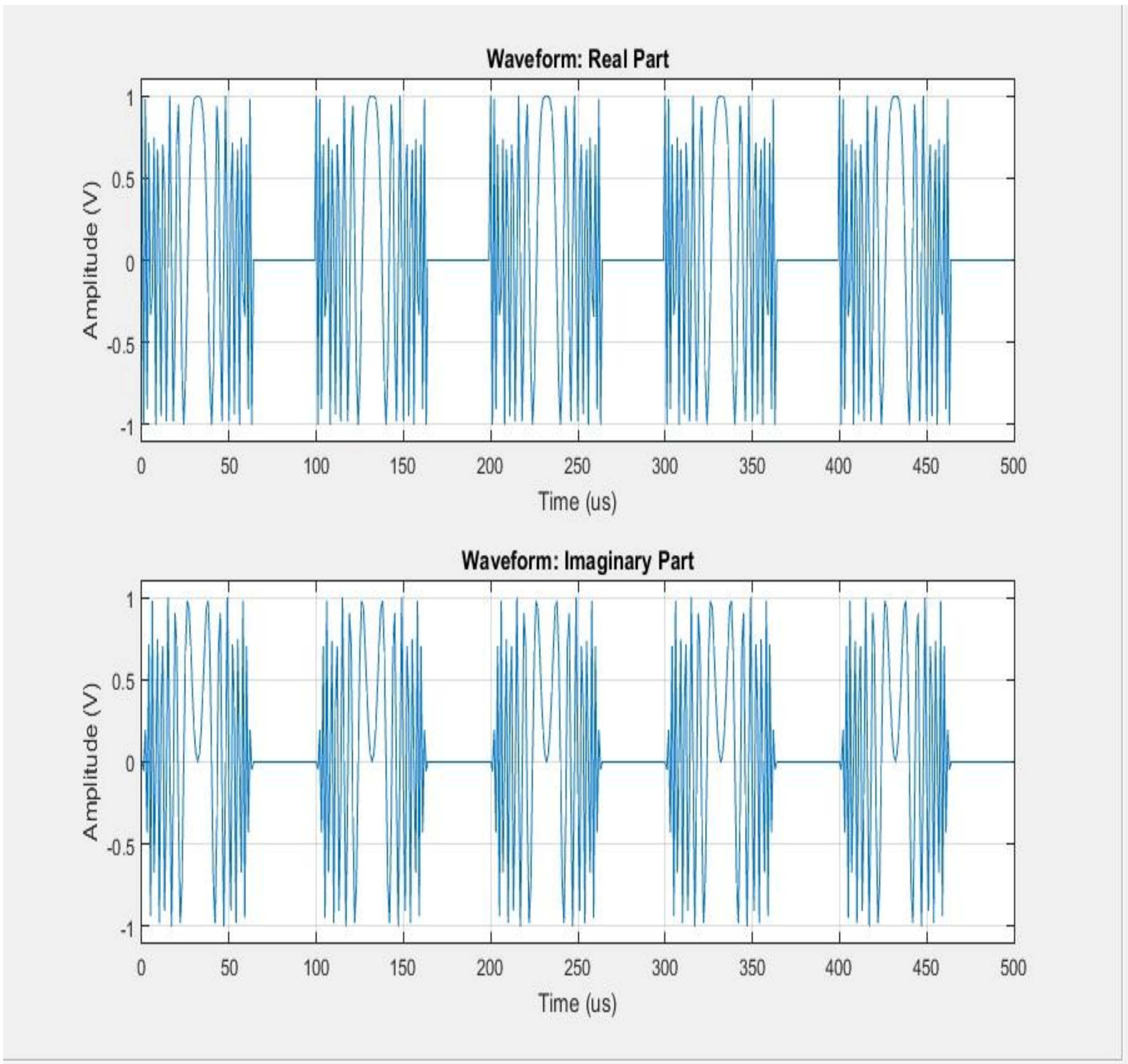

Figure 4.9: the waveform (real, imaginary) part of five element P4 code

Delay cut:

