JULY 2018

M.Sc. in Electrical and Electronics Engineering

HUSAIN ALI

UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES

DESIGN AND IMPLEMENTATION OF FMCW RADAR USING RASPBERRY PI SINGLE BOARD COMPUTER

M. Sc. THESIS
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

BY
HUSAIN ALI

JULY 2018

Design and Implementation of FMCW Radar

Using Raspberry Pi Single Board Computer

M.Sc. Thesis

in

Electrical and Electronics Engineering

University of Gaziantep

Supervisor

Prof. Dr. Ergun ERÇELEBİ

by

Husaın ALI

July 2018

REPUBLIC OF TURKEY
UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
DEPARTMET OF ELECTRIC AND ELECTRONIC ENGINEERING

Name of the thesis: Design and Implementation of FMCW Radar Using Raspberry Pi Single Board Computer

Name of the student: Husaın ALI

Exam date: 23/07/2018

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. A. Necmeddin YAZICI

Director

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

Prof. Dr. Ergun ERÇELEBİ

Head of Department

This is to certify that we have read this thesis and that in our consensus/majority opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Ergun ERÇELEBİ

Supervisor

Examining Committee Members	Signature
Prof. Dr. Ergun ERÇELEBİ	…………………..
Prof. Dr. İlyas Eker	…………………..
Doç Dr. Mete Vural	…………………..

ABSTRACT

DESIGN AND IMPLEMENTATION OF FMCW RADAR USING RASPBERRY PI SINGLE BOARD COMPUTER

ALI, Husaın
M.Sc. in Electrical and Electronics Eng.
Supervisor(s): Prof. Dr. Ergun ERÇELEBİ
July 2018
42 pages

Frequency Modulated Continuous Wave (FMCW) radar measures the target's range and velocity by emitting a continuous wave, frequency modulated signal by a sawtooth or triangular function. With this technology, many advantages can be achieved compared to the pulse radar including ability to measure target range and its velocity, ability to measure small ranges to the target. Also, it has better accuracy when comparing to other radar types, and simpler signal processing due to low frequency at baseband. This thesis presents a complete design and implementation of a 6 GHz FMCW radar system using the Raspberry Pi single board computer as a signal processing platform. The proposed system consists of 6 GHz RF front-end architecture, analog to digital interface, and control unit.

One of the key challenges in generating FMCW signals is the non-linearity of VCOs, which have been resolved in the proposed design by using a closed loop structure based on fractional-N frequency synthesizer along with VCO. At baseband, a high pass filter used to equalize signal before digital interface stage, which reduce significant differences in power level between close targets and far targets. With the developed radar, the velocity and distance information of the target has been successfully extracted from the signal processing stage of the radar and displayed on the TFT screen.

Key Words: Frequency Modulated Continuous Wave Radar, Voltage-controlled oscillators, Baseband, Chirp signal.

ÖZET

RASPBERRY Pİ TEK KARTLI BİLGİSAYAR KULLANARAK FMCW RADARI TASARIMI VE GERÇEKLEMESİ

ALI, Husaın
Yüksek Lisans Tezi, Elektrik-Elektronik Müh. Bölümü
Tez Yöneticisi(leri): Prof. Dr. Ergun ERÇELEBİ
Temmuz 2018
42 sayfa

Frekans Modülasyonlu Sürekli Dalga (FMCW) radarı, sürekli dalga, testere dişi veya üçgen fonksiyon ile frekans modülasyonlu sinyal göndererek hedefin menzilini ve hızını ölçer. Bu teknoloji ile, hedef aralığın ve hızının ölçülebilmesi, hedefe küçük aralıkları ölçebilme yeteneği dâhil olmak üzere, puls radarına kıyasla birçok avantaj elde edilebilir. Ayrıca, diğer radar tipleriyle kıyaslandığında daha iyi bir doğruluğa ve btemel bantta düşük frekans nedeniyle daha basit sinyal işlemeye sahiptir.

Bu tez, Raspberry Pi tek kartlı bilgisayar kullanılarak sinyal işleme platformu olarak 6 GHz FMCW radar sisteminin eksiksiz bir tasarımını ve gerçekleştirilmesini sunmaktadır. Önerilen sistem 6 GHz RF ön uç mimarisi, dijital ara yüze analog ve kontrol ünitesinden oluşmaktadır.

FMCW sinyallerinin oluşturulmasındaki temel zorluklardan biri, VCO'lar ile birlikte kesirli-N frekanslı sentezleyiciye dayanan kapalı bir döngü yapısı kullanılarak önerilen tasarımda çözülmüş olan VCO'ların doğrusal olmamasıdır. Temel bantta, dijital arayüz aşamasından önce sinyali dengelemek için kullanılan yüksek geçirgen süzgeç, yakın hedefler ve uzak hedefler arasındaki güç seviyesindeki önemli farklılıkları azalmaktadır. Geliştirilen radar ile radarın işaret işleme katında hedefin hızı ve mesafe bilgileri başarıyla çıkartılmış ve TFT ekranında gösterilmiştir.

Anahtar Kelimeler: Frekans Modülasyonlu Sürekli Dalga Radarı, Voltaj kontrollü osilatörler, temel bant , cıvıltı işareti.

To free Syria..

ACKNOWLEDGEMENTS

This thesis is written as part of master study at the Department of Electrical and Electronic Engineering, Gaziantep University, TURKEY.

Both hardware and software design efforts expressed in this thesis were key challenges in my career as an electrical engineer. It was the very first high frequency complicated hardware design with signal processing capabilities I have ever made in my career.

I would like to express my deepest gratitude to my supervisor Prof. Dr. Ergun ERÇELEBİ and for his guidance, advice, criticism, encouragements and insight throughout the research.

I am very grateful to my mother, my wife and my little daughter for their understanding, support and love.

CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER 1

INTRODUCTION

FMCW radar was originally developed for radar altimeters for aircraft in the mid 1930's. Today, FMCW is useful in applications where wide-band high resolution time-of-flight measurements must be made with low-power transmitters. Applications include automotive radar, short-range imaging, avionic altimeters, and many others. FMCW radar have many advantages compared to the pulse radar such as: reducing the transmitted power, ability to measure target range and its relative velocity simultaneously, and ability to perform signal processing after mixing at a low frequency range, which considerably simplifying the processing circuits.

FMCW radars send out continuous frequency modulated microwave signal by low frequency waveform, e.g. a sawtooth shape. The distance information of the target can be obtained through spectrum analysis by identifying a target (or beat) signal.

Performance of FMCW radars significantly depends on the linearity of frequency sweep and especially in long distance applications, where the frequency sweep non-linearity results in range resolution degradation. The Voltage Controlled Oscillator (VCO) is used for sweep generation. However, VCOs with linear transfer function are very limited in market, and one of the key challenges in FMCW Radar design is to solve non-linearity in VCO’s transfer function.

This study presents a practical design and implementation of FMCW radar system based on the Raspberry Pi single board computer.

1.1 Motivation

The basic motivating factor behind this study is to propose a low-cost design of an FMCW radar with fully dependent on Raspberry Pi single board computer for signal processing and visualization purpose. Using microwave components that being in use for wireless Wi-Fi applications make the proposed radar cheaper and easier to implement, so it will be more affordable.

Meanwhile, using the well-known Raspberry Pi single board computer enables the design to be useful by students and researchers as an experimental platform for developing radar algorithms and a good choice for high frequency signal processing applications.

1.2 Literature Review

The word RADAR was introduced in 1940 as an acronym for **RA**dio **D**etection **A**nd **R**anging. Radars originally designed for military purposes in World War II when the existing detection technology like field glasses and directional microphones were ineffective especially in high speed conditions. Nevertheless, due to its high performance in object detection, the use of radars has spread recent years in civil applications such as automobile industry and geosciences.

Radar is an object detection system that transmits electromagnetic energy and receives the reflected portion of transmitted energy to determine information of objects such as range and velocity. A radar system consists of the following components: transmitting antenna emitting electromagnetic radiation generated by an oscillator, a receiving antenna, and an energy detecting device or receiver.

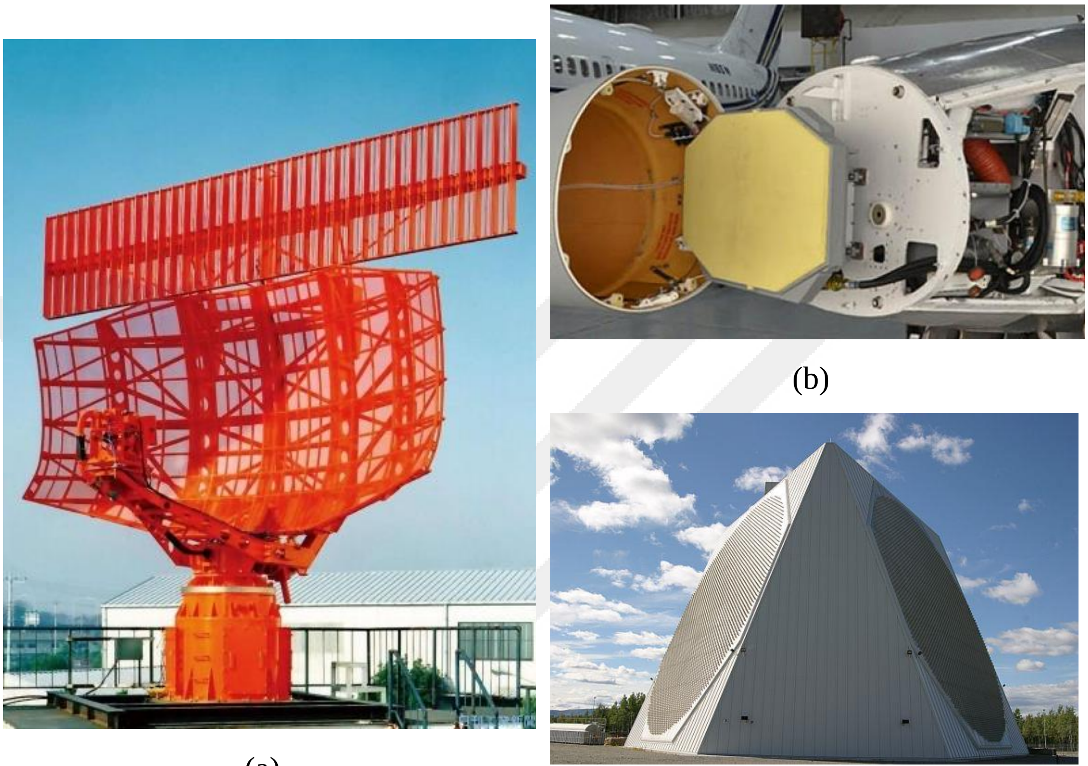
The major areas of radar application refer to [5]:

- Military field (air defense systems, guided missiles, and other weapons);
- Environmental remote sensing (weather, planetary, and sea ice observation);
- Air traffic control;
- Highway safety;
- Ship safety and other.

1.2.1 Radar Types and Classifications

Radars can be classified into numerous categories based on installation platform, specific radar characteristics, or functionality.

Classification according to installation platform includes: ground based, airborne, spaceborne, or ship-based radar systems. They can also be classified by specific radar characteristics, such as the frequency band, antenna type, and waveforms utilized. Functionality classification includes: weather, acquisition and search, tracking, track-while-scan, fire control, early warning, over the horizon, terrain following, and terrain avoidance radars. Figure 1.1 shows three examples of different radar systems.



(b)

(a)

(c)

Figure 1.1. Examples of radar systems: (a) ASR-9 air traffic control radar, (b) APG-83 Scalable Agile Beam Radar (SABR) AESA for the F-16, and (c) PAVE PAWS Phased Array Warning System

1.2.2 Pulse Radar Systems

Pulse radars are generally designed for long distances systems. This type of radars emits short and high-power pulses toward the target and receives the echo signal in the silent period between pulses and then measures the targets range by calculating time delay between transmitted and received pulses where transmitter is turned off before the measurement is finished [9]. The waveform of pulse radar is represented in Figure 1.2.

By integrating doppler frequency detection mechanism, resulting radar will be able to measure target’s velocity along with its range. This structure called Pulse-Doppler radar, which combines the features of pulse radars and continuous-wave radars.

