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Simulation of Multiple Target Detection with Frequency Modulated Continuous Wave Radar

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Abstract - *This study is about the FMCW Radar System Simulation for detecting multiple targets. The FMCW Radar system is a type of radar system that is capable of providing high range resolution and protection against electronic warfare techniques. It does this by emitting a frequency modulated chirp signal from a transmitting antenna, which allows the frequency of the signal to increase or decrease linearly over time. This modulation technique improves the range resolution of the radar system. Therefore, FMCW Radar system is widely used in military applications. The study aimed to improve the range resolution of the FMCW Radar system by optimizing the modules used in the system and processing the transmitted and received signals with advanced algorithms such as CA-CFAR and MUSIC. For evaluating the effectiveness of the system, the study created an environment with multiple targets and conducted a modeling and simulation study to determine the distances, velocities, and angular positions of the targets.*

Key Words: Radar, Signal, FMCW Radar, Simulation, Detection

1.INTRODUCTION

A radar system is basically an electronic system used to propagate electromagnetic waves transmitted through the transmitting antenna when examined and to obtain information such as position, speed and distance of the object by using a signal processing method by taking these electromagnetic waves from moving or immobile objects after they are reflected from moving or stationary objects. The word radar consists of the initials of the English words "Radio Detecting and Ranging". When the structure of a radar system is examined, it consists of transmitter, receiver and signal processor. Radar systems can be classified in different ways depending on their working principle, process, frequency, aim, application, structure, antenna, waveform, and installation area. FMCW Radar systems are typically classified under the structure classification, as they are characterized by their unique structure and components. FMCW Radar Systems consist basically transmitter antenna, receiver antenna, mixer and Radar Control Board. FMCW Radars generally are simple structure, cheap production cost , range detection capability and less noise exposure. The majority of Pulsed Doppler radars are based on military battlefield radar technology and are typically used for wide area surveillance. In contrast, FMCW Radar technology has been specifically designed and widely used in many different fields. These are level measurement, precision range measurement, hidden object detection, and target detection.In addition, FMCW Radar is also used in the automotive industry for short-range radars, such as anticollision warning and cruise control systems[1]. Continuous Wave(CW) radars use the Doppler effect to calculate the speed of a target, but not its distance. FMCW Radars emerged to overcome this limitation by modulating and developing the CW waveform to generate a chirp signal, which can calculate both the range and speed of the target at the same time. A chirp signal is created by modulating a continuous wave with a sawtooth, triangular, or sinusoidal signal, which causes a frequency shift. This frequency shift can be used to determine the range and velocity of the target[2]. So when FMCW Radar compare to other radars[3], FMCW Radars are one step ahead of pulse radars. In addition, the disadvantage of CW radars not being able to detect multiple targets is eliminated with FMCW Radar [4]. FMCW Radars have the detection to multiple targets based on FMCW Radar in range resolution.

In this study, the aim is Ambiguity Multiple Target Detection with Frequency Modulated Continuous Radar System. Ambiguity Multiple Target Detection can be called a technique. The technique is based on the principle of range-Doppler ambiguity, which states that the range and Doppler frequency of a target cannot be uniquely determined from a single radar measurement.

This is due to the fact that the range and Doppler frequency are related by the radar's sweep rate and carrier frequency. One of the main advantages of Ambiguity Multiple Target Detection is that it allows for the detection of multiple targets in a single radar measurement[5]. This is particularly useful in situations where multiple targets are present in close proximity to each other, such as in crowded airspace or in battlefield scenarios. The implementation of Ambiguity Multiple Target Detection in a FMCW Radar system requires advanced signal processing techniques, such as pulse compression, matched filtering, CFAR, MUSIC and FFT. These techniques are used to improve the signal-to-noise ratio of the received signal, which in turn improves the accuracy and resolution of the target detection. FMCW

Radar is simulated in an environment where there is more than one target, and targets are detected by using FFT, CFAR and MUSIC algorithms in this study.

Fast Foruier Transform(FFT) algorithm is widely used to common for extracting range and Doppler information from the received signals. The signal processing chain in FMCW Radar involves transmitting a frequency-modulated signal and receiving the reflected signal, which is mixed with the transmitted signal to produce a beat signal. The beat signal is then sampled and processed using FFT to obtain the range and Doppler information. The FFT is a computationally efficient method for spectral analysis and can quickly transform time-domain data into frequency-domain data. The Range-Doppler map can be generated by using FFT. It can be shown the range and velocity information of detected targets. This information is then used to identify and track moving targets, while stationary objects can be eliminated using clutter removal algorithms. Despite its computational complexity, FFT is an essential tool for FMCW Radar signal processing and plays a critical role in achieving accurate and reliable target detection and tracking[6].

The Cell Averaging Constant False Alarm Rate (CA-CFAR) algorithm is widely used in FMCW radar systems to maintain robust detection performance in complex environments with high levels of background noise and clutter. The algorithm is based on the principle of setting a detection threshold based on the predicted background level, which is calculated as the weighted average of clutter data in the reference window. This predicted background level is commonly referred to as the mean level. The CA-CFAR algorithm dynamically adjusts the detection threshold based on the local clutter level, reducing the likelihood of false alarms caused by variations in the background level[7].

Multiple Signal Classification (MUSIC) is a high-resolution spectral estimation algorithm that can be used in FMCW Radar systems to improve target detection and tracking in the presence of multiple interfering sources. The algorithm is based on the eigenvalue decomposition of the received signal's covariance matrix and estimates the direction of arrival (DOA) of the target signals. The DOA information can then be used to estimate the range and velocity of the targets. The MUSIC algorithm can provide a significant advantage over traditional FFT-based methods in scenarios where the number of targets is greater than the number of sensors or when targets have similar range and Doppler characteristics. The algorithm is also effective in reducing the effects of interference from stationary and moving clutter sources, improving target detection and tracking accuracy. However, the MUSIC algorithm can be computationally demanding and requires more complex hardware than FFT-based approaches[8,9]. Nevertheless, its high-resolution capabilities make it a valuable tool for improving the performance of FMCW Radar systems in complex environments.

In the next parts of the study, the examination of the features of the FMCW Radar System, the examination of its general structure, the stages of the simulation carried out in the MATLAB software for ambiguity multiple target detection were mentioned, and finally the results obtained were evaluated and an idea was given about what the future works could be.

2. AMBIGUITY MULTIPLE TARGET DETECTION WITH FMCW RADAR

2.1 Ssytem Information

FMCW Radars are defined as FMCW Radars that have been developed by applying Frequency Modulation or Numerical Modulation techniques to Continuous Wave(CW) radars. Frequency Modulated Continuous Wave (FMCW) radar is a type of radar that uses a continuous transmission of electromagnetic waves at a specific frequency, which is then modulated over time. The frequency of the transmitted wave is continuously varied over a period of time, and the resulting frequency of the reflected wave is then analyzed to determine the range, velocity, and other characteristics of a target.

