PERFORMANCE IMPROVEMENTS WITH PREDISTORTION ON FMCW RADARS

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ABSTRACT

PERFORMANCE IMPROVEMENTS WITH PREDISTORTION ON FMCW RADARS

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This thesis investigates the application of predistortion techniques in Frequency-Modulated Continuous-Wave (FMCW) radar systems, with a primary focus on enhancing range measurement accuracy and overall system performance. The study addresses the challenge of distortions in high-frequency radar designs, often resulting from non-ideal behavior of components, and examines the efficacy of predistortion in compensating for these imperfections.

Initially, the thesis establishes a foundational understanding of FMCW radar operations, their application areas, and the intricacies of their components. It then explores the specific system model utilized for simulations, addressing the selected parameters and their consequences. The core of the research is presented through an analysis of simulation results, where the impacts of distortion and the benefits of predistortion on system performance are thoroughly examined. The study extends beyond theoretical models, incorporating real-world experiments to compare the performance of radar systems using both standard and predistorted signals.

The research is driven by the goal of demonstrating how predistortion can bridge the gap between ideal model assumptions and the realities of component behaviors in radar systems. By integrating theoretical analysis, simulations, and empirical data, the thesis aims to offer a comprehensive insight into the vulnerabilities of FMCW radar systems and the potential improvements achievable through predistortion.

Keywords: FMCW, RADAR, predistortion, VCO, nonlinearities

ÖZ

FMCW RADARLARINDA ÖN BOZULMA İLE PERFORMANS İYİLEŞTİRMELERİ

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Bu tez, Frekans Modüle Edilmiş Sürekli Dalga (FMCW) radar sistemlerindeki ön bozunum (predistortion) tekniklerinin uygulanmasını araştırmaktadır ve özellikle menzil ölçüm doğruluğunu ve genel sistem performansını artırmaya odaklanmaktadır. Tez, yüksek frekanslı radar tasarımlarında, genellikle bileşenlerin ideal olmayan davranışlarından kaynaklanan bozulmaların üstesinden gelme zorluğunu ele almakta ve bu eksiklikleri telafi etmede ön bozunum tekniklerinin etkinliğini incelemektedir.

Başlangıçta, tez FMCW radar işlemlerinin, uygulama alanlarının ve bileşenlerinin karmaşıklıklarının temel bir anlayışını oluşturur. Daha sonra, simülasyonlar için kullanılan belirli sistem modeline ve seçilen parametrelere ve bunların sonuçlarına ilişkin ayrıntılara giriş yapar. Araştırmanın temelini, bozulmanın etkileri ve sistemin performansına ön bozunum uygulamanın faydaları üzerine yapılan simülasyon sonuçlarının analizi oluşturur. Araştırma, teorik modellerin ötesine geçerek, standart ve ön bozunumlu sinyaller kullanılarak radar sistemlerinin gerçek dünya deneyimlerini karşılaştırır.

Araştırmanın amacı, radar sistemlerinde ideal model varsayımları ile bileşen davranışlarının gerçeklikleri arasındaki boşluğu ön bozunum teknikleri ile nasıl köprüleyebileceğini göstermektir. Teorik analiz, simülasyonlar ve deneysel verileri entegre ederek, tez FMCW radar sistemlerinin zayıf yönlerini ve ön bozunum aracılığıyla elde edilebilecek potansiyel iyileştirmeleri kapsamlı bir şekilde sunmayı hedeflemektedir.

Anahtar Kelimeler: FMCW, RADAR, Ön bozulma, VCO, doğrusal olmama

To myself

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LIST OF ABBREVIATIONS

FMCW	Frequency Modulated Continuous Wave
VCO	Voltage Controlled Oscillator
LNA	Low Noise Amplifer
PA	Power Amplifer
FMCW	Frequency Modulated Continuous Wave
FFT	Fast Fourier Transform
DAC	Digital-to-Analog Converter

CHAPTER 1

INTRODUCTION

The initial approach to solving real-life problems in engineering often involves applying ideal models. These models provide a simplified representation of complex systems. However, when the outcomes derived from these models diverge from actual expectations, a reevaluation and modification of the model to better align with real-world conditions is necessary. This process is crucial, as understanding the imperfections and their characteristics enables engineers to reach solutions more effectively. By doing so, expectations and realities can converge more closely. Furthermore, if the nature of the distortion in a system is identified accurately, engineers can employ a technique known as 'pre-distortion.' This involves adjusting the input to counteract the known imperfections and ensuring that the system's output closely resembles the desired ideal response. Such strategies highlight the dynamic and adaptive nature of engineering problem-solving, where theoretical models and practical realities continuously interact to achieve optimal solutions.

In RF design, the behavior of materials and components can vary significantly within the frequency band. Such variations are critical because even minor imperfections can produce substantial differences in the final results. For example, it is shown by Sevinç that the surface roughness of the material used in a cavity filter can alter the filter's characteristics [1]. This aspect might shift the filter's response curve, affecting its effectiveness in filtering specific frequencies. To address this, accurate modeling of these imperfections becomes very important. By incorporating the detailed physical characteristics of materials, including surface roughness, into the design models, engineers can predict these shifts more accurately. This leads to the development of filters whose simulation performance closely aligns with real-world measurement results. This approach shows the importance of detailed and realistic modeling in RF design, ensuring that the manufactured components perform as expected, effectively bridging the gap between theoretical predictions and practical outcomes.

In wide-band systems like Frequency-Modulated Continuous-Wave (FMCW) radars present unique challenges. These radars operate by sweeping across a broad frequency range, involving various components, each with its own specific characteristics. The accurate characterization of these components is crucial for the system's design and overall performance.

An ideal FMCW radar system is presumed to have linear frequency sweep characteristics, linear signal power output, and constant receiver gain response across the operational bandwidth. However, most of the time, these assumptions do not hold true in practical scenarios in the real world. The discrepancies occur due to various factors, such as non-linearities in frequency sweeping, variations in signal power, and fluctuations in receiver gain across the frequency band in the used circuits and components.

Because of these imperfections, it is important to consider these distorted characteristics during the design process of radar systems. Engineers can develop more accurate and reliable radar systems by considering component behavior and system response imperfections. This involves developing a more realistic model of component performance and system dynamics, ensuring that the designed system can work with the complexities of real-world operation. Such an approach improves the accuracy and efficacy of FMCW radar systems, ensuring that they perform optimally under real-world conditions.

1.1 Research Questions and Approach

The primary motivation behind this thesis is to show the benefits of predistortion techniques in real-world Frequency-Modulated Continuous-Wave (FMCW) radar systems. Predistortion, a method that involves intentionally altering the input signal based on the known nonlinear characteristics of the system, aims to compensate for the imperfections in the system's components. By applying predistortion, the overall system performance, particularly the accuracy and reliability of range measurements, can be improved.

One of the key objectives of this research is to identify which components or aspects of the FMCW radar system are most susceptible to distortion and how these vulnerabilities impact system performance. Additionally, this thesis aims to quantify the level of improvement that can be achieved through the application of predistortion. By conducting experimental studies and simulations, the research seeks to provide empirical evidence supporting the effectiveness of predistortion in enhancing the accuracy and reliability of FMCW radar systems. The findings of this study are expected to contribute valuable insights into the optimization of radar systems, highlighting the importance of addressing non-idealities in component behavior for the advancement of high-frequency radar technology.

1.2 Structure of the Thesis

The structure of this thesis is methodically organized into several chapters, each focusing on a distinct aspect of the research to thoroughly explore the application of predistortion in FMCW radar systems.

In Chapter 2, the fundamental operation principles of FMCW radars are detailed, along with their various application areas. This chapter investigates the system components, explaining how each part contributes to the overall functioning of the radar system. It explains various techniques for linearizing VCOs, focusing on predistortion methods. By reviewing previous studies, this chapter sets the context for the current research

The next chapter, Chapter 3, thoroughly describes the chosen system model for simulation. It elaborates on the system parameters, the rationale behind their selection, and the assumptions made to analyze the effects of distortion and predistortion. The results obtained from the simulations are presented. The simulation environment and parameters are explained and presented with simulation results. Different scenarios of VCO nonlinearity and their impact on radar performance are analyzed, demonstrating the potential benefits of predistortion.

In Chapter 4, the experimental validation of the simulation results is presented. It describes the experimental setup and procedures for characterizing the VCO and implementing predistortion techniques. The performance of the radar system with and without predistortion is compared using empirical data. The findings from the experiments are evaluated against the simulation results to verify the effectiveness of predistortion in real-world conditions.

The final chapter summarizes the key findings of the research, discussing the implications for FMCW radar technology. It addresses the limitations of the study and suggests directions for future research. The chapter concludes with final remarks on the significance of predistortion in improving radar performance and the contributions of this thesis to the field.

CHAPTER 2

LITERATURE REVIEW

2.1 Operation of FMCW Radars

Frequency-Modulated Continuous-Wave (FMCW) Radar is a type of radar system that determines the range and relative radial velocity of targets by transmitting continuous wave signals with changing frequency over time. The frequency modulation is typically linear-shaped, increasing or decreasing with time, and called chirp. This signal is transmitted and reflected back from targets. The echo signals are processed in the radar to measure the frequency difference between the transmitted and received signals. They can be implemented using compact and cost-effective hardware for integration into various platforms and used in various applications, ranging from automotive collision avoidance systems to weather monitoring and level measurements in industry to military applications.

A typical application diagram is given in Figure 2.1 [2]. The output of the Voltage Controlled Oscillator (VCO), as a signal generator, is modulated with a chirp signal. The frequency-modulated signal can pass through a power amplifier (PA) before a directional coupler if the required output power is not enough and it is transmitted from the antenna. The transmitted signal is reflected from the target and is captured by the antenna. It passes through a directional coupler; if required, a low-noise amplifier is used after the coupler. A portion of the transmitted signal and received signal are mixed and filtered. The resultant signal is called a beat signal and contains information about the target's distance and velocity in terms of frequency. After filtering and applying FFT to signal range and velocity information can be achieved.

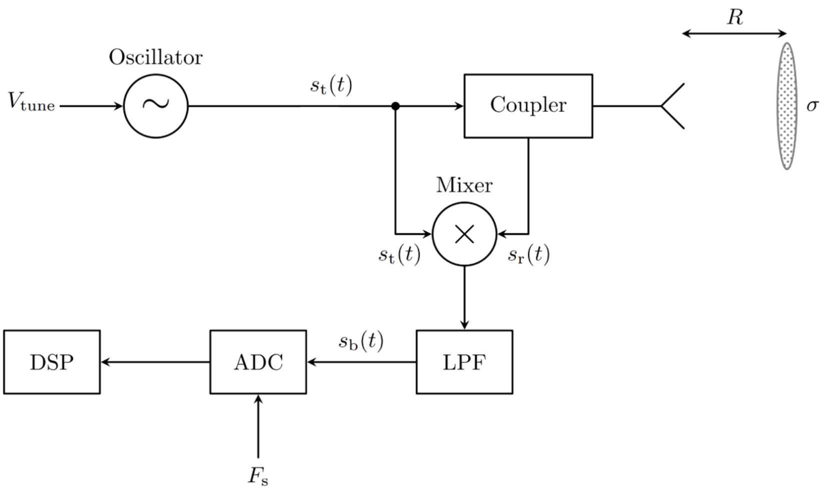

Figure 2.1: A typical FMCW radar block diagram with single antenna

The delay between transmitted and received signals is proportional to the distance of the target. At the same time, delay means there is a frequency difference between these signals. If the chirp has a linear form and monotonically decreases or increases, we can say that the frequency difference is proportional to the distance of the target. In Equation 2.1, the relation is given.

$$t_{delay} = \frac{2R}{c} = \frac{f_{beat}}{chirp\ slope} \tag{2.1}$$

Typically, chirp has a sawtooth or triangular waveform that meets the requirements of radar. If the target is stationary and the chirp is linearly modulated, the frequency difference found in the end will be proportional to the target's distance. In Figure 2.2, sawtooth modulation is given as an example. If we adjust Equation 2.1 for distance, we will have Equation 2.2.

$$R = \frac{cT_{sweep}f_{beat}}{2B} \tag{2.2}$$

The measured distance is expressed in terms of four variables. If we consider the speed of light and sweep time to be constant, it only depends on bandwidth and beat frequency. The bandwidth of modulation should be chosen carefully. It is an important design parameter for determining the range resolution of the radar. For each sweep, the signal is sampled for sweep time duration. This time determines the fre-

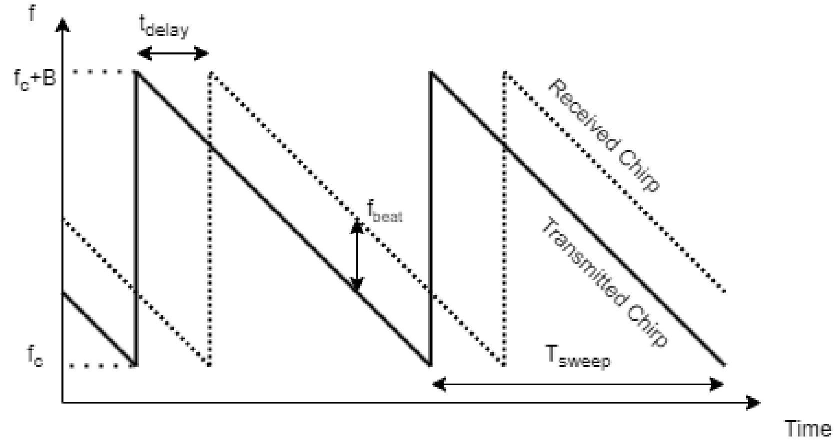

Figure 2.2: Sawtooth modulated chirp

quency resolution of the FFT operation. If the frequency resolution , $\frac{1}{T_{sweep}}$, is used as resolution of f_{beat} and insert in Equation 2.2, the Equation 2.3 is reached as range resolution of the radar. Range resolution only depends on the bandwidth of the radar. Changing sweep time also changes beat frequency and frequency resolution but the terms cancel each other.

$$\Delta R = \frac{c}{2.Bandwidth} \tag{2.3}$$

The Doppler effect will affect the operation for detecting a moving target with FMCW radar. The delay between the received and transmitted signal shifted the chirp along the time axis. The Doppler effect will shift the chirp along the frequency axis. The shift amount depends on the instantaneous carrier frequency and relative radial velocity of the target with the radar. It is expressed as in Equation 2.4. The sign of the shift depends on the target's direction of relative radial motion to the radar.

$$f_d = \frac{2\Delta v f_c}{c} \tag{2.4}$$

2.1.1 FFT and Target Detection

Various techniques can be used to retrieve frequency information to estimate the range of the target from an intermediate frequency (IF) signal. Fast Fourier Transform (FFT) is a widely used method in FMCW radars. It is an efficient way of Discrete Fourier Transform(DFT) that reduces the number of necessary arithmetic operations and reduces computation time. The popular radix-2 FFT algorithm reduces the number of complex multiplications to $\frac{N}{2}log_2N$ compared to N^2 in N point DFT [3].

From time-domain methods, the zero crossing technique can determine the frequency by measuring time intervals of transitions to zero but has low accuracy and strongly depends on the signal's harmonics and noise [4]. There are also some hybrid methods such as DFT with zero crossing technique.

The most common method for detecting a target with FFT is peak detection, in which the frequency component with the highest amplitude is considered the target. When targets are not apart from each other, targets with different reflectivity can result in false alarms. It is better to use it in high SNR with distant targets. Estimating frequencies of targets between peak frequency bins and their neighbor bins can be utilized in different interpolation methods or weighing-based estimation techniques, enhancing detection accuracy [5].

Another method is threshold detection. This method uses a constant or adaptive threshold level for each frequency bin to detect the target. This way enables the system to be more resilient to false alarms but reduces the accuracy. Because of spectral leakages, neighboring frequency bins corresponding to the target frequency bin pass the threshold, which makes it difficult to determine the exact distance.

2.1.2 Linear Sweep

Linearity of the chirp is one of the main challenges to achieving high-accuracy FMCW radar. However, in practice, the nonlinear behavior of the amplifiers, mixers, and VCOs, along with harmonic and intermodulation distortions, could affect system performance. In the scope of this thesis, only nonlinearities in frequency sweep will be discussed.

Linearly swept sawtooth modulated radar will detect a single frequency as a target. When the sweep is not linear the change in the slope of the chirp will result in changing frequency in the beat signal. An exaggerated example is given in Figure 2.3. Deviation in the slope causes spectral spread in the beat frequency.

