Target Detection Using FM Chirp and GNU Radio-Based FMCW Radar

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***Abstract*—This paper investigates the accuracy of GNU radio-based frequency-modulated continuous wave (FMCW) radar for multiple target detection using different waveforms of frequency modulation (FM) chirp. The three waveforms analyzed are sinusoidal, triangular, and sawtooth. The analysis is conducted through the utilization of GNU Radio, an open-source software-defined radio project. Two methods, namely the real-condition simulation method and the USRP-based implementation method, are employed for the detection process. Targets at various ranges are characterized using both methods to determine the accuracy of target range. The results, obtained using the QT GUI Frequency Sink and QT GUI Time Sink from GNU Radio, demonstrate that the sawtooth waveform exhibits the highest average accuracy compared to other two waveforms. The findings reveal that the USRP-based implementation method yields superior average accuracy compared to the real-condition simulation method.**

***Index Terms*—Frequency-modulated continuous wave radar, FM chirp, GNU Radio, Target detection**

I. Introduction

Radar networks have become prevalent in numerous developed countries over the last few decades. These networks employ modulated waveforms and directive antennas to transmit electromagnetic energy towards specific volumes in space, enabling the detection of target ranges [1]. The transmitted radio frequency signal is reflected by the targets, with a portion of the signal returning to the radar system, commonly referred to as an echo. Radar technology finds applications in both civilian and military domains, encompassing traffic monitoring, air/land/sea surveillance, weather forecasting, Doppler Radar for vehicle speed detection, navigation, and more.

In general, radars are commonly classified based on the modulation waveform or operating frequency. When considering waveform types, radars can be grouped into two categories: continuous wave (CW) radars or pulse radars (PR).

1) CW Radar: CW radars are characterized by the continuous emission of electromagnetic energy and typically employ separate transmit and receive antenna systems.

2) PR Radar: On the other hand, pulse radars periodically transmit high-power electromagnetic energy in pulsed form and may employ a single antenna system for operation.

In continuous wave (CW) radars, wider operating bandwidths or improved target detection accuracy can be achieved by employing frequency- or phase-modulated waveforms. Linear frequency modulation (LFM) is a commonly used waveform modulation technique in CW radar.

Traditional pulse radars utilize a powerful transmitter, such as a magnetron or klystron, and a highly sensitive receiver, making them expensive. To address this, radar researchers have proposed a cost-effective alternative known as frequency-modulated continuous wave (FMCW) radar.

In recent years, FMCW radar has gained popularity due to advancements in solid-state microwave transmitters and fast digital circuits [2]. Furthermore, FMCW radar offers a convenient approach to improve the signal-to-noise ratio and reduce system complexity [3].

A. FMCW Radar

One type of radar that can be implemented using Software Defined Radio (SDR) is Frequency Modulated Continuous Wave (FMCW) radar [4]. FMCW radars typically employ linear frequency modulation and emit waves continuously throughout a periodic span, in contrast to pulse radars that transmit short pulses within a periodic time interval. FMCW radar does not require a high transmitting power to achieve a sufficient Signal to Noise Ratio (SNR) for target detection, as is the case with pulse radars [5].

From a hardware perspective, FMCW radars, which can be constructed using solid-state amplifiers, are smaller and less expensive than pulse radars that utilize magnetrons as amplifiers. Doppler CW (Continuous Wave), FMCW (Frequency Modulated Continuous Wave), and FH (Frequency Hopping) techniques can be applied in a radar system to measure the distance and speed of a moving target over a specific time period. The capability of CW radar to detect targets depends on the SNR of the beat signal and the radar's resolution, which refers to its ability to distinguish adjacent targets in terms of range or Doppler direction.

The main limitation of CW radar is that it can only provide resolution in one direction, either range or Doppler. FMCW radar is shown to offer 2D resolution, achieved through FMCW radar measurements and range-Doppler 2D Fourier transform processing. One widely used signal processing technique in FMCW radar systems is to extract beat frequencies and utilize the Fast Fourier Transform (FFT) to obtain distance information of the target.