The basic principle of FMCW Radar is based on the concept of frequency shift. When an electromagnetic wave is reflected off of an object, the frequency of the reflected wave will be shifted by an amount proportional to the distance of the object from the radar. This frequency shift is known as the Doppler shift. By analyzing the frequency shift of the reflected wave, the range and velocity of the object can be determined.

FMCW Radar systems typically use a frequency modulated waveform, in which the frequency of the transmitted wave is linearly swept over a specific range. The frequency modulated waveform has several benefits, including a high range resolution and a low probability of intercept (POI) by an enemy radar system.

One of the main advantages of FMCW Radar is its ability to determine the range of an object with high accuracy. This is due to the linear nature of the frequency sweep, which allows for a high range resolution. Additionally, FMCW Radar is able to detect small and slow-moving objects, making it ideal for applications such as automotive radar and industrial process control.

FMCW Radar is also commonly used in military applications, such as air defense and surveillance. The radar's ability to detect small and slow-moving targets, as well as its low POI, makes it well-suited for these types of applications.

2.2 Ssytem Overview

FMCW Radar system is composed of a transmitter, receiver, modulator, demodulator, and antenna as shown Figure 1. The transmitter generates a continuous wave at a specific frequency, which is then modulated by the modulator, creating a frequency modulated waveform. The frequency modulated waveform is then transmitted by the antenna and the reflected wave is received by the antenna and sent to the receiver, demodulator and analyzed to determine the range and velocity of the object.

FMCW Radar Systems have same concenpt, and work with using same principle that is Frequency Modulation. The Signal of FMCW Radar can be four different modulated signals . These are Triangular, Sinusodial, Square and Sawtooth. Also these signal types can offer in signal processing.

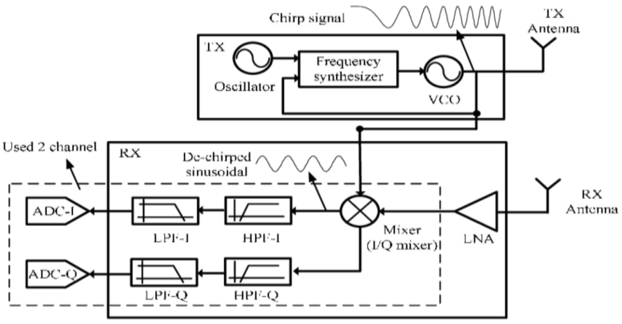

Figure 1 : The Block Diagram of FMCW Radar[10]

The System Block Diagram of FMCW Radar is typically includes the following components:

Transmitter: This component generates and amplifies the radio frequency (RF) signal that will be transmitted by the antenna. The signal is typically a continuous waveform that is frequency modulated to provide range information.

Transmit/Receive (T/R) Switch: This component directs the RF signal from the transmitter to the transmit antenna and receives the reflected signals from the target via the receive antenna.

Antennas: These components transmit and receive the RF signals. The transmit and receive antennas can be separate or combined into a single element.

Mixer: This component combines the transmitted and received signals, creating an intermediate frequency (IF) signal.

Local Oscillator (LO): This component generates a reference frequency that is mixed with the received signal in the mixer.

Signal Processor: This component performs various signal processing functions on the IF signal, such as filtering, amplification, and demodulation. The signal processor also extracts range and velocity information from the IF signal.

Display: This component presents the radar data to the operator in a meaningful way, such as on a radar scope or map.

Control Unit : This component control the overall system, it contains all the parameters of the radar system and it communicate with the signal processing unit.

2.2 The Usage Areas of FMCW Radar

FMCW Radar system is a type of radar technology that is widely used in a variety of applications due to high accuracy and ability to provide real-time data. FMCW Radar system operates by emitting a continuous wave signal that varies in frequency over time, and then analyzing the reflected signal to determine the distance, velocity, and other characteristics of the target. This technology can be used for a wide range of applications, including level measurement, vehicle collision avoidance, precision range measurement, hidden object detection, and more. In this way, FMCW Radar system has become an important role in many fields, from aviation and marine navigation to environmental monitoring and construction.

2.2.1 Radio Altimeter

A radio altimeter is a type of radar that is specifically designed to measure the altitude of an aircraft above the ground. FMCW Radar is a type of radar that uses frequency modulation to transmit and receive signals. In an FMCW Radar, the transmitted signal is modulated in frequency, and the received signal is compared with the transmitted signal to determine the range to the target.

In a radio altimeter that uses FMCW Radar, the radar transmits a frequency-modulated continuous wave signal towards the ground. The signal reflects off the ground and returns to the radar. By comparing the frequency of the reflected signal with the frequency of the transmitted signal, the radar can determine the range to the ground. This range measurement is used to determine the altitude of the aircraft above the ground as shown in Figure 2.

Radio altimeters using FMCW Radar are commonly used in commercial and military aircraft for landing and takeoff operations. They are particularly useful in situations where the aircraft is operating in low visibility conditions, such as during fog, rain, or snow. By providing accurate altitude information, they help pilots to maintain a safe altitude during critical phases of flight, such as takeoff and landing.

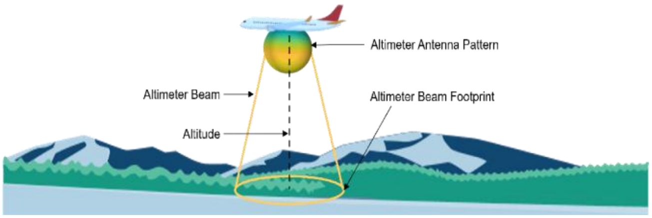

Figure 2 : The measurement of altitude[11]

2.2.2 Proximity Fuse

A proximity fuse is a type of electronic device that is used in munitions, such as bombs and missiles, to detonate them when they are close to their intended target. In FMCW Radar, a proximity fuse can be implemented by using the radar to measure the distance between the munition and its target.

In an FMCW Radar proximity fuse system, the radar emits a continuous wave signal towards the target. The signal reflects off the target and returns to the radar. By comparing the frequency of the reflected signal with the frequency of the transmitted signal, the radar can determine the range to the target.

The proximity fuse system uses this range information to determine when the munition is close enough to the target to detonate. Once the munition reaches the predetermined distance from the target, the proximity fuse sends a signal to detonate the munition.

FMCW Radar is particularly well-suited for use in proximity fuse systems because it provides very accurate range information. This accuracy is essential in proximity fuse systems because even small errors in range measurement can cause the munition to detonate too early or too late, which can reduce its effectiveness.

Proximity fuses using FMCW Radar are commonly used in military munitions, such as air-to-air missiles and anti-ship missiles. They allow these munitions to be more effective by increasing their accuracy and reducing the risk of collateral damage An example proximity fuse by manufactured as shown in Figure 3.

2.2.3 Level Measuring Radar

Level measuring radar is a type of radar that is used to measure the level of liquid or solid materials in tanks or containers. FMCW Radar technology can be used to implement level measuring radar systems as shown in Figure 4.