There are various linearity concepts defined in the literature. One of them is to address frequency deviation with respect to bandwidth [6]. This approach of Wang can carry valuable information about beat frequency characteristics. As in Wang's case, distortion in the source's linearity both results in slope variation and change in the frequency band. The nonlinear characteristics can affect both beat frequency and range resolution. However, this definition does not always correlate with performance degradation. When the whole swept frequency band shifted from the desired band as a constant offset, this definition defines this shift as a distortion in linearity, but this situation may not affect the measurements if the slope remains constant. Another meaningful definition for linearity is Fractional Slope variation (FSV) of Brennan [7]. Brennan defines linearity as frequency deviation with respect to the mean sweep rate.

$$FSV = \frac{\Delta f' T}{B} \tag{2.5}$$

The sweep rate is constant for a perfectly linear chirp as B/T_{sweep}. When there is a significant chirp nonlinearity, the beat frequency will be a time-variant over the sweep duration. The frequency spread around f_{beat} can be expressed as follows:

$$\Delta f_{beat} = \frac{2BR(FSV)}{cT_{sweep}} \tag{2.6}$$

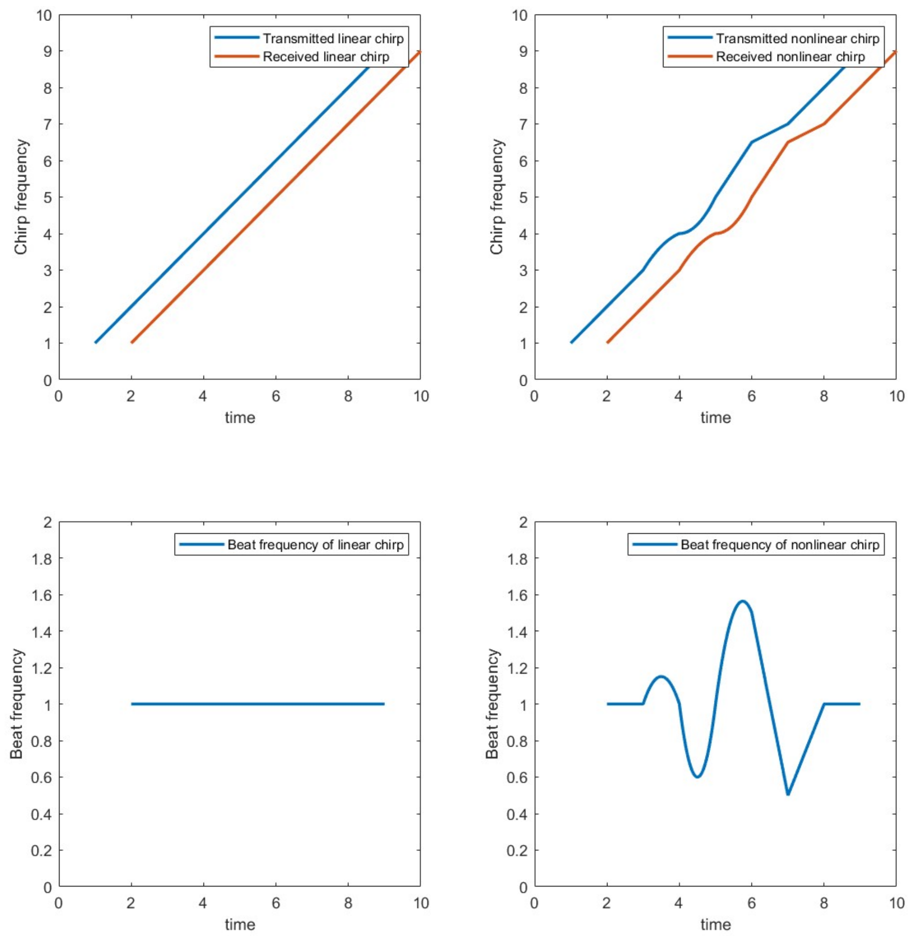

Figure 2.3: Linear and nonlinear modulated chirps

FSV expression can be used to determine the system's linearity requirements [7]. Brennan defines frequency tolerance of the system in terms of frequency resolution and a constant *a* and Equation 2.6 simplifies to Equation 2.7. In this equation, *a* represents the maximum tolerated range resolution error for a given range for a square law source nonlinearity model.

$$FSV = \frac{ac}{2BR} = \frac{a\Delta R}{R} \tag{2.7}$$

2.1.3 Applications in Radar Systems

FMCW radars have diverse and critical applications across various fields. They can provide precise range and velocity measurements.

In the automotive industry, they enhance vehicle safety and can be used in advanced driver assistance systems. Adaptive cruise control systems measure drivers to maintain a safe following distance. Collision avoidance systems and blind spot detection systems help drivers by alerting and sometimes automatically applying brakes to avoid collisions. [8]

In industrial automation, FMCW radars can be used to detect and navigate obstacles to navigate automated machinery for safe and efficient operations. In tanks and silos, it can be used for measuring levels of liquids and solids for process control.

Drones can benefit from FMCW radars to follow the terrain and navigation by maintaining a constant altitude above ground. It can track moving targets, making them valuable surveillance tools and search and rescue operations. Missiles can benefit from it by detonating before impact to increase its effectiveness.

They can be used for medical applications such as monitoring vital signs such as heart rate and respiration without physical contact.

Their ability to provide precise and reliable range and velocity measurements makes them valuable tools for wider application areas as technology advances further.

2.2 Voltage Controlled Oscillators

As their name says, voltage-controlled oscillators(VCOs) are oscillators whose output signal can be controlled by their control voltage signal. Changing its oscillation frequency from voltage input enables it to be used for frequency modulation in many systems. However, its theory of operation introduces many nonlinearities in practice.

These oscillators can operate almost linearly in narrow bands, but their sensitivity and rate of oscillation frequency change per voltage changes over the operation bandwidth. If they are used in low fractional bandwidth, the nonlinear characteristics will affect system performance minimally. However, when they are used in wider bands and near the edges of VCO's operational bandwidth, sensitivity changes become observable in the output and as a decrease in system performance. Designed frequency modulation is disrupted if this characteristic is not considered. If we consider linear FMCW (LFMCW) radar, radar frequency is swept linearly, and frequency change over time is constant. We can quickly deduct the range information of a single target from the frequency components of transmitted and received signals. When the sweep rate is not constant and changes over time, beat frequency also changes during sweep time. Its spectrum is spread, and the signal loses its power to adjacent bins. This effect decreases SNR values and can result in false detection depending on the deduction algorithm. There are other non-idealities in VCOs that can impact radar performance. They are discussed in the following paragraphs.

One of the critical non-idealities in VCOs is phase noise. In an ideal oscillator, all signal power is at a single frequency because the output signal has a single-tone pure sinusoidal waveform. Phase noise is due to random fluctuations in the phase of the oscillator and results in the spread of the signal's power around oscillation frequency. Its effects are mainly observed at lower offset frequencies from carrier frequency. The significant cancellation of phase noise in the IF signal at low offset frequencies can be explained intuitively. For short distances, the round-trip delay of the received signal is negligible compared to the periods of low-frequency noise components. This means that low-frequency noise components in the LO signal are strongly correlated to those in the received signal. Eventually, low-frequency noise components in the IF signal are canceled [9]. When sweep rates are low, resultant beat frequencies for the range are lower, and phase noise can be a problem since its components are in the region of interest of frequencies. If we use shorter sweep times or higher sweep rates, expected beat frequencies will be higher, and noise around carrier frequency will remain in the same region. This noise is separated from our area of interest. To analyze predistortion performance, we focus on faster sweep rates in this research to avoid other non-idealities like phase noise.

During the operation of VCO, the ambient temperature or chip temperature can change. The circuit can be heated up, or the operation temperature of the system can be excessive. The oscillation frequency of an open loop working VCO can be subject to drift due to temperature changes. This phenomenon can cause a shift in the overall frequency band. This change can be about MHz/°C region. This drift mainly affects the operation frequency band, but the width of the band does not change much, which is more important than an overall shift of the frequency band. Since the evaluation of distance information from FMCW radar is made for each sweep, shorter sweep duration and higher sweep rates can help us to reduce frequency drift during a sweep due to the heating up of the circuit. While initiating the radar, the temperature of the VCO can change fast in the very first seconds. Waiting until temperature stability is reached or the changes in the frequency become negligible helps us to get healthy measurements. Choosing low sweep rates can affect operation bandwidth and, if the delay is significant, beat frequency, too. For analyzing predistortion performance, we choose faster sweep rates again and wait for the circuit to reach a more stable thermal region in this research.

Due to manufacturing differences and tolerances, same-model VCOs can differ in frequency characteristics. In some high-performance designs, a calibration for each radar can be required. If the design has lower performance requirements or other limitations in accuracy and resolution, a calibration for a batch can be used.

One oscillator generates both transmit and local oscillator signals in a single antenna design. It has many advantages since it is easy to implement and has a low cost. However, imperfect isolation between RF and LO signals results in DC offset in the mixer IF output and can saturate the signal in the following analog circuit. To overcome this problem, there are some solutions that use two separate VCOs. This method is mostly used again with a DDS-referenced PLL system to overcome the uncorrelation of different VCOs and achieve a highly linear chirp [10].

2.3 FMCW VCO Linearization Techniques

One of the most common techniques is the closed-loop feedback technique, which uses a reference delay line close to the target range. For a TEM delay line in a linear FM, the phase of the delayed line is a linear function of time. Using this delay line can provide dynamic calibration for system [11]. A system using this method can benefit from part to part to variations and changing environmental conditions. However, this method needs a complex design and a space for delay lines. This technique can also be prone to instabilities, and its bandwidth can be limited [12]. In a compact and mobile design, this method may not be applicable.

Another method uses PLL(Phase-locked-Loop) with DDS(direct digital synthesis) frequency reference [13] [14]. In this method, the phase of free-running VCO is compared with the reference signal phase. The error signal from this comparison is fed to the loop filter, which adjusts the frequency of VCO. A frequency divider feeds The VCO output frequency to the phase detector. This closed-loop locks the VCO frequency to an adjusted frequency. DDS is a technique for generating analog signals, typically sine waves. Its frequency can be tuned digitally fast and in high resolution. When the frequency reference DDS is used, VCO can lock the DDS output frequency and sweep it by digitally controlling the DDS. Figure 2.4 gives a complex PLL architecture for 77 GHz FMCW radar [15]. This approach is used to have better linearity in high-range and high-resolution applications.

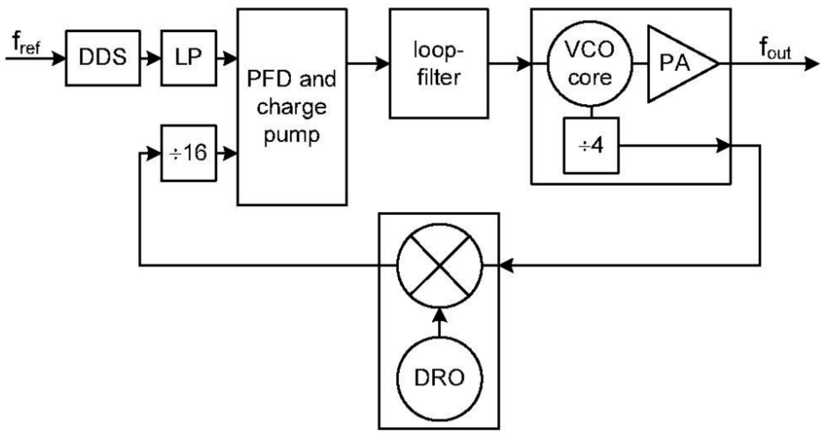

Figure 2.4: PLL architecture for 77GHZ FMCW Radar

A third method is measuring the nonlinearity of the VCO and adjusting the tune signal with this measurement to have a linear frequency response in the output [16]. Free-running VCO can be controlled with this predistorted nonlinear tune voltage. It is a simple technique that does not affect system complexity and cost.

This predistortion method can be beneficial in short ranges and fast FMCW applications compared to close-loop structures since this method does not add bandwidth limitations and phase noise to the system. In the scope of this thesis, these open loop predistorted signals are used and evaluated in performance in short-range fast FMCW radar [17].

A nonlinear chirp can also be used for FMCW operation. It can be used to decrease side-lobe levels, increase SNR, and for electronic counter-countermeasures. It is not preferred since it is hard to design, produce, and process in the radar [18]. Increasing the sweep rate near the ends of the transmitted pulse and decreasing it near the center can lower the side lobes of the response. Similarly, when the sweep slope is made to vary inversely with the square root of the Hamming function, it produces a response of approximating Hamming-weighted linear chirp but without matching loss [19]. If the side-lobe suppression is crucial for the design, using nonlinear waveform provides an advantage over linear waveform [20].

2.4 Predistortion

The term predistortion is a technique for mitigating nonlinearities by controlling input signals. Predistortion mechanisms are widely used for RF power amplifiers in which the nonlinear gain response of the amplifier is dealt with by predistortion applied to the amplitude of the input signal. This allows it to run at its maximum output power while performing in the wideband operation [21]. A similar nonlinear relationship can be observed between the tuning voltage and output frequency of VCOs. The predistortion technique for this characteristic involves preprocessing input tune signal to counteract this characteristic. The input tune signal is shaped to compensate for VCO's nonlinear characteristics. The resultant frequency output can be made more linear. This reduces the distortion in the modulated signal and enhances the radar's performance.

2.4.1 Impact of Predistortion/Distortion on System Performance

The nonlinear response of VCO results in deviations in the chirp rate of chirps in FMCW radars. Since the measurements are a function of this chirp rate, the frequency of the beat signal will distort and spread. The expected SNR will decrease, range resolution will degrade, and the error rate will be higher than the ideal case[12].

When predistortion is applied to tune the signal accordingly, it is expected to increase SNR and decrease measurement errors. The success of predistortion can be evaluated by comparing ideal cases and distorted cases.

2.4.2 Mathematical Model of Predistortion

The predistortion method can be mathematically modeled with VCO's transfer function. Let V_{tune} be the input tune voltage and f_{out} be the output frequency. The nonlinear relation can be expressed as:

$$f_{out} = F(V_{tune}) \tag{2.8}$$

Where F is a nonlinear function representing the VCO's characteristics. Predistortion aims to find a function P such that:

$$V'_{tune} = P(V_{tune}) \tag{2.9}$$

and

$$f_{out} = F(P(V_{tune})) = a.V_{tune} + b \tag{2.10}$$

where a and b are constants, ensuring that the output frequency f_{out} varies linearly with input voltage V_{tune} in the region of operation.

2.4.3 Implementation of Predistortion

Implementing predistortion involves designing a predistorter circuit or algorithm to generate the required predistorted signal. This can be achieved through various techniques such as polynomial predistortion, look-up tables, or adaptive algorithms [22].

Polynomial predistortion uses a polynomial function to approximate the inverse of the nonlinear characteristic of the system. The coefficients of the polynomial are determined through calibration.

Look-up tables store precalculated values of the predistorted signal corresponding to each input control signal. This type of predistortion is usually used in the baseband signal for achieving constant signal amplitude at the output of the power amplifiers [23]. This method can be used to linearize VCO output frequency while sweeping. It can offer high accuracy but requires significant memory.

Adaptive predistortion algorithms continuously adjust the predistortion function in real time to account for changes in the VCO's behavior due to temperature variations or aging. For calibration processes, iterative approaches can be used to estimate predistortion function [22].

2.4.3.1 Future Trends and Challenges

Future advancements can benefit more sophisticated adaptive predistortion algorithms. These algorithms can dynamically adjust predistortion to varying conditions in real-time. These systems can use live data from other sensors, and with this live feedback, optimal performance conditions can be reached under varying operational conditions.

Enhanced calibration techniques can be used to achieve higher precision and with reduced complexity. Calibrations can be automated in the mass production of radars with more advanced systems similar to R&S®FSPN Phase Noise Analyzer and VCO tester [24]. These kinds of devices enable designers to characterize VCOs easily. As technology advances, these kinds of complex measuring devices become more affordable and can find wide usage areas in terms of calibrating. For more complex systems, self-calibrating mechanisms can be designed, which can be beneficial in overcoming the problem of periodic recalibration.

In the next chapter, model based evaluation of distortions and predistortions will be presented to evaluate their effects on the performance.

CHAPTER 3

MODEL-BASED EVALUATION OF DISTORTIONS AND PREDISTORTIONS

In this chapter, a MATLAB simulation environment is created to examine the impact of distortion in the VCO tune signal and possible predistortion applied to its nonlinear frequency modulation on the performance of an FMCW Radar system in terms of spectral purity and target detection accuracy. The model focuses on distortion in VCO frequency sweep. Most parameters for simulation and radar are chosen accordingly to show this effect and ease the comparison with the ideal model. To simulate and evaluate different sweeps on a single target, the transmitted waveform is delayed for different distances, and the delayed signal is multiplied by the transmitted signal. The resultant signal sampled and beat frequency spectrum is achieved with the FFT of this signal. Different scenarios are simulated for evaluation along with a perfectly linear FMCW signal.

To better analyze and compare with experimental results, FMCW radar parameters are chosen as in Table 3.1 unless stated otherwise.

For the detection algorithm of a single target, peak detection is used, which means that the bin with the highest amplitude in the spectrum represents the target. The peak levels and the location of the peak are compared with the ideal case for different scenarios.

As will be seen distortion decreases the spectral purity and spreads the received power to multiple bins. The signal level of the target decreases, and as a result, the selectivity of the target position decreases, making the system more prone to error under the effects of noise and interference. When the peak location is not at the expected

Table 3.1: Default FMCW radar parameters for simulation and experiments

Parameters	Values
Sweep Bandwidth	300 MHz
Sweep Duration	128 us
Carrier frequency	4 GHz
Chirp type	Falling sawtooth
Frequency resolution	7.812 kHz
Range resolution	0.5 m
Sampling rate	2 MSps
FFT points	256
Windowing	Hann

ideal position, the result is indeed a wrong determination of the target range, which decreases target detection accuracy.

This comparison will demonstrate that performance decreased due to distortion; by using predistortion, the degradation of performance will be recovered, and its reliability will be increased under noise and interference.

3.1 Simulation Objectives

The primary objective of this MATLAB simulation is to quantitatively assess the impact of distortion in the VCO tune signal on the performance of an FMCW radar system, specifically regarding its spectral purity and target detection accuracy. This simulation is designed to compare two scenarios:

Scenario 1 - Perfectly Linear VCO Tune Signal: In this baseline scenario, the radar system employs a VCO tune signal that is perfectly linear, devoid of any non-linear distortions. This scenario serves as a control to benchmark the ideal performance metrics of the radar system, providing a clear understanding of the system's capabilities in an idealized setting.

Scenario 2 - Distorted VCO Tune Signal: This scenario introduces a predetermined level of distortion into the VCO tune signal, mirroring practical non-linearities that may occur due to manufacturing variances, temperature fluctuations, or other factors. The focus is to determine the level of distortion at which the performance degradation becomes significant, specifically leading to a one-bin error in the radar's target detection algorithm.

Both scenarios will utilize a Hann window function in the signal processing stage to minimize spectral leakage and improve the resolution of the spectral analysis. A peak-based detection algorithm will be employed to identify targets within the radar's range, directly comparing detection accuracy between the two scenarios.

The simulation will carefully monitor and compare several key performance metrics across these scenarios, including spectral spread and target detection accuracy. By maintaining all other potential non-idealities at their ideal states, the simulation aims to isolate and understand the specific impact of VCO tune signal distortion. The outcome of this simulation is expected to provide valuable insights into the level of VCO frequency sweep distortion that can be tolerated before adversely affecting the radar system's performance.This will guide the development of more robust radar systems, where predistortion techniques or other compensation mechanisms can be designed to mitigate these effects, ensuring reliable and accurate target detection even under non-ideal VCO conditions.

Real-world experiments to study the impact of VCO frequency sweep distortion on FMCW radar performance have many challenges. Physical setups introduce numerous uncontrollable variables, such as environmental noise, temperature fluctuations, and component variability. These factors can make it difficult to clearly identify the specific effects of VCO tune signal distortion. A MATLAB simulation, by contrast, allows for a controlled environment where these variables can be held constant or entirely eliminated, providing a clear view of how distortion impacts radar system performance.