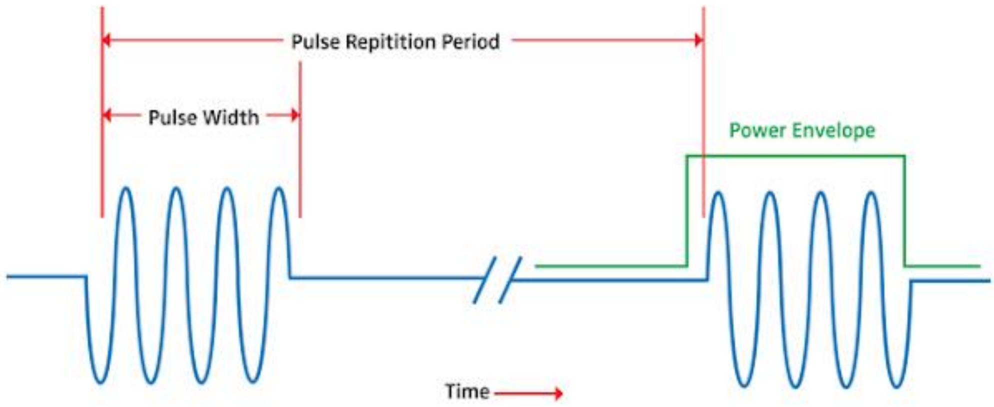


Figure 1.2. Pulse radar waveform

1.2.3 Continuous Wave Radar Systems

Continuous wave (CW) radar systems continuously radiate electromagnetic power and receive reflected portion all the time. It directly measures the Doppler shift of reflected signal to measure the angular velocity of moving target. Conventional CW radars can’t measure range without use kind of modulation in transmitted signal.

This structure is the fundamental operation of CW radar, where it only measures frequency modulation due to the Doppler Shift. Other structures of CW can measure phase shift of the received signal instead of frequency shift which common in precise interferometry applications. Adding frequency modulation to emitted signal will result-in FMCW radar which have many advantages over pulse radars as well as CW radars. Figure 1.3 shows a set of radar waveforms including pulse, CW and FMCW radars waveforms.

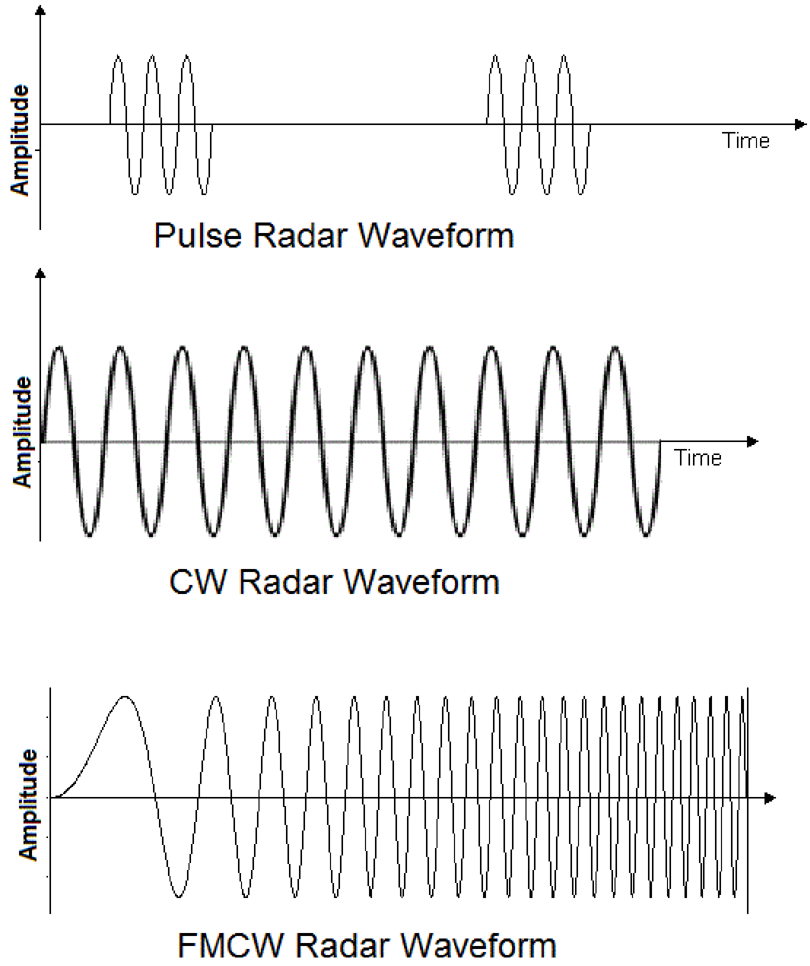


Figure 1.3. Waveform of pulse, CW, and FMCW radars

1.2.4 Information Available in Radar Signal

Reflected signal from target may contain much information about target. Although target detection is important, it may be not useful without additional information. On the other hand, target information without radar detection is meaningless [1].

Information available in radar signal may differ depending on the principle that is use, but in general, the following information can be obtained:

- **Range:** Target's range is the most important feature of radar is ability to measure the range of target because no other sensor can measure range at long distances with accuracy of radar. Range calculation depends on accurately measuring the radar signal travel time out to the target and back to the radar. The range can be calculated from the duration Δt and the speed of propagation C_0. For more accurate calculations, actual speed of propagation can be used instead of C_0 if any significant influence is available.

- **Radial Velocity:** In the case of moving target detection, velocity can be obtained from range change rate or directly from Doppler shift equation 2.7. Speed and direction measurement of a moving target can be obtained from its track, which can be calculated from range measurement over a period [1].
- **Angular Direction (Azimuth, Elevation):** Angular direction can be determined from the antenna position by determining the angle where the power level of reflected signal is maximum. The accuracy of angular direction measurement is determined by antenna directivity, so narrow beam width (or high directivity) will increase accuracy [1].
- **Size and Shape:** Radar resolution in cross range may enable radar to measure some physical properties of target. However, limitations of antenna beam width may limit measurement results. Employing a doppler frequency domain based on SAR (Synthetic Aperture Radar) or ISAR (Inverse Synthetic Aperture Radar) will significantly improve resolution in the cross-range dimension, but it will need a relative motion between radar and target [1].

1.3 Problem Statement

In recent years, many industries have shown an increasing interest in compact, short range, and low power radar systems. This including automotive, avionics, manufacturing, and consumer electronics industries. The key factor led to prefer radar-based systems is their capabilities of to work under different weather conditions, such as rain and fog, where other sensors may fail to operate, or even other conditions where other sensor lack to operate due to physical limits, such as long-range detection, and through-wall imaging.

Several types of radar are available nowadays such as Pulsed radars and Continuous Wave (CW) radars; however, the Frequency Modulated Continuous Wave (FMCW) is widely used due to its capability to simultaneously detect the range and the velocity of different objects.

The objectives of this thesis are as the followings:

1. To develop a low-cost C-band FMCW radar system

2. To apply detection algorithms for range and speed detection
3. To investigate the performance of the proposed design

1.4 Organization of Thesis

This thesis is organized into 5 Chapters. In first chapter, a literature review and purpose of thesis are given. In Chapter 2, common applications and fundamentals of FMCW radars are described. The radar equation and Doppler shift are also described in brief. Key calculations and structure of FMCW radars are also described in detail at the end of chapter. The proposed design, which is the key effort in thesis is described in Chapter 3. The block diagrams, schematics, and key challenges are discussed in detail. Chapter 4 shows summary of work results with brief of resulting system performance and experimental results. Finally, the study is concluded in Chapter 5 and future works are described.

CHAPTER 2

FUNDAMENTALS OF FMCW RADARS

FM signals used first time for ranging on 1920s for ionospheric research. After few years, Jetson 0. Bentley filed the American patent [2] titled “airplane altitude indicating system” which recognized as the first practical implementation of frequency-modulated continuous-wave (FMCW) radar. Structure of Bentley’s radar was quite simple, it consists of transmitter and receiver with a synchronous tuning mechanism.

A triangular modulation waveform is generated by an electric motor that controls an adjustable capacitor in transmitter, and the same motor controls an adjustable capacitor in receiver to match transmitter’s frequency all time.

Transmitted signal is radiated down toward surface, then the receiver collects a small portion of reflected signal which have slightly different frequency which is directly proportional to the delay time (i.e., to range from the aircraft to the surface), except for the short time intervals following slope reversal [2].

Most development of FMCW radar took place between late 1940s to the early 1960s [2]. After that, pulse radars dominated the radar applications because it met most requirements of different military and civil applications. Recently, FMCW radars returned to the spot of light when requirements have appeared to measure very small ranges in different industries.

2.1 Radar Equation

Radar equation provides a fundamental understanding for radar operation and it is used as a basis for designing radar systems. It represents the relationship between the range and the characteristics of radar components such as transmitter, receiver, antenna, and target.

One of the main purposes of Radar equation is to calculate the power of received signal. Generally, target's dimensions are considered very small in comparison to illumination width of the radar antenna ($R*\theta_{BW}$).

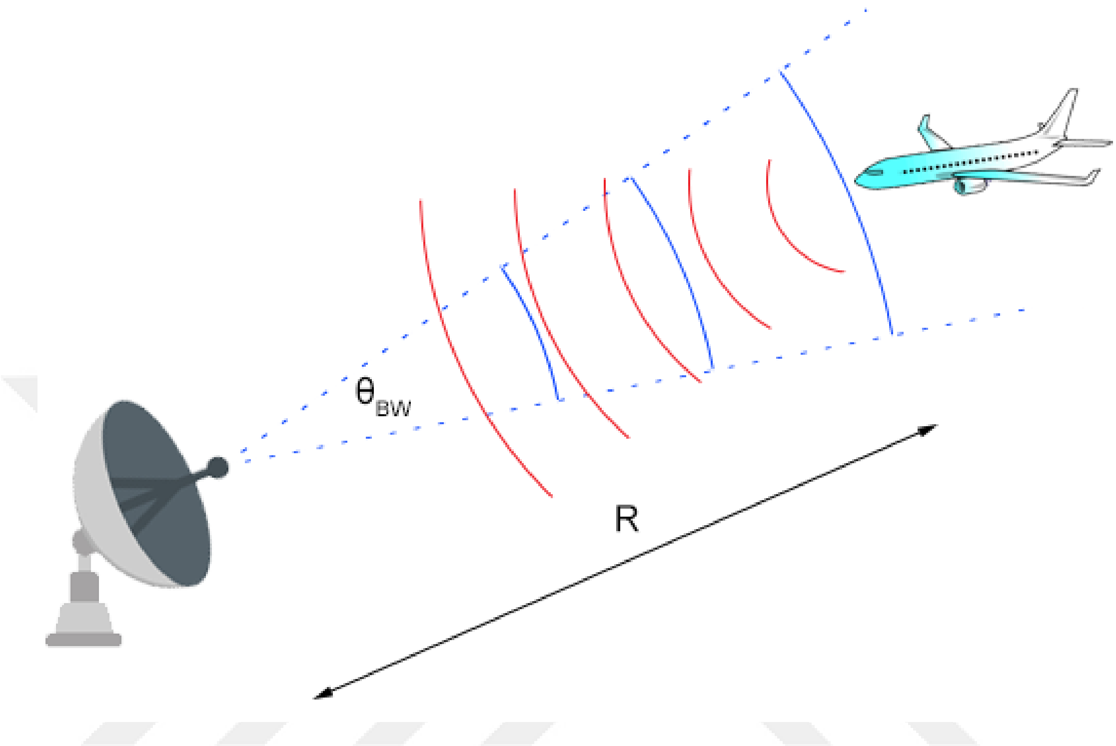


Figure. 2.1. Radar principle illustration

Considering P_t as the transmitted power and the transmitter antenna is isotropic antenna, we can calculate the power density at target using the equation:

$$P = \frac{P_t}{4\pi R^2} \tag{2.1}$$

Using an omnidirectional antenna in transmitter will spread out the signal in all directions equally, and likewise, omnidirectional receiver antenna will receive signals from all directions at the same level. In order to enable a radar system to detect direction to a target, we must use a directional antenna in both transmitter and receiver. The gain of directional antenna G represents the increase in power radiated in the direction of target in comparison with power radiated by isotropic antenna. We can introduce antenna gain to equation:

$$P = \frac{P_t G}{4\pi R^2} \tag{2.2}$$

As described before, a portion of radiated power will be intercepted by target and reradiated in various directions. Target cross section σ represents the reradiated power from targets surface in the direction of radar receiver and can be defined as:

$$P = \frac{P_t G}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^2} \tag{2.3}$$

By introducing the effective area of receiver antenna A_e to the last equation:

$$P = \frac{P_t G}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^2} \cdot A_e = \frac{P_t G A_e \sigma}{(4\pi)^2 R^4} \tag{2.4}$$

The most widely accepted radar range equation is solved for maximum range R_{max} where the power of received signal equals the minimum detectable signal S_{min} so targets cannot be detected beyond this distance.

$$R_{max} = \left[\frac{P_t G A_e \sigma}{(4\pi)^2 \, S_{min}}\right]^{1/4} \tag{2.5}$$

Where: R_{max} = maximum range of radar system (m)

Pt = average transmit power (watts)

G = transmit antenna gain

Ae = receive antenna effective aperture (m2)

σ = radar cross section (m2) for target of interest

S_{min} = minimum detectable signal by radar receiver

2.2 Radar Cross Section (RCS)

The RCS of a target is the fictional area describes the target's ability to reflect radar signals in the direction of the radar receiver, or in other terms, the ratio of backscatter power from the target per steradian (unit solid angle) in the direction of the radar to the power density that is intercepted by the target. The common way to define the Radar cross-section is with use of the Radar equation:

$$\sigma = \frac{Power\ reflected\ to\ radar\ /\ unit\ solid\ angle}{incident\ power\ density\ /\ 4\pi} = \lim_{R \to \infty} 4\pi R^2 \left|\frac{E_r}{E_i}\right|^2 \tag{2.6}$$

Where

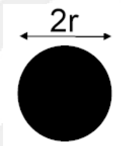
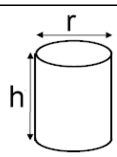
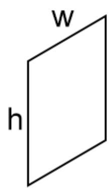
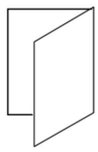
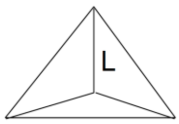
R = distance between radar and target

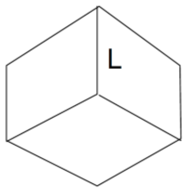
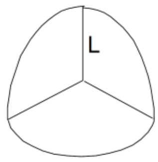
E_r = reflected field strength at radar

E_i = strength of incident field at target

The RCS is strongly frequency dependent and is influenced also by the size, shape, surface roughness and material of target. For most common objects such as aircraft, ships, and terrain, the radar cross section does not necessarily bear a simple relationship to the physical area, except that the larger the target size, the larger the cross section is likely to be. Table 2.1 shows expressions for the RCS of typical radar reflectors.