In an FMCW Radar level measuring system, the radar emits a continuous wave signal towards the material in the tank. The signal reflects off the surface of the material and returns to the radar. By comparing the frequency of the reflected signal with the frequency of the transmitted signal, the radar can determine the range to the surface of the material.

The level of the material in the tank can be determined by subtracting the distance between the radar and the surface of the material from the height of the tank. The radar can continuously measure the level of the material in the tank and provide real-time data to a control system.

Figure 3 : An example of manufactured proximity fuse[12]

FMCW Radar level measuring systems are widely used in industrial applications, such as oil and gas production, chemical processing, and wastewater treatment. They are highly accurate and reliable, even in harsh environments, and can be used to measure the level of a wide range of materials, including liquids, powders, and granular materials.

In addition to level measurement, FMCW Radar level measuring systems can also be used to monitor the volume, flow rate, and density of materials in tanks and containers. They are an important tool for process control and can help to optimize production and reduce costs.

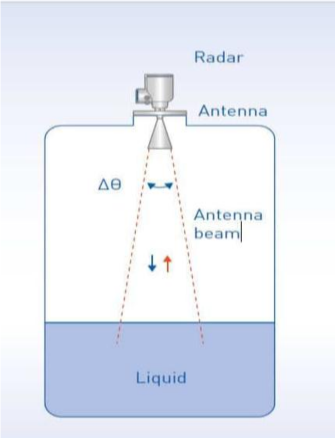

Figure 4 : Level Measurement in Liquid Tank[13]

2.2.4 Naval Navigational Radar

Naval navigational radar is a type of radar that is used by naval vessels to detect and track other vessels, obstacles, and land masses. FMCW Radar technology can be used to implement naval navigational radar systems as shown in Figure 5.

In an FMCW Radar naval navigational system, the radar emits a continuous wave signal towards the surrounding environment. The signal reflects off any objects in its path and returns to the radar. By comparing the frequency of the reflected signal with the frequency of the transmitted signal, the radar can determine the range to the object.

Naval navigational radar can be used to detect other vessels, including surface ships and submarines, as well as obstacles such as icebergs, reefs, and shorelines. It can also be used to provide information on the location and movement of land masses, which is important for navigation and avoiding hazards.

FMCW Radar naval navigational systems are highly accurate and can provide real-time data to a ship's navigation system. They are essential for safe navigation in all weather conditions, including low visibility conditions such as fog and heavy rain.

In addition to navigation, FMCW Radar naval navigational systems can also be used for surveillance and reconnaissance. They can detect and track other vessels and aircraft, providing early warning of potential threats and allowing the ship's crew to take appropriate action.

Figure 5 : ALPER Naval Radar produced by ASELSAN[14]

Overall, FMCW Radar naval navigational systems are an important tool for naval vessels, providing essential information for safe navigation and effective surveillance.

2.2.5 Vehicle Collision Avoidance

Vehicle collision avoidance radar is a type of radar that is used in vehicles, such as cars, trucks, and buses, to detect and avoid collisions with other vehicles or obstacles. FMCW Radar technology can be used to implement vehicle collision avoidance radar systems as shown in Figure 6.

In an FMCW Radar vehicle collision avoidance system, the radar emits a continuous wave signal towards the surrounding environment. The signal reflects off any objects in its path and returns to the radar. By comparing the frequency of the reflected signal with the frequency of the transmitted signal, the radar can determine the range to the object.

Vehicle collision avoidance radar can be used to detect other vehicles, as well as pedestrians, cyclists, and other obstacles. It can provide information on the range, speed, and direction of these objects, allowing the vehicle's control system to take appropriate action to avoid a collision.

FMCW Radar vehicle collision avoidance systems are highly accurate and can provide real-time data to a vehicle's control system. They are essential for improving the safety of vehicles, particularly in urban environments where there are high densities of vehicles and pedestrians.

In addition to collision avoidance, FMCW Radar vehicle collision avoidance systems can also be used for adaptive cruise control and lane departure warning systems. These systems use the radar to maintain a safe distance from other vehicles and to provide warnings when the vehicle is drifting out of its lane.

Overall, FMCW Radar vehicle collision avoidance systems are an important tool for improving the safety of vehicles and reducing the risk of accidents. They are increasingly being adopted by car manufacturers as a standard safety feature.

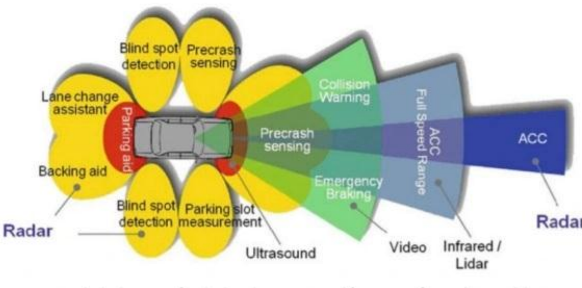

Figure 6 : Vehicle User Warning System[15]

2.2.6 Precision Range Meter for Fixed Targets

A precision range meter is a type of radar that is used to measure the range to fixed targets, such as buildings or landmarks. FMCW Radar technology can be used to implement precision range meter systems.

In an FMCW Radar precision range meter system, the radar emits a continuous wave signal towards the target. The signal reflects off the target and returns to the radar. By comparing the frequency of the reflected signal with the frequency of the transmitted signal, the radar can determine the range to the target.

FMCW Radar precision range meters are highly accurate and can provide precise range measurements with a resolution of a few centimeters. They are often used in applications where accurate range information is required, such as in surveying, mapping, and construction.

In addition to range measurement, FMCW Radar precision range meters can also be used to provide information on the location and size of the target. This information can be used for detailed mapping and 3D modeling of the target.

Overall, FMCW Radar precision range meters are an important tool for a range of applications where accurate range measurements are required. They are highly accurate and can provide real-time data to a control system. The experimantal setup for precision range meter with FMCW Radar system is shown as Figure 7.

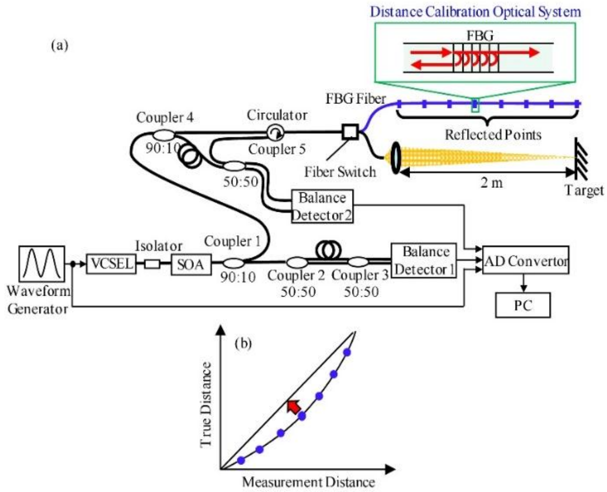

Figure 7 : The schematic of Experimental Setup for Precision Range Meter with FMCW Radar(a), The Graph of Measurement Distance-True Distance(b) [16]

2.2.6 Measurement of Very Small Motions

FMCW Radar technology can be used to measure very small motions with high precision. An example of measuring small movements is monitoring the vibrations of different parts in machines. A device is needed that is no physical contact with the vibrating component for such measurement. This can be achieved using a technique called interferometry, which is based on the interference between two or more radar signals.