By simulating different distortion levels in the VCO tune signal, the study aims to identify the level at which distortion begins to significantly degrade the radar's spectral purity and target detection accuracy. This understanding is crucial for the design and calibration of radar systems, enabling engineers to specify tolerance levels for VCO non-linearity based on the data. Discussions of the results are detailed in the conclusion section.

The simulation also seeks to explore the efficacy of predistortion in mitigating the adverse effects of VCO tune signal distortion. By applying predistortion and comparing the performance metrics with those of the undistorted and distorted scenarios, the study can provide concrete evidence of predistortion's potential to enhance radar system performance. This is particularly relevant in the context of developing more resilient radar systems that can maintain high levels of accuracy and reliability despite inherent non-linearities in their components.

3.2 Theoretical Background on Nonlinearities in VCOs

3.2.1 Presence of Nonidealities in VCOs

Voltage-Controlled Oscillators (VCOs) are pivotal components in Frequency-Modulated Continuous-Wave (FMCW) radar systems, generating the signals that are essential for radar operation. The ideal behavior of a VCO is a linear relationship between the input control voltage (Tune voltage) and the output frequency. However, VCOs exhibit nonlinear response characteristics in practice due to various factors such as component limitations and oscillator topology. These nonlinearities can be described as deviations from the expected linear frequency-tune relationship, where the output frequency does not change proportionally with the input voltage level. Such nonlinearities can lead to harmonic distortion, phase noise, and frequency instability, which are critical parameters in the performance of radar systems. Specific effects on FMCW radars are demonstrated in the simulations.

In order to include nonlinearities in the simulations, an analytical model is required. The nonlinear response of a VCO can typically be represented by a polynomial equation where higher-order terms describe the deviation from linearity.

3.2.2 Detrimental Effects on Radar System Performance

The presence of nonlinearities in VCOs can have several detrimental effects on the performance of radar systems, particularly FMCW radars, which rely on precise frequency modulations for range and velocity measurements. Nonlinearities can lead to the generation of undesired spectral components such as harmonics and intermodulation products. This spectral impurity can mask or distort the radar return signal, complicating the process of target detection and identification. FMCW radar systems determine the distance and speed of targets by analyzing the frequency difference between the transmitted and received signals. Nonlinear frequency modulation causes inaccuracies in this frequency difference, leading to errors in range and velocity measurements. Nonlinearities contribute to phase noise, which is the rapid, short-term, random fluctuations in the phase of the waveform. In sweeps with high sweep rates, these phase noises affect resultant IF frequency measurements in negligible amounts. To compensate for VCO nonlinearities, radar systems may require complex calibration procedures, increasing system complexity and reducing operational flexibility. Calibration must often be performed across different operating conditions to account for the non-static nature of the nonlinearity.

Given these effects, it is clear that nonlinearities in VCOs can significantly impact the accuracy, reliability, and efficiency of radar systems. Addressing these nonlinearities, either through hardware design improvements, signal processing techniques, or predistortion methods, is critical for enhancing radar performance. The theoretical understanding of these nonlinear effects forms the basis for developing effective strategies to mitigate their impact, ensuring that radar systems can operate with the precision required for their intended applications. In conclusion, the nonlinearity of VCOs presents a complex challenge that directly influences the operational capabilities of radar systems. A thorough comprehension of these nonlinear dynamics is essential for advancing radar technology, highlighting the importance of the study in contributing to this field.

3.2.3 Principle of Predistortion

Predistortion involves intentionally applying an inverse distortion to the input signal of a nonlinear system to counteract the system's inherent nonlinearities. The core idea is to "pre-distort" the signal so that the output closely approximates the desired linear response when it passes through the nonlinear system (in this case, a VCO). Predistortion aims to cancel out the nonlinearity effects, resulting in an output that aligns more closely with the ideal performance characteristics of the system.

3.2.4 Characterizing VCO linearity

The nonlinear response of VCOs can often be modeled accurately by polynomial functions, where each term represents a different aspect of the nonlinearity. A polynomial predistortion function, by mirroring this structure, can effectively counteract these specific nonlinear characteristics. Polynomial functions offer considerable flexibility, as adjusting the coefficients and the order of the polynomial allows for fine-tuning the predistortion to match the specific nonlinear response of the VCO. This adjustability is crucial for accommodating variations in VCO behavior due to manufacturing differences or environmental conditions. Polynomial functions are well-understood mathematically, allowing for easier analysis and simulation of the predistortion effects. This facilitates the design and optimization of the predistortion parameters before implementation in the actual radar system.

When commercially available VCOs are investigated, most of them have a monotonically increasing VCO frequency vs tune voltage characteristics. Sensitivity curves decrease monotonically with tune voltage, and the sensitivity slope decreases as well. According to these characteristics, a minimum third-order polynomial is required to characterize VCO and evaluate its performance according to this approach. If we suggest an equation with third-order polynomial terms for characterizing nonlinearities in the frequency characteristics and it is given in Equation 3.1.

$$f_m(t) = \frac{B}{T_{sweep}} \frac{\frac{c_3 t^3}{T_{sweep}^2} + \frac{c_2 t^2}{T_{sweep}} + c_1 t}{c_3 + c_2 + c_1} \tag{3.1}$$

In the equation above, f_m represents modulation frequency as a function of time. The first term $\frac{B}{T_{sweep}}$ is the ideal sweep rate of the linear sawtooth modulated FMCW. The expression drops to this ideal sweep rate when c_3 and c_2 are zero. When the function is investigated between times 0 to $\frac{B}{T_{sweep}}$, swept frequency in the edges remains constant as desired bandwidth. This allows us to investigate only the change rate of the sweep on the performance without changing the range resolution in the radar.

Brennan defined the nonlinearity term by a constant change in the slope, corresponding to the expression's coefficient of the order term c_2. If we use the third-order term with the FSV definition, the expression given in Equation 3.2 is reached. This time, FSV is a function of time and polynomial coefficient.

$$\Delta f_{beat}(t) = \frac{2R}{c} \frac{B}{T_{sweep}} \frac{\frac{c_3 t^3}{T_{sweep}^2} + \frac{c_2 t^2}{T_{sweep}} + c_1 t}{c_3 + c_2 + c_1} \tag{3.2}$$

3.3 Simulation Environment and Parameters

For the simulation environment, the MATLAB 2023b version is used.

For FM type, linear sawtooth modulation is generally chosen for easiness of implementation; therefore, this modulation scheme is preferred in the simulation. It helps us to understand distortion effects in the modulation of the performance. Types of sawtooth modulation, falling and rising, are also examined. The effects are observed to be the same. Separate results are not included in this thesis document. In the simulations, radar and target are assumed to be stationary, which eliminated Doppler effects. In the presence of the Doppler effect, rising and falling edges may have different results as a function of relative speed.

While simulating VCO characteristics and predistortion, 3rd-order polynomials are used, and the polynomial coefficients are chosen in such a way that the overall bandwidth remains the same. This isolates simulation results from possible range resolution alteration. Most of the commercially available VCOs have sensitivity characteristics that are monotonically increasing or monotonically decreasing. The segment used for VCO's frequency vs. tune voltage characteristics can be fitted to a polynomial.

Even if the inverse of a polynomial is not a polynomial, the very close polynomial function can be fitted for the inverse of it in an interval. Sensitivity characteristics can help us to choose a 3rd-order polynomial that is sufficient for approximation. Use of this inverse polynomial can help us reach a more linear sweep form for FMCW. The effect of distortion is examined by parametric analysis of polynomial coefficients.

Hann window is used for windowing and suppressing side lobes. The use of windowing for various purposes is common. Other types of windowing can be applied. Our practical experience implies that the effect on the examined performance will be negligible.

Changing carrier frequency is examined while keeping the bandwidth and other parameters constant. Because the changes in the results are insignificant, details are not included.

Range resolution is a function of the bandwidth used in the equation. Changing range resolution is examined by changing swept bandwidth.

3.4 Simulations and Results

3.4.1 Examined Nonlinear Behaviour

Different types of distortions can be achieved depending on the coefficients of the polynomials. The coefficient values are selected to represent different sensitivity profiles. For all simulations $c_1 = 1$, since the ratio of other coefficients to c_1 is important and the sweep is normalized to have the same bandwidth. The first one is to represent most of the commercial VCOs that have decreasing sensitivity with increasing frequency. Its coefficients are determined as $c_3 = 0.2$ and $c_2 = -0.6$. The second one has opposite characteristics, increasing sensitivity with increasing frequency. Its coefficients are determined as $c_3 = 0.4$ and $c_2 = 0.6$.

In both cases, their slope passes through the sweep rate of the ideal VCO in the middle portion of the sweep since the average slope of all simulations is kept constant to keep the bandwidth and range resolution the same. Otherwise, a shift in the average sweep rate will result in a shift in the spectrum. Keeping the bandwidth constant will help show the effects of the nonlinear sweep without changing the range resolution of the radar.

The third one is the hybrid form of the first two. An inflection point is in the middle part of the sweep and passes through the average sweep rate twice. The coefficients are determined as $c_3 = -1$ and $c_2 = 1.5$.

Figure 3.1 shows three nonlinear sweeps with different sensitivity profiles with increasing(red), decreasing(pink), and alternating(blue) slopes. Their sweep rates are shown in Figure3.2. In both Figures, the ideal sweep is demonstrated with a black line.

The examples of spectrum[1] of three sweeps are given in Figures 3.3, 3.4, 3.5. In the first two cases, peak shift occurs to lower distances, and spectrum spread is at similar levels. As increasing distance the error will become larger, starting from 0.5m error at 4m error to 2m at 16m, which corresponds to about 12.5% fractional error on the measured distance. In the third Figure, the amount of error is similar, even though the spectral spread looks smaller. However, the shape of the distortion and shift direction are different from the other two distortions. This is due to different frequency sweep rate shapes during the sweep.

[1] In spectrum figures of nonlinear sweep responses, false detection is shown with a red bar along with a yellow bar at the correct distance. When detection is at a correct distance, it is shown with a green bar.

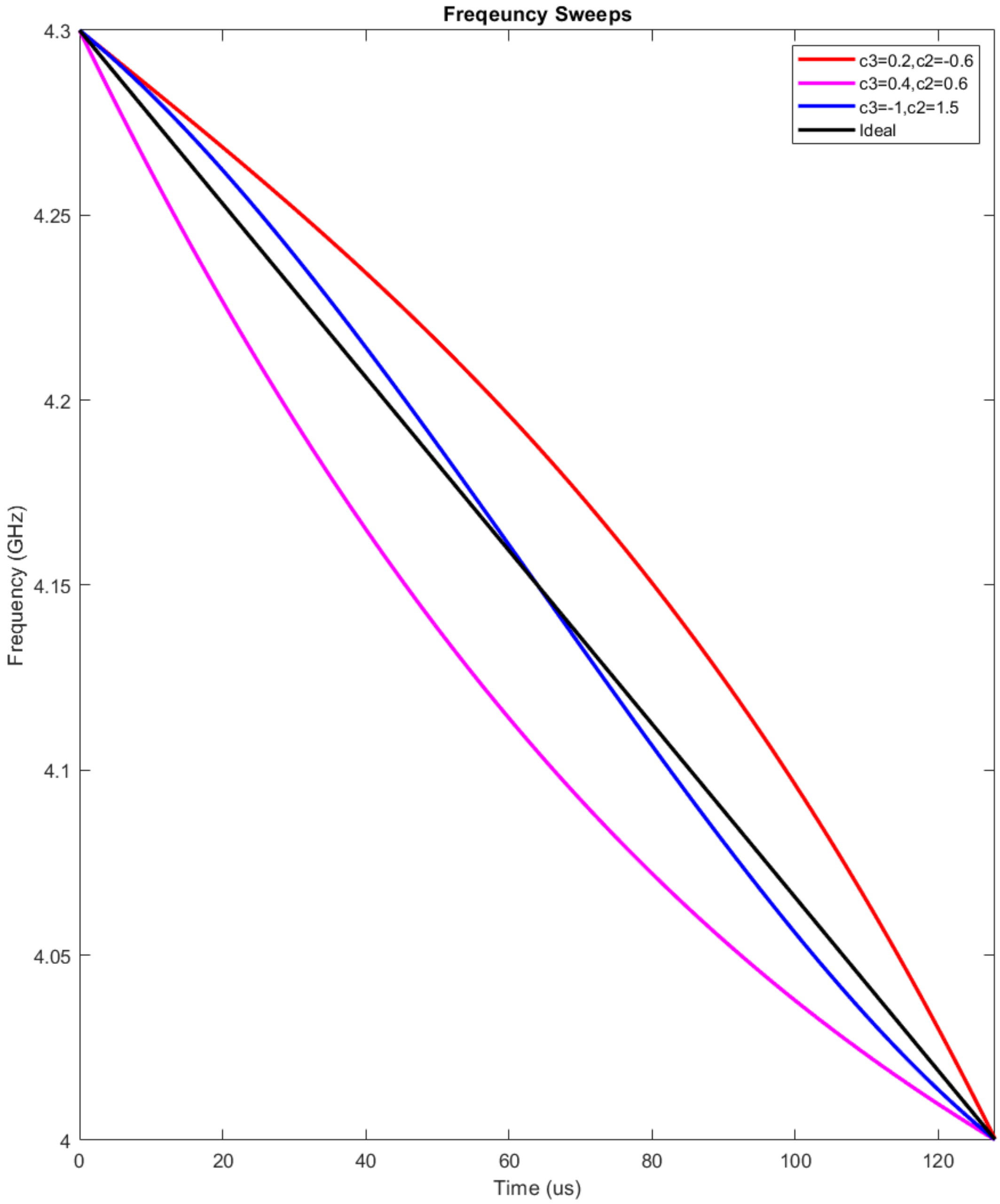

Figure 3.1: Different sweeps with polynomial coefficients: decreasing(red), increasing(pink), alternating(blue), ideal(black) sweep rates

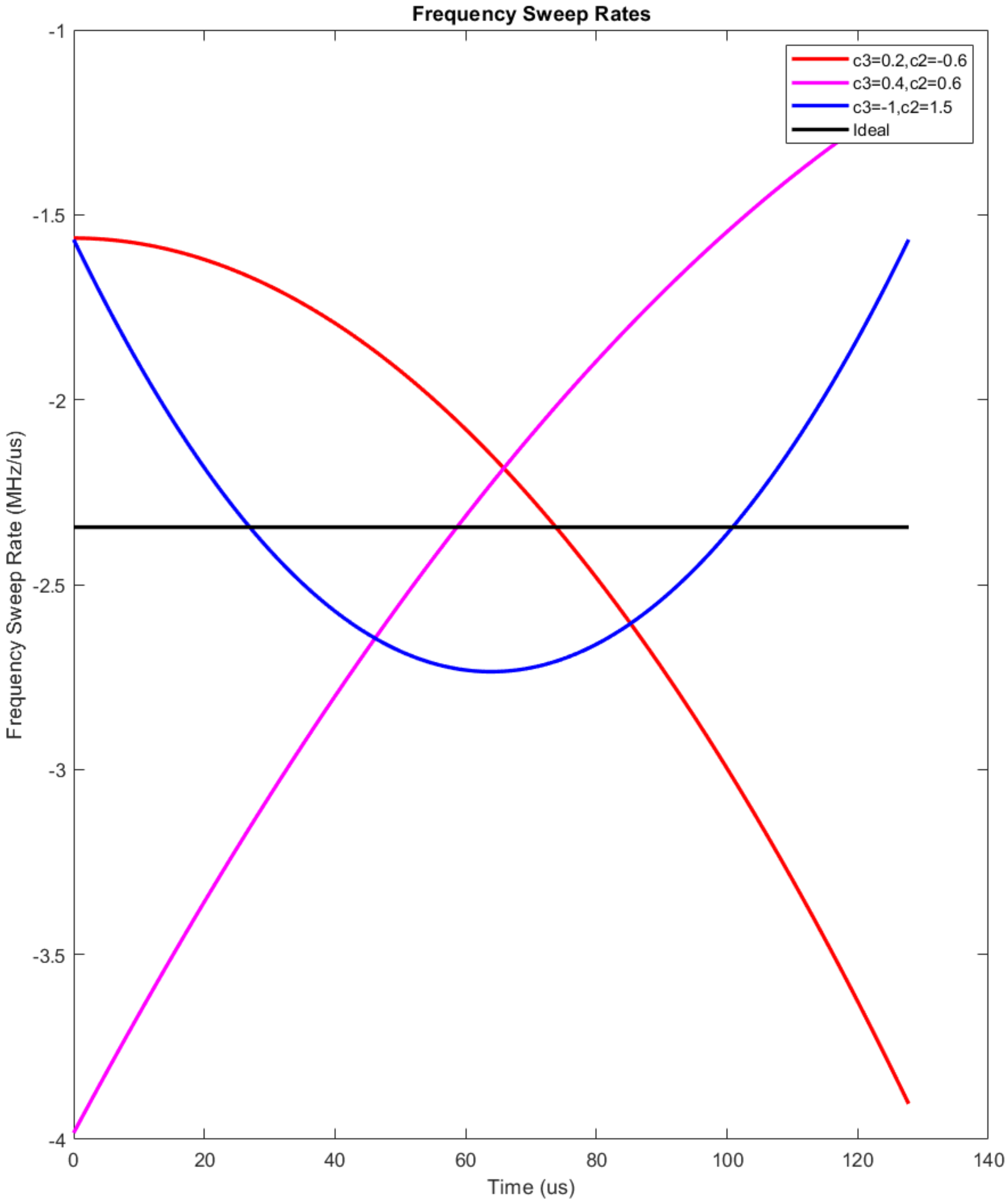

Figure 3.2: Sweep rates of different sweeps, decreasing(red), increasing(pink), alternating(blue), ideal(black) sweep rates