In this paper, we utilize the Frequency Modulated Continuous Wave (FMCW) radar with Frequency Modulated (FM) chirp to evaluate the precision of detecting multiple targets. The FMCW radar system is implemented using GNU Radio, which is an open-source software-defined radio project renowned for its ability to implement advanced and cost-effective software-defined radios [6]-[7]. We employ three different waveforms for the FM chirp analysis: sinusoidal, triangular, and sawtooth waveforms. For the triangular and sawtooth waveforms, the frequency of the FM chirp is linearly swept, while for the sinusoidal waveform, it is swept non-linearly across the pulse width. The matched filter bandwidth is set proportionally to the sweep bandwidth and remains unaffected by the pulse width. To explore the accuracy of target detection characterization, we introduce two methods: real-condition simulation and USRP-based implementation. Furthermore, we provide a discussion on the characterization results and their analysis.

The structure of this paper is as follows. In Section II, we introduce the problem statement and the system model. In Section III, we present the proposed solution for the problem statement. In Section IV we discuss the numerical results and analyze the evaluation of the performance of the proposed model. Finally, Section V mentions the conclusion of the research problem.

II. Problem Statement

Multi-target detection is a crucial aspect of radar systems used in various applications such as surveillance, automotive radar, and aerospace. However, conventional radar systems often face challenges in accurately detecting and characterizing multiple targets in complex environments. These challenges include range ambiguities, doppler ambiguities, and overlapping echoes, which can lead to reduced detection accuracy and false alarms.

A. System Model

In order to tackle the mentioned issues, this paper presents a solution that involves the adoption of Frequency Modulated Continuous Wave (FMCW) radar systems utilizing Frequency Modulated (FM) chirp waveforms, which are implemented using GNU Radio. FMCW radar systems possess several benefits, including high range resolution, low power consumption, and the capability to simultaneously detect multiple targets. By employing FM chirp waveforms, improved range and Doppler resolution are achieved, leading to precise target detection and characterization.

By implementing FM chirp waveforms within the FMCW radar system using GNU Radio, we aim to improve the accuracy of multi-target detection. The flexible and open-source nature of GNU Radio allows for customization and optimization of the radar signal processing algorithms. The FM chirp waveforms, including sinusoidal, triangular, and sawtooth waveforms, enable precise frequency modulation for target analysis.

The combination of FMCW radar, FM chirp waveforms, and GNU Radio offers a comprehensive solution to address the challenges of multi-target detection in complex environments. This research aims to investigate the performance and capabilities of this integrated approach and provide insights into the development of advanced radar systems for efficient and reliable multi-target detection.

III. Proposed Solution

In this project, our goal is to develop and test the models based on real condition and USRP based implementation with GNU Radio.

A. System Design

Fig. 1 presents the block diagram of a fundamental Frequency Modulated Continuous Wave (FMCW) radar system [8]. The system comprises a chirp generator, serving as the signal source for both the transmitter and the mixer input of the receiver. The transmitter antenna emits the FMCW signal towards the intended targets, and subsequently, the receiver antenna captures the reflected signal from these targets. The received signal is then subjected to processing to extract target properties.

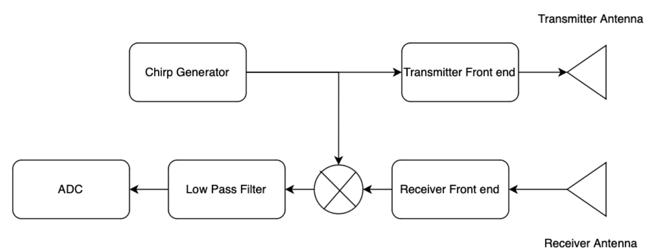

Fig. 1. Block diagram of a basic FMCW radar system.

The FMCW signal, often referred to as a chirp, encompasses diverse signal waveform types, offering flexibility in radar applications. These waveform types enable the radar system to adapt to specific operational requirements and target scenarios. The selection of a suitable waveform type is crucial for achieving desired performance in terms of range resolution, target detection, and parameter estimation.

By employing various waveform types for the FMCW signal, the radar system can leverage the characteristics of different waveforms to enhance target detection and tracking capabilities. These waveform variations facilitate effective signal processing algorithms for extracting target information accurately.