In an interferometry-based FMCW Radar system, the radar emits two or more signals with slightly different frequencies towards the target. The signals reflect off the target and return to the radar, where they are compared to each other. The difference in the frequency of the reflected signals is proportional to the distance travelled by the target during the emission of the signals.

By comparing the frequency difference of thereflected signals at different times, the radar can determine the motion of the target. This is because any motion of the target during the emission of the signals will cause a change in the frequency difference of the reflected signals.

Interferometry-based FMCW Radar systems can be used to measure very small motions, such as vibrations or deformations of structures, with high precision. This is because they can detect changes in the frequency difference of the reflected signals that are as small as a few millihertz.

Overall, interferometry-based FMCW Radar systems are an important tool for measuring very small motions with high precision. They are increasingly being used in applications such as structural health monitoring as shown in Figure 8, where they can provide valuable information on the condition of infrastructure and other structures.

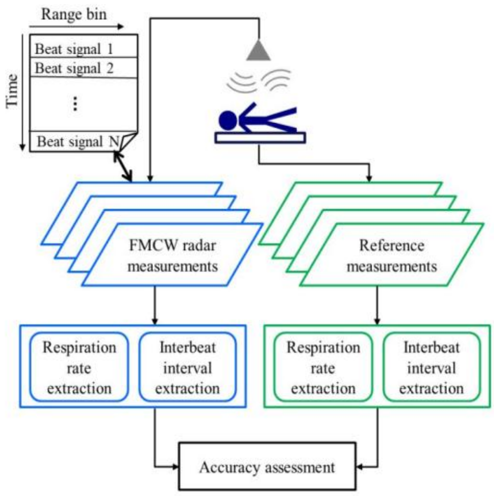

Figure 8 : The Example Flowchart of Small Motion Detection with FMCW Radar in Health Monitoring[17]

2.2.8 Hidden Object Detection

FMCW Radar technology can be used for detecting hidden objects that are not visible to the naked eye. This can be achieved by analyzing the radar signals reflected off the objects and identifying patterns that indicate the presence of hidden objects.

In a hidden object detection FMCW Radar system, the radar emits a continuous wave signal towards the surrounding environment. The signal reflects off any objects in its path and returns to the radar. The reflected signals are then analyzed to identify patterns that indicate the presence of hidden objects.

One of the key techniques used for hidden object detection is synthetic aperture radar (SAR). SAR is a method of using radar signals to generate high-resolution images of objects that are not visible to the naked eye. It works by emitting a series of radar signals from different positions and combining the reflected signals to generate an image of the object.

Another technique used for hidden object detection is ground-penetrating radar (GPR). GPR is a type of radar that is used to image objects beneath the ground. It works by emitting a radar signal into the ground and measuring the reflections from subsurface objects.

Hidden object detection FMCW Radar systems are used in a variety of applications, including security, search and rescue, and archaeological surveys. They can detect objects that are hidden from view, such as buried objects, hidden compartments, and concealed weapons.

Overall, FMCW Radar technology is an important tool for hidden object detection. It allows for the detection of objects that are not visible to the naked eye and can provide valuable information for a variety of applications. In the earthquake disaster in Kahramanmaraş, The imaging was provided from under the debris with the DAR Radar produced by STM as shown in Figure 9.

Figure 9 : The Through The Wall Radar (DAR) produced by STM[18]

3. FREQUENCY MODULATION TYPES OF FMCW RADAR

Modulation is applied to the transmitter signal to enable the measurement of range and velocity of targets in FMCW Radar systems.The type of modulation used depends on the critical data that needs to be obtained, and the desired range-speed resolution. These modulation types are sawtooth, triangle and sinusodial wave modulation.

The sawtooth wave modulation is used in radar systems where range measurement is critical. The sawtooth wave allows for high range resolution since it has a linearly increasing frequency.

The triangle wave modulation is used in radar systems where both range and velocity information are critical. This is because the linear ramp of the triangle wave allows for accurate measurement of range, while the frequency modulation enables the measurement of velocity.

The sinusoidal wave modulation is used in radar systems where velocity measurement is critical. By measuring the Doppler shift of the reflected signal, the velocity of the target can be calculated.

It is important to note that the modulation type to be applied may vary according to the bandwidth and modulation time depending on the desired range-speed resolution. In general, the higher the bandwidth and modulation time, the better the range-speed resolution.

The general equations related to Frequency Modulation and according to wave types are given below. The frequency modulation in transmitted signal is defined that used generally as

$$s_T = cos\left(2\pi f_C t + \int_0^t f_{sig}\, d\tau\right)$$
(1)

where fc is carrier frequency and f_{sig} is the signal that the carrier frequecy. The maximum or minimum difference between the modulated signal and the carrier frequency is $\pm\Delta f$. This equation demonstrates the transmitted frequency; the received frequency is delayed by $t_d = 2\Delta f \frac{R(t)}{cT}$), with $R(t) = \frac{R_0}{T/2} + vt$ and doppler shift by $f_d = \frac{2vf_c}{c}$, where T is the period of the modulated signal.

3.1 The Sawtooth Wave Modulation

A sawtooth wave modulation is a type of frequency modulation used in radar systems. In this modulation technique, the frequency of the transmitted signal is varied in a linear ramp over time, creating a sawtooth waveform. An example of Sawtooh Waveform is shown as Figure 10. The sawtooth modulation is typically used in radar systems where range measurement is critical. When the transmitted signal reflects off a target, the received signal is shifted in frequency due to the Doppler effect. The sawtooth modulation allows for accurate measurement of the Doppler shift, which can be used to determine the target velocity. The linear ramp of the sawtooth waveform also provides a high range resolution since it provides a linearly increasing frequency. The general equations about the sawtooth wave modulation are given below.

$$f_t(t) = 2\Delta f(t - T/2)$$
(2)

$$f_r(t) = 2\Delta f\left(t - t_d - {}^{T}/_{2}\right) + f_d$$
(3)

$$s_t(t) = \cos\left(2\pi f_C t + 2\pi \int_0^t f_t\, d\tau\right)$$
$$= cos\, 2\Pi(f_c t + \Delta f t T)$$
(4)

$$s_r(t) = \cos 2\pi(f_c(t - t_d) + \Delta f t^2 - \Delta f t(T + t_d) + f_d t)$$
(5)

Where f_t is the frequency of transmitted frequency, f_r is the frequency of received signal, s_t is the transmitted signal and s_r is the received signal.