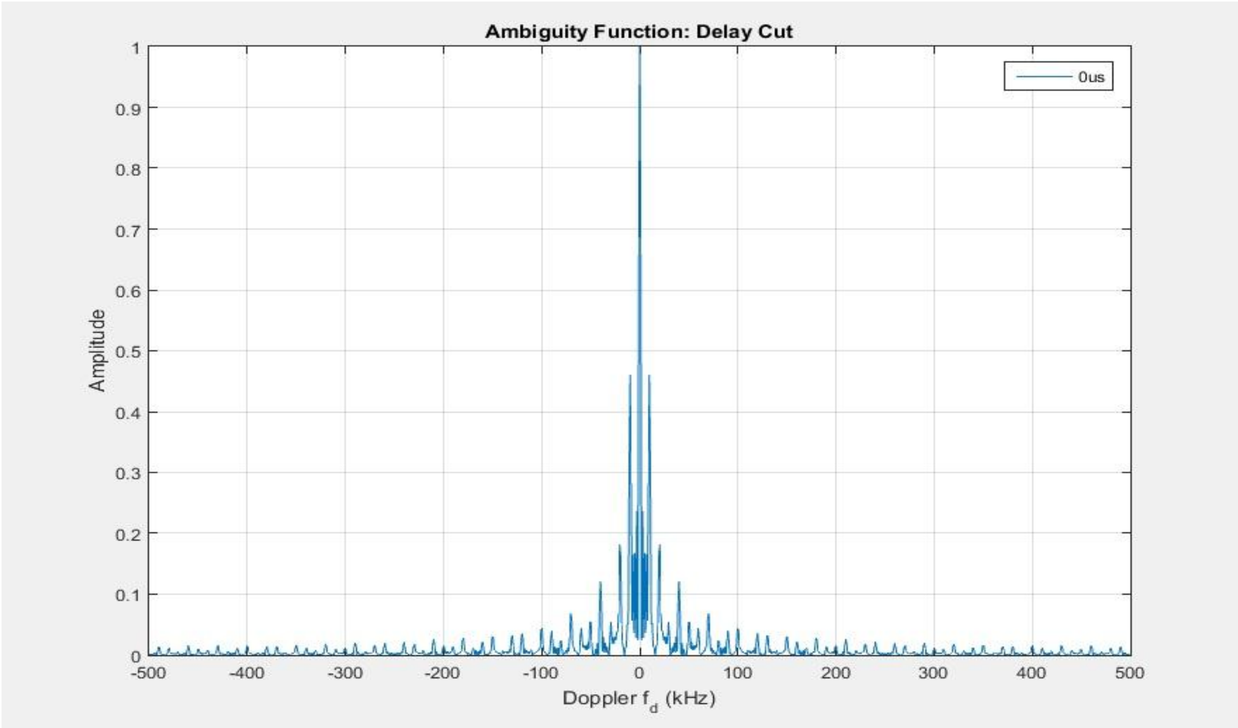

Figure 4.10: Zero delay cut corresponding to Fig.4.9.

Doppler cut:

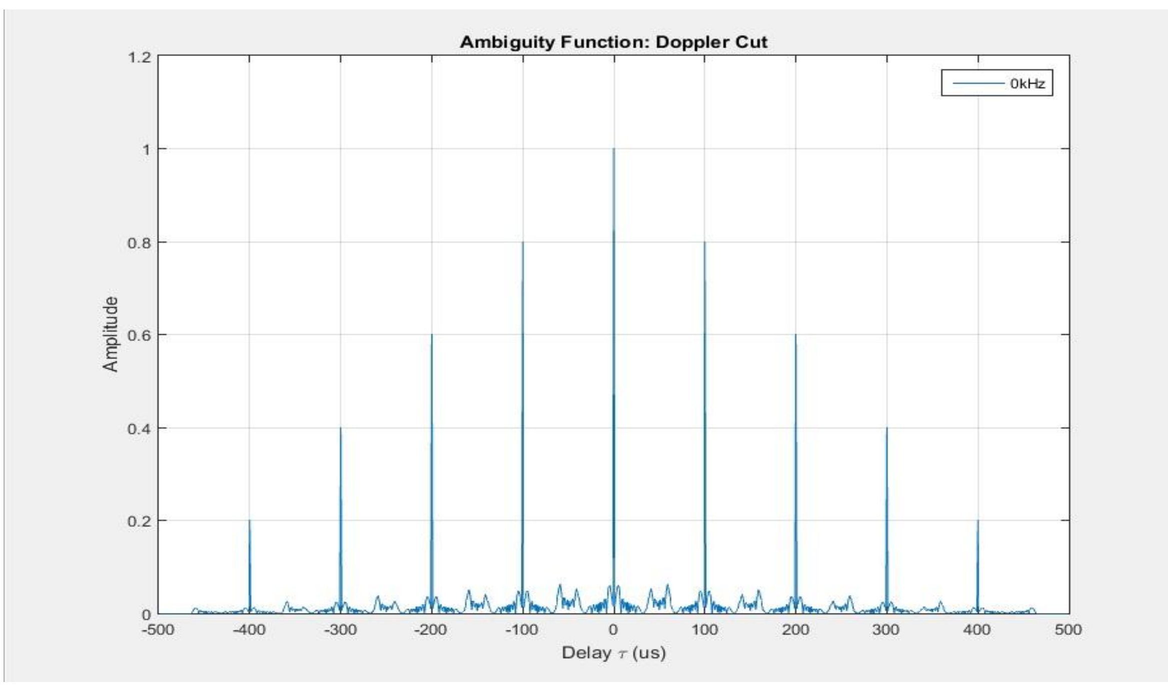

Figure 4.11: Zero Doppler cut corresponding to Fig.4.9.

From these figures, one can make the following observations:

- The first null in Doppler is still at 1 kHz, so it has the same Doppler resolution as the 5-pulse frank pulse train. The sidelobes in the Doppler domain still present as in the frank pulse train case.
- The first null in delay is still at 1 microseconds, so the range resolution is preserved. Notice that because each subpulse is similar , the sidelobes in the range domain disappear.

Autocorrelation function ACF:

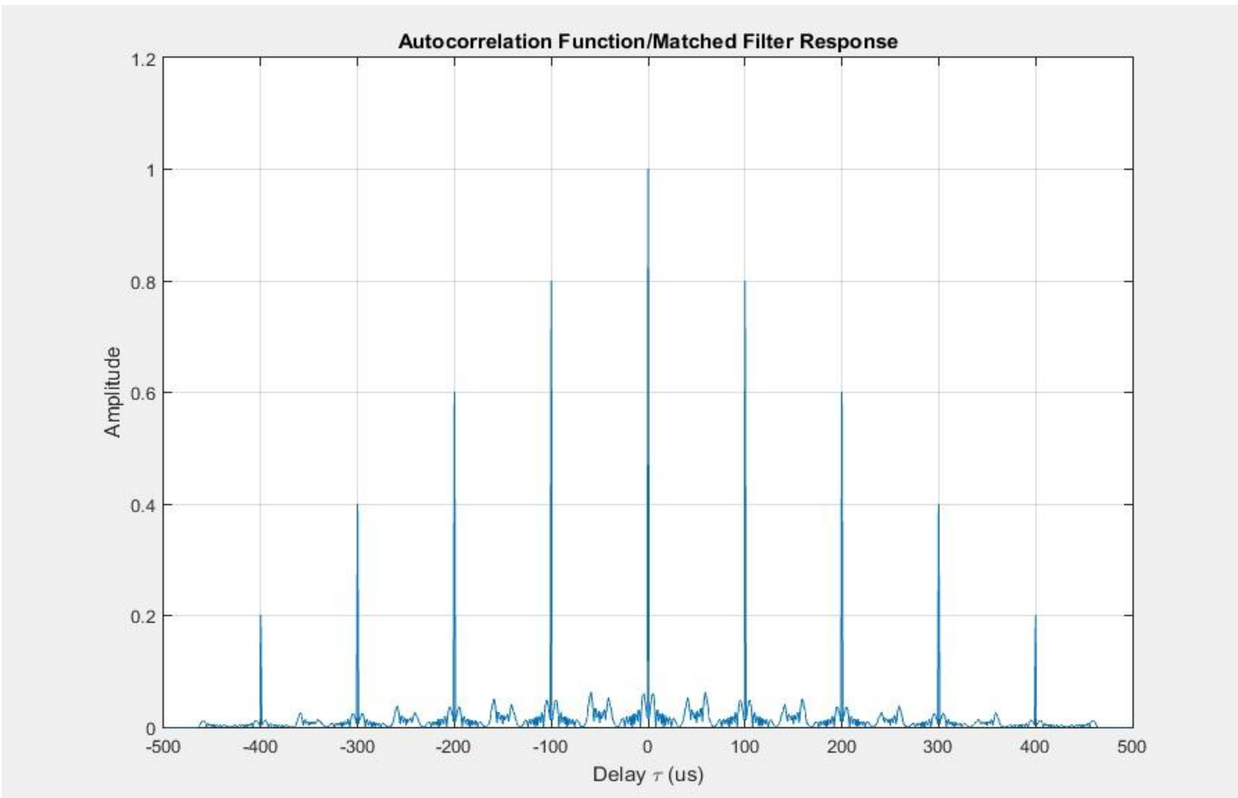

Figure 4.12: Autocorrelation function (ACF) plot corresponding to Fig.4.9.

Meanwhile, Figure 4.11, figure 4.12 and Figure 4.13 give the corresponding distance ambiguity function diagram (**Delay Cut**), speed ambiguity function diagram (**Doppler cut**) and Autocorrelation function (**ACF**), We can see that this code could get high and narrow main lobe and flat distance side-lobe .the autocorrelation function of P4 code degrades at much slower rate than that for Barker code, however the peak shifts in position rapidly and a range error occurs due to this shift. The P4 code length is 5. The peak side lobe level is -23.9 dB.

The largest phase increments from code element to code element are on the two ends of the P4 code but are in the middle of the frank code. Thus the P4 code is more pre-compression bandwidth limitation tolerant but has same Doppler tolerance than the Frank code.

All results to all frank code and p4 code was appear similar, the unique different is the p4 code is give better resolution incase found two targets closer for as.

CHAPTER FIVE

CONCLUSION AND RECOMMUNDATIONS

5.1 CONCLUSION

In this chapter, the finish of the entire postulation is introduced and future research issues are sketched out for assist examination in the same or related subjects. In this theory examination has been made on creating effective pulse compression methods for phase modulated waveforms. The fundamental commitment of the proposal is the utilization of software defined techniques for pulse compression.

As we know, we cannot take account of distance and distance resolution at the same time in the common pulse radar system. The pulse compression concept in radar systems appears as a solution to the dichotomous problem of simultaneously obtaining high transmitted pulse energy, in order to achieve long range, along with high local energy concentration after processing in the radar receiver, to yield high range resolution. Of course, using matched filter to compress signal with large time and frequency band, the output pulse can be narrow. Although pulse compression waveforms bear low side-lobes in their autocorrelations.

This project discusses and shows the results of the pulse compression performance of Barker, Frank and P4 codes under equal elements , and I have reviewed the autocorrelation properties that describe the performance of a phase-code modulated pulse, I am find the best code has narrow main lobe and flat side lobe they Poly-phase code are Frank and P4 codes and P4 code so good because the P4 code which possess these features such as narrow main lobe and low range-time-side-lobe, ease of implementation, low cross-correlation between codes, large Doppler tolerance and compatibility with band-pass limited receivers at the same time is the best of them.

In fact, I could find the pulse compression using phase modulation is binary phase coded (Barker) and Poly-phase coded (Frank, P1… P4) best methods to allow radar to simultaneously achieve the energy of a long pulse and the resolution of a short pulse

According to the practical applications, I should choose the suitable method to play up strengths and avoid weakness, of course, do some corresponding improvements when needed, finally, I could realize the design better.

5.2 RECOMMUNDATIONS

The work can be extended by improving PSL performance, SNR performance and Doppler shift interference by implementing the sidelobe cancellation technique which exactly cancels all the sidelobes as in the case of complementary code. There is a scope of designing a polyphase code which has lower sidelobes and is more Doppler tolerant by using the advance P4 code concept.