B. Multiple Target Detection

An initial multiple target detection system using FMCW Radar system design is developed as presented in Fig. 2, employing the generation of a frequency-modulated (FM) signal for transmission. The FM signal is generated by combining a signal source with a voltage-controlled oscillator (VCO). The resulting signal is then transmitted to the desired targets, which are represented by delay blocks.

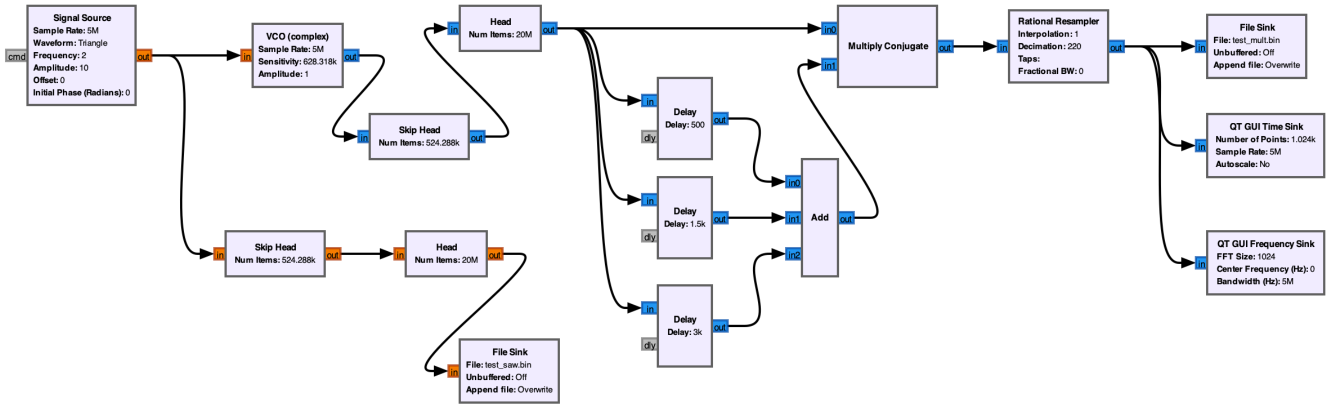

Fig. 2. Flowgraph for multiple target detection using chirp and GNU Radio.

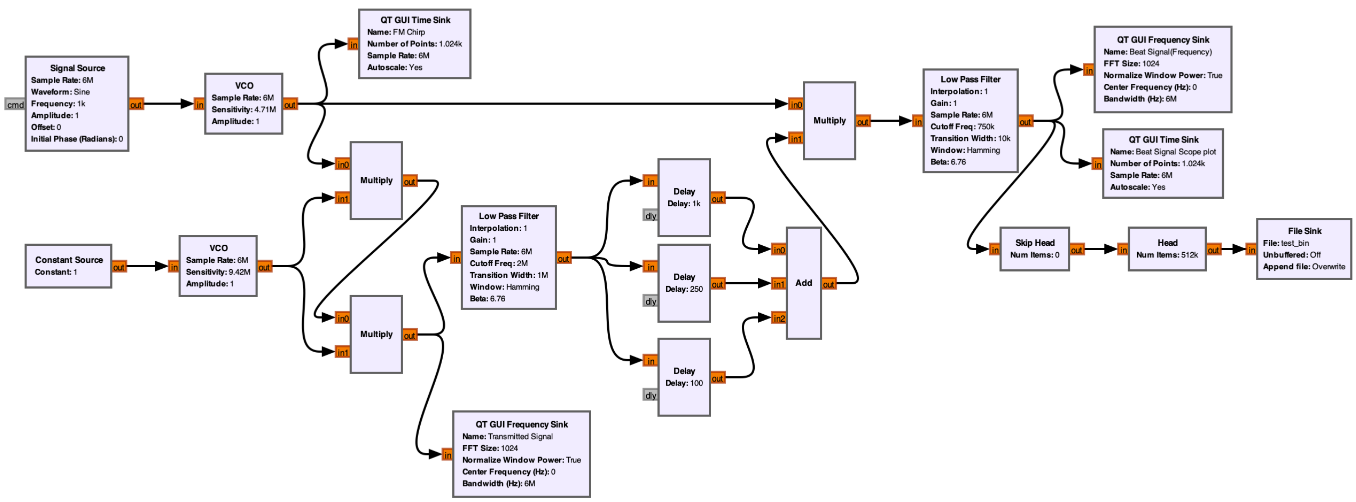

Fig. 3. Flowgraph for real condition simulation method using GNU Radio.