The transmitted and received signals are mixed by multiplying in the time domain. The mixed signal can be expressed as

$$mixed(t) = \frac{1}{2} cos\, 2\pi(f_c t_d + (\Delta f t_d - f_d)t)$$
$$= \frac{1}{2}\cos 2\pi\left(f_c t_d + \left(\frac{4\Delta f R}{Tc} - \frac{2f_c v}{2}\right)t + \frac{2v}{c}t^2\right)$$
(6)

The expression being referred to in the above equation both time-dependent and non-time-dependent terms, which can be observed in the Fourier transform of the signal. The time-dependent terms include those that are proportional to t^2, and their effects are visible in the phase of the Fourier transform. The terms that are proportional to t can be observed in the spectrum of the signal. Two of the time-dependent terms are considered negligible, and the frequency peak can be expressed as with both doppler and range value

$$f = \frac{4\Delta f R}{Tc} + \frac{2f_c v}{c}$$
(7)

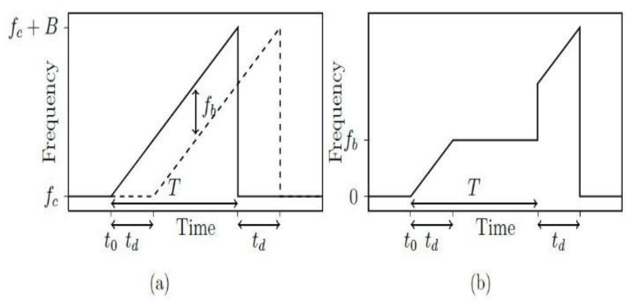

Figure 10 : The Transmitted and Received Signal with Sawtooth Waveform (a), the corresponding beat frequency (b) [19]

3.2 The Triangle Wave Modulation

A triangle wave modulation is a type of frequency modulation used in radar systems. In this modulation technique, the frequency of the transmitted signal is varied in a linear ramp over time, creating a triangular waveform. An example of Triangular Waveform is shown as Figure 11. The triangular modulation is typically used in radar systems where both range and velocity information are critical.

When the transmitted signal reflects off a target, the received signal is shifted in frequency due to the Doppler effect. The triangular modulation allows for accurate measurement of the Doppler shift, which can be used to determine the target velocity. The linear ramp of the triangular waveform also enables accurate measurement of the time delay between the transmitted and received signals, which can be used to calculate the range of the target

The triangular wave modulation analysis is similar to the sawtooth wave modulation, since the signal for 0 < t < T/2 is like a sawtooth signal with half the period, and the signal for T/2 < t < T is the negative of the signal for 0 < t < T/2.

$$f_t(0 < t < T/2) = 4\Delta f\,(t - T/4)$$
(8)

$$f_t(T/2 < t < T) = 4\Delta f(t - t_d - T/4) + f_d$$
(9)

$$f_t(0 < t < T/2) = 4\Delta f\,(-t - T/4)$$
(10)

$$f_t(T/2 < t < T) = 4\Delta f(-t - t_d - T/4) + f_d$$
(11)

The frequency equations for up ramp and down ramp can be expressed as when the transmitted and received signals are mixed

$$f_{up}(0 < t < {}^{T}/_{2}) = \frac{2f_c v}{c} - \frac{4\Delta f R}{Tc} \qquad (12)$$

$$f_{down}(T/2 < t < T) = \frac{2f_c v}{c} + \frac{4\Delta f R}{Tc} \qquad (13)$$

When the spectrum of mixed signal is analyzed, two frequency terms can be observed. By utilizing these frequencies, it is possible to calculate the values of velocity and range

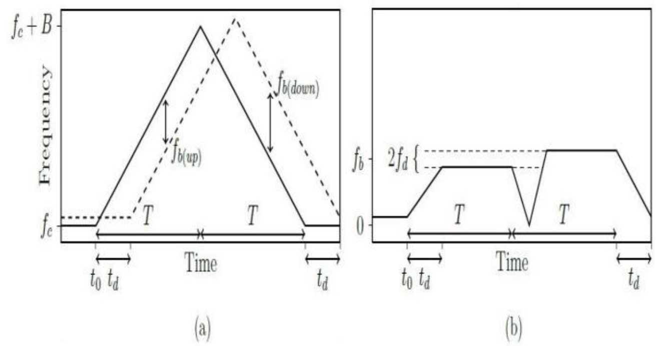

Figure 11 : The Transmitted and Received Signal with Triangular Waveform (a), the corresponding beat frequency (b) [19]

3.3 The Sinusodial Wave Modulation

A sinusoidal wave modulation is a type of frequency modulation used in radar systems. In this modulation technique, the frequency of the transmitted signal is varied sinusoidally over time. An example of Sinusodial Waveform is shown as Figure 12. The sinusoidal modulation is typically used in radar systems where the measurement of target velocity is critical.

When the transmitted signal reflects off a moving target, the frequency of the reflected signal is shifted due to the Doppler effect. By measuring this frequency shift, the velocity of the target can be calculated. The sinusoidal modulation allows for accurate measurement of the Doppler shift and thus enables the determination of the target velocity.

The general equations about the sinusodial wave modulation are given below.

$$f_t(t) = \Delta f\, cos(2\pi f_m t)$$
(14)

$$f_r(t) = \Delta f\, cos\big(2\pi f_m (t - t_d)\big) + \frac{f_d}{2}$$
(15)

Once modulation is applied, the signals are expressed using complex exponential terms as shown below, where ϕ_n is a phase that can take on arbitrary phase value.

$$s_t = \exp\{j\Delta f / f_m(\sin(2\pi f_m t) + \phi_1\}$$
(16)

$$s_r = \exp\{j\,\frac{-2\pi f_c t_d + \Delta f}{f_m(\sin(2\pi f_m(t - t_d)) + \phi_1}\}$$
(17)

By using exponential notation, the mixed signal can be expanded and then subjected to low pass filtering, which produces the following equation

$$mixed(t) = s_t^{*}.s_r$$

$$= \exp\{j[2fdt + D\cos(2\pi/T(t - R/c) + \phi_2]\}$$

$$\cong J_0(D)\exp[j(2\pi f_d t + \phi_3)$$
$$+J_1(D)\exp[j(2\pi f_d t + 2\pi f_m(t - R/c) + \phi_3)]$$

$$+J_1(D)\exp[j(2\pi f_d t - 2\pi f_m(t - R/c) + \phi_3)] \quad (18)$$
$$+other\ Beseel\ terms$$

Although the spectrum of the signal may contain multiple frequency peaks, only a few of them are relevant. Specifically, the center frequency located at the Doppler frequency f_d, and the upper and lower sidebands. The phases of these sidebands are different from the dominant frequency by a factor of $\pm 2\pi f_m R/c$, where $D = \frac{2\Delta f}{f_m} sin(2\pi f_m R / C)$, f_m is the modulation frequency, R is the distance of the target, and c is the speed of light.