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7.APPENDIXA

In this research the MATLAB code is divided into 3 stages and each stage gives 4 outputs:

- **Barker MATLAB code:**

```
%MATLAB Code to barker

%Generated real and imaginary

%Generated daley cut

%Generated doppler cut

%Generated Autocorreation

h = phased.PhaseCodedWaveform;

   % Set the values of the properties

   h.SampleRate = 1000000;

   h.Code = 'Barker';

   h.PRF = 10000;

   h.NumPulses = 5;

   h.ChipWidth = 1e-06;

   h.NumChips = 11;

   % Generate and scale the plot

   Fs = h.SampleRate;

   x = step(h);

   l = (0:length(x)-1)/Fs;

   haxes1 = subplot(2,1,1);

   [~, scale, Units] = engunits(l(end));

   l = l*scale;
```

```
plot(l,real(x));

xlim([0  499]);

ylim([-1.1         1.1]);

xlabel('Time (us)');

ylabel('Amplitude (V)');

title('Waveform: Real Part');

grid on;

haxes2 = subplot(2,1,2);

plot(l,imag(x));

xlim([0  499]);

ylim([-1  1]);

linkprop([haxes1 haxes2],'XLim');

xlabel('Time (us)');

ylabel('Amplitude (V)');

title('Waveform: Imaginary Part');

grid on;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'Barker';

h.PRF = 10000;

h.NumPulses = 5;
```

```
h.ChipWidth = 1e-06;

h.NumChips = 11;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.SweepTime;

else

    prf = hA;

end

val = 0;

legend_str = cell(1,length(val));

for i = 1:length(val)

    ambgfun(x,Fs,prf,'Cut','Delay','CutValue', val(i)*1e-6);

    hold all;

    legend_str{i} = [num2str(val(i)) 'us'];

end

legend(legend_str);

ylabel('Amplitude');

title('Ambiguity Function: Delay Cut');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


h = phased.PhaseCodedWaveform;

% Set the values of the properties
```

```
h.SampleRate = 1000000;

h.Code = 'Barker';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;

h.NumChips = 11;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.SweepTime;

else

    prf = h.PRF;

end

val = 0;

legend_str = cell(1,length(val));

for i = 1:length(val)

    ambgfun(x,Fs,prf,'Cut','Doppler','CutValue', val(i)*1000);

    hold all;

    legend_str{i} = [num2str(val(i)) 'kHz'];

end

legend(legend_str);

ylabel('Amplitude');
```

```
   title('Ambiguity Function: Doppler Cut');

   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

   h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'Barker';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;

h.NumChips = 11;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.SweepTime;

else

    prf = h.PRF;

end

ambgfun(x,Fs,prf,'Cut','Doppler');

ylabel('Amplitude');

title('Autocorrelation Function/Matched Filter Response');

##########################################################
```

Frank MATLAB code:

```
%MATLAB Code to Frank

%Generated real and imaginary

%Generated daley cut

%Generated doppler cut

%Generated Autocorreation

h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'Frank';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;

h.NumChips = 64;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

l = (0:length(x)-1)/Fs;

haxes1 = subplot(2,1,1);

[~, scale, Units] = engunits(l(end));

l = l*scale;

plot(l,real(x));

xlim([0  500]);
```

```
ylim([-1.1         1.1]);

xlabel('Time (us)');

ylabel('Amplitude (V)');

title('Waveform: Real Part');

grid on;

haxes2 = subplot(2,1,2);

plot(l,imag(x));

xlim([0  500]);

ylim([-1.1         1.1]);

linkprop([haxes1 haxes2],'XLim');

xlabel('Time (us)');

ylabel('Amplitude (V)');

title('Waveform: Imaginary Part');

grid on;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'Frank';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;

h.NumChips = 64;
```

```
% Generate and scale the plot
Fs = h.SampleRate;
x = step(h);
if isa(h, 'phased.FMCWWaveform')
    prf = 1/h.SweepTime;
else
    prf = h.PRF;
end
ambgfun(x,Fs,prf,'Cut','Doppler');
ylabel('Amplitude');
title('Autocorrelation Function/Matched Filter Response');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
h = phased.PhaseCodedWaveform;
% Set the values of the properties
h.SampleRate = 1000000;
h.Code = 'Frank';
h.PRF = 10000;
h.NumPulses = 5;
h.ChipWidth = 1e-06;
h.NumChips = 64;
% Generate and scale the plot
Fs = h.SampleRate;
x = step(h);
```

```
if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.SweepTime;

else

    prf = h.PRF;

end

val = 0;

legend_str = cell(1,length(val));

for i = 1:length(val)

    ambgfun(x,Fs,prf,'Cut','Delay','CutValue', val(i)*1e-6);

    hold all;

    legend_str{i} = [num2str(val(i)) 'us'];

end

legend(legend_str);

ylabel('Amplitude');

title('Ambiguity Function: Delay Cut');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'Frank';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;
```

```
h.NumChips = 64;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.Time;

else

    prf = h.PRF;

end

val = 0;

legend_str = cell(1,length(val));

for i = 1:length(val)

    ambgfun(x,Fs,prf,'Cut','Doppler','CutValue', val(i)*1000);

    hold all;

    legend_str{i} = [num2str(val(i)) 'kHz'];

end

legend(legend_str);

ylabel('Amplitude');

title('Ambiguity Function: Doppler Cut');
```