Table 2.1. RCS of typical radar reflectors

Target Type	Illustration	RCS
Sphere		$\sigma = \pi r^2$
Cylinder		$\sigma = \frac{2\pi r h^2}{\lambda}$
Flat plane		$\sigma = \frac{4\pi w^2 h^2}{\lambda^2}$
Dihedral reflector		$\sigma = \frac{8\pi w^2 h^2}{\lambda^2}$
Triangular Trihedral		$\sigma = \frac{4\pi L^2}{3\lambda^2}$

Square Trihedral		$\sigma = \dfrac{12\pi L^4}{\lambda^2}$
Circular Trihedral		$\sigma = \dfrac{15.6\pi L^4}{3\lambda^2}$

2.3 Doppler Effect

The Doppler phenomenon is the shift in frequency of a wave for an observer due to the target relative motion with respect to the source of radiation. It is named after the Austrian physicist Christian Doppler, who described the phenomenon in 1842 [8].

Radars use Doppler frequency to measure the velocity of detected objects (range rate) in the direction of radiation between the radar and the detected object, as well as to distinguish between moving and stationary targets or objects such as clutter.

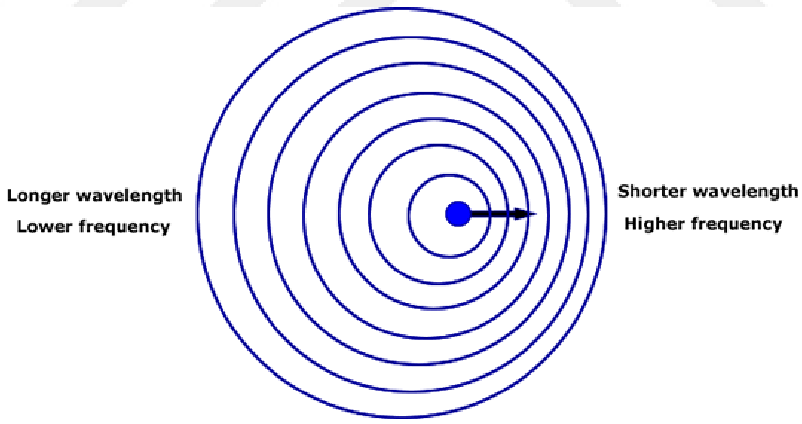


Figure 2.2. Doppler effect illustration

Depending on the direction of the target's motion this frequency shift may be positive or negative. The target produces positive Doppler frequency if it approaches the radar, otherwise a negative Doppler frequency is determined for the situation where the target moves away from the radar. Figure 2.2 illustrates the physical principle of Doppler effect.

When the radar transmitter and receiver are located very closely, the Doppler frequency f_d can be written as:

$$f_D = \frac{1}{2\pi} \cdot \frac{d\varphi}{dt} = 2 . \frac{1}{2\pi} \frac{2\pi}{\lambda} \cdot \frac{dR}{dt} = \frac{2v_r f_T}{C_0} \tag{2.7}$$

where

v_r = the radial velocity of the target to the radar,

f_T = the transmit frequency and

c_0 = propagation velocity of light.

Figure 2.3 shows the angular velocity of a moving vehicle target.

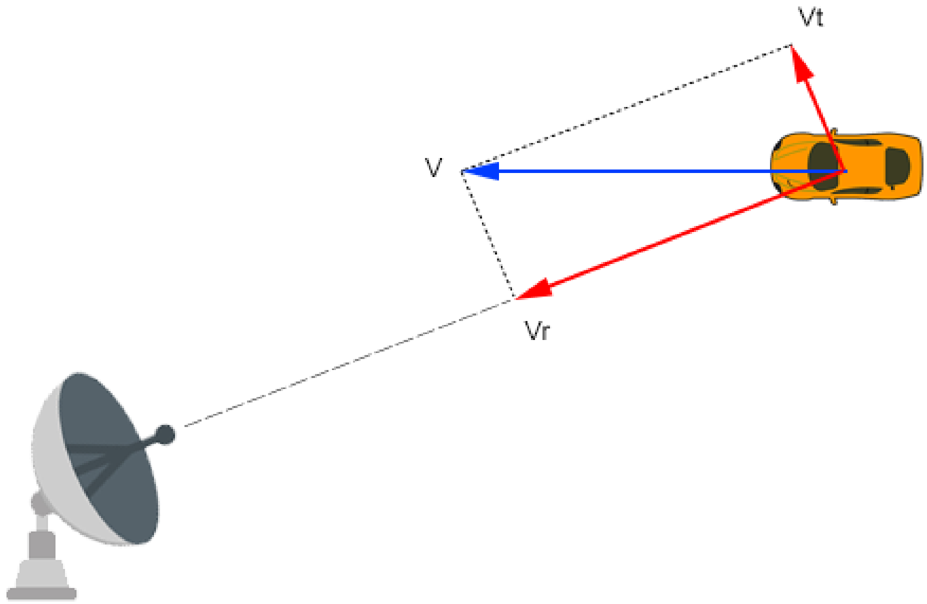


Figure 2.3. Radial velocity of moving target

2.4 Theory of Frequency Modulated Continuous Wave Radar

In pulse radar, object range is detected by measuring the time interval between transmitted pulse and received echoes. A key challenge of pulse radar is the large peak power to produce average signal power that can achieve maximum detection range determined by radar equation.

In contrast with pulse radar, CW radar depends on doppler effect in measuring target's velocity, but it cannot detect target's range because continuous radiation is used which make separation of transmitted and reflected signals in time impossible. In other words, CW radar doesn't have timing functions necessary to calculate the range, while the pulse is used as timing mark in pulse radar. This lack is recognized as major limitation of CW radar. To resolve this lack, FMCW radar adds FM modulation to emitted signal which provide timing marks.

FMCW radar chirp can be generating using different modulation waveforms such as sawtooth, triangle, and sinusoidal. Triangular waveform signal shown in Figure 2.4 is the most popular one because it enables the system to measure both range and velocity [3,4], and it is easier to generate. IF signal contains the most two important signals: Beat frequency and Doppler frequency.

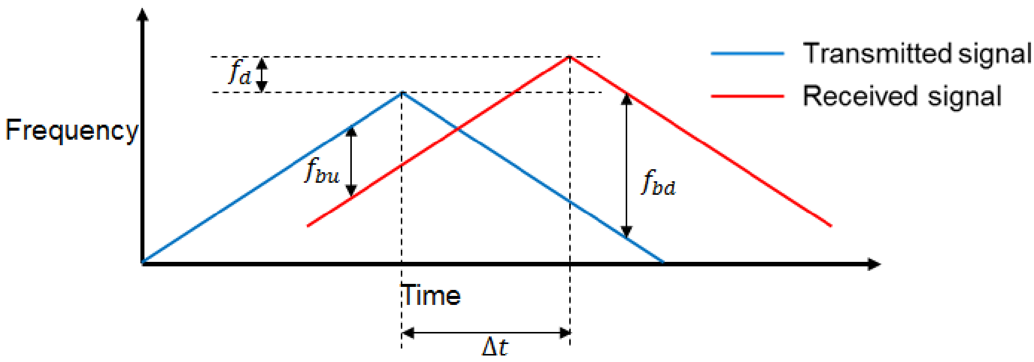


Figure 2.4. FMCW radar triangular sweep

2.5 FMCW Radar Features and Applications

FMCW radars have many features in comparison to other types of radars, the can be summarized in following [2]:

- Ability to measure very small ranges;
- Ability to measure range and velocity simultaneously;
- Small error of range measurement;
- Ability to measure small range changes;
- Simpler signal processing due to low frequency at baseband
- Safety from absence of pulse radiation;
- Less energy consumption.

These features, especially small size, simplicity, and economy of FMCW radars enabled them to be the ultimate solution in many applications. Some key examples are described below.

2.5.1 Radio Altimeters

International Telecommunication Union (ITU) defined radio altimeter as: “Radio navigation equipment, on board an aircraft or spacecraft, used to determine the height of the aircraft or the spacecraft above the Earth's surface or another surface” [10]. Figure 2.5 shows operation principle of radio altimeter.

Using FMCW radars as radio altimeter become very common nowadays due to better accuracy than the pulse radar. Accordingly, all commercial radio altimeter use kind of FMCW radar as of 2010. [10]

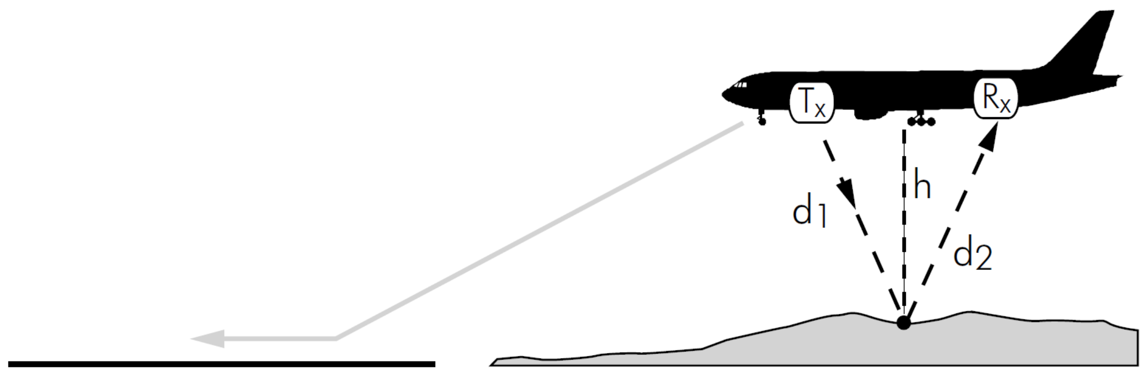


Figure 2.5. Radio altimeter principle

2.5.2 Proximity Fuse

A proximity fuse used in military to detonate the explosive warhead of a weapon when the distance to the target reach the predefined range. Proximity fuse increases the lethality by 5 to 10 times, compared to these other fuses [2]. Figure 2.6 shows proximity fuse antenna mounted on missile [15].

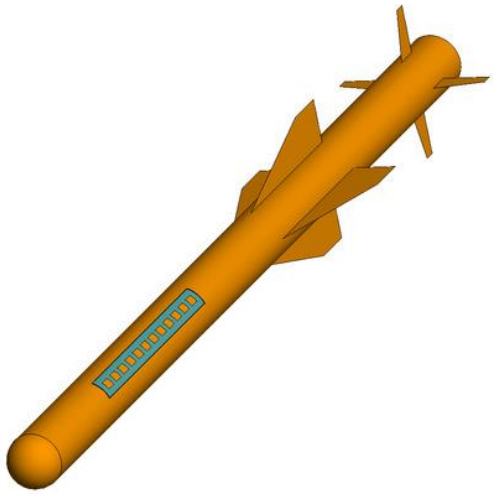


Figure 2.6. Proximity fuse antenna mounted on missile

2.5.3 Level-Measuring Radar

Radar based liquid level sensors are installed on the top of liquid tank and radiate a narrow beam radio signal vertically toward the liquid surface as shown in Figure 2.7.