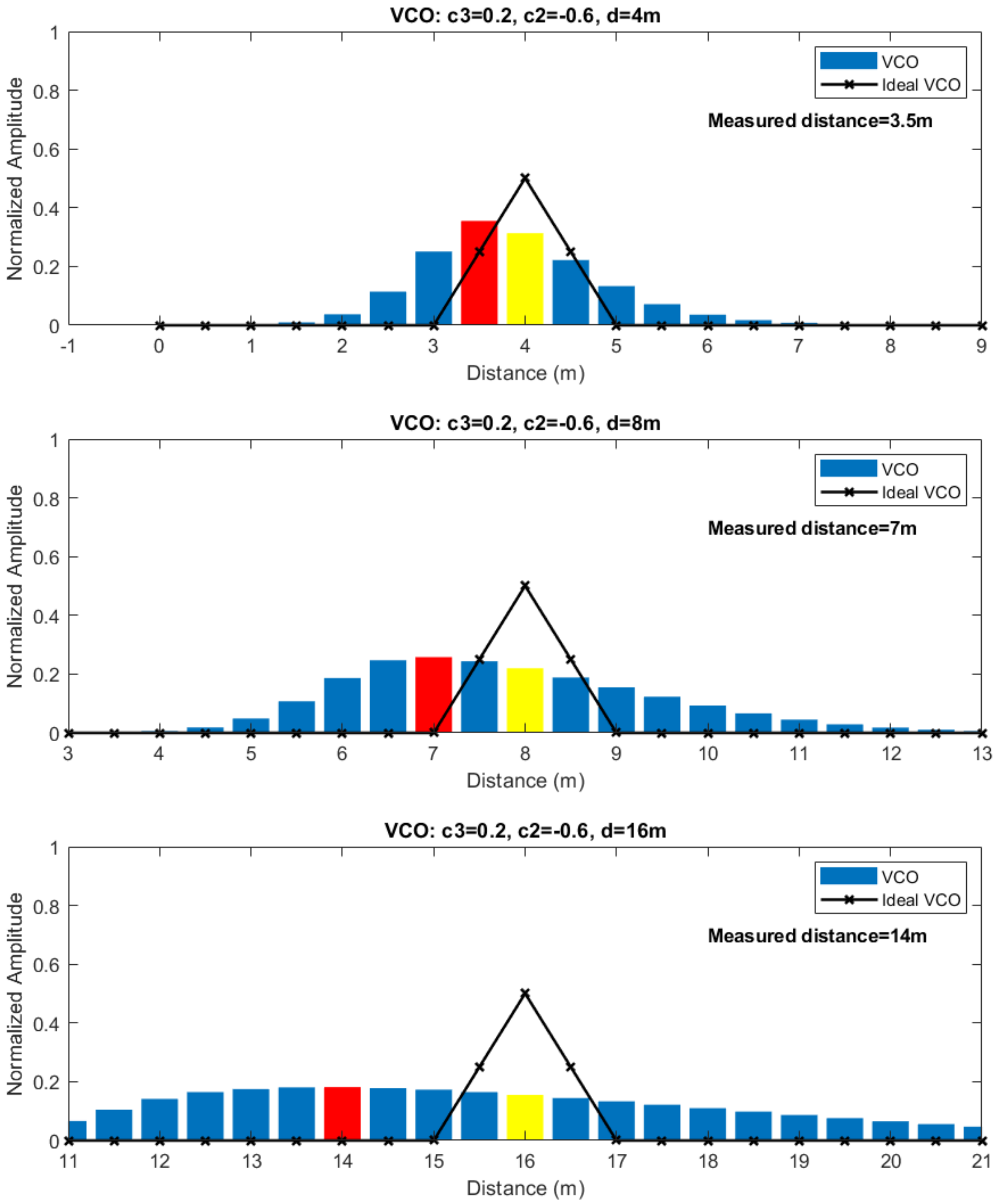

Figure 3.3: $c_3 = 0.2$ and $c_2 = -0.6$ FFT spectrum @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

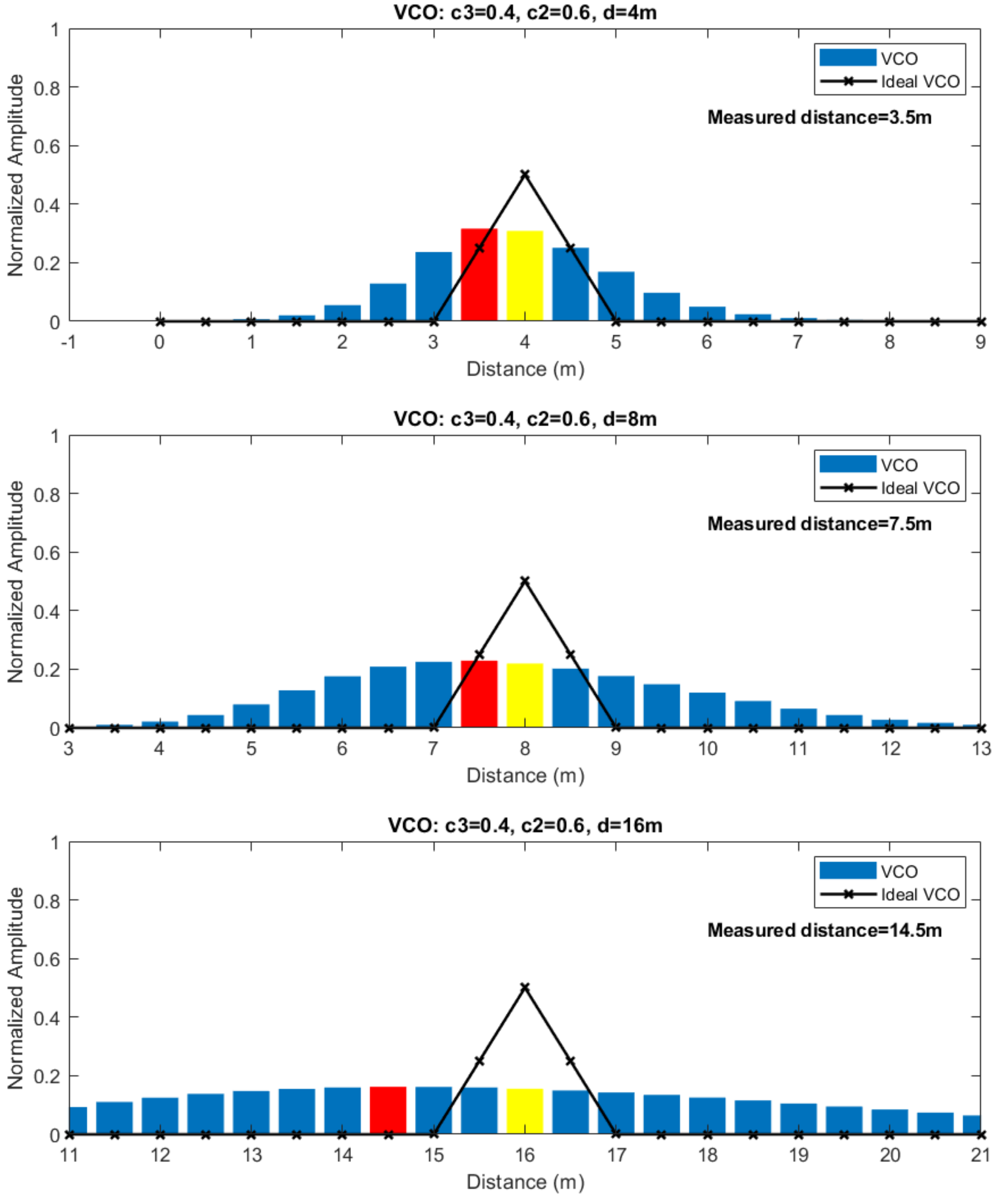

Figure 3.4: $c_3 = 0.4$ and $c_2 = 0.6$ FFT spectrum @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

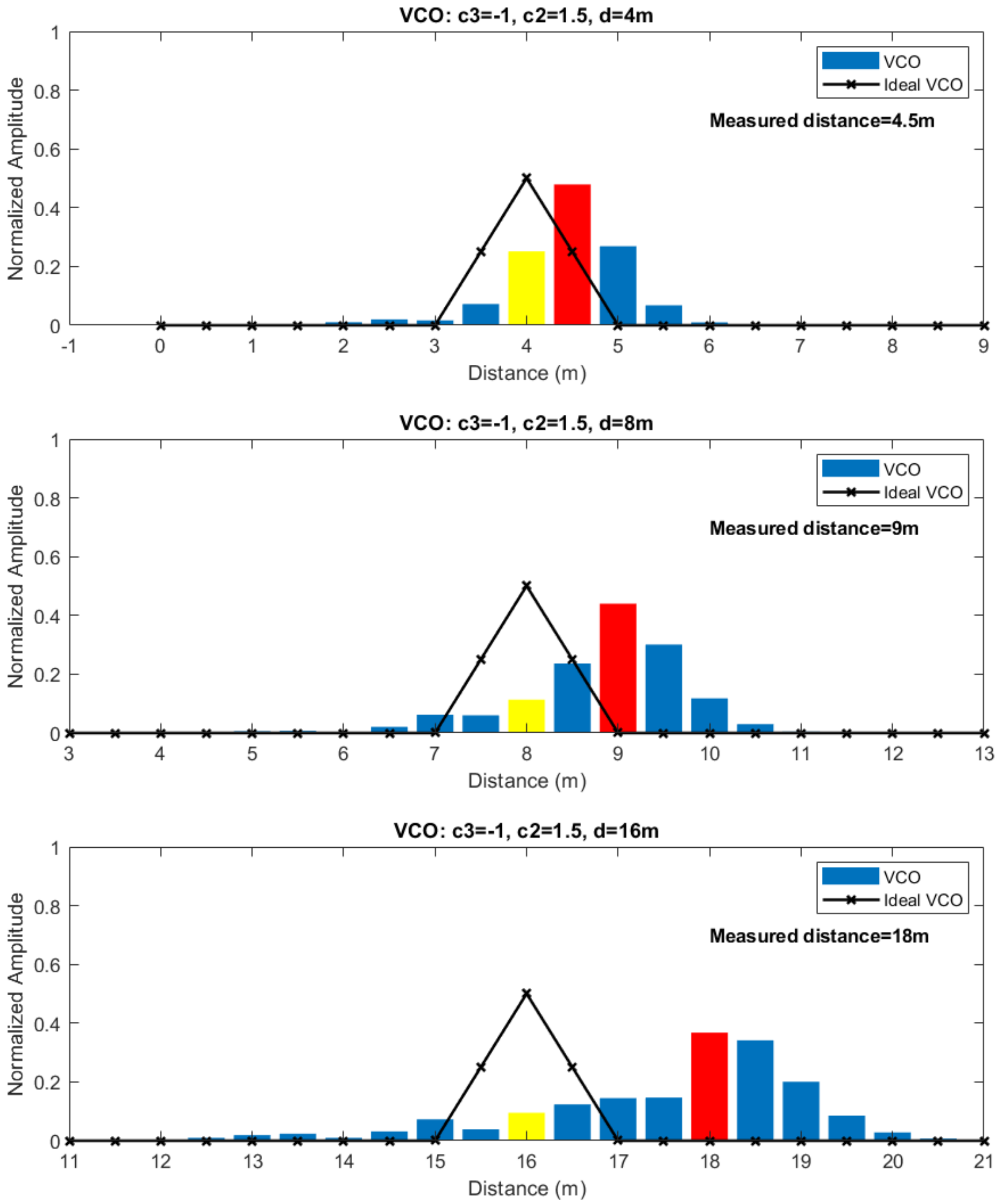

Figure 3.5: $c_3 = -1$ and $c_2 = 1.5$ FFT spectrum @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

3.4.2 Range Resolution Analysis

This part shows the effects of changing range resolution with distorted VCO characteristics. While doing this, the same distortion parabolic coefficients are used to enable us to compare results for different swept bandwidths. Three different parabolic setups and three different Bandwidths are used. Figures 3.6 3.7, 3.8 are given for range resolution of 25cm and Figures 3.9 3.10, 3.11 are given for 12.5cm. In Figures with the same distortion types, spectrum shapes and error levels are preserved between different range resolutions. 12.5 cm range resolution provides higher resolution and more detail for error levels and distortion characteristics. If the spread in the spectrum is examined, having a more detailed spectrum enables us to investigate distortion characteristics better. However, in practice, changing the bandwidth of operation changes the distortion characteristic of signal source.

In Table 3.2, amplitude and distance measurement responses of the radar at three different range resolutions and different distances are given. Distance errors are increasing in all three cases with increasing distances. The amplitude of the signal of the correct distance decreases with increased distance till a distance. After some point when the error increased, the amplitude of this peak lost this trend since the meaningful signal from the target shifts significantly, and this amplitude presents only in the spread in the spectrum and distortion characteristics. The Figure 3.11 shows the shape of the response with given distortion in Table 3.2. Some notches and peaks are distinguished from each other when the target's distance is increased. When the other two distortions are examined, their spectral leakage is smoother. The changing slope of the sweep rate results in different shapes in the FFT responses.

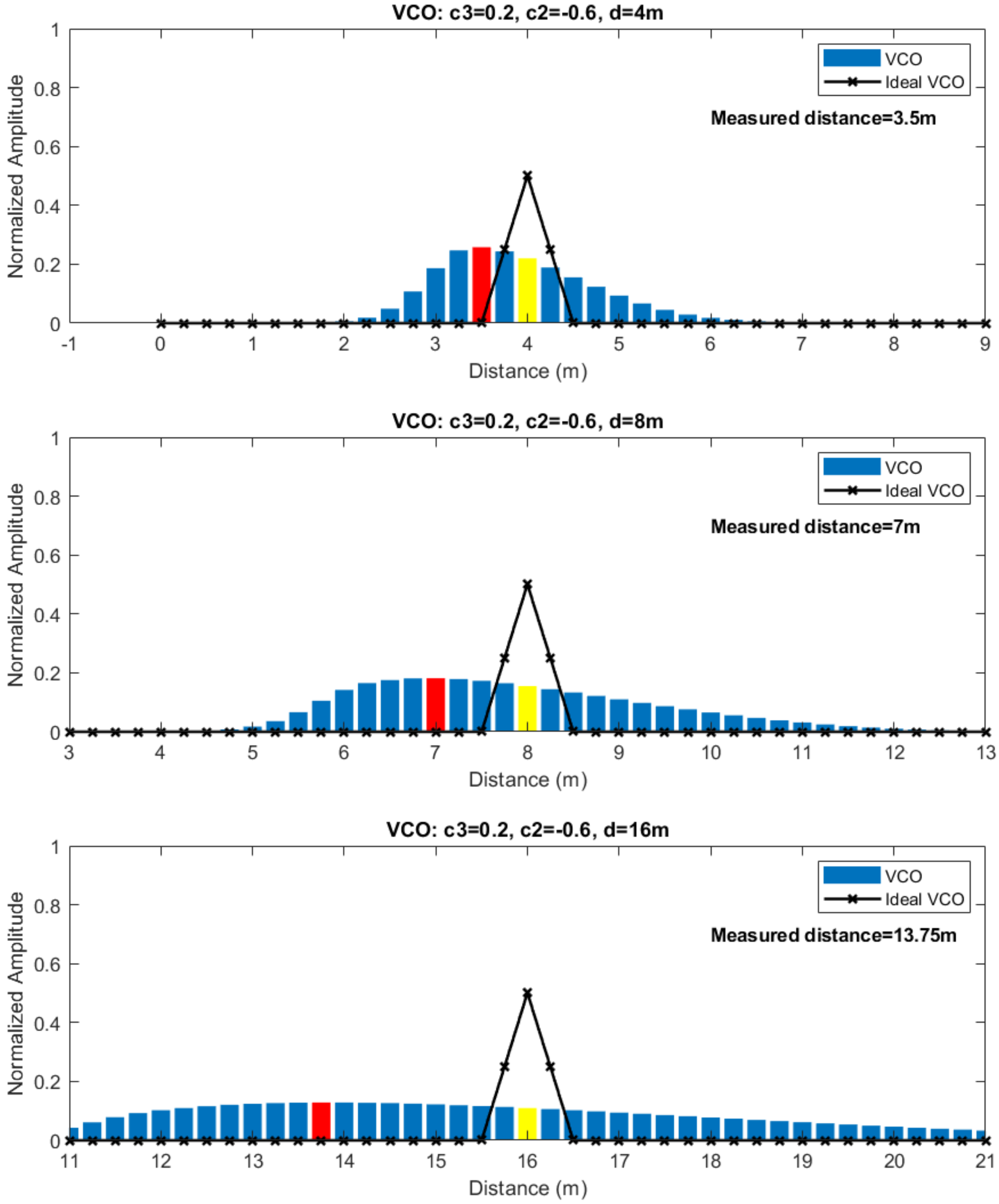

Figure 3.6: $c_3 = 0.2$ and $c_2 = -0.6$ $\Delta R = 0.25m$ FFT spectrum @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