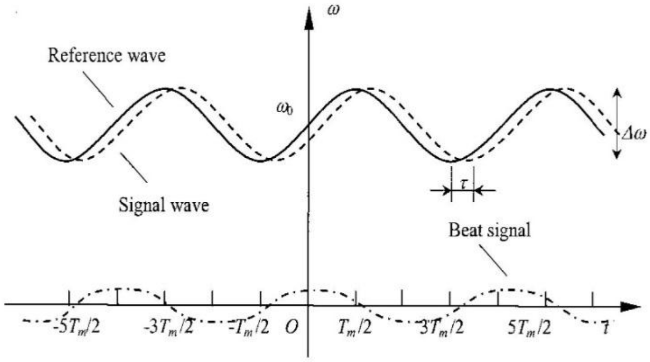

Figure 12 : The Transmitted and Received Signal with Sinusodial Waveform[20]

4. FMCW RADAR WAVEFORM DESIGN

Gradually Changing Waveform is a method used to improve the range resolution of radar systems using pulse compression techniques. This method is made possible by the adjustable bandwidth feature of frequency modulated radars, which allows for the range resolution to be improved within a certain frequency range. The technique involves dividing the transmitter signal into sub-pulses with smaller bandwidths within an adjustable frequency band as shown in Figure 13. This allows for the received echo signal to be accurately assigned to each carrier frequency, resulting in an effective greater wider bandwidth and improved range resolution. Additionally, this technique improves receiver immunity to interference and minimizes mutual interference with other radars operating in the same frequency band. The mathematical equations applied in transmitted, received and mixed signals of FMCW Radar are specified.

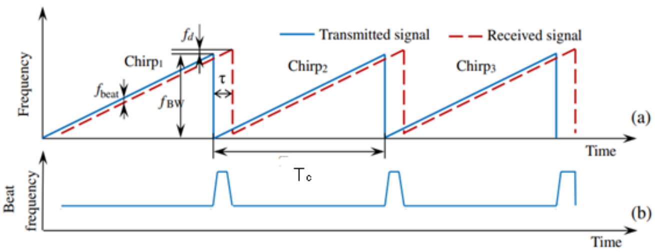

Figure 13 : FMCW Radar waveform princple for a single moving target the transmitted and received signal (a), the corresponding beat frequency (b)

FMCW (Frequency Modulated Continuous Wave) radar systems are used to measure the distance to an object by transmitting a continuous wave signal that is frequency-modulated with a linear ramp. This signal is known as the "chirp" signal, and it is used to determine the range of an object by measuring the time delay between the transmitted and received signals. The transmitted signal is a continuous wave with a frequency that increases linearly with time. The equation for the transmitted signal is shown in equation (19). The frequency of received signal is shown in equation (20) which is a linear function of time and is affected by the Doppler shift caused by the motion of the reflecting object. The time delay t_d is also accounted for in equation (20). The received signal is shown in equation (21) which is the echo of the transmitted signal after it has been reflected off of the object. This signal is affected by the time delay and the Doppler shift, as represented by equation (20). Trasnmitted signal $S_T(t)$ and received signal $S_R(t)$ are mixed by multiplication for obtaining doppler frequency and beat frequency. The intermediate frequency (IF) signal $S_{IF}(t)$ is shown in equation (22) for the up ramp and in equation (23) for down ramp. The beat frequency equations are shown in equations (24) and (25) for up and down. The target range R and the radial velocity V are shown in equations (26) and (27).

In summary, FMCW Radar systems use a frequency-modulated continuous wave signal to measure the distance and velocity of an object. The transmitted signal is a continuous wave with a frequency that increases linearly with time, while the received signal is the echo of the transmitted signal after it has been reflected off of the object. By measuring the frequency difference between the transmitted and received signals, the distance and velocity of the object can be determined.

The transmitted signal of an FMCW Radar System can be expressed as

$$s_T(t) = A_T \cos\left(2\pi f_C t + 2\pi \int_0^t f_T(\tau)\, d\tau\right)$$
(19)

where $f_T(\tau) = \frac{B}{T}$, τ is transmit frequency as a linear function of time, fc is carrier frequency, B is the bandwith, A_T is amplitude of transmitted signal , T is the time period of signal. The frequency of received signal can be expressed as

$$f_R(t) = \frac{B}{T}(t - t_d) + f_D$$
(20)

Where $t_d = 2 \cdot \frac{R_0 + vt}{c}$, $f_D = -2 \cdot \frac{f_c v}{c}$, t_d is time delay due to reflected signal, f_D :is doppler shift, R_0 is therRange at t=0, v is the velocity of target, c is the speed of light. The received signal can de expressed as

$$S_R(t) = A_R \cos(2\pi f_C (t - t_d) + 2\pi \int_0^t f_R(\tau)\, d\tau$$

$$= A_R \cos\left(2\pi\left(f_c(t-t_d)+\frac{B}{T}\left(\frac{1}{2}t^2-td^t\right)+f_D t\right)\right)$$
(21)

where A_R is the amplitude of received signal.

$S_T(t)$ and $S_R(t)$ are mixed by multiplication for obtaining doppler frequency and beat frequency. The intermediate frequency (IF) signal $S_{IF}(t)$ can be obtained for the up ramp as

$$S_{IF}(t) = \frac{1}{2}\cos\left(2\pi\left(f_c\frac{2R_0}{c}\right)+2\pi\left(\frac{2R_0}{c}\cdot\frac{B}{1}+\frac{2f_c v}{c}\right)t\right)$$
(22)

Similarly, the IF signal $SIF(t)$ can be obtained for the down ramp as

$$S_{IF}(t) = \frac{1}{2}\cos\left(2\pi\left(f_c\frac{2R_0}{c}\right)+2\pi\left(-\frac{2R_0}{c}\cdot\frac{B}{1}+\frac{2f_c v}{c}\right)t\right)$$
(23)

Consequently, The beat frequency equations for up and down can as shown in Figure 14 and be expressed as

$$f_{bu} = \frac{2R_0}{c}\cdot\frac{B}{T}+\frac{2f_c v}{c}$$
(24)

$$f_{bd} = -\frac{2R_0}{c}\cdot\frac{B}{T}+\frac{2f_c v}{c} \quad (25)$$

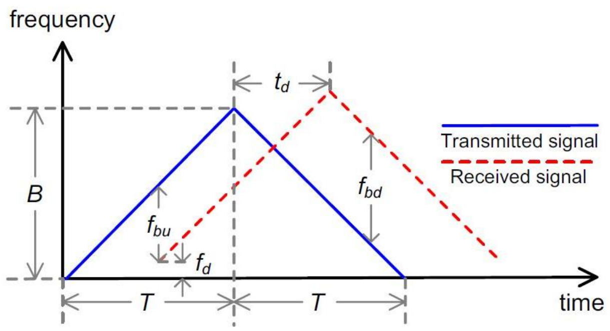

Figure 14 : The Transmitted and Received Frequencies of signal waveform for the FMCW Radar System[21]

$$Range = R = \left(\frac{C\cdot T}{2\cdot B}\right)\cdot\left(\frac{f_{bu}+f_{bd}}{2}\right) \quad (26)$$

$$Velocity = v = \left(\frac{c}{2f_c}\right)\cdot\left(\frac{f_{bu}-f_{bd}}{2}\right) \quad (27)$$