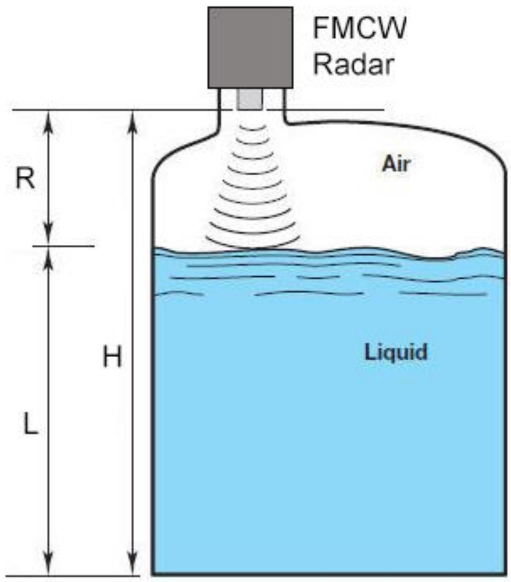


Figure 2.7. Fluid level sensor based on FMCW radar

The range between sensor and liquid surface R can be obtained from reflected signal, and as the tank height H is known, the level can be determined as [2]:

$$L = H - R \tag{2.8}$$

2.5.4 Navigation Radar

Pulse radars are used in long range navigation applications more than FMCW radars although there is no limitation at such ranges. Generally, FMCW radar is preferred to be used at short ranges because of its outstanding performance over other radar types at these ranges, which enable FMCW radar to realize very special applications that cannot be achieved by other types.

In practice, FMCW navigation radars are using in range sensitive missions such as ship docking and passing through a lock chamber, where the distances between hull and other objects such as wall and another vessel are very critical [2].

2.5.5 Vehicle Collision Warning Systems

The vehicle collision avoidance system is used generally to ensure safety of vehicle and manage traffic efficiently. At present, vehicle collision avoidance systems are pre-installed in most intelligent vehicles. Figure 2.8 shows an example of sensor combination used by vehicle collision avoidance system, where green colored zones represent radar-based sensors coverage areas.

The front radar continuously provides the information of targets ahead of the vehicle to the computer to recognize any possible danger and activate warning or even brakes if necessary. The operation of tail radar is like front radar, but it is commonly used for parking and driving back. Side-mirror radar provides the information of next automobile within its coverage.

FMCW radar sensors are very common in such applications due to their compactness, economy, and low power consumption [2].

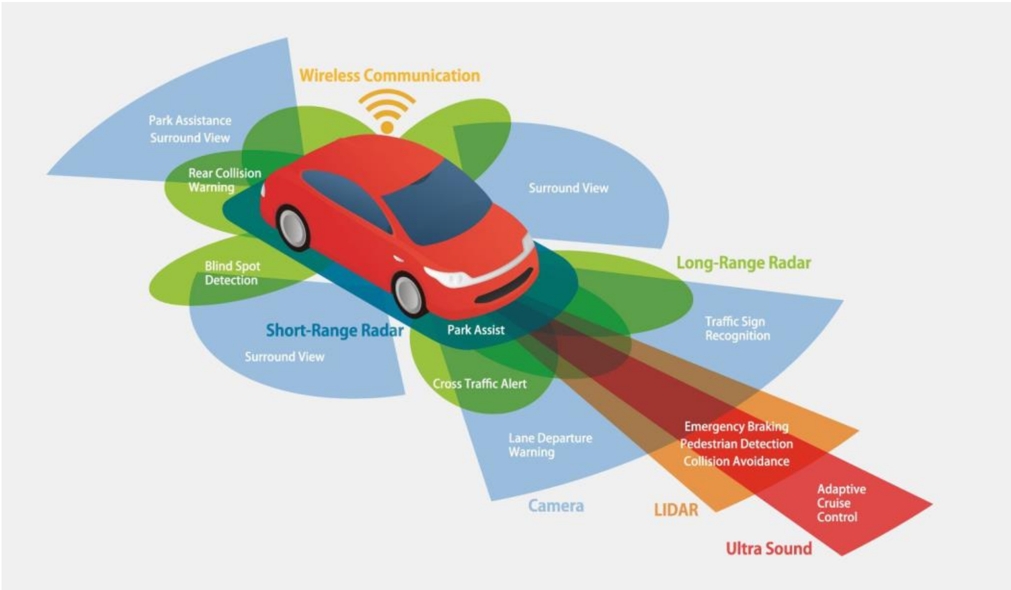


Figure 2.8. Sensors set of vehicle collision avoidance system

2.5.6 Precision Range Meter for Fixed Targets

By using a passive reflector (e.g., comer reflectors), FMCW radars can be used to measure distances up to tens of kilometers with relative error of 10^{-6} to 10^{-5} [2].

This idea can be used for example to monitor the behavior of glaciers and snow avalanches in mountains and measure displacement of walls of high buildings, towers, and other structures [2].

2.5.7 Measurement of Very Small Motions

Measurement of very small motions such as machine vibration without physical contact with the machine is another complex mission simplified by using FMCW radar. The methodology depends on the fact of phase difference between radiated and reflected signals determines the range change of target, and this information can be obtained from the low-frequency signal at the mixer output of the receiver [2].

2.5.8 Medical Applications

Technological advance over the last decades has expanded radar applications to include some biomedical applications along with traditional military and civil applications.

Medical radars use the electromagnetic radiation to detect small dielectric discontinuities which can detect some tumors embedded in healthy tissues and remotely monitor physiological activities, like breathing and heart-movement as shown in Figure 2.9 [11,12].

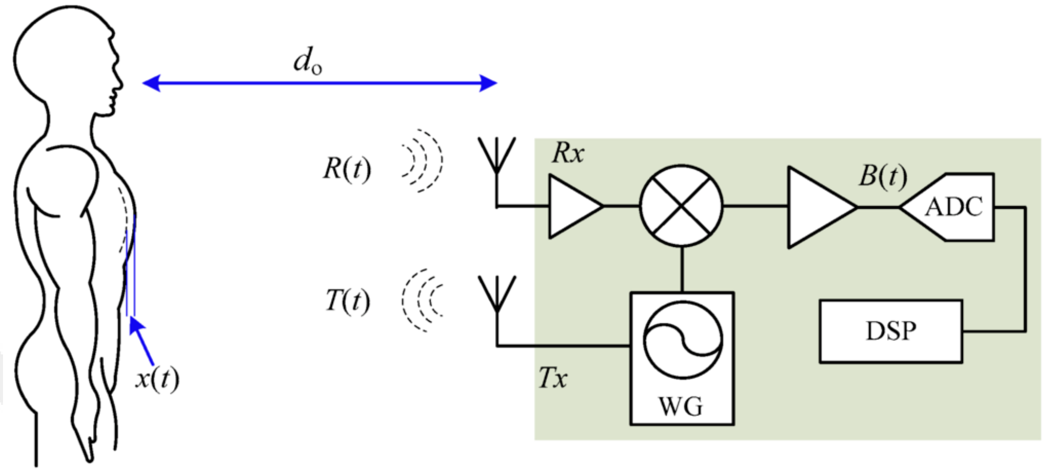


Figure 2.9. Simplified block diagram of CW/FMCW radar sensor and the mechanism of noncontact vital sign detection.

2.5.9 Gesture Sensors

Using short-range radar sensor in gesture tracking/recognition applications have many advantages over optical sensors. For example, robustness to bad lighting conditions, low computational complexity, and occlusion handling because of the penetration capability of electromagnetic waves [13].

For example, Soli chip, showed in Figure 2.10, is very new radar-based single chip gesture sensor developed by Google. It incorporates the entire sensor and antenna array into an ultra-compact 8mm x 10mm package to be usable in wearable electronics and portable devices [14].

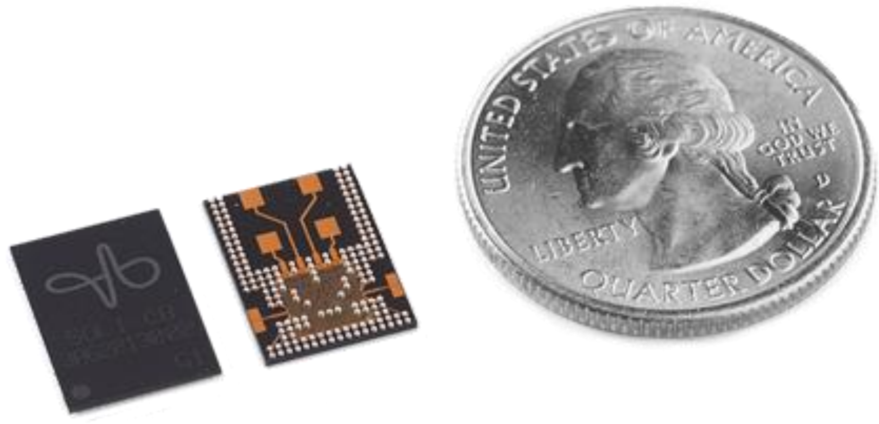


Figure 2.10. The single chip radar-based gesture sensor Soli

2.6 Range Resolution in FMCW Radars

Target's range can be resolved by calculating the frequency difference between the received signal and the transmitted signal, which increases with delay, and the delay is linearly proportional to the range.

This process can be performed by mixing the echo with a copy of transmitted signal to produce a beat signal which is linearly proportional to the target range after demodulation.

In sawtooth form, high speed ramp waveform with increasing slope and bandwidth makes Doppler frequency negligible, thus, sawtooth chirp modulation can only measure the target's range but not its velocity. Figure 2.11 shows the transmitted and received ramp signals [4].

The delay between transmitted and received signals is given by [4]:

$$t_d = \frac{2R}{C} \tag{2.9}$$

Where

R = the target range

C = the free-space speed of light.

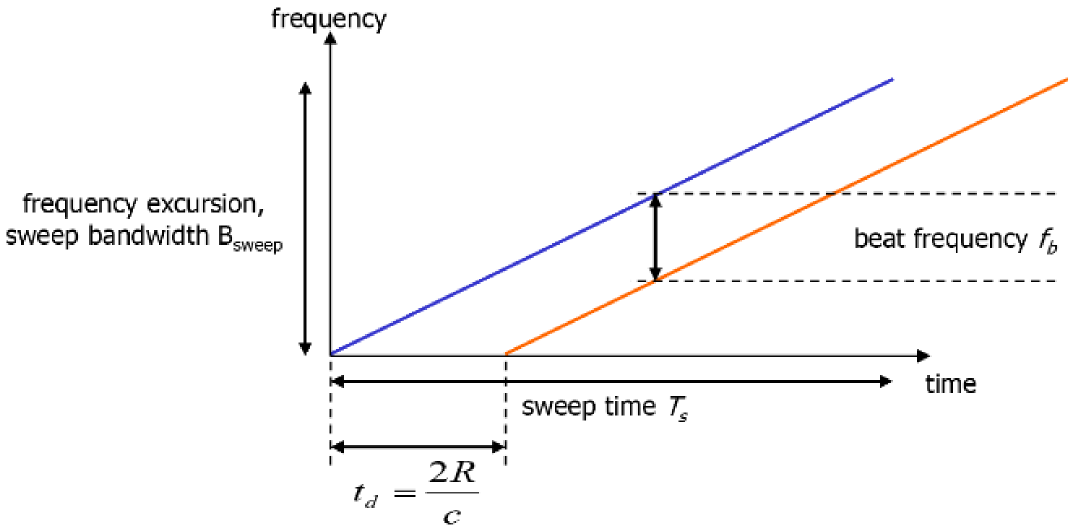


Figure 2.11. Sawtooth modulated chirp

The beat frequency is given by [4]:

$$fb = \frac{B_{sweep}}{T_s} t_d \tag{2.10}$$

Where B_{sweep} is the total frequency deviation of the chirp signal, and T_s is the sweep time (or chirp) period. The target range is thus found from the following equation [4]:

$$R = \frac{cT_s}{2B_{sweep}} f_b \tag{2.11}$$

2.7 Moving Targets

For moving targets, measuring velocity requires a triangular wave chirp modulation as shown in Figure 2.12 [4].