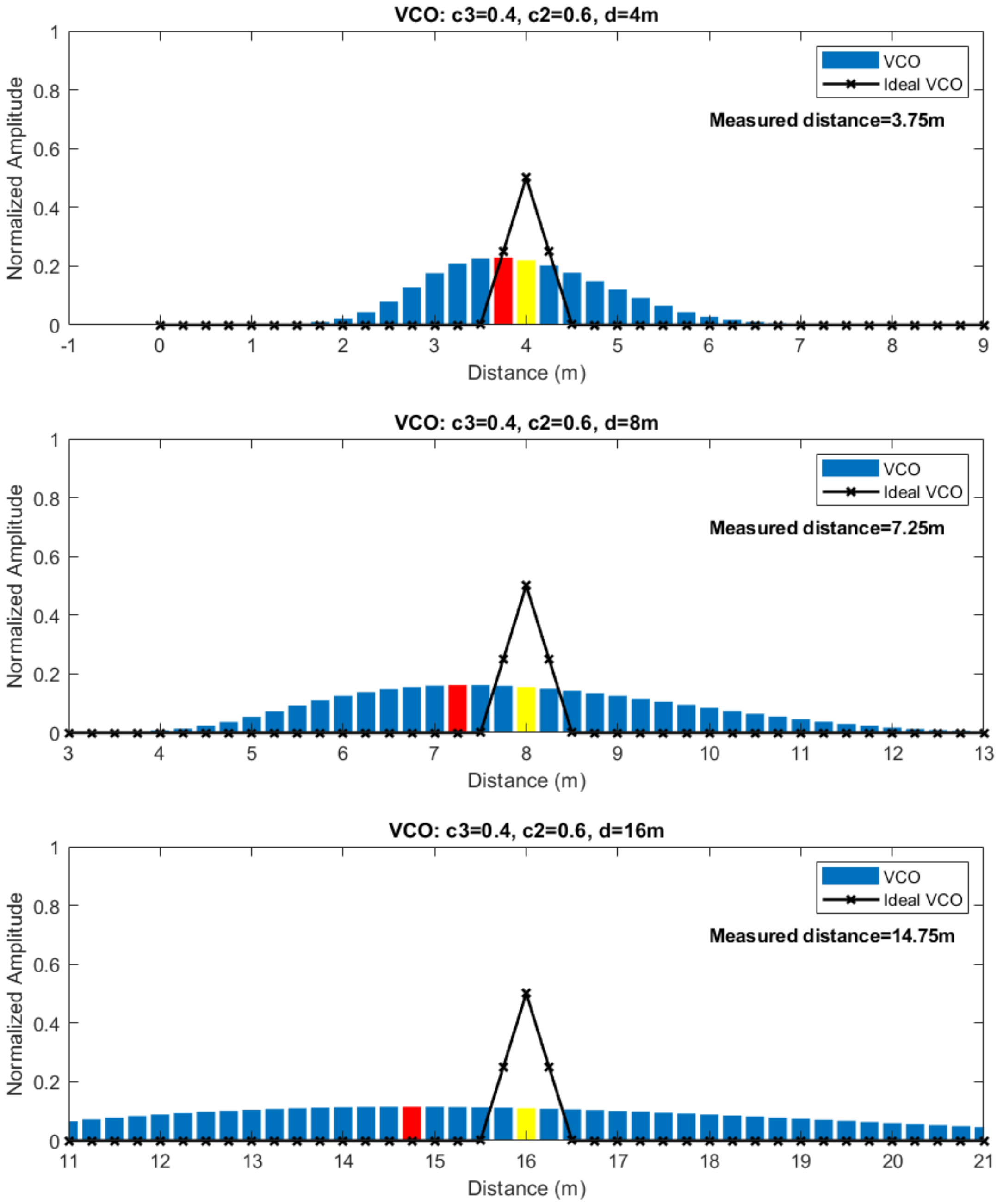

Figure 3.7: $c_3 = 0.4$ and $c_2 = 0.6$ $\Delta R = 0.25m$ FFT spectrum @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

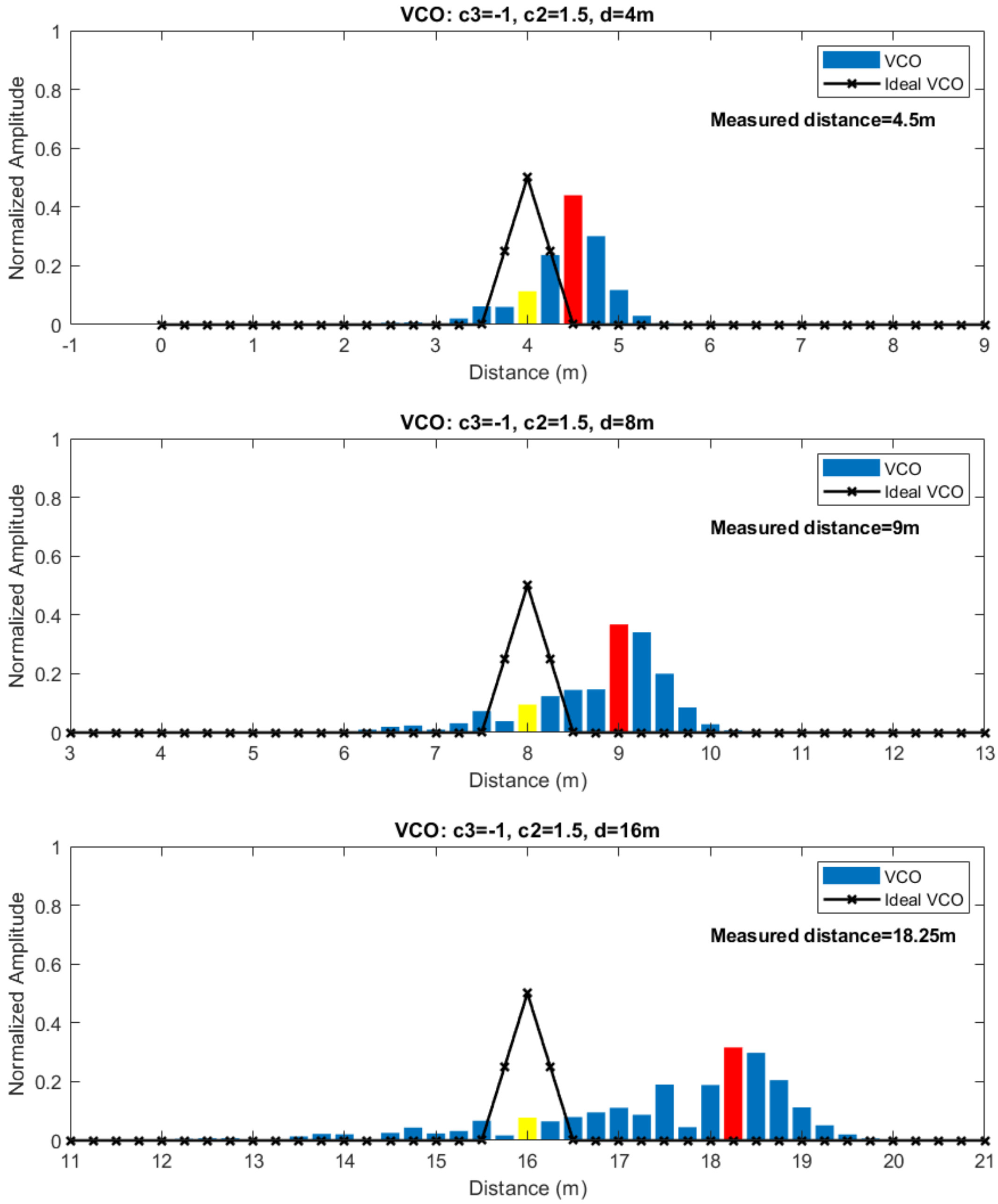

Figure 3.8: $c_3 = -1$ and $c_2 = 1.5$ $\Delta R = 0.25m$ FFT spectrum @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

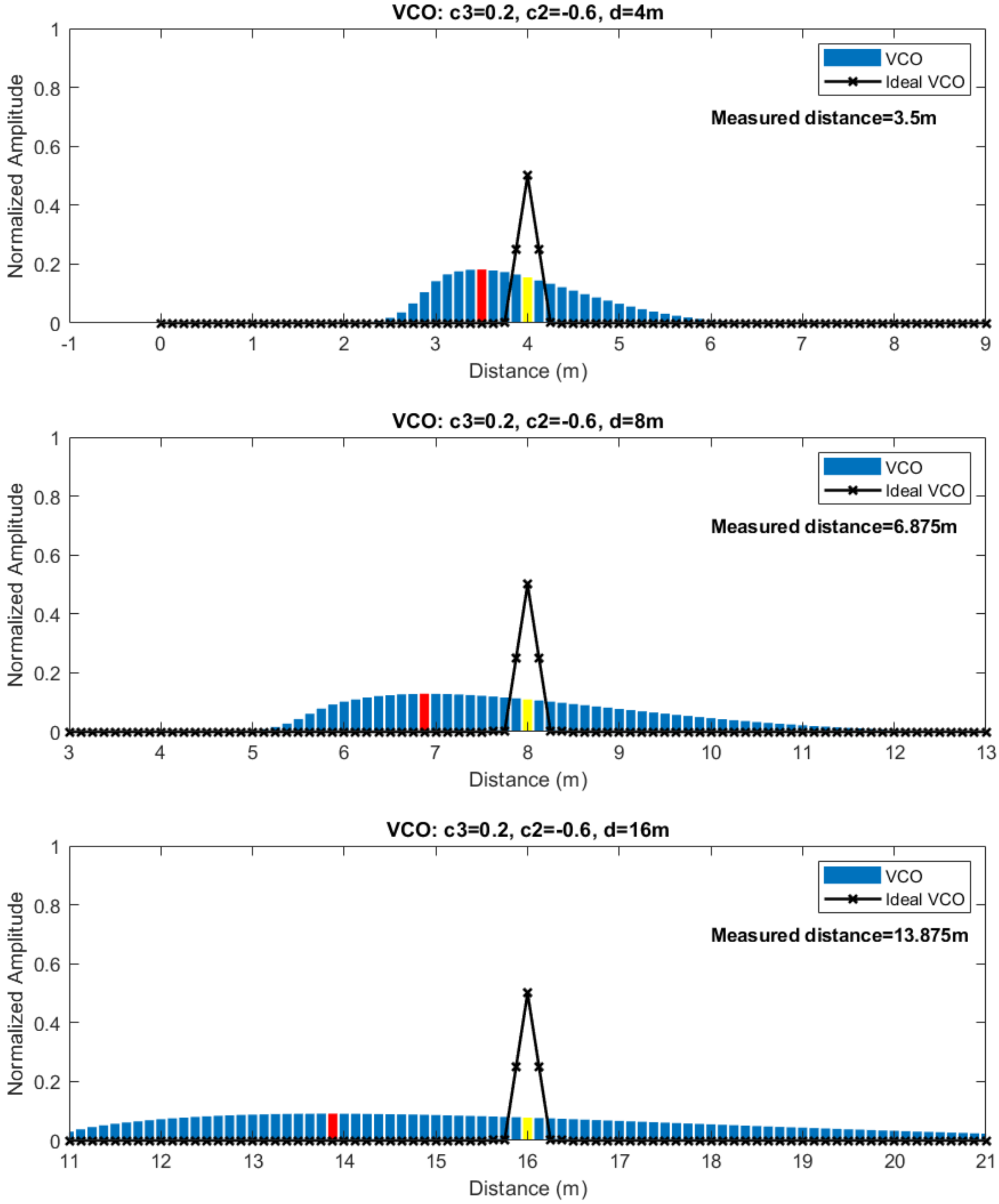

Figure 3.9: $c_3 = 0.2$ and $c_2 = -0.6$ $\Delta R = 0.125m$ FFT spectrum at @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

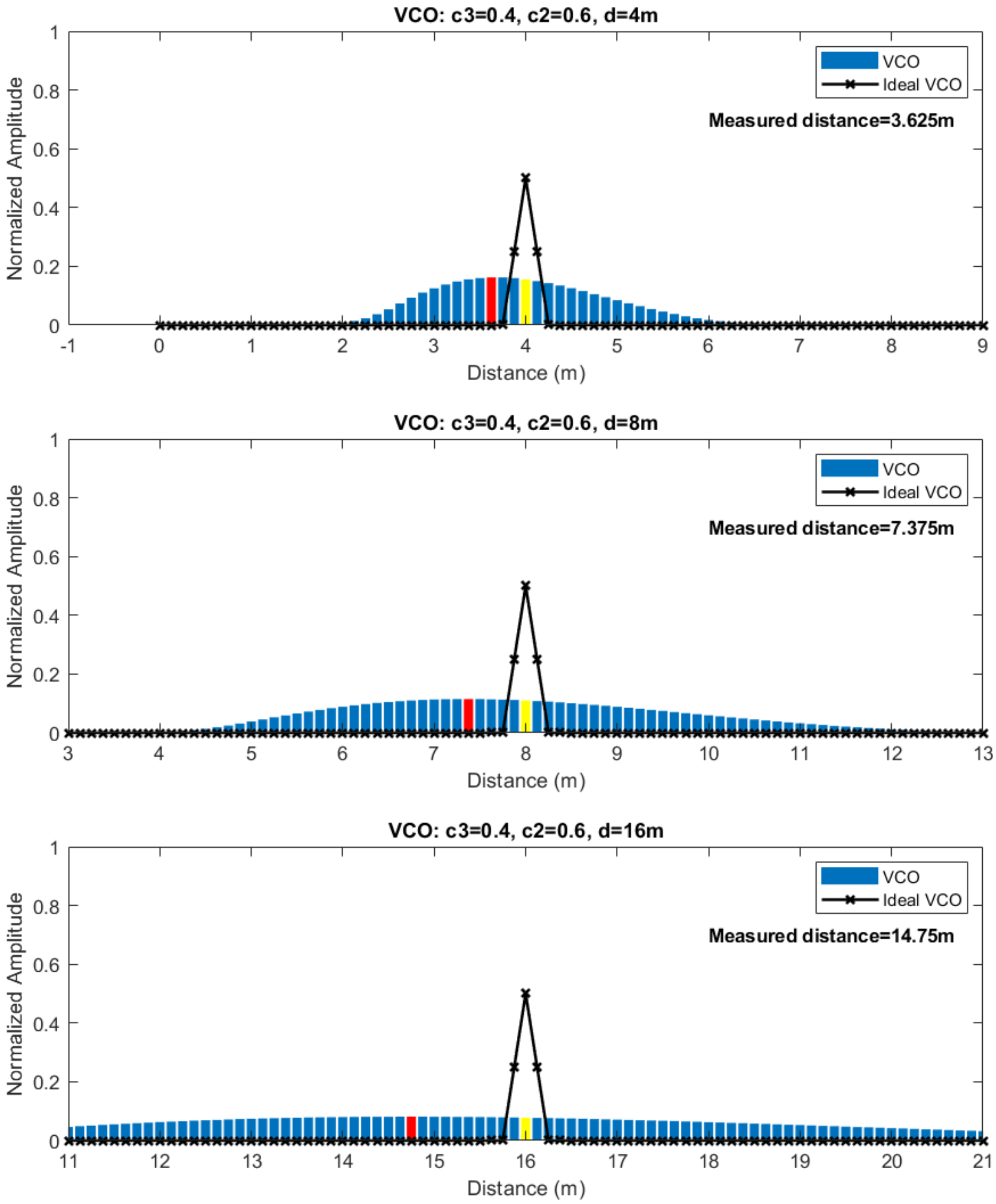

Figure 3.10: $c_3 = 0.4$ and $c_2 = 0.6$ $\Delta R = 0.125m$ FFT spectrum at @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

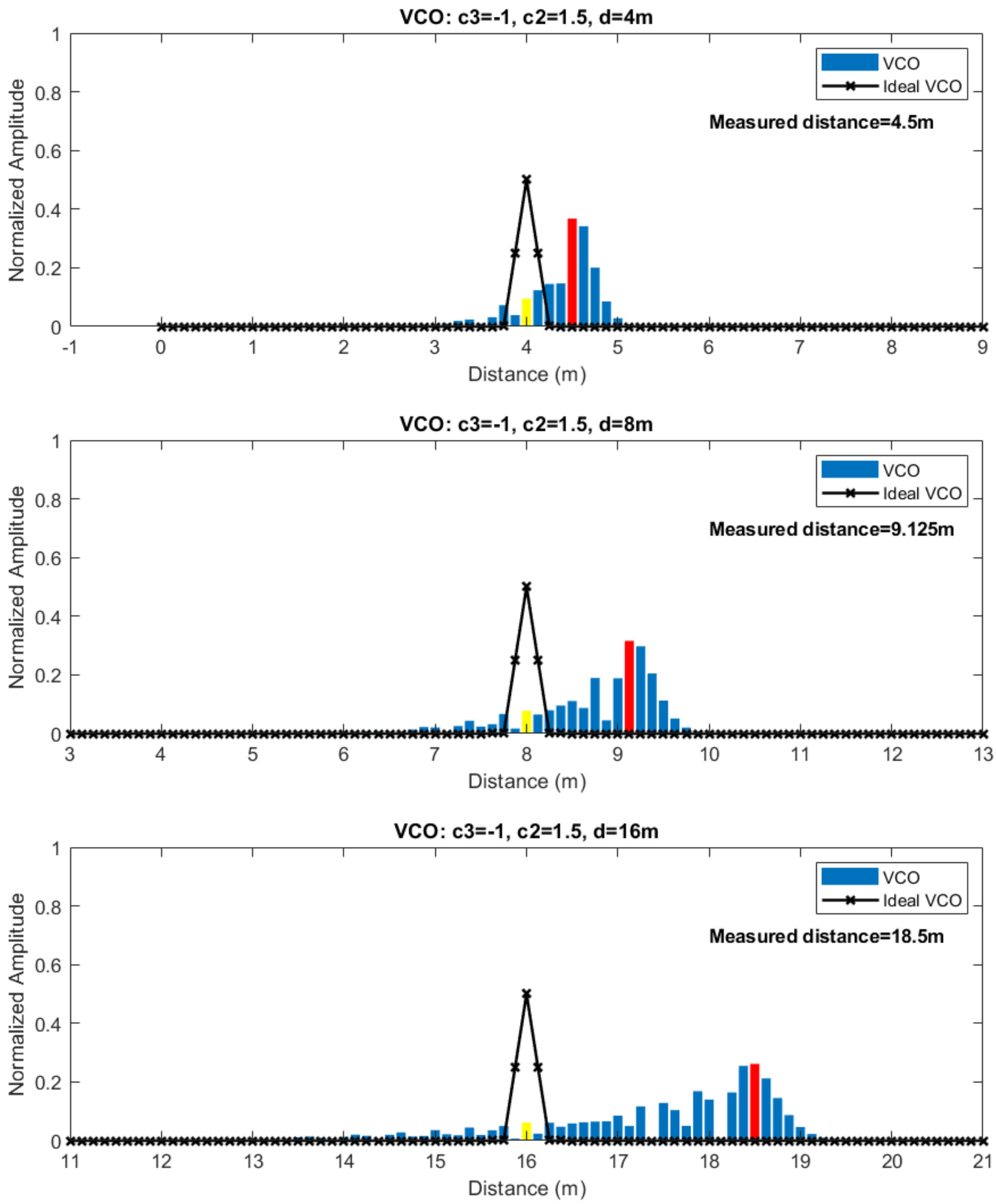

Figure 3.11: $c_3 = -1$ and $c_2 = 1.5$ $\Delta R = 0.125m$ FFT spectrum at @4-8-16m(yellow-target, red-peak measurement, blue-other bins, black-ideal)

Table 3.2: $c_3 = -1, c_2 = 1.5$ for different range resolutions(ΔR) at different ranges, with peak amplitudes and distance errors(Δd)

	ΔR=0.5m		ΔR=0.25m		ΔR=0.125m	
Distance,m	Amplitude	Δd,m	Amplitude	Δd,m	Amplitude	Δd,m
2	0.430	0.000	0.251	0.250	0.113	0.250
3	0.350	0.500	0.041	0.250	0.104	0.375
4	0.251	0.500	0.113	0.500	0.095	0.500
5	0.145	0.500	0.161	0.750	0.069	0.750
6	0.041	0.500	0.104	0.750	0.084	0.875
7	0.047	1.000	0.005	1.000	0.050	1.000
8	0.113	1.000	0.095	1.000	0.078	1.125
9	0.152	1.000	0.118	1.250	0.037	1.375
10	0.160	1.500	0.068	1.500	0.073	1.500
11	0.143	1.500	0.017	1.500	0.027	1.625
12	0.104	1.500	0.084	1.750	0.069	1.750
13	0.051	1.500	0.096	1.750	0.019	2.000
14	0.005	2.000	0.050	2.000	0.065	2.125
15	0.056	2.000	0.023	2.250	0.012	2.250
16	0.095	2.000	0.078	2.250	0.062	2.500
17	0.116	2.500	0.082	2.500	0.006	2.625
18	0.118	2.500	0.037	2.750	0.059	2.750
19	0.101	2.500	0.028	2.750	0.001	2.875
20	0.069	3.000	0.073	3.000	0.056	3.125
21	0.027	3.000	0.071	3.250	0.004	3.250
22	0.017	3.000	0.027	3.250	0.053	3.375
23	0.056	3.500	0.032	3.500	0.008	3.625
24	0.084	3.500	0.069	3.500	0.050	3.750
25	0.098	3.500	0.062	3.750	0.012	3.875
26	0.096	3.500	0.019	4.000	0.047	4.125
27	0.079	4.000	0.034	4.000	0.015	4.250
28	0.050	4.000	0.065	4.250	0.044	3.750

3.4.3 Parabolic Coefficients Analysis

This part shows the dependency of decreased performance in distorted VCO characteristics with different parabolic coefficients. Parametric analysis is done on 3rd and 2nd-order polynomial coefficients. In Tables 3.3 and 3.4 c_2 and c_3 are swept separately. The tables show measured distances, amplitudes at correct distances, and distance errors. Sweeping c_2 does not affect the location of the peak. Only amplitude is degrading with increasing coefficient. Sweeping c_3 affects both the amplitude of the correct distance and the location of the peak.