5. MATLAB SIMULATION

The FMCW Radar Simulation for detecting Ambuguity Multiple Target on Matlab is follows steps and explains with flowchart in Figure 15:

1. It defines the parameters of the radar system as shown in Table 1, such as the speed of light, bandwidth, carrier frequency, number of ADC samples, number of chirps per frame, pulse repetition interval, and others.
2. It defines the two target according to informations in Table 2. It simulates the movement of two targets over time by calculating their locations at each point in the time axis. It sets up some variables such as range and velocity axis, and angle axis.
3. It simulates Transmitted Signal
4. It simulates Received Signal
5. It simulates Mix Signal with Transmitted and Received Signal
6. It simulates FFT Operations
7. Apply CA-CFAR Algorithm for detecting multiple target
8. Appy MUSIC Algorithm for detecting multiple target

Table -1: Parameters of FMCW Radar

Parameters of FMCW Radar	
Center Frequency	24 GHz
Bandwith	150 MHz
Number of ADC Samples	256
Number of Chirps	256
Time Period	10 microsecond
Number of Transmitter Antenna	1
Number of Receiver Antenna	4
Range Resolution	1

Table -2: Target Range, Angle, Velocity and Coordinates

Target Informations	Range	Angle	Velocity	Coordinate X	Coordinate Y
Target 1	60	-25	15	-25.3571	54.3785
Target 2	80	15	-35	20.7055	77.2741

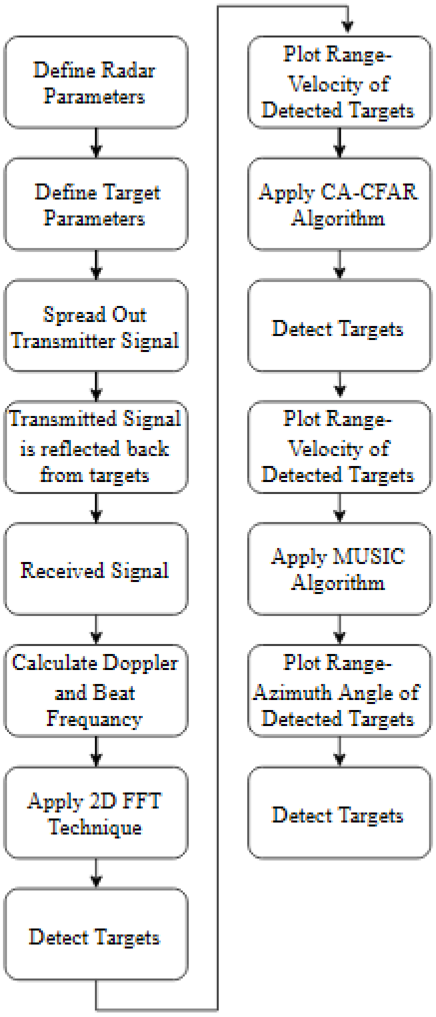

Figure 14 : Flowchart of FMCW Radar Matlab Simulation

5.1 Transmitted Signal

Some processing is performed before generating the transmitter signal on MATLAB Simulation Code. These processing is a part of a MATLAB simulation that calculates the time delays between targets and transmitter-receiver pairs in a 3D space. It creates arrays of transmitter and receiver locations and target locations over time, and uses the Euclidean distance formula to calculate the delays, which are stored in cell arrays. After these processes, the transmitter signal is generated according to the radar signal parameters that specified in Parameters of FMCW Radar as shown in Figure 16.

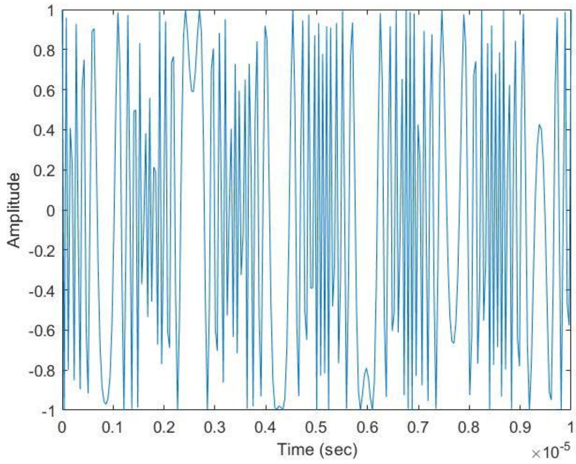

Figure 16 : Tranmitted Signal

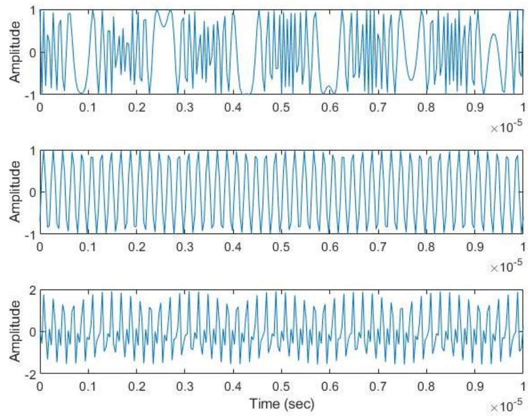

Figure 17 : Transmitted, Received and Mixed Signal

5.2 Mixed Signal

This part generates a mixed signal and plot the mixed signal as shown in Figure 17 by mixing the two target signals with the transmitted signal in MATLAB Simulation Code . It uses specific functions to calculate the phase of the transmitted and received signals, and defined range-dependent and doppler-dependent frequency and intermediate frequency for the two targets. It uses a nested for loop to iterate over all the transmitter-receiver pairs, and within that, over all the chirps and pulses in the data. It calculates the phase of the transmitted signal, the phase of the received signals from the two targets and the difference in phase between the transmitted and received signals, uses the exp() function with the calculated phase to generate the time-domain signal and adds the two target signals. The resulting mixed signal is then stored in a cell array called "mixed"

5.3 FFT Operations

The FFT part of code reshapes the mixed signal data and applies a 2D Fourier transform to create a Range-Doppler Map (RDM). It reshapes the mixed signal data into a 3D array called "RDC" and applies a 2D FFT on it using "fft2" and "fftshift" functions to create a 4D array called "RDM" with dimensions of number of ADC, number of Chirps, multiplying the number of receiver and transmitter antennas, number of CPI and plots the Range-Doppler Map using the "imagesc" function as shown in Figure 18. It also applies a colormap, sets the color axis limits and adds x and y labels.