To detect the targets, the received delayed FM signal is mixed with the original transmission signal. This mixing process allows for the calculation of the beat signal, as well as the determination of the beat frequencies associated with each target. By analyzing these beat frequencies, the system can identify and locate multiple targets.

C. Real-condition Simulation

To conduct the real condition simulation, we consider factors such as noise, clutter, and interference that are commonly encountered in practical radar environments. These factors are incorporated into the simulation model to accurately reflect the challenges faced by the radar system during target detection.

Fig. 3 illustrates the essential components and signal processing stages employed in the real-condition simulation method utilizing GNU Radio. This method involves mixing the transmitted and received signals while applying suitable delays to generate the necessary beat signal. The beat signal is subsequently utilized for further analysis and characterization of the system.

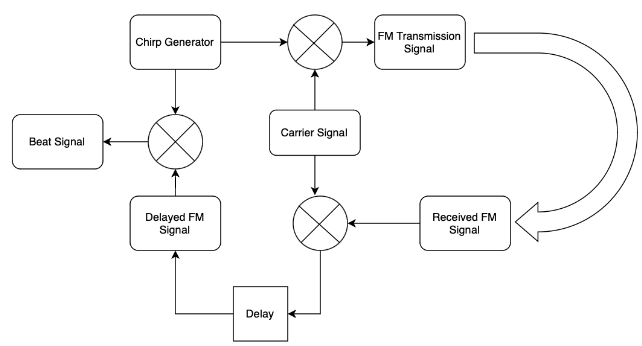

Fig. 4. Block diagram of a real condition simulation method.

The real condition simulation method [10], as illustrated in the Fig. 4, involves the mixing and transmission of the LFM Chirp Signal and Carrier Signal to generate the Transmitted FM Signal. Upon reception at the receiver antenna, the received FM signal is mixed with the carrier signal and then delayed using delay blocks with specific delays. Subsequently,

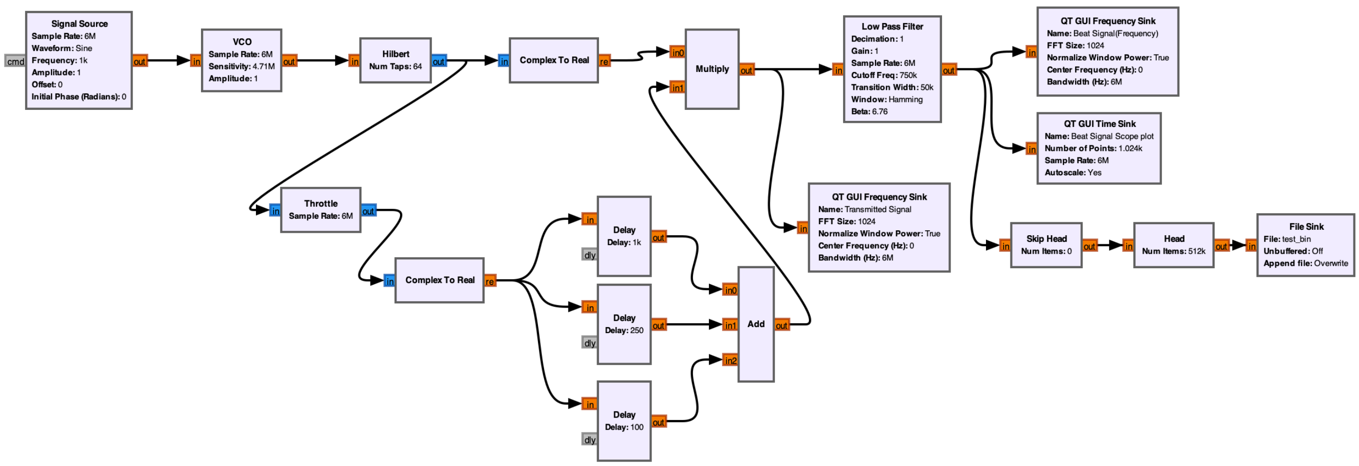

Fig. 5. Flowgraph for USRP based simulation method using GNU Radio.

the delayed FM signal is multiplied with the LFM chirp signal, resulting in the generation of the desired beat signal.