Table 3.3: $c_2 = 0, c_3$ is swept for different values at 10m distance,with peak amplitudes and distance errors(Δd)

c_3	d,m	Amplitude	Δd,m
-0.48	14.000	0.118	4.000
-0.4	12.500	0.139	2.500
-0.32	12.000	0.165	2.000
-0.24	11.500	0.201	1.500
-0.16	10.500	0.259	0.500
-0.08	10.000	0.394	0.000
0	10.000	0.500	0.000
0.08	10.000	0.418	0.000
0.16	9.500	0.307	-0.500
0.24	9.500	0.257	-0.500
0.32	9.000	0.231	-1.000
0.4	9.000	0.212	-1.000
0.48	8.500	0.199	-1.500
0.56	8.500	0.189	-1.500
0.64	8.500	0.181	-1.500
0.72	8.500	0.175	-1.500
0.8	8.500	0.170	-1.500

Table 3.4: $c_3 = 0, c_2$ is swept for different values at 10m distance, with peak amplitudes and distance errors(Δd)

c_2	d,m	Amplitude	Δd,m
-0.5	10.000	0.158	0.000
0	10.000	0.500	0.000
0.5	10.000	0.272	0.000
1	10.000	0.223	0.000
1.5	10.000	0.204	0.000
2	10.000	0.193	0.000
2.5	10.000	0.187	0.000
3	10.000	0.182	0.000
3.5	10.000	0.179	0.000
4	10.000	0.176	0.000
4.5	10.000	0.174	0.000
5	10.000	0.173	0.000
5.5	10.000	0.172	0.000
6	10.000	0.170	0.000
6.5	10.000	0.169	0.000
7	10.000	0.169	0.000
7.5	10.000	0.168	0.000
8	10.000	0.167	0.000
8.5	10.000	0.167	0.000
9	10.000	0.166	0.000
9.5	10.000	0.166	0.000
10	10.000	0.165	0.000
10.5	10.000	0.165	0.000
11	10.000	0.165	0.000
11.5	10.000	0.165	0.000
12	10.000	0.164	0.000
12.5	10.000	0.164	0.000
13	10.000	0.164	0.000

3.4.4 Predistortion Analysis

This part shows the dependency of a decrease in performance in distorted VCO characteristics and target range. The distorting coefficients and characteristics are well known. From this information, when a perfect predistortion, an inverse function of distortion, is applied, a perfectly linear sweep and a perfect response can be achieved. To handle the problem more realistically, another third-order polynomial is used for the predistortion signal. The distorted signal is sampled, and for its inverse, another polynomial is fitted using the least squares method. This method allows us to evaluate a more practical predistortion signal on performance by adding ambiguity.

3 different ranges with 3 different distortions and predistortions are used.In Figures 3.12, 3.13 and 3.14 results are presented. In all three cases, applied distortions fixed the peak shift error and increased the peak amplitude at the correct distance. The spectral purity is recovered significantly even at the target of 16m.

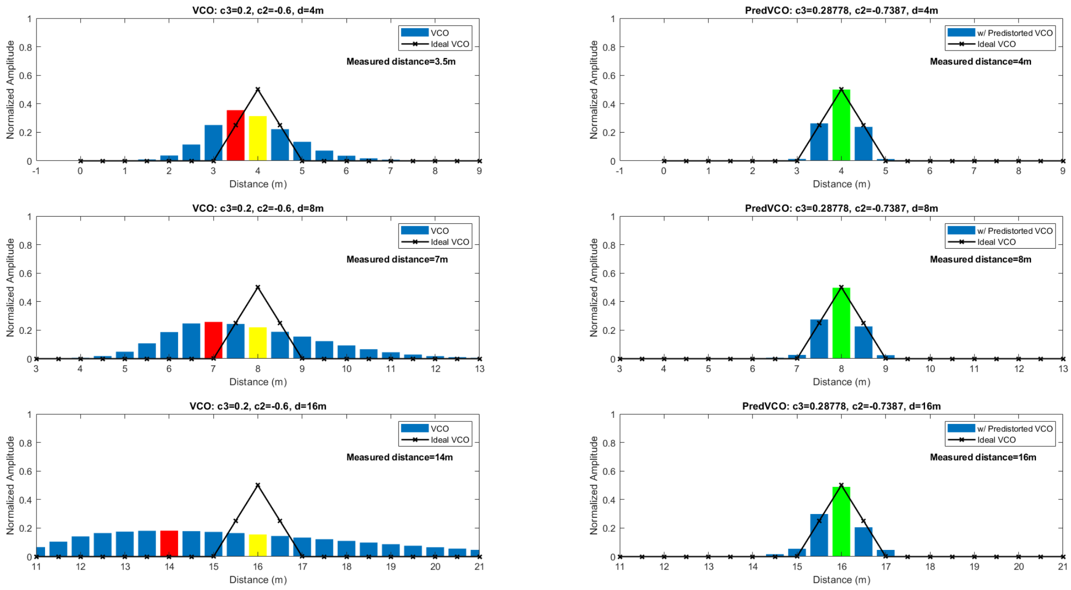

Figure 3.12: FFT results with $c_3 = 0.2, c_2 = -0.6$ @4-8-16m, left-distorted, right-predistorted (yellow-target, red-peak measurement,green-correct measurement(target=peak) blue-other bins, black-ideal)

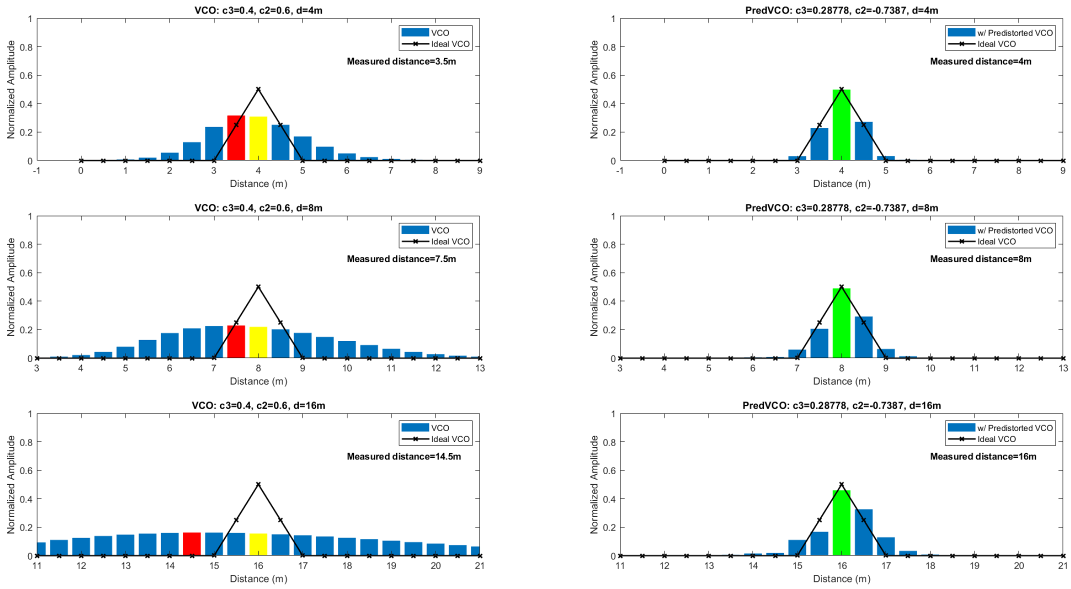

Figure 3.13: FFT results with $c_3 = 0.4, c_2 = 0.6$ @4-8-16m, left-distorted, right-predistorted(yellow-target, red-peak measurement,green-correct measurement(target=peak) blue-other bins, black-ideal)

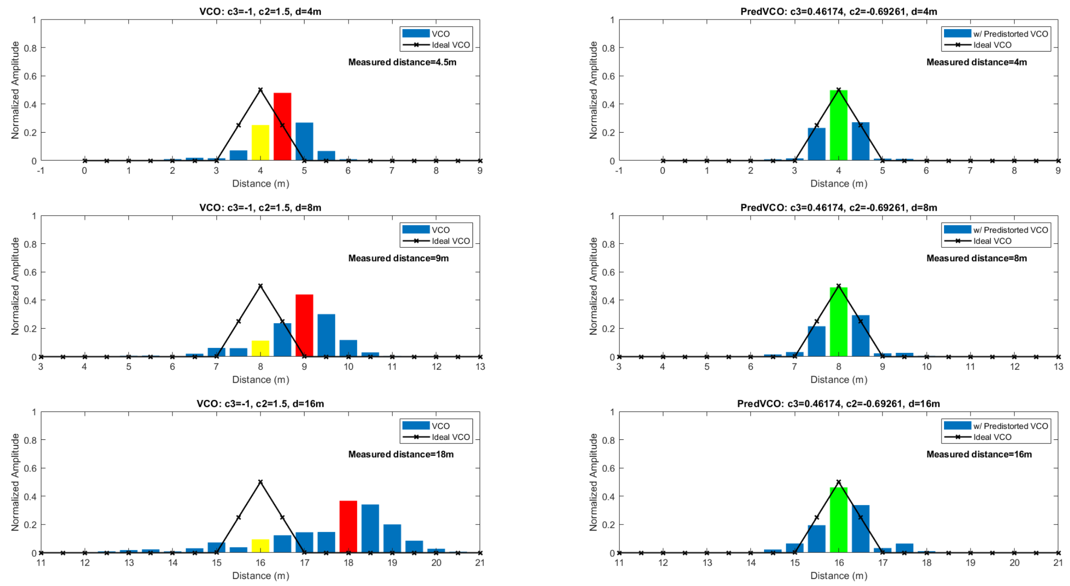

Figure 3.14: FFT results with $c_3 = -1, c_2 = 1.5$ @4-8-16m, left-distorted, right-predistorted(yellow-target, red-peak measurement,green-correct measurement(target=peak) blue-other bins, black-ideal)

3.4.5 Evaluation

In this chapter, a benchmarking circuit is introduced for simulations. The simulation environment is also presented, and the results are evaluated.

The simulation environment can show measurement results for different distorted VCO characteristics with third-order polynomials and explain how distortion in VCO frequency characteristics can degrade the performance of the FMCW radar in different ways. Different types of distortions are presented.

Distortion effects are more observable at longer distances since the effects of distortion are proportional to the delay between TX and RX signals.

Increasing bandwidth and decreasing range resolution while keeping the same distortion characteristics result in similar error levels and spread in the spectrum. Decreasing range resolution only increases the precision of error levels and error bin count. This changes only the resolution of the distance error and increases spectral leakage around the peak.

The effects of sweeping c_2 and c_3 coefficients are presented. Keeping $c_3 = 0$ and sweeping c_2 does not result in distance error in the peak detection algorithm. It only decreases peak amplitude and spread in the spectrum. This can be explained with a sweep rate graph since it is symmetric around the middle of the sweep and has the same level as the ideal sweep rate at that point. Keeping $c_2 = 0$ and sweeping c_3 results in both distance error in the peak detection algorithm and spread in the spectrum. Parabolic shape in the sweep rate will shift distance measurements depending on the sign of the c_3.

The effects of predistortion on distorted VCOs are presented. This method is applied by simulating distortions by third-order polynomials and approximating their predistorted signals with different third-order polynomials approximating their characteristics. It showed that applied predistortion increased performance and decreased range errors in given conditions. Predistortion must be carefully prepared for targets at greater distances, as the response is not ideal in these cases, and degradation of performance for remaining distortions can be significant.

In the next chapter, experimental validation is presented. A VCO characterized in the radar system and its distorted characteristics are investigated. The effects of predistortion on the performance of the radar are evaluated.

CHAPTER 4

PRACTICAL EVALUATION OF DISTORTIONS AND PREDISTORTIONS

This chapter has two main experiments. The first experiment focuses on characterizing the VCO Tune signal and VCO output frequency. VCO output frequency vs. tuning voltage characteristics are usually given in their datasheet with a graph with sensitivity. Sensitivity is defined as the change in output frequency per volt. However, these graphs are not very detailed enough to retrieve data for determining predistortion. They are given to provide users with preliminary information about their characteristics. The first experiment enabled us to characterize the VCO that will be used in the radar. In the second experiment, with the results from the first one, its predistorted VCO tune signal is used in the radar on single target measurements, and these results are compared with results from the simulation environment. These experiments aim to show the performance increase of FMCW radar with commercially available VCO and examine the method with real-world measurements.

Before the experiments, the predistortion stages are explained in the following section. This section provides a general flow for designers to implement predistortion in their systems.

4.1 Predistortion Stages

Implementing predistortion involves several key stages, each critical to ensuring effective compensation for the nonlinearities in the VCO, which include characterization, design, calibration, and validation.

4.1.1 Characterization of the VCO

The first stage is accurately characterizing the nonlinear behavior of the VCO. The nonlinear frequency response curve can be obtained by applying a range of tune voltages to the VCO in the region of operation and measuring corresponding output frequencies. Using this measured data, the nonlinear transfer function $F(V_{tune})$ of the VCO is identified as in Section 2.4.2. This can be done by fitting a polynomial or another suitable model to the measured data.

4.1.2 Predistortion Design

When the VCO's nonlinear characteristics are acquired accurately, the next stage is designing the predistortion function $P(V_{tune})$. The ideal predistortion function P should be inverse of the VCO's transfer function F, such that $F(P(V_{tune}))$ is approximately linear. This can be analytically derived or numerically approximated.

Different methods can be chosen for implementing P depending on the complexity and required precision. If polynomial predistortion is selected, appropriate polynomial order and its coefficients should be determined. This method can chosen when the data acquired is limited or the system has limited memory. When look-up tables are chosen, a table of precomputed predistortion values for each data point should be determined. For adaptive algorithms, P should be dynamically adjusted based on real-time feedback.

4.1.3 Calibration

Calibration is a critical stage in checking if the predistortion function accurately compensates for VCO's nonlinearities. A test is generated with a predistorted signal and applied to the VCO. The output frequency is measured and compared with the desired linear response to determine the error. If the error level is not low enough, the predistortion function P is iteratively adjusted to minimize the error. This can be done through techniques such as least squares fitting or gradient descent[25].

4.1.4 Implementation and validation

After calibration, the predistortion function is implemented in the radar system. The function can be implemented using digital signal processing hardware or field-programmable gate arrays.

For validation, the FMCW radar can be run with and without predistortion, and its key performance metrics, such as range resolution, accuracy, and signal levels, can be compared. Its operation can be tested over extended periods and under varying environmental conditions to ensure predistortion works effectively. The radar's target detection and measurement performance can be evaluated in real-world scenarios.

4.2 VCO Characterization Experiment

4.2.1 Experiment Setup

This experiment uses VCO with part number HMC391LP4 from Analog Devices. The aim is to characterize its frequency vs. tuning voltage in detail so that the data can be used to determine the predistorted VCO tune signal. A FMCW Radar, which uses HMC391LP4 as an oscillator, is under test(DUT). The radar has a built-in antenna as a transceiver and is placed in an anechoic box with an equivalent receiver antenna. They face each other, and their polarizations are aligned to receive maximum signal. The receiver antenna is connected to a spectrum analyzer that is controlled by a PC. The same PC controls DUT and VCO. DUT is powered by a DC power supply. The figure explaining the experiment setup is given in Figure 4.1.

This setup allows us to evaluate VCO with other components in the radar. The aim is to characterize the target bandwidth of 4-4.3 GHz. VCO tune signal is derived from a 12-bit Digital-to-analog converter (DAC) in the sensor, which has 0-3.33V output. DAC is connected to analog filters, which filter and give a gain of about 2.7 to reach target voltages for target frequencies. The characteristics from the datasheet of VCO are given in Figure 4.2 [26].