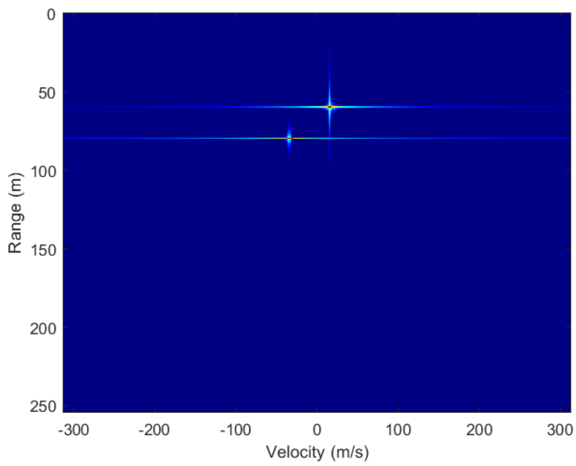

Figure 18 : The Range-Velocity Graph after FFT Operations

5.4 CA-CFAR Algorithm

This part of code applies a Constant False Alarm Rate (CFAR) detection algorithm to a Range-Doppler Map (RDM) in order to identify target returns as shown in Figure 19. The CFAR algorithm compares the power of the target return to the power of the surrounding noise and decides if the target return is real. It defines the number of guard cells and training cells and the desired false alarm rate and also defines an SNR offset value in dB. The RDM data is passed in dB scale. It calls the “ca_cfar” function which takes in RDM data, number of guard cells, number of training cells, desired false alarm rate, and SNR offset as inputs, and returns the range-Doppler map with a CFAR mask applied to it, CFAR detected ranges, CFAR detected Doppler values and the threshold value. The CFAR algorithm used here is Cell Averaging CFAR (CA-CFAR) which compares the power of the target return to the average power of the surrounding noise.

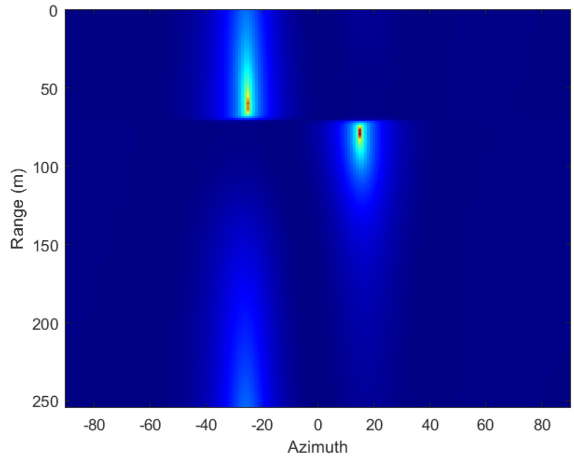

Figure 19 : The Range-Velocity Graph after applying CA-CFAR Algorithm

5.5 MUSIC Algorithm

This part of code applies the Multiple Signal Classification (MUSIC) algorithm to the RDC data to estimate the angle of arrival (AoA) of the targets. MUSIC is a subspace-based technique that is used to estimate the AoA of multiple signals in a noisy Environment. It applies 1D FFT on the RDC along the range dimension and uses a for loop to iterate over all range bins, creating the matrix by summing the outer product of the signal vector for each snapshot and divide it by the number of snapshots and plot "MUSIC Spectrum" as shown in Figure 20. It then applies the MUSIC algorithm to the created matrix using the estimator object and obtains the DOA estimates. It creates a new figure and plots the range-angle map using the "imagesc" function with the angle values and range values. It also applies a colormap, sets the color axis limits and plot "MUSIC Range-Angle Map" as shown in Figure 21.

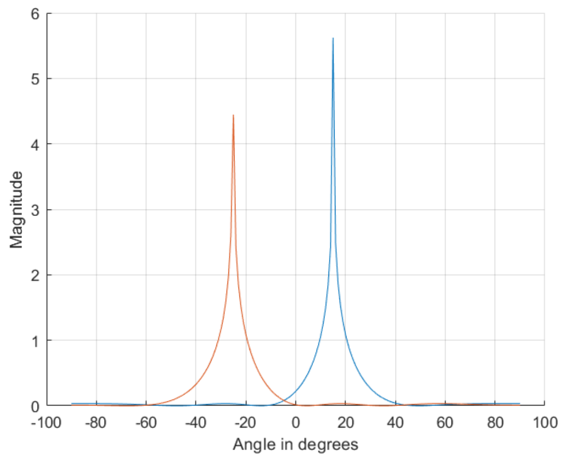

Figure 20 : The Spectrum Graph for angle values of Targets with MUSIC Algorithm

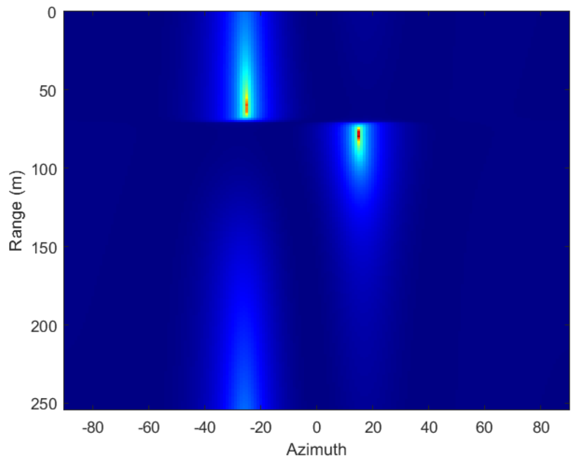

Figure 21 : Range-Azimuth Graph of Targets with MUSIC Algorithm

5. CONCLUSION

Some signal processing algorithms were applied in the simulation study for the detection of ambiguity multiple targets with FMCW Radar in Matlab software. These are FFT, CA-CFAR and MUSIC algorithms. The Range and Velocity information of the targets were determined by the CA-CFAR algorithm. Azimuth angles of the targets were successfully determined with the applying MUSIC algorithm. The location information detected on the targets are Target1(-13.2,49.26), Target2(17.54,99.40). However, the defined target locations are specified as Target1(-12.94,48.30), Target2(17.36,98.48). When the actual and determined results related to the location are compared, it has been observed that there is a 1% margin of error. As a result of this study, it has been confirmed that the detection of ambiguity multiple targets can be successfully performed with FMCW Radar and the performances of CA-CFAR, MUSIC algorithms have been verified.

In future work, the different signal processing algorithms that are not used in this study and their performance for target detection can be examined. For example, in this study, the success of detecting target information can be measured by examining signal processing algorithms such as Order Statistic CFAR (OS-CFAR), Adaptive CFAR (ACFAR) and similar instead of CA-CFAR signal processing algorithm, which is one of the CFAR Signal Processing algorithms. This study would provide a more comprehensive understanding of their strengths and weaknesses. Additionally, it would be utility to see how these different algorithms perform under various conditions, such as different noise levels, target ranges, and clutter environments. Furthermore, some other techniques like Machine learning techniques, deep learning techniques can be used to improve the performance of target detection. These techniques can be used to detect target in noisy, cluttered and adaptive environment.

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