A moving target generates Doppler frequency shift. Beat frequency components due to range and Doppler frequency shift are given by [4]:

$$f_b = \frac{T_{sweep}}{T_s} . \frac{2R}{c} \tag{2.12}$$

$$f_d = \frac{2v_r}{\lambda} \tag{2.13}$$

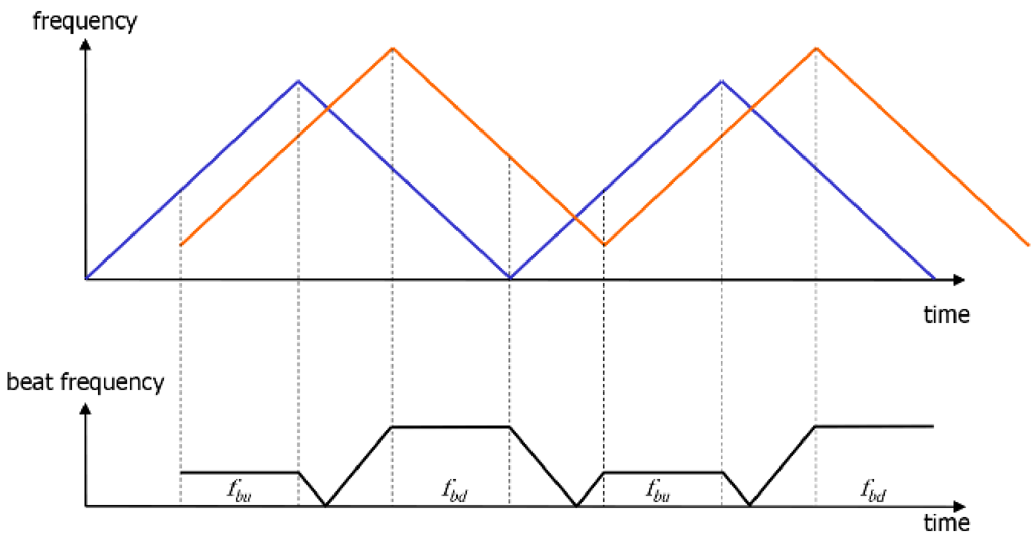


Figure 2.12. Triangular modulated chirp

Doppler and Beat frequencies are superimposed as [4]:

$$f_{bu} = f_b - f_d \tag{2.14}$$

$$f_{bd} = f_b + f_d \tag{2.15}$$

So, range and radial velocity can be obtained as [4]:

$$R = \frac{cT_S}{4B_{sweep}}(f_{bd} + f_{bu}) \tag{2.16}$$

$$v_r = \frac{\lambda}{4}(f_{bd} - f_{bu}) \tag{2.17}$$

2.8 FMCW Radar Architecture

A typical block diagram of an FMCW radar is shown in Figure 2.13. Voltage-controlled oscillator (VCO) is used to generate radar sweep signal. VCO generates a frequency in linear proportion to its input control voltage, so applying modulation waveform to the VCO's input will directly generate the sweep signal on VCO's output.

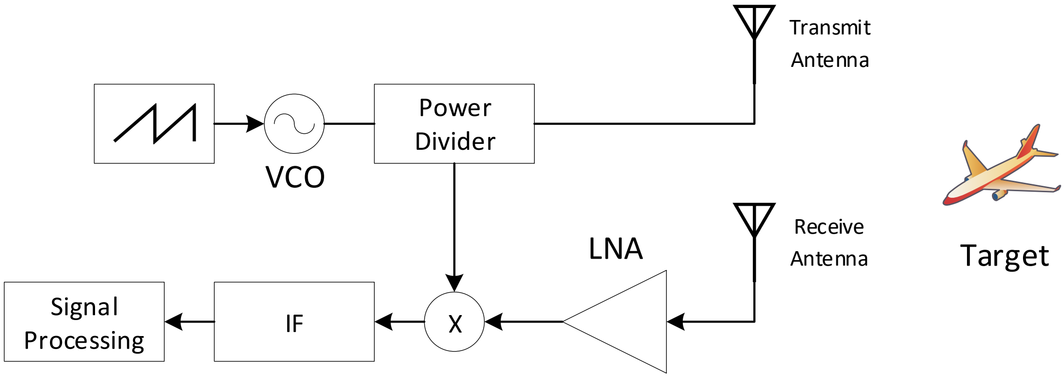


Figure 2.13. FMCW radar block diagram

Sweep signal will be divided by power divider before being properly amplified and then radiated through antenna toward the target. If any target is available in the propagation direction, the signal will scatter and propagate back to the receiving antenna, which will collect a portion of reflected signal. Low Noise Amplifier (LNA) will amplify the needed band of received signal and fed it to the mixer. A portion of transmitted signal taken by power divider is also fed into the mixer, so Intermediate Frequency (IF) signal will be extracted at the output of mixer. IF signal contains all useful information about target, such as beat frequency and doppler frequency, so it is fed to signal processing stage to do proper processing [3].

CHAPTER 3

DESIGN OF PROPOSED FMCW RADAR

3.1 Introduction

The block diagram of proposed system is shown in Figure 3.1 and its specifications are listed in Table 3.1. It consists of the following units: RF front end, baseband, digital interface and control, and signal processing.

Table 3.1. Proposed FMCW Radar specifications

Maximum Bandwidth	400 Mhz
Sweep period	20 ms
IF frequency	10kHz - 1MHz
Tuning signal	Triangular/Sawtooth
Transmitted power	20 dBm
Antenna Gain	23 dBi
Beam width (Azimuth/elevation)	12°/12°
Maximum range	500m

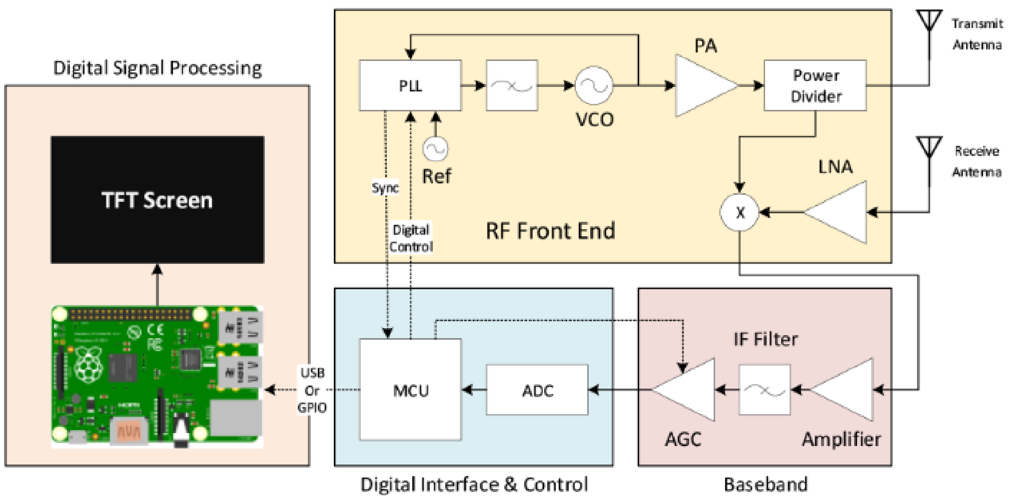


Figure 3.1. Block diagram of proposed FMCW radar

3.2 RF Front End

RF front end is implemented with baseband stage on a single 4-layered PCB. Selected components are listed in Table 3.2. All components are described in detail in next sections.

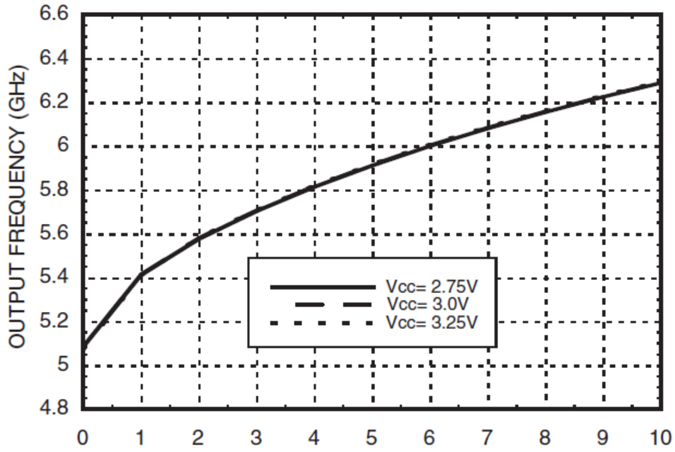
Table 3.2. Proposed system key components

Component Function	Component Number	Frequency Band
VCO	HMC431LP4	5.5 ~ 6.1 GHz
PLL	ADF4158	6.1 GHz
LNA	SKY65404-31	4.9 ~ 5.9 GHz
PA	MGA-25203	4.9 ~ 5.9 GHz
Mixer	ADL5801	6 GHz
Gain Block	HMC313	6 GHz

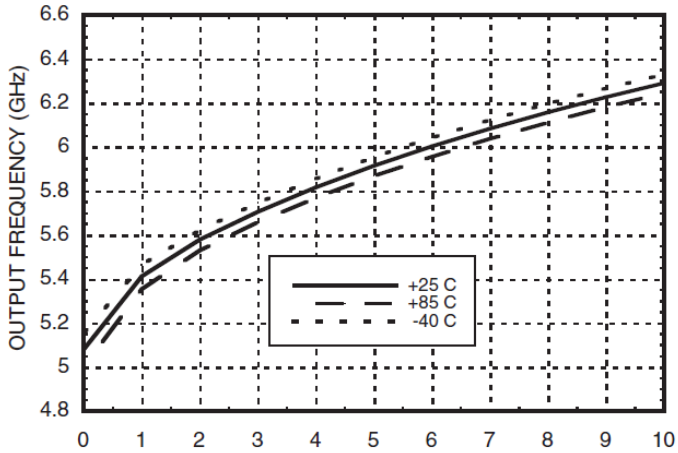
3.2.1 Voltage Controlled Oscillator (VCO)

The well-known VCO chip HMC431 is selected. It has integrated resonators, negative resistance devices, varactor diodes, and buffer amplifiers. It’s phase noise performance is excellent over temperature, shock, vibration and process due to the oscillator’s monolithic structure. It’s frequency range is 5.5-6.1 GHz and output power of 2 dBm typical from a 3V supply voltage.

The main problem of VCO is that it uses an exponential converter, which is extremely temperature sensitive. It consequently exhibits a drifting oscillation frequency when the operation temperature changes, so when a linear ramp is applied as a tuning voltage, it generates non-linear frequency sweep, which lead to non-constant mixing tone at the baseband and affects the range resolution negatively. Figure 3.2 illustrates the VCO’s nonlinearity.



(a)



(b)

Figure 3.2. VCO's Frequency vs. Tuning Voltage: (a) Fixed Temperature T= 25°C (b) Fixed Supply Vcc= +3V

3.2.2 Fractional-N PLL

To solve VCO nonlinearity problem, a fractional-N frequency synthesizer is used with direct modulation and waveform generation capability. It depends on a phase locked loop (PLL) with a frequency divider and a feedback loop, which can adjust VCO tuning voltage. A linear sweep can be generated by sweeping the divider value in small fractional steps.

The selected fractional-N frequency synthesizer was ADF4158. It is designed especially for radars and it can be programmed to generate various waveforms in the frequency domain, for example, sawtooth and triangular waveforms. It also features cycle slip reduction circuitry, which leads to faster lock times, without the need for modifications to the loop filter. Controlling all on-chip registers is performed via a simple 3-wire interface. A temperature compensated crystal oscillator generates the 30 MHz reference frequency. A bridged-T attenuator is used to implement the feedback loop. Schematic diagram is shown in Figure 3.3.

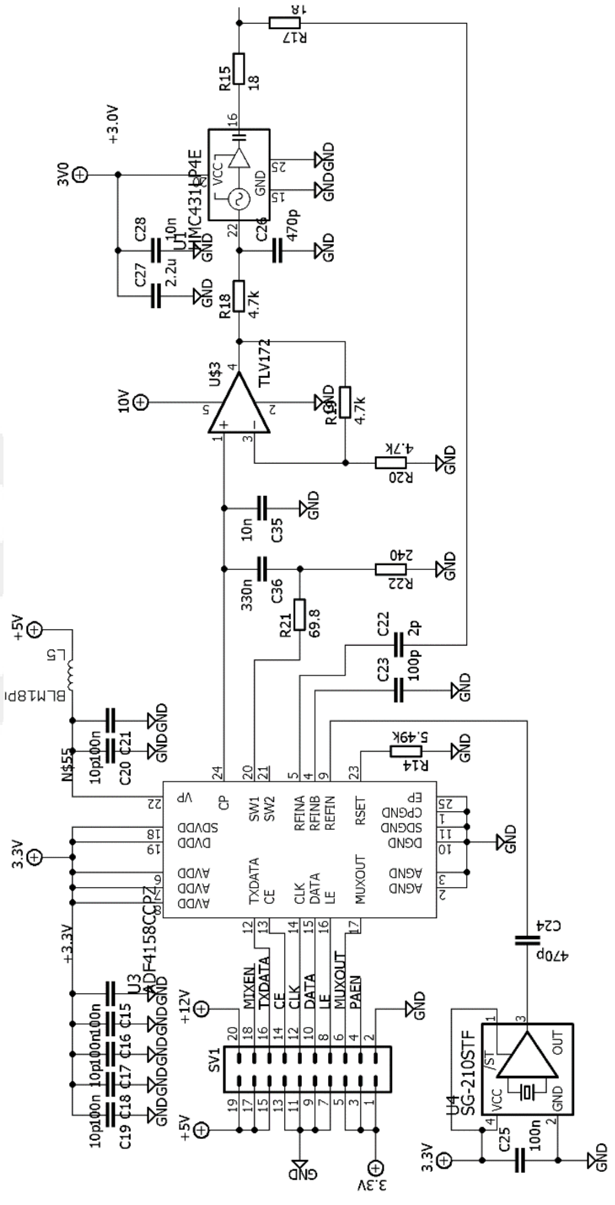


Figure 3.3. PLL and VCO configuration

3.2.3 Power Amplifier

A linear power amplifier with 4.9 to 5.9 GHz frequency range is used to amplify the VCO’s output signal with gain of 30dB. The amplified signal then passes via coupler and propagate toward the target with transmitter antenna. Figure 3.4 shows Power Amplifier circuit diagram.