The PC controls DAC in the radar while taking frequency measurements from the

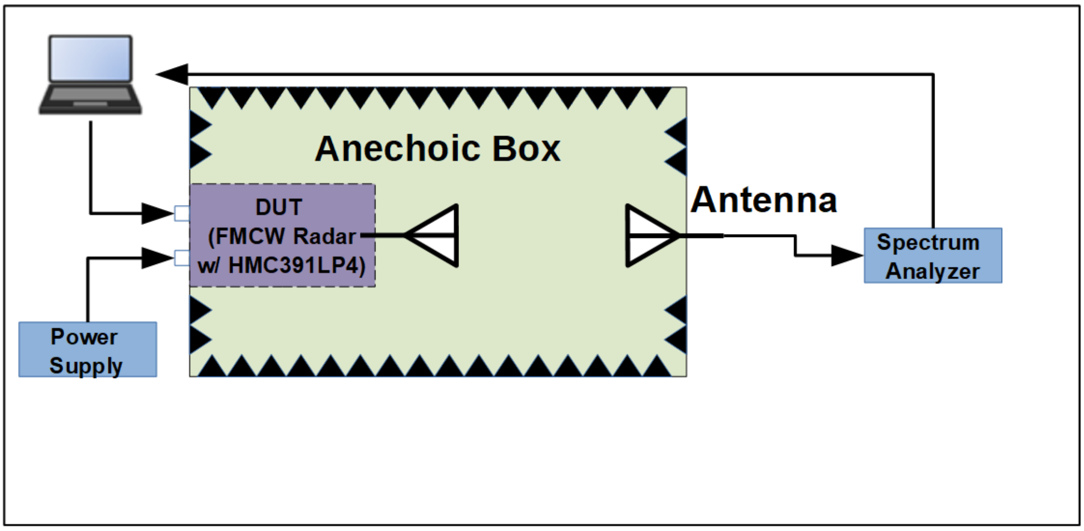

Figure 4.1: VCO Characterization Experiment Setup with Spectrum Analyzer

spectrum analyzer. 12-bit DAC is swept between 000-FFF in 256 steps. This means that the VCO Tune voltage is changed between each step to approximately 35.12 mV, and we can see the radar's frequency limits in the given design between $0 - 9V$. Values between consecutive steps are extrapolated from these values.

The anechoic box that can provide RF isolation in the operation band helps us to take more controlled measurements and provide repeatable and more reliable experiments.

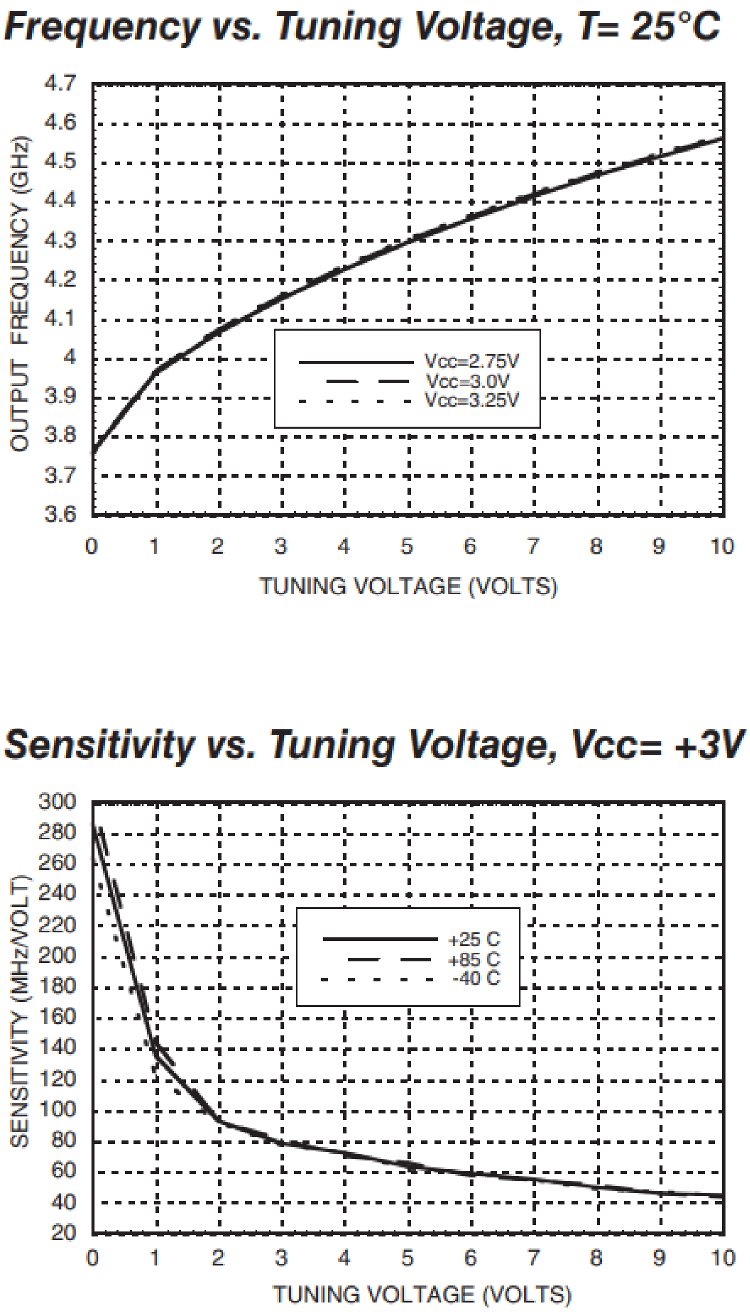

Figure 4.2: HMC391 frequency characteristics

Another method of determining the frequency characteristics of VCO can be using an oscilloscope with minimum sampling frequency according to Nyquist Criteria ($N_s = 2f_c$). An oscilloscope with $20GS/s$ (MSOS054A with $6GHz$ upgrade)is used in the setup given in Figure 4.3. Time domain data is acquired from one linear sweep and post-processed in the MATLAB environment by using STFT(Short Time Fourier Transform). With this method, measurement can be made with less effort and more accuracy. Internal group delays should be considered when measuring and evaluating DAC data with measured frequencies for synchronization. For characterizing VCOs with much higher frequencies, downconverting them to a more stable LO can be helpful since oscilloscopes with higher sampling rates may not be available.

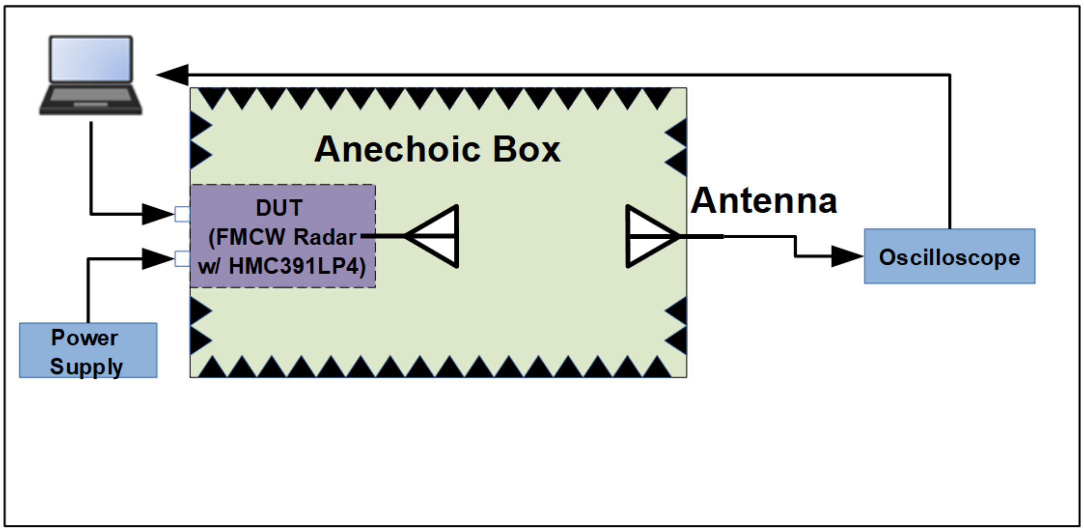

Figure 4.3: VCO Characterization Experiment Setup with Oscilloscope

There are also upgraded devices that can measure VCO in terms of phase noise and tune characteristics, such as R&S®FSPN Phase Noise Analyzer and VCO tester [24]. These state-of-the-art devices can analyze a wide range of characteristics quickly and accurately. However, these devices are not available in the scope of this research.

4.2.2 Measurements

Rather than evaluating only the VCO, the VCO is evaluated within the radar system PCB. Using this PCB to characterize VCO helps us combine other distortions from components and the environment. The frequency drift rate is given in the datasheet as $0.5MHz/C$. This can be a problem when it is not considered with operating conditions. The temperature drift can damage measurements for characterization.

For more stable and consistent measurements, we should consider heating up and cooling down VCO between measurements or wait for thermal equilibrium to be reached. Because DUT will not be operating in thermal equilibrium, we should decide the times for heating up and cooling down in the measurements before getting data for characterization. Due to the rapid temperature change in the first 5 seconds, the frequency will drift significantly. In Figure 4.4, drift from power-up to 60th seconds is given for a single frequency. About 10 MHZ of drift is observed.

Figure 4.4: HMC391 VCO Temperature drift for the first 60s

For more stable operations and heating up of the VCO, 5 seconds are needed after powering up the VCO. From 5 to 15 seconds, the output frequency is measured in 4 steps of DAC. VCO is powered down for the next measurement, and 60 seconds is waited for cooling down and to start the next measurement. For 256 steps, 4 x 64 measurements are taken.

While temperature drift is shifting all frequencies, radar is not expected to use frequency modulation that is not distorted in terms of linearity and bandwidth. Only drift will be in carrier frequency. Each sweep is evaluated in their sweep time, and temperature drift during short sweep time is negligible.

For measurement with the oscilloscope setup, taking one measurement for a full sweep is enough to characterize VCO. Desired band limits and frequencies for each DAC value are determined from this sweep.

To compare both setups, bandlimits determined by two methods are measured with the spectrum analyzer and shown in Figures 4.5 and 4.6.

Figure 4.5: HMC391 VCO Band Measurement w/Spectrum Analyzer

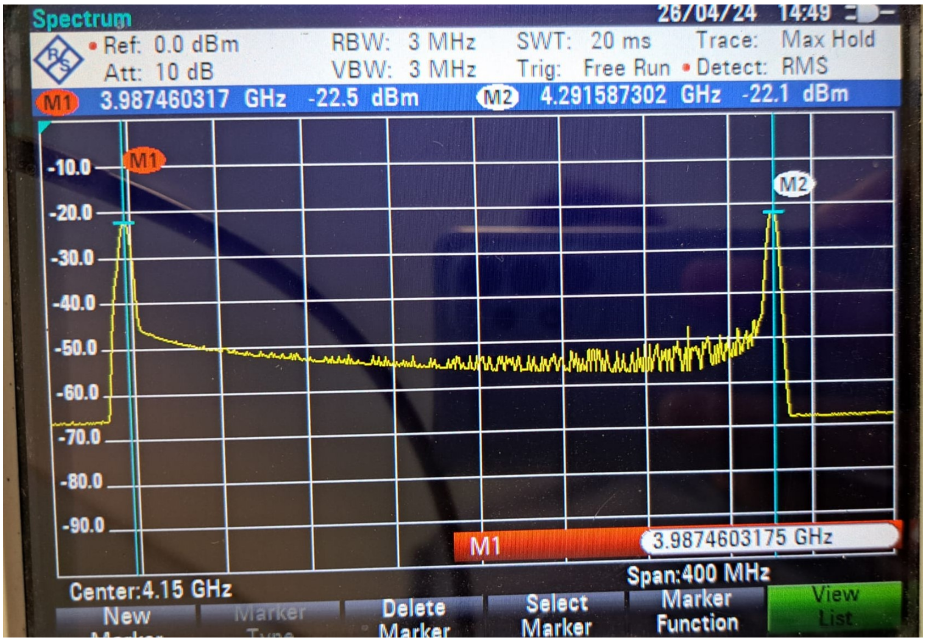

Figure 4.6: HMC391 VCO Band Measurement w/Oscilloscope

The results from the first measurement are very close to the desired bandwidth and operation frequencies $(4 - 4.4GHz)$. However, the second measurement shows a drift in operation frequencies. This is due to the difference between measuring the frequency of a single-tone signal and measuring the whole sweep in the time domain. The group delay and other systematic delays from DAC output to VCO output become significant for calibration and preparing the look-up table. Since the radar uses sweeps for measurement, results and calibration data from the setup with the oscilloscope are more suitable for the desired operation. If we calibrate only the VCO, the first setup can be more suitable, but for calibration, the whole system time response of the sweep becomes important. To compare, two sweeps are measured and post-processed in the oscilloscope setup and shown in Figure 4.7. The difference can also be seen in this figure. Data from the second setup are used for the rest of the measurements and experiments.

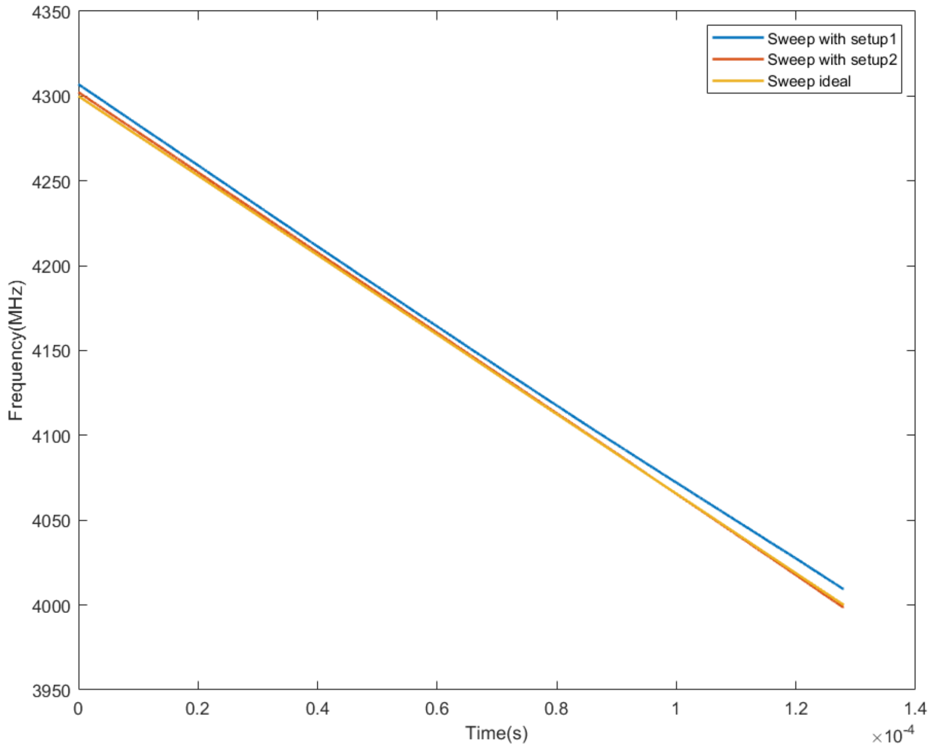

Figure 4.7: HMC391 sweeps calibrated with two setups and ideal sweep

Figure 4.8 shows measured frequencies vs. tune voltage values for calibration. The region of interest is plotted with red lines. The sensitivity characteristics are consistent with the data in the datasheet. Two measurements are taken at two different temperatures. The first measurement is taken in the 5th second of the system operation. The second measurement is taken in the 60th second. The temperature drift can be seen in Figure 4.8. The drift for most of the band is below $2.5MHz$ and near constant after $4GHz$.

The sensitivity data can be extracted from the measured data. Calculating corresponding voltages for tune signal from DAC data and consecutive frequency measurements can result in a graph like in the datasheet. Calculated sensitive data is given in Figure 4.9. Results are also consistent with datasheet values. With this measurement, we achieved more detailed data for the operation region of radar. This data can be used to find predistorted tune signals. The sensitivity in the region of interest is changing from $128MHz/V$ to $69MHz/V$. If VCO is swept linearly, the frequency sweep rate

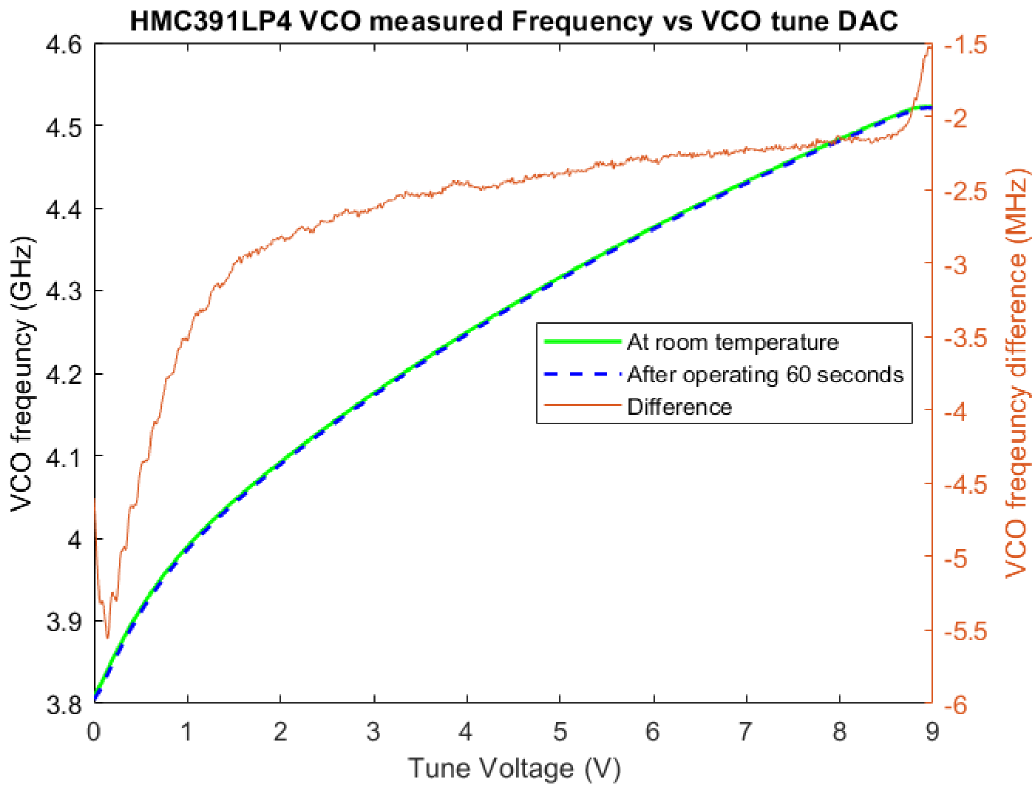

Figure 4.8: HMC391 Frequency vs VCO tune at two different temperatures

will multiply from one bandwidth edge to the other end.