P4 MATLAB code:

```
%MATLAB Code to p4

%Generated real and imaginary

%Generated daley cut

%Generated doppler cut

%Generated Autocorreation


h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'P4';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;

h.NumChips = 64;

% Generate and scale the plot

Fs = h.Rate;

x = step(h);

l = (0:length(x)-1)/Fs;

haxes1 = subplot(2,1,1);

[~, scale, Units] = engunits(l(end));

l = l*scale;

plot(l,real(x));
```

```
xlim([0  499]);

ylim([-1.1         1.1]);

xlabel('Time (us)');

ylabel('Amplitude (V)');

title('Waveform: Real Part');

grid on;

haxes2 = subplot(2,1,2);

plot(l,imag(x));

xlim([0  499]);

ylim([-1.0987      1.0987]);

linkprop([haxes1 haxes2],'XLim');

xlabel('Time (us)');

ylabel('Amplitude (V)');

title('Waveform: Imaginary Part');

grid on;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'P4';

h.PRF = 10000;

h.NumPulses = 5;
```

```
h.ChipWidth = 1e-06;

h.NumChips = 64;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.SweepTime;

else

    prf = h.PRF;

end

val = 0;

legend_str = cell(1,length(val));

for i = 1:length(val)

    ambgfun(x,Fs,prf,'Cut','Delay','CutValue', val(i)*1e-6);

    hold all;

    legend_str{i} = [num2str(val(i)) 'us'];

end

legend(legend_str);

ylabel('Amplitude');

title('Ambiguity Function: Delay Cut');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h = phased.PhaseCodedWaveform;

% Set the values of the properties
```

```
h.SampleRate = 1000000;

h.Code = 'P4';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;

h.NumChips = 64;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.SweepTime;

else

    prf = h.PRF;

end

val = 0;

legend_str = cell(1,length(val));

for i = 1:length(val)

    ambgfun(x,Fs,prf,'Cut','Doppler','CutValue', val(i)*1000);

    hold all;

    legend_str{i} = [num2str(val(i)) 'kHz'];

end

legend(legend_str);

ylabel('Amplitude');
```

```
title('Ambiguity Function: Doppler Cut');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

h = phased.PhaseCodedWaveform;

% Set the values of the properties

h.SampleRate = 1000000;

h.Code = 'P4';

h.PRF = 10000;

h.NumPulses = 5;

h.ChipWidth = 1e-06;

h.NumChips = 64;

% Generate and scale the plot

Fs = h.SampleRate;

x = step(h);

if isa(h, 'phased.FMCWWaveform')

    prf = 1/h.SweepTime;

else

    prf = h.PRF;

end

ambgfun(x,Fs,prf,'Cut','Doppler');

ylabel('Amplitude');

title('Autocorrelation Function/Matched Filter Response');
```