The simulation model takes into account the characteristics of the radar system components, including the antenna, signal generator, mixer, and receiver. By simulating the propagation of the radar signals in the presence of realistic conditions, we can assess the system's performance in terms of detection range, accuracy, and signal-to-noise ratio.

This approach provides a means to simulate real-world conditions and evaluate the performance of the LFM chirp signal in target detection scenarios. The simulated beat signal can be analyzed and compared to expected results, allowing for a comprehensive assessment of the accuracy and effectiveness of the system under various conditions.

D. USRP based Simulation

The USRP-based simulation using GNU Radio offers a reliable and flexible platform for studying the performance of radar systems. It allows for detailed analysis and optimization, enabling researchers to explore various scenarios and parameters to improve target detection capabilities.

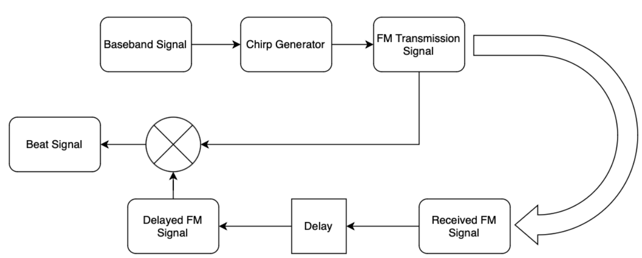

Fig. 6. Block diagram of a USRP based simulation method.

Fig. 5 illustrates the practical implementation of the USRP-based simulation utilizing GNU Radio, as described in the aforementioned approach.

In this method, we employ a block diagram as in Fig. 6 to illustrate the signal processing steps involved [10]. Initially, a baseband signal and a Voltage Controlled Oscillator (VCO) are utilized to generate the Frequency Modulated (FM) signal for transmission. Subsequently, the received FM signal is subjected to delay blocks, each with an appropriate delay value. These delay blocks introduce a time delay to the received FM signal.

Finally, the delayed FM signal is multiplied with the transmitted FM signal to generate the desired beat signal. This beat signal contains valuable information about the targets detected by the radar system.

The block diagram of the USRP-based simulation method encompasses the stages of signal generation, transmission, reception, and processing. By simulating this process, we can evaluate the accuracy and performance of our radar system in detecting and characterizing multiple targets.

IV. Numerical Results and Analysis

For conducting the simulations, we have taken into account specific design system parameters which are outlined in Table I.

TABLE I. DESIGN SYSTEM PARAMETERS

Parameter	Specifications
Signal source carrier frequency	1.5MHz
FM chirp rate	6M sample/second
FM chirp sweep frequency	1kHz
Signal source bandwidth	750kHz
Signal source delay blocks	100, 250, and 1000 sample

1) Theoretical Approach: Considering a sample rate of 6Msps, each sample corresponds to a duration of 166ps. Consequently, the conversion of 100, 250, and 1000 samples results in time intervals of $16.67\mu s, 41.67\mu s$, and $166.7\mu s$, respectively. By employing equation (1), the distance(R) to the target can be calculated [9].

$$R = \frac{c.\delta t}{2} \tag{1}$$

The variable c represents the speed of light. Additionally, the symbol δt denotes the time delay.

In this study, we analyze the accuracy of distance measurement using three FM chirp waveforms: sinusoidal, triangular, and sawtooth waveforms. To determine the distances of the samples, we consider the beat frequencies and employ the following equations:

For the sinusoidal waveform, the distance (R) is calculated using the equation:

$$R = \frac{f_b . c}{12. f_m . \delta f} \tag{2}$$

For the triangular waveform, the distance (R) is calculated using the equation:

$$R = \frac{f_b . c}{4. f_m . \delta f} \tag{3}$$

For the sawtooth waveform, the distance (R) is calculated using the equation:

$$R = \frac{f_b . c}{2. f_m . \delta f} \tag{4}$$

Here the variables $f_b, f_m, \delta f$ represents beat frequency, sweep frequency and bandwidth of signal source.