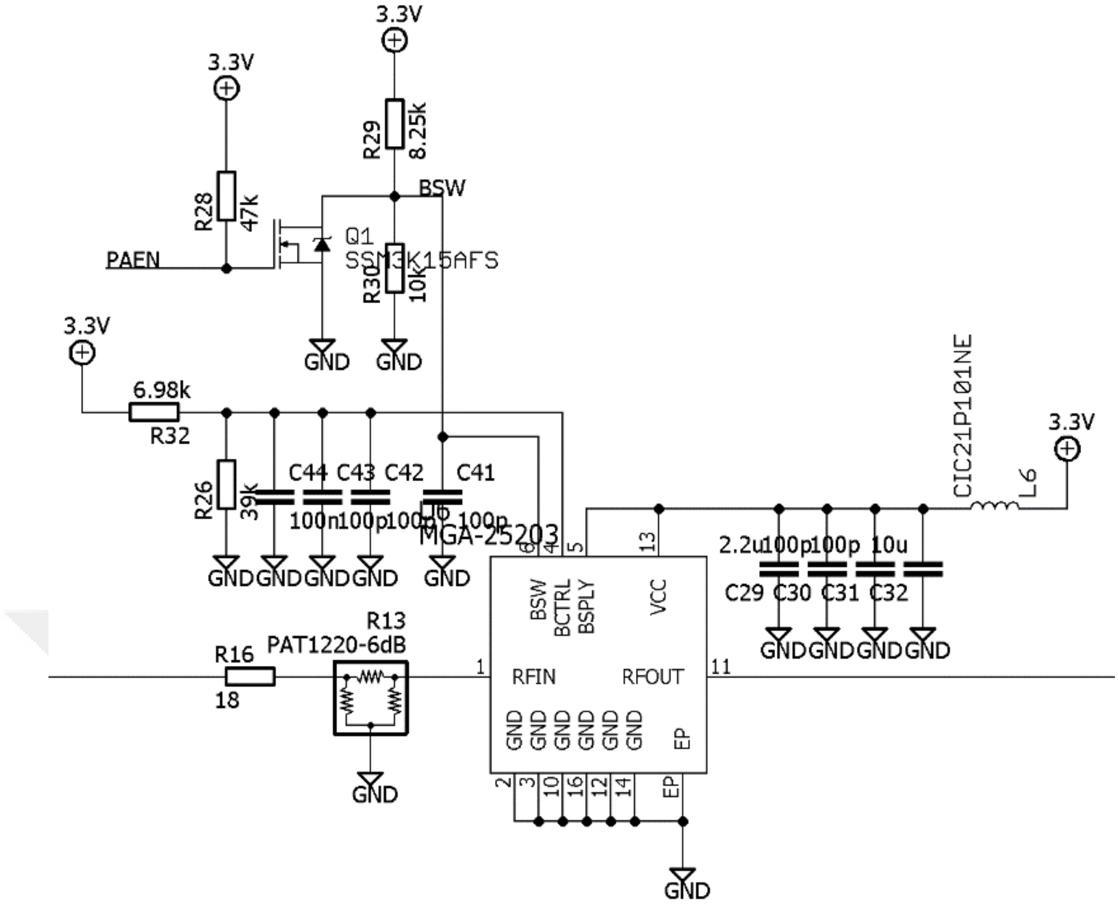


Figure 3.4. Power Amplifier circuit schematic

3.2.4 Mixer

To provide down converting stage with the local oscillator signal, a 15dB coupler is designed. We choose the ADL5801 high linearity, doubly balanced, active mixer core with integrated LO buffer amplifier. Figure 3.5 illustrates mixer configuration.

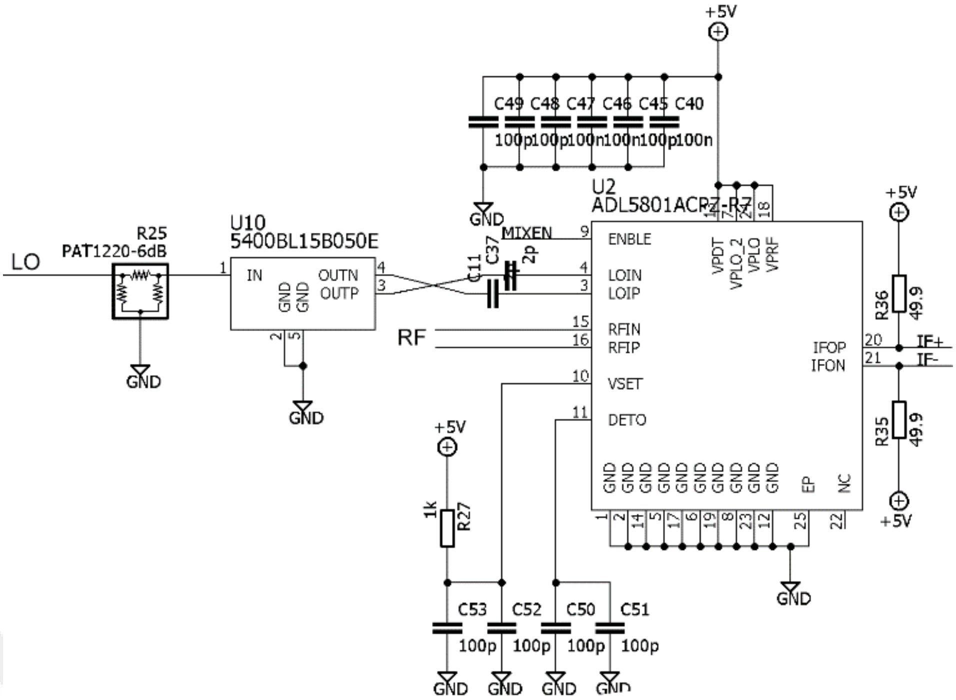


Figure 3.5. Mixer circuit schematic diagram

3.2.5 LNA

Figure 3.6 illustrates LNA circuit diagram. The output signal is followed by 17dB gain block HMC313 to reach desired power level at the input of mixer.

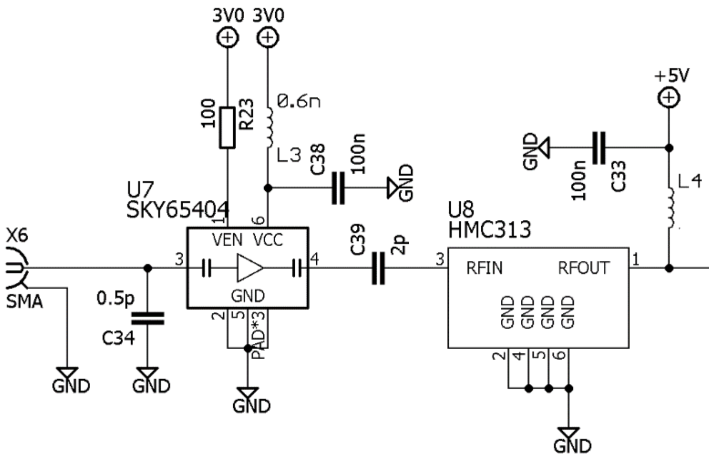


Figure 3.6. LNA circuit schematic diagram

3.3 Baseband

The function of baseband stage is to equalize the IF signal to be ready for A/D conversion. A key challenge in baseband is the difference in power levels of reflected signal from multiple targets. Targets close to radar reflects higher power than the farther target.

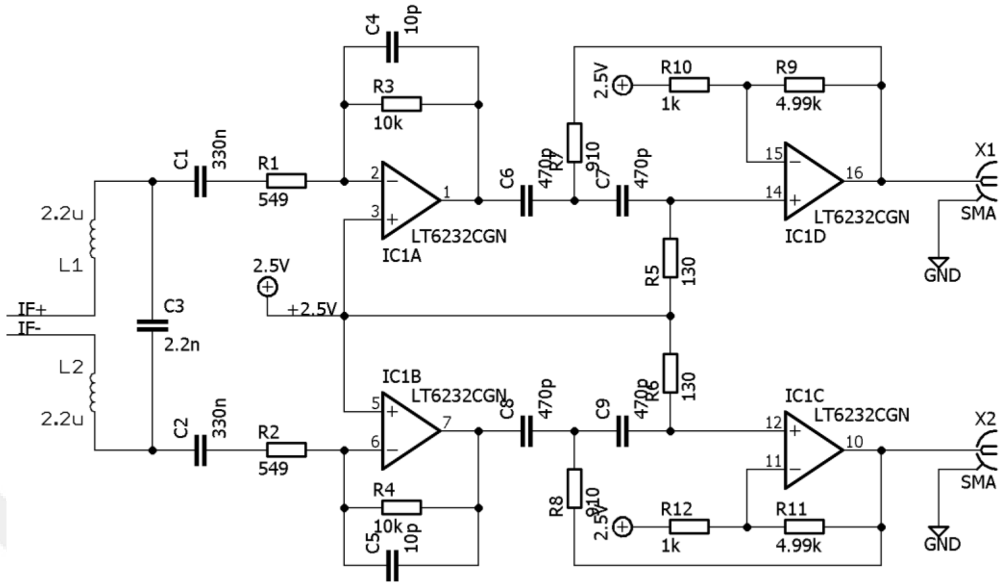


Figure 3.7. Baseband circuit schematic diagram

Figure 3.7 shows the baseband filtering stage. First, a low pass filter is implemented to remove high frequency noise. An active high pass filter with 40dB/decade slope is then used to equalize the signals from far apart targets which results in a same amplitude for different targets. Finally, an automatic gain controller (AGC) adjusts the signal amplitude to be ready for A/D conversion.

3.4 Digital Interface and Control

This unit is separated into two boards: ADC board and control board. This separation allowed us to design a general-purpose high-speed ADC board to be used in any other application based on Raspberry Pi and leave control functions to be done by a ready development board, so development time is reduced.

3.4.1 ADC Board

The selected ADC is LT2292 from linear Technology, which is very common in RF applications. Key specifications of ADC are:

- Integrated Dual 12-Bit ADCs
- Sample Rate: 40Msps

- Single 3V Supply (2.7V to 3.4V)
- Low Power: 235mW
- 71.3dB SNR
- 90dB SFDR

ADC board includes the ADA4940-2 differential ADC drivers, the LT2292 ADC, and Raspberry Pi GPIO connector. Figures 3.8 and 3.9 show the ADC board schematic diagrams.