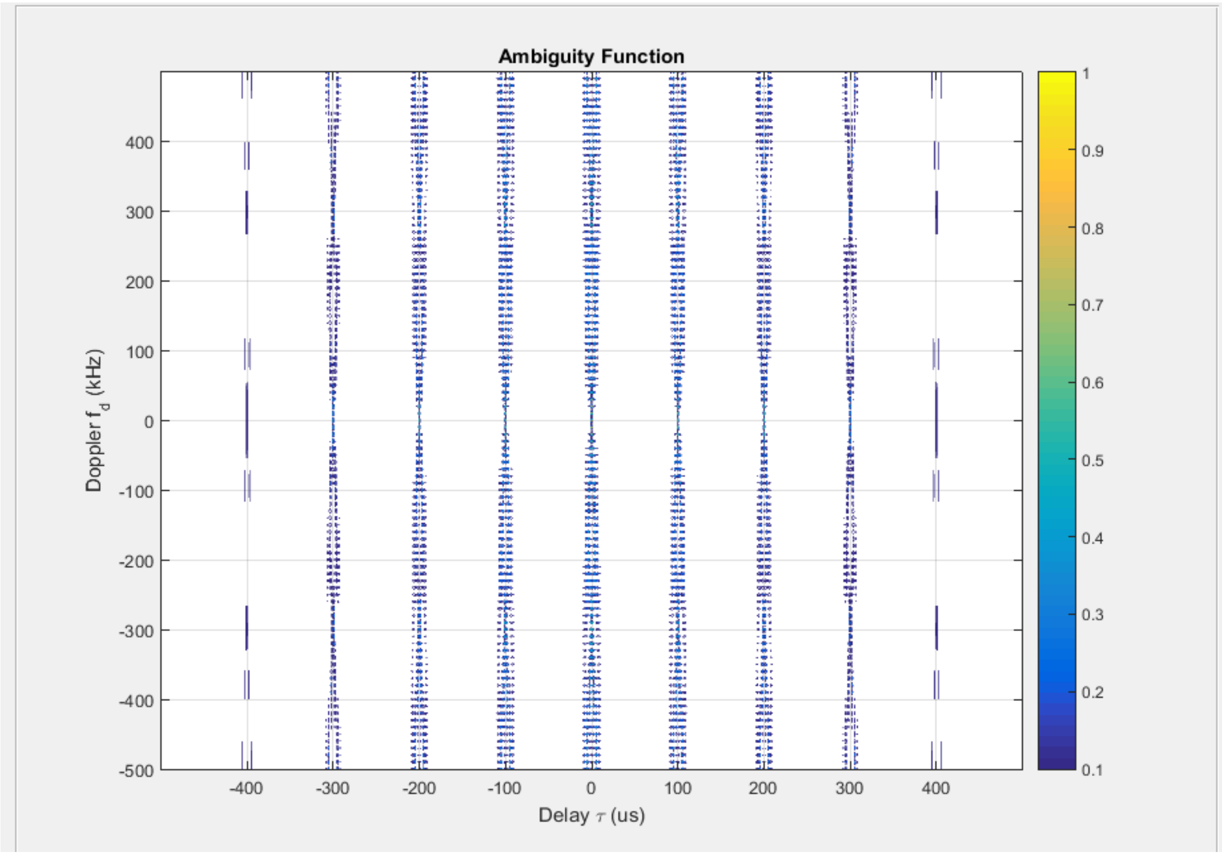
8.APPENDIX B

RADAR AMBIGUITY FUNCTION

an ambiguity function is a two-dimensional function of time delay and Doppler frequency χ(τ, *f*) {\displaystyle \chi (\tau ,f)}showing the distortion of a returned pulse due to the receiver matched filter. Named Ambiguity Diagram-Contour

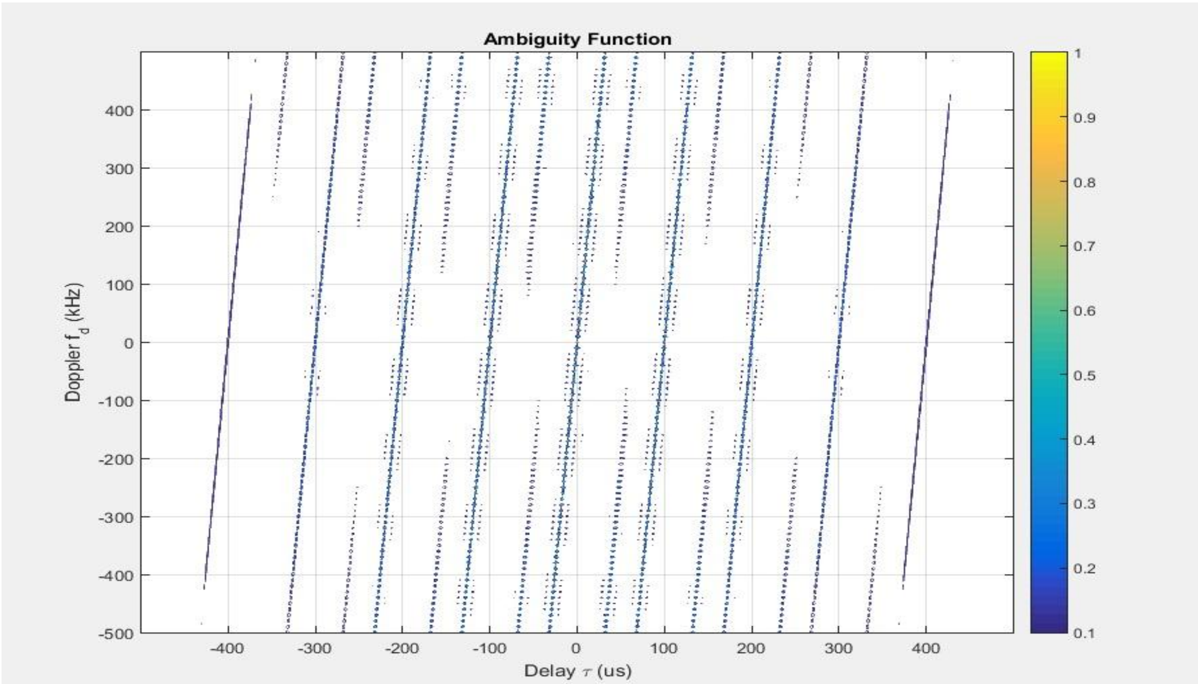
Ambiguity Diagram-Contour:

Barker code:



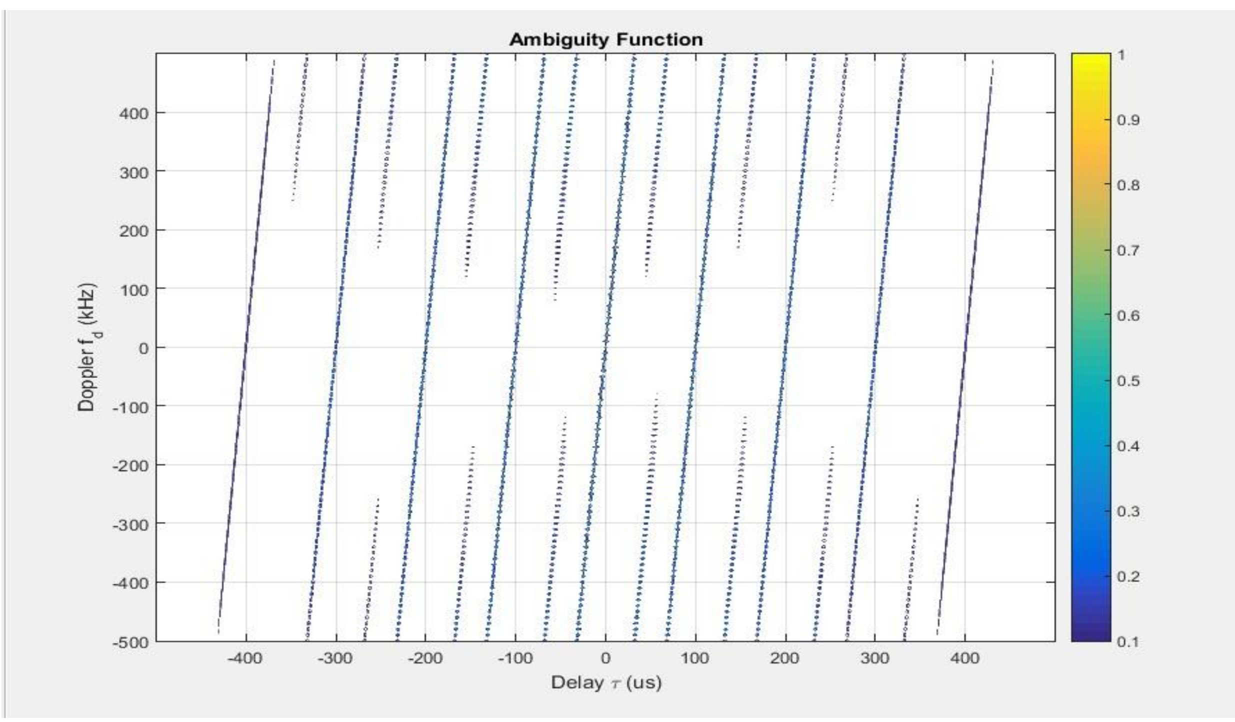
Contour plot to barker code

Frank code:



Contour plot to frank code

P4 code:



Contour plot to p4 code