2) Multiple Target Detection: In the study on multiple target detection using chirp, the beat signal and beat frequencies of the target were generated.

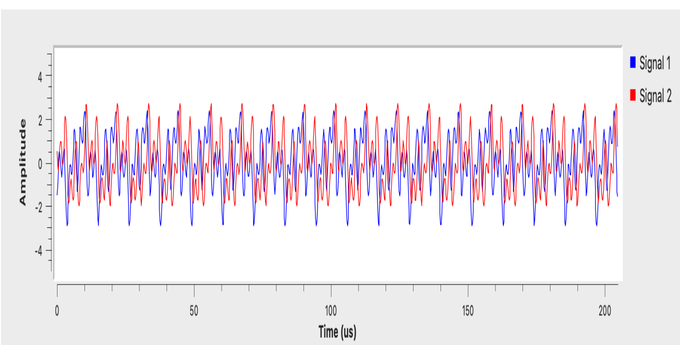

Fig. 7. Beat signal of triangular waveform obtained from target detection using chirp.

The beat signal obtained from the transmitted and received signal is shown in Fig. 7. The signals are in the same domain but have a time difference due to delay blocks.

To extract the beat frequencies, the QT GUI Frequency Sink block from GNU Radio was employed. The three peaks in the plot correspond to the targets resulting from the varying delay block.

By analyzing Fig. 8, the beat frequencies were captured and utilized in the relevant equations for target determination. The depicted figures illustrate the results obtained for the triangular FM chirp waveform.

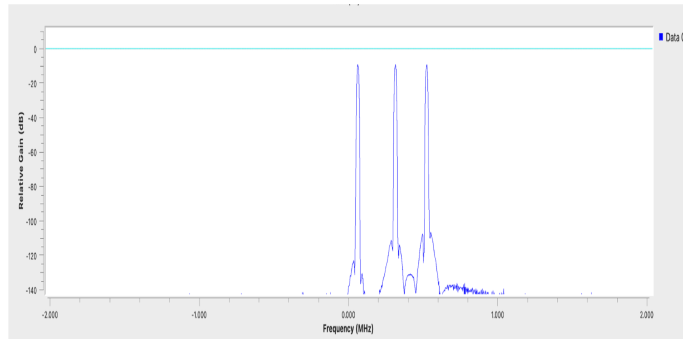

Fig. 8. FFT beat frequency of triangular waveform obtained from target detection using chirp.

3) Real-condition Simulation: We conducted simulations to analyze three FM chirp waveforms and obtained corresponding beat signals for target detection. Fig. 9 illustrates the beat signal acquired for the sawtooth waveform, while Fig. 10 showcases the Fast Fourier Transform (FFT) beat frequencies of the detected targets. To perform these simulations, we utilized GNU Radio with the Blackman-Harris window type.

The target distance calculation was performed using the beat frequencies extracted from the beat frequency plots presented in Fig. 10.

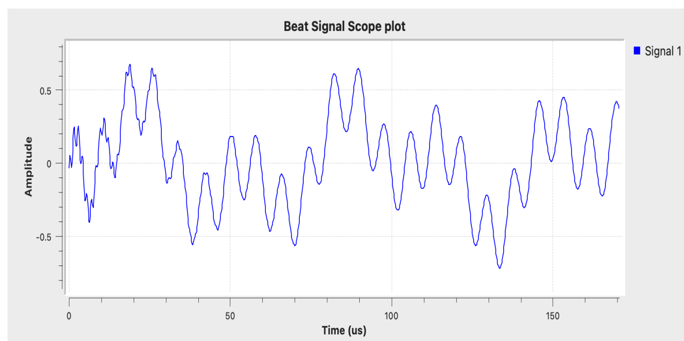

Fig. 9. Beat signal of sawtooth waveform obtained from real condition simulation.