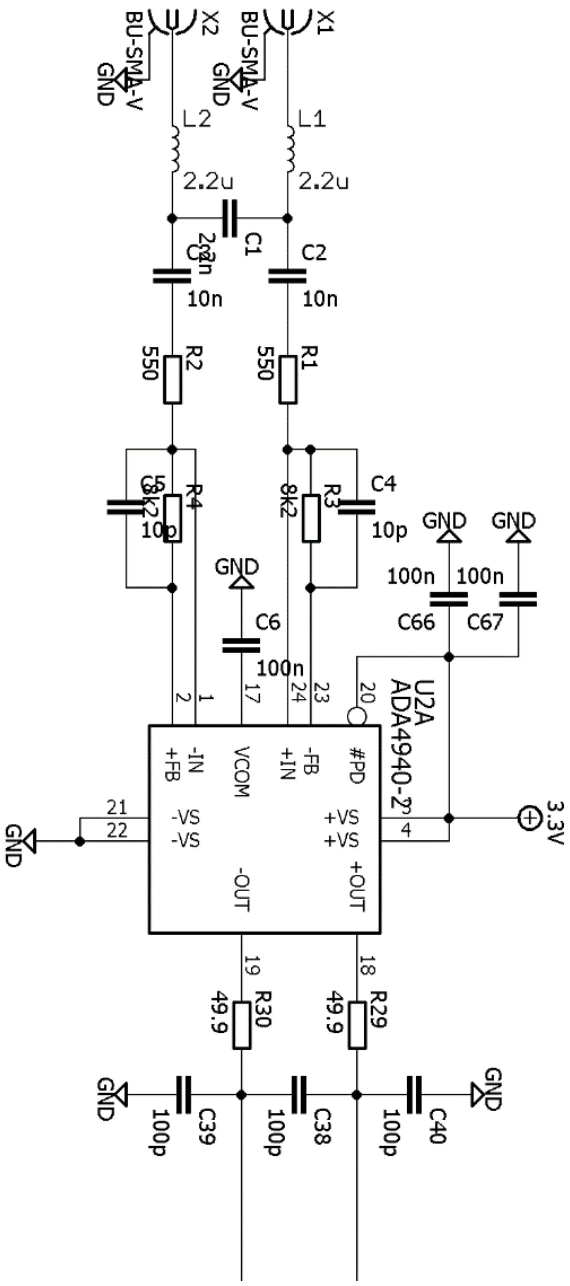


Figure 3.8. ADC driver circuit schematic diagram

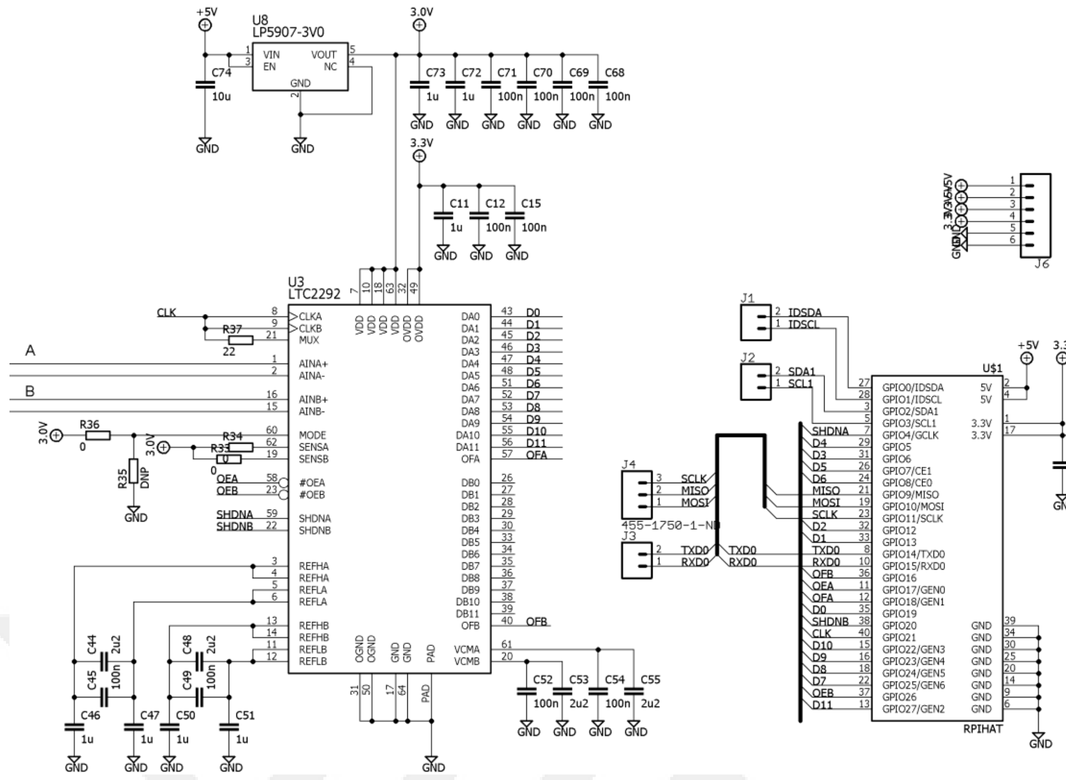


Figure 3.9. ADC interface circuit schematic diagram

3.4.2 Control Board

This board acts as central controller for all radar functions to dedicate all Raspberry pi resources to the signal processing functions. PIC32-HMZ144 board from Olimex shown in Figure 3.10 is selected. Its main features are:

- PIC32MZ2048EFG144 (512KB SRAM; 2MB flash)
- USB-OTG interface with mini USB connector
- MicroSD card connector
- ICSP for debugging and programming
- JTAG pins
- PWR and STATUS LEDs
- Li-Po battery charger and connector

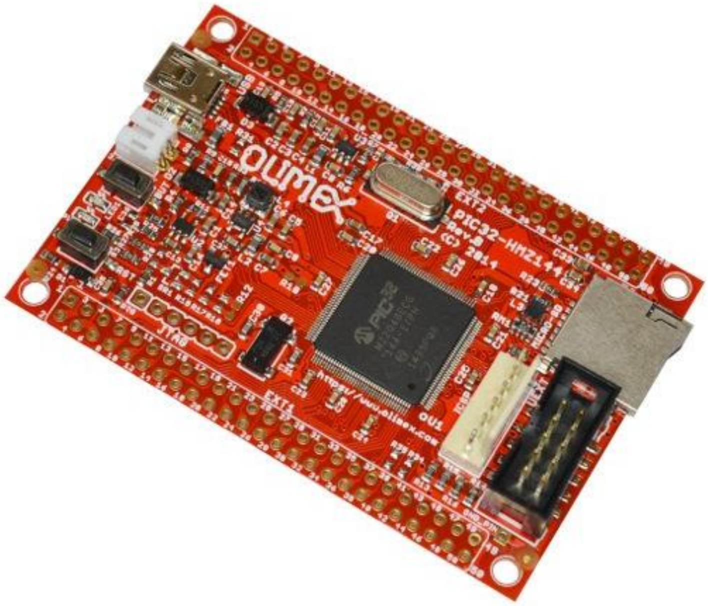


Figure 3.10. PIC32-HMZ144 board

3.5 PCB Design and Fabrication

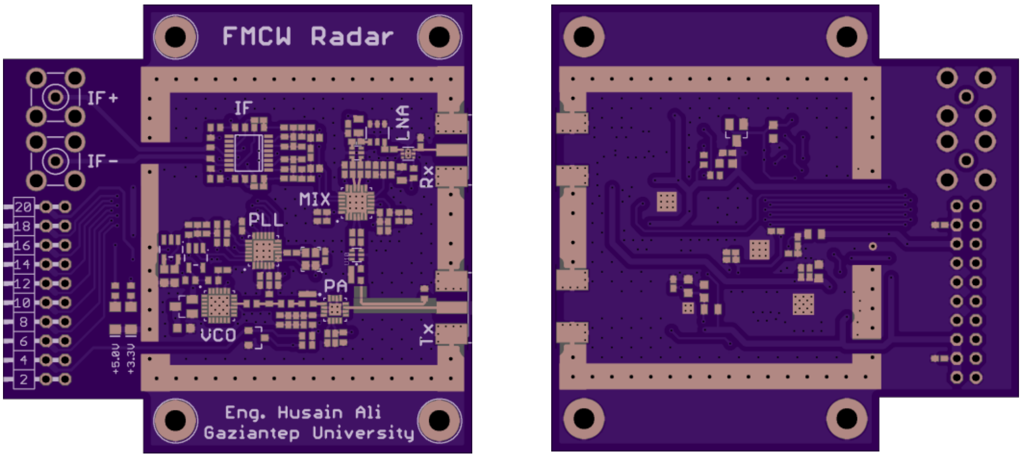
The desired system consists of many stages with different requirement for each. The RF front end is high frequency board which need 4 layered PCB to reduce microstrip line width. In contrast, baseband is analog low frequency stage and ADC is digital high-speed circuit, and both don’t need the 4-layers.

To minimize number of boards and cost of prototype, and maximize usability of boards, the design has been separated into two PCBS:

- Analog board shown in Figure 3.11: a four layered PCB contains RF front end and baseband;
- ADC board shown in Figure 3.12: contains differential ADC driver and high-speed differential ADC with Raspberry pi GPIO connector.

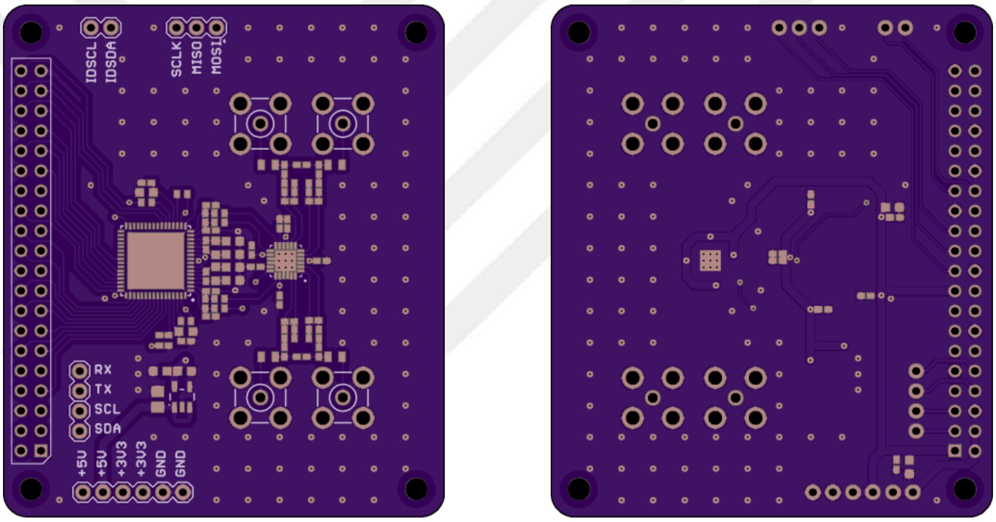
Specifications of 4-layer board as provided from supplier are:

- ENIG (gold) finish for superior soldering and environmental resistance.
- PCB substrate is FR408 (180Tg).
- PCB substrate is compatible with a lead-free process.
- Lead free and RoHS compliant.
- PCB Substrate dielectric constant of 3.66 at 1GHz



(a) top view (b) bottom view

Figure 3.11. RF Front end and baseband PCB board



(a) top view (b) bottom view

Figure 3.12. ADC PCB board

3.5.1 Microstrip Calculation

Microstrip structure shown in Figure 3.13 is a transmission line fabricated on printed circuit board. The dimensions of microstrip are very critical in microwave design because its dimensions determine the line impedance in terms or physical characteristics of substrate. To save time, all related calculations have don by using multiple online calculators to verify the results.

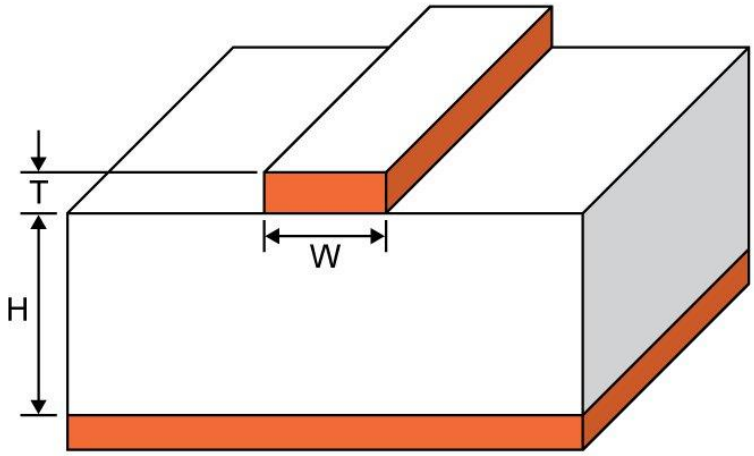


Figure 3.13. Microstrip transmission line structure

3.5.2 Directional Coupler

To provide down converting stage with the local oscillator signal, a 15dB coupler is used. Designing directional coupler may be a complex task if depended only on calculations. To reduce design time, a ready microstrip-based directional coupler configuration is used and optimized through simulation.

3.6 Antennas

Selected antenna is TL-ANT5823B from TP-Link with gain of 23dBi and beam width of 12° as illustrated in Figure 3.14. This antenna is commonly used in outdoor Wi-Fi applications and have a suitable bandwidth for our radar application.

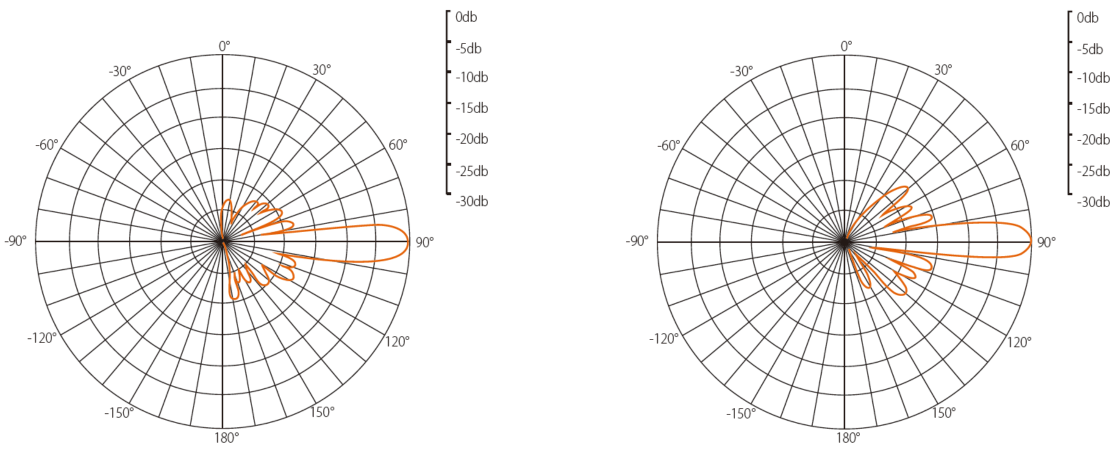


Figure 3.14. TL-ANT5823B antenna radiation patterns

3.7 Signal Processing

Two Fast Fourier Transform processing are used to detect range and velocity as illustrated in figure 3.15. The first FFT processing of each single chirp extracts mainly target range information. Next, the Doppler frequency is obtained by the second FFT processing, using the discrete data in each range-bin over the PRI (Pulse Repetition Interval).