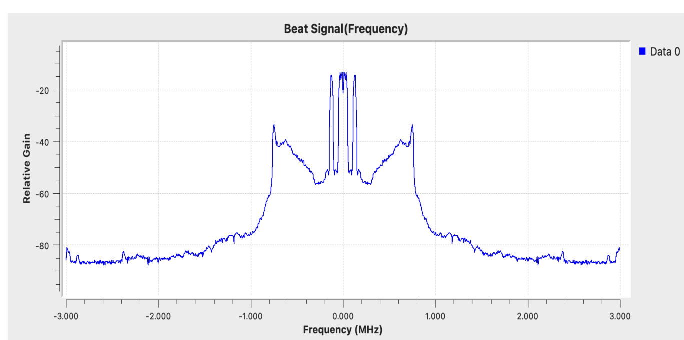

Fig. 10. FFT beat frequency of sawtooth waveform obtained from real condition simulation method.

For all three waveforms, the target distance was determined utilizing the equations mentioned earlier. Following Tables II, III and IV illustrates the target distance comparisons.

TABLE II. COMPARATIVE ANALYSIS OF TARGET DISTANCE USING TRIANGULAR WAVEFORM

Time Step	R(Theoretical)	R(GNU Radio)	Accuracy
100	2.5	2.7	92.5
250	6.25	6.36	98.2
1000	25	25.2	99.2

TABLE III. COMPARATIVE ANALYSIS OF TARGET DISTANCE USING SAWTOOTH WAVEFORM

Time Step	R(Theoretical)	R(GNU Radio)	Accuracy
100	2.5	2.53	98.8
250	6.25	6.35	98.4
1000	25	25	100

TABLE IV. COMPARATIVE ANALYSIS OF TARGET DISTANCE USING SINUSOIDAL WAVEFORM

Time Step	R(Theoretical)	R(GNU Radio)	Accuracy
100	2.5	2.68	93.28
250	6.25	6.47	96.59
1000	25	25.8	96.89

Based on the simulations conducted under this method, it is observed that the sawtooth waveform of FM chirp demonstrates the highest average accuracy among the three waveform types analyzed.

4) USRP based Simulation: Simulations were performed to analyze three FM chirp waveforms and extract beat signals for target detection. The acquired beat signal for the sawtooth waveform is illustrated in Fig. 11, while Fig. 12 displays the Fast Fourier Transform (FFT) beat frequencies of the detected targets. These simulations were conducted using GNU Radio with the implementation of the Blackman-Harris window type for signal processing.

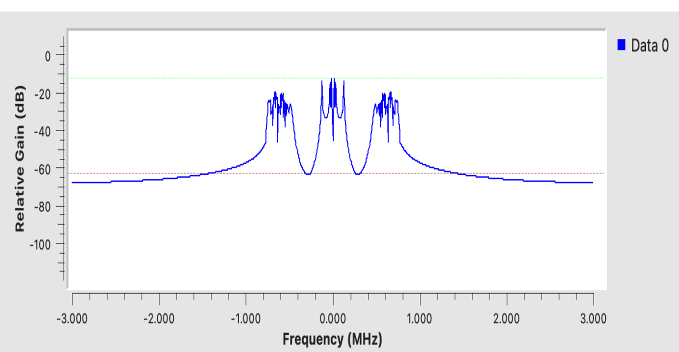

Fig. 11. Beat signal of sawtooth waveform obtained from usrp based simulation.

The calculation of target distance in this study involved extracting beat frequencies from the beat frequency plots, as shown in Fig. 12. The target distance was determined using the equations mentioned earlier, which are applicable to all three waveforms considered. The obtained target distance

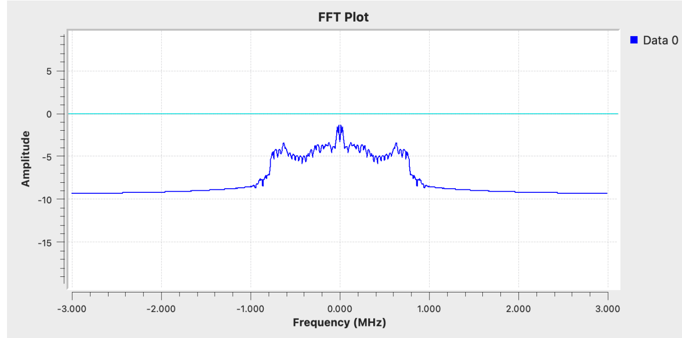

Fig. 12. FFT beat frequency of sawtooth waveform obtained from usrp based simulation method.

comparisons are presented in Tables V, VI, and VII for reference and analysis.