In this approach, since the clutter falls into range-bins with zero-Doppler, stationary targets including clutter can be easily suppressed [6].

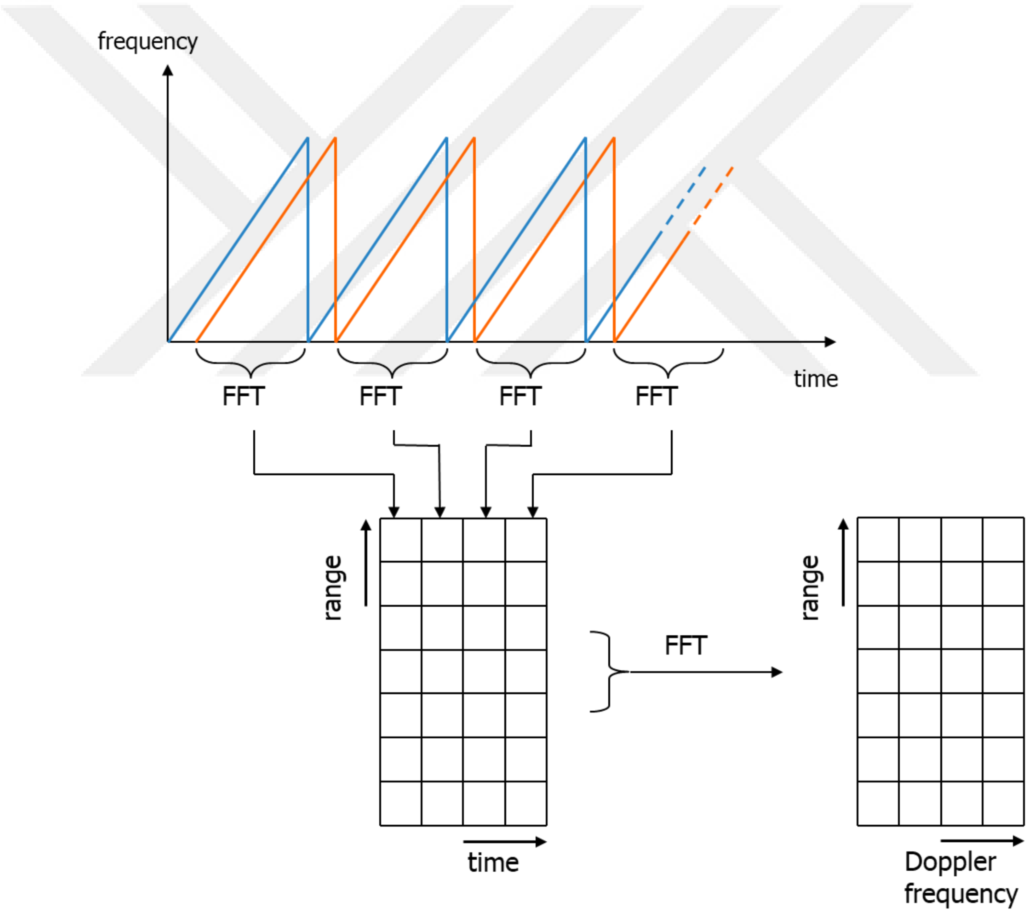


Figure 3.15. FMCW signal processing

To perform FFT processing, the library GPU_FFT is used, which exploits the BCM2835 SoC V3D hardware to deliver ten times the performance that is possible on the 700 MHz ARM.

GPU_FFT uses single-precision floating point for data and twiddle factors, so it does not compete on accuracy with double-precision libraries; however, the relative root-mean-square (rms) error for a 2048-point transform is less than one part per million.

The library runs on dedicated 3D hardware in the BCM2835 SoC, and communication between ARM and GPU adds 100µs of latency [7].

CHAPTER 4

RESULTS

System assembly is shown in Figure 4.1 and 4.2. RF and digital PCBS are mounted on the back of Raspberry Pi case and attached to the antennas’ cables. The first power up of the designed system is shown in Figure 4.3

Figure 4.1. Connecting antennas to designed system

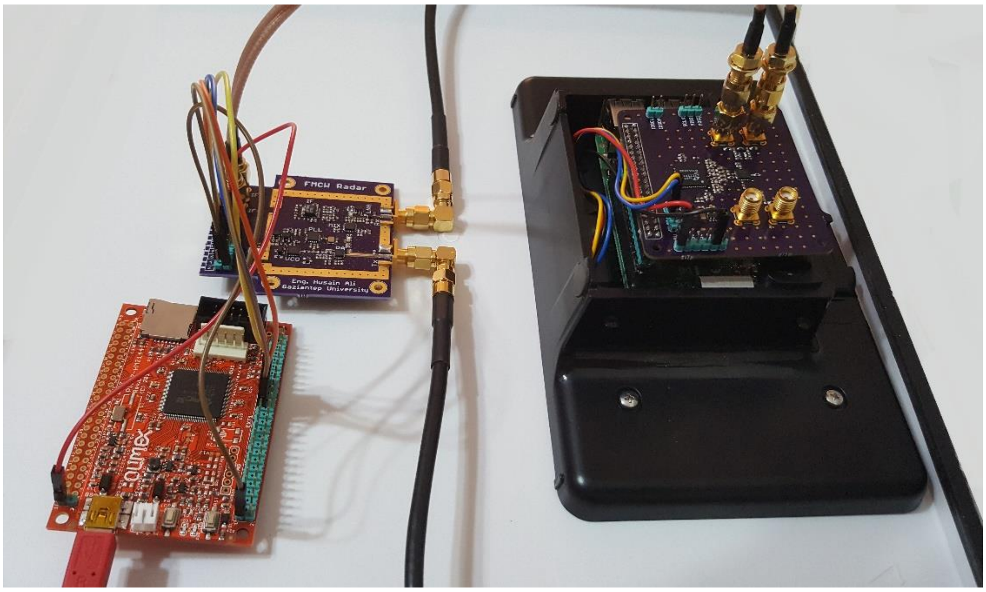


Figure 4.2. System modules connection

Figure 4.3. First power up of designed system

A simple software is sampling the IF signal through ADC board and calculating its FFT and then display it in the real time. A sample output is shown in Figure 4.4 which represents a detected target and clutter spectrum representation.

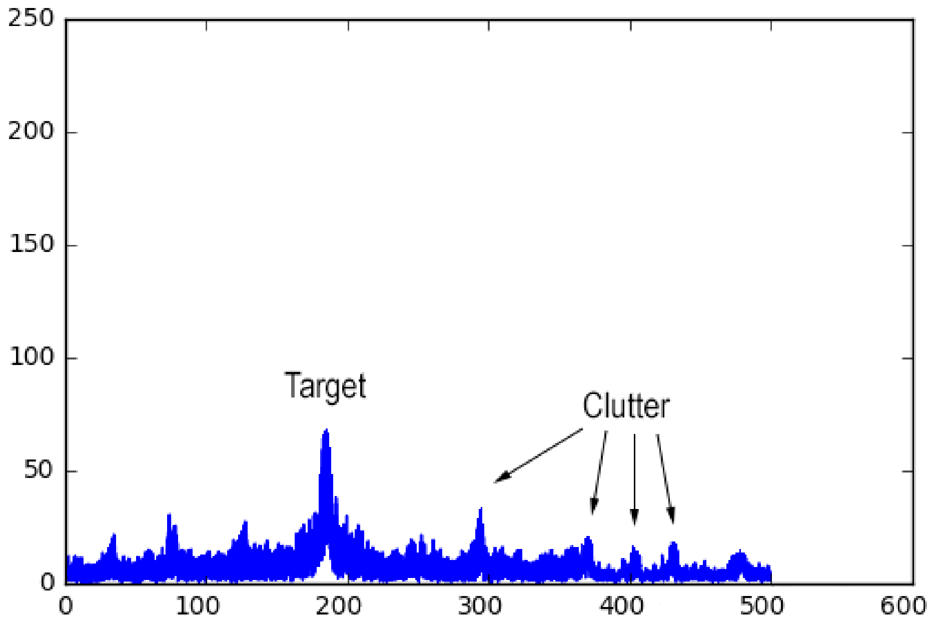


Figure 4.4. Target spectrum screenshot

Detailed experements can be conducted for each component of the system in order to assess its performance and improve it in future designs. In this study, only functional experements took place because of time constraints.

Using a simple target directly in front of antennas showed the pervious results on Raspberry Pi's screen.

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this study, a 6 GHz FMCW radar system has been designed and implemented with capability of detecting both range and velocity. The chirp generation is implemented by digital-controlled frequency synthesizer which enables the user to adjust chirp waveform and period. Signal processing is performed by a Raspberry Pi single board computer exploiting its SoC V3D hardware to implement FFT processing in real time and results are displayed on a TFT screen also in real time. Decision to develop this design in modular structure provided flexibility and make debugging easier and faster, but in real world, a compact design on single PCB with onboard antennas will present an integrated solution that can be developed for market.

As the system is built on Raspberry Pi, a programmable control unit and digitally programmable signal synthesizer, the whole function may be configured according to user requirement. For example, the same hardware may be configured to operate as SAR radar instead of FMCW, but it should be mounted on a moving platform to perform as SAR.

Many improvements also can be added to the design, first, designing dedicated power supply using low dropout regulators instead of traditional switching power supply to suppress the noise generated by switching elements which affect performance negatively. Adding digital beamforming feature will enable the system to detect targets direction without the need to rotate antennas. Beamforming can be implemented by adding second receiver and detect the phase difference between two receivers to calculate the horizontal angle. This will need additional signal processing, so Raspberry Pi board should have additional resources to handle this function. Improving sampling speed can reduce needed processing resources, which can be achieved by ignoring samples between sweeps, which don’t have any information about target as there is no transmitted sweep.

REFERENCES

[1] Skolnik, M. (2008). Radar Handbook. 3rd edition. McGraw-Hill, USA.

[2] Komarov, I. V., Smolskiy, S. M. (2003). Fundamentals of Short-Range FM Radar. Artech House Publishers, USA.

[3] Charvat, G. L. (2014). Small and Short-Range Radar Systems. CRC Press, USA.

[4] Otto, T., Principle of FMCW radars. Delft University of Technology. Available at: www.slideshare.net/tobiasotto/principle-of-fmcw-radars. Accessed 22.04.2018.

[5] De Maio, A., Greco, M. S. (2015) Modern Radar Detection Theory. SciTech Publishing, UK.

[6] Hwang, Y. T., Chen, Y. C., Hong, C. R., Pei, Y. T., Chang, C. H., Huang, J. C., (2012). Design and FPGA implementation of a FMCW radar baseband processor. IEEE Asia Pacific Conference on Circuits and Systems.

[7] Upton, E. (2014). Accelerating Fourier transforms using the GPU. Available at: www.raspberrypi.org/blog/accelerating-fourier-transforms-using-the-gpu/. Accessed 18.04.2018.

[8] Possel, M. (2017). Waves, motion and frequency: the Doppler effect. *Einstein Online*, **5**, 2.

[9] Radar Basics - Pulse Radar. Available at: www.radartutorial.eu/02.basics/Pulse%20Radar.en.html. Accessed 12.04.2018.

[10] Raney, R. K. (1998). The Delay/Doppler Radar Altimeter. *IEEE Trans. Geoscience and Remote Sensing.* **36**, 1578–1588.

[11] Pisa, S., Pittella, E., Piuzzi, E. (2016). A survey of radar systems for medical applications, *IEEE Aerospace and Electronic Systems Magazine*, **31**, 64-81.

[12] Gu, C. (2016), Short-Range Noncontact Sensors for Healthcare and Other Emerging Applications: A Review, *Sensors*, **16**, 8.

[13] Molchanov, P., Gupta, S., Kim, K., Pulli, K. (2015). Short-Range FMCW Monopulse Radar for Hand-Gesture Sensing, 2015 IEEE Radar Conference (RadarCon).

[14] Project Soli. Available at: atap.google.com/soli/ Accessed 11.05.2018.

[15] Design and Analysis of a Proximity Fuse Antenna for an Air Defence Missile. Available at: www.altair.com/RelatedCaseStudy.aspx?id=10383. Accessed 17.05.2018.