TABLE V. COMPARATIVE ANALYSIS OF TARGET DISTANCE USING TRIANGULAR WAVEFORM

Time Step	R(Theoretical)	R(GNU Radio)	Accuracy
100	2.5	2.6	96.15
250	6.25	6.32	98.8
1000	25	25.32	98.7

TABLE VI. COMPARATIVE ANALYSIS OF TARGET DISTANCE USING SAWTOOTH WAVEFORM

Time Step	R(Theoretical)	R(GNU Radio)	Accuracy
100	2.5	2.5	100
250	6.25	6.35	98.4
1000	25	25	100

TABLE VII. COMPARATIVE ANALYSIS OF TARGET DISTANCE USING SINUSOIDAL WAVEFORM

Time Step	R(Theoretical)	R(GNU Radio)	Accuracy
100	2.5	2.56	97.6
250	6.25	6.38	97.9
1000	25	25.6	97.6

According to the simulations conducted using this approach, it is noted that among the three waveform types investigated, the sawtooth waveform of the FM chirp exhibits the highest average accuracy.

V. CONCLUSIONS

This study focuses on the utilization of FM chirp and Frequency Modulated Continuous Wave (FMCW) Radar for multiple target detection. A comprehensive framework has been developed utilizing GNU Radio to facilitate the experimentation. The accuracy of FM chirp has been thoroughly investigated using various waveforms. The results indicate that the sawtooth waveform outperforms the other two waveforms in terms of target detection due to the linear sweep and higher bandwidth. Additionally, a comparison between the real condition simulation and the USRP-based simulation demonstrates the superiority of the latter in terms of accuracy and performance.

REFERENCES

[1] B. R. Mahafza, "Radar systems analysis and design using MATLAB," © 2000 by Chapman Hall/CRC.

[2] A. Wojtkiewicz, J. Misiurewicz, M. Nalecz, K. Jedrzejewski, and K. Kulpa, "Two-dimensional signal processing in FMCW radars," Politechnika Warszawska, Warszawa, 1996.

[3] R. L. Smith, "Micro Synthetic Aperture Radar Using FM/CW Technology," Master's thesis, Brigham Young University, 2002.

[4] A. Prabaswara, A. Munir, and A. B. Suksmono, "GNU Radio Based Software Defined FM-CW Radar for Weather Surveillance Application," in 6th International Conference on Telecommunication Systems, Services, and Applications, 2011.

[5] F. Ali and M. Vossiek, "Detection of Weak Moving Targets Based on 2-D Range-Doppler FM-CW Radar Fourier Processing," Institute of Electrical Information Technology, Clausthal University of Technology, Germany, 2010.

[6] L. K. Patton, "A GNU radio based software defined radar," M.S. thesis, Dept. of Electrical Engineering, Wright State University, 2007.

[7] M. Dillinger, K. Madani, and N. Alonistioti, "Software defined radio: architectures, system and functions," Wiley and Sons, 2003.

[8] S. Aulia, A. B. Suksmono and A. Munir, "Stationary and moving targets detection on FMCW radar using GNU radio-based software defined radio," 2015 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS), Nusa Dua Bali, Indonesia, 2015, pp. 468-473, doi: 10.1109/ISPACS.2015.7432817.

[9] Y. P. Saputera, M. Wahab and Y. Wahyu, "Linear frequency modulation - continuous wave (LFM - CW) radar implementation using GNU radio and USRP," TENCON 2015 - 2015 IEEE Region 10 Conference, Macao, China, 2015, pp. 1-5, doi: 10.1109/TENCON.2015.7373118.

[10] E. J. Amin, A. B. Suksmono and A. Munir, "Accuracy analysis of FM chirp in GNU radio-based FMCW radar for multiple target detection," 2014 International Conference on Computer, Control, Informatics and Its Applications (IC3INA), Bandung, Indonesia, 2014, pp. 115-119, doi: 10.1109/IC3INA.2014.7042611.