Figure 4.10 shows the difference between the two sensitivity graphs. For tune voltages bigger than 1V, temperature drift only results in fluctuations near zero. According to acquired data, temperature drift only causes changes in carrier frequency as bandwidth and sensitivity are not affected by temperature differences in the experiments made at room temperature.

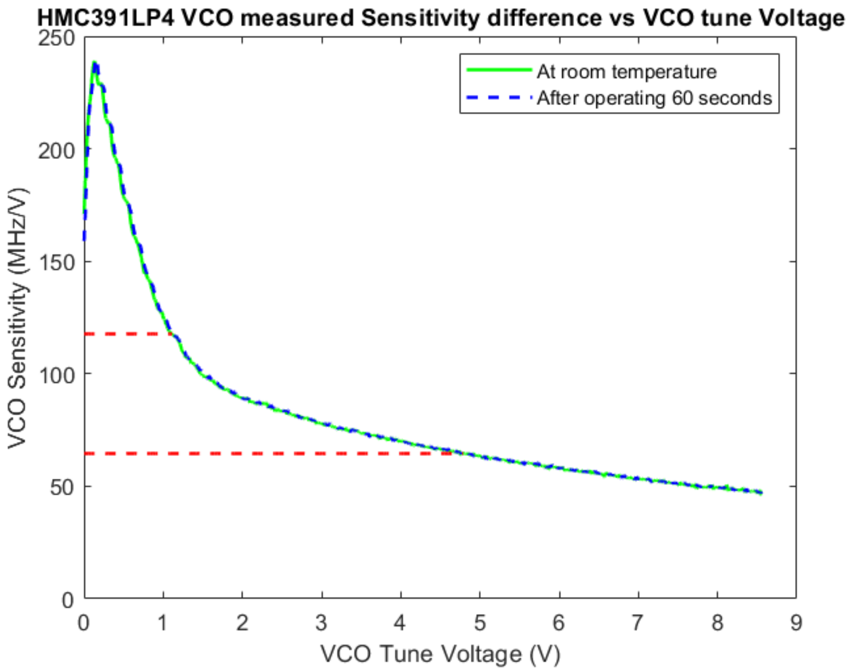

Figure 4.9: HMC391 Sensitivity vs VCO tune at two different temperatures

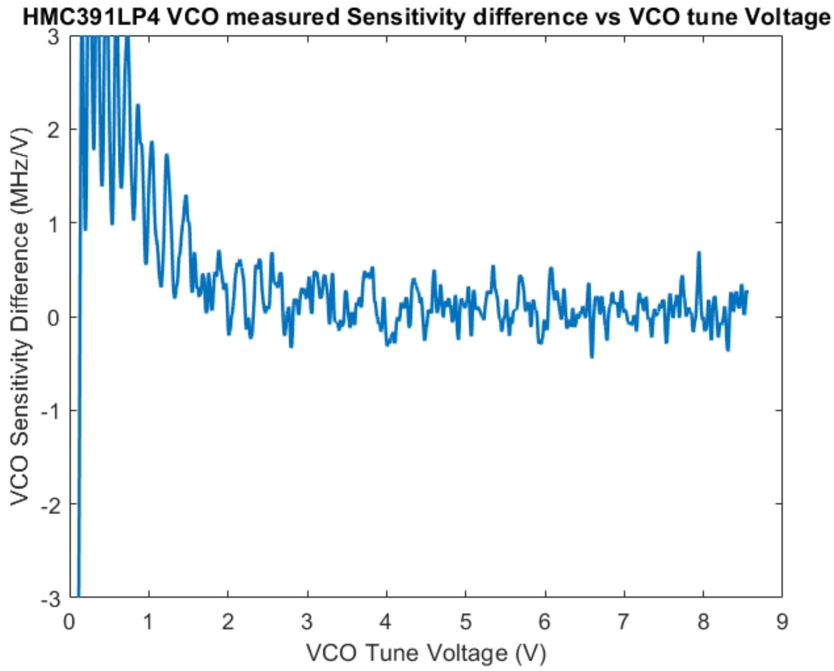

Figure 4.10: HMC391 Sensitivity difference vs VCO tune at two different temperatures

4.3 Predistortion Performance Experiment

In this experiment, the same DUT is used. According to data acquired from previous experiments, a predistorted tune signal is created. With this predistorted tune signal, distance measurement performance is evaluated. Also, an intentionally distorted tune signal is applied. All distance performances are compared with simulation results containing the same tune signal applied to simulated VCO. This experiment evaluates predistortion performance and validates the simulation environment for different distortions.

4.3.1 Experiment Setup

This experiment setup is very similar to the previous one. Instead of the spectrum analyzer, RF coaxial cables are connected to the receiver antenna. The radar signal will travel to the end of the cable, and most of the reflected back to the radar. Before taking measurements, the cable is terminated with a matched load, and a calibration measurement is taken to subtract this measurement from other measurements. This helps us avoid unwanted spectrum bins from the environment and radar itself and isolate the response of the signal only from the reflected signal from the cable. The test setup is given in Figure 4.11.

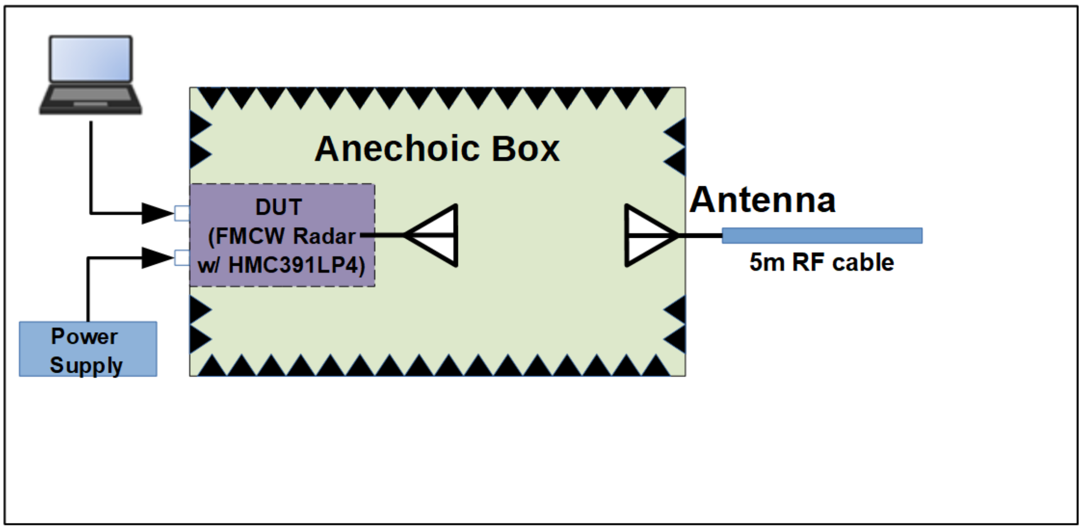

Figure 4.11: Predistortion Performance Experiment

Table 4.1: Corresponding distances for different setups in box(B)

	B+4m	B+4m+4"	B+4m+12"	B+5m	B+5m+11"
Distance(m)	5.88m	6.02m	6.31m	7.13m	7.53m

For measurements, LMR-240 50 Ohms RF cables are used. The cable's propagation velocity is given as $0.83c$ in its datasheet. DUT is replaced with a test antenna to measure the delay in the whole system, and two ends of the anechoic box are connected to the network analyzer. The delay is measured, and the corresponding electrical lengths between transmitted and received signals are calculated and given in Table 4.1.

While measuring the output of the end of the delay line with the oscilloscope, an amplitude modulation is observed, which is caused by multiple reflections in the delay line and the box. This multiple reflection is added to the simulation to observe spectrum bins at $2d$.

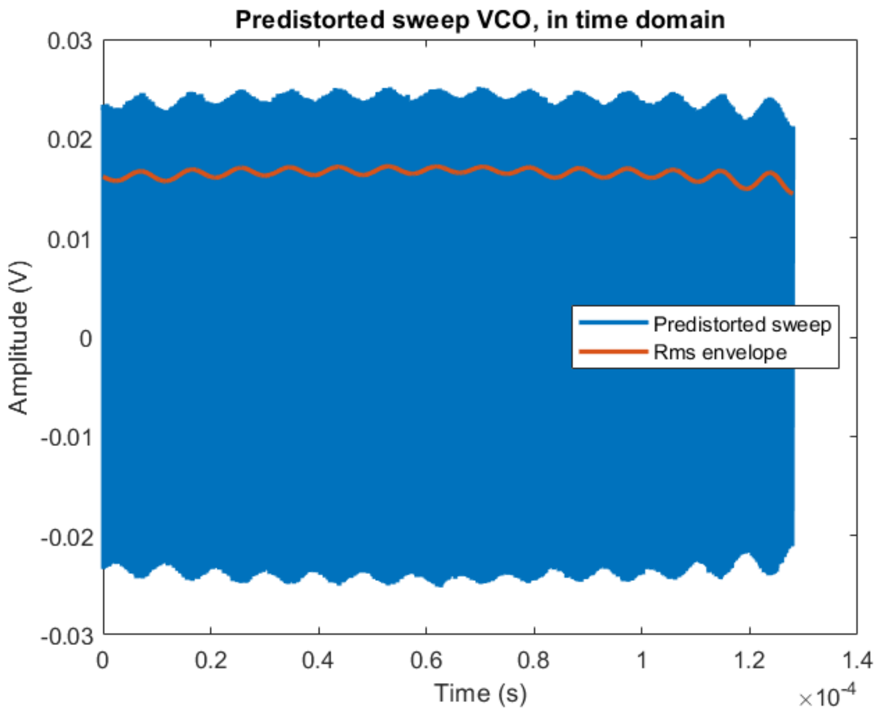

Figure 4.12: Signal measured in time domain with 5m cable, blue-signal, red-rms envelope of the signal

4.3.2 Measurements

The predistorted tune signals are acquired using two different calibration methods. The comparison for two calibrations is shown in Figures 4.13 and 4.14. The black lines show the ideal response of a single target of $7.13m$. Red lines are experimental measurements, and blue bars are simulation results of predistortion. Predistortion with 2nd setup shows more correlation with the ideal case.

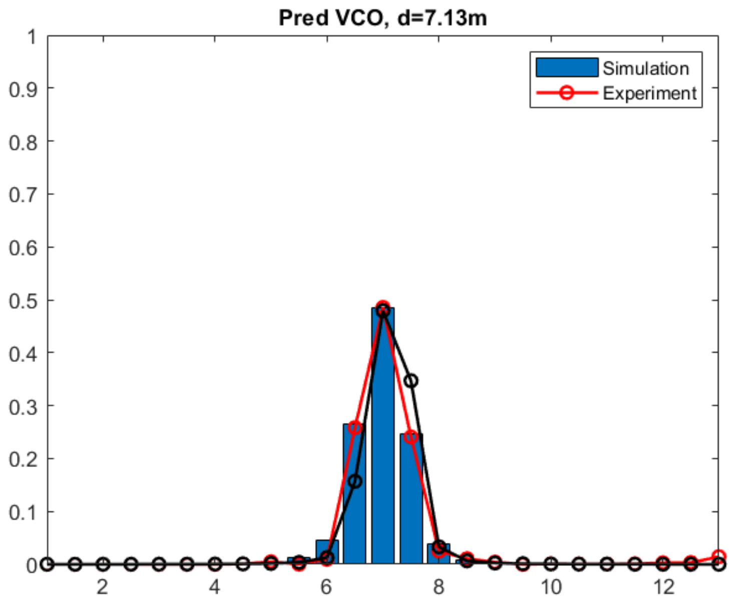

Figure 4.13: Predistortion applied with first calibration setup @7.13m, red-experiment, blue-simulation, black-ideal

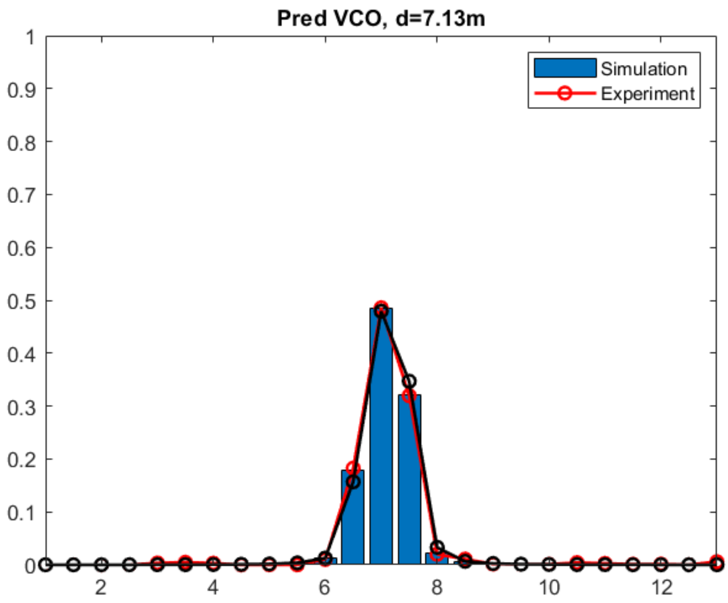

Figure 4.14: Predistortion applied with second calibration setup @7.13m, red-experiment, blue-simulation, black-ideal

For ideal tune voltage and predicted data, applied VCO sweep is given along with frequency sweep rates in Figures 4.15 and 4.16. With applied predistortion, change in the sweep rate is reduced dramatically and gets close to the ideal sweep rate. The frequency sweep of the predistorted signal is between 4.003 to $4.301GHz$. The overall bandwidth of the predistorted sweep shifted about $3MHz$ upwards, which is not expected to affect distance measurement. However, bandwidth is decreased by about $2MHz$ in $300MHz$, corresponding to 1% distance error. In the experiments, this error can be neglected since experiments are done at short distances, and windowing can help reduce distance error caused by edges of the sweep. In Figure 4.16, a small decrease in sweep rate can be seen as a result of this bandwidth decrease.

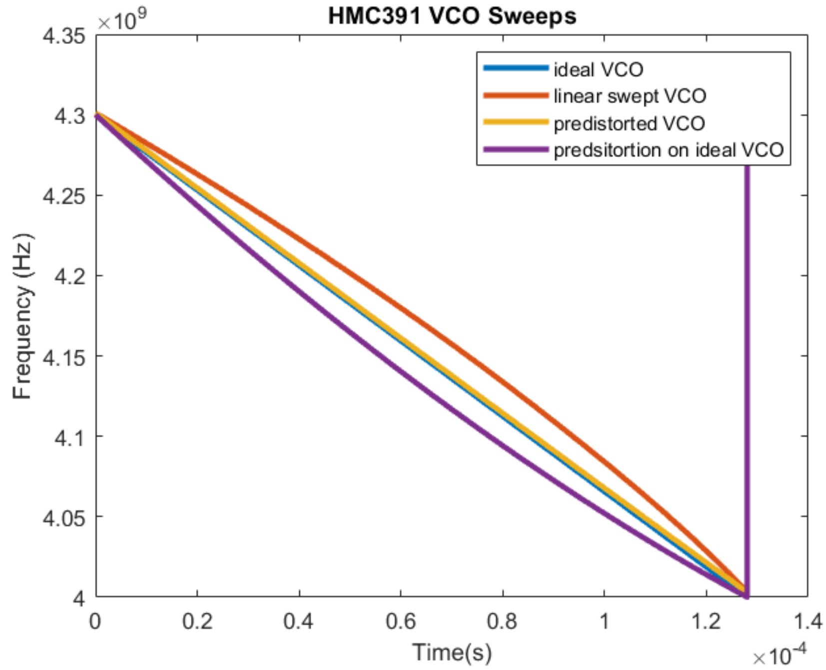

Figure 4.15: HMC391 VCO Sweeps, blue-ideal, red-linear swept, yellow-predistorted, purple-predistorted on ideal VCO

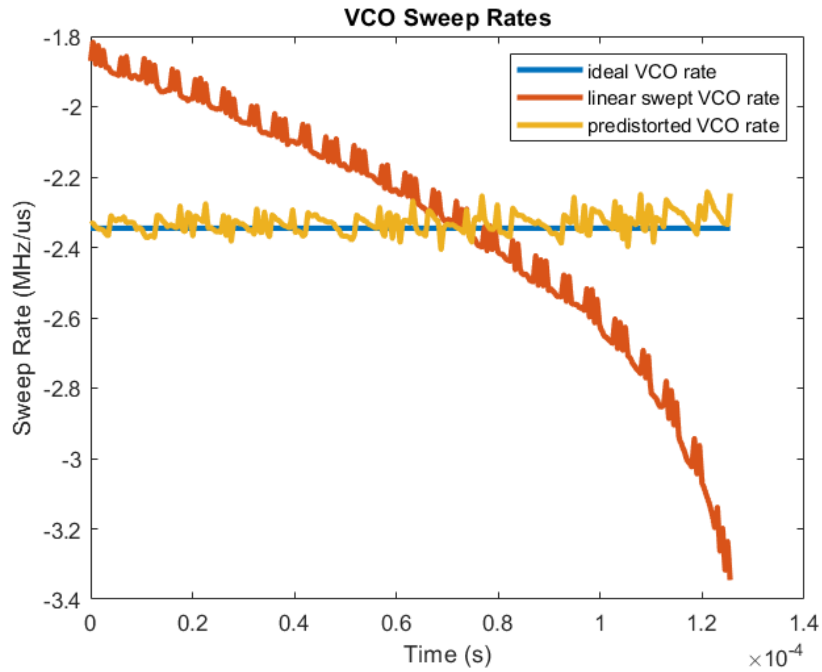

Figure 4.16: HMC391 VCO Sweeps Rates, blue-ideal, red-linear swept, yellow-predistorted, purple-predistorted on ideal VCO

The following figures compare measurements and simulations at different distances with and without predistortion applied. The results are compatible with each other. Measurement errors and spectral leakage are reduced in predistorted measurements, enabling the radar to measure correct distances.

With small adjustments in the delay lines, measurements of single target at exact frequency bin are given in Figures 4.19, 4.20 and 4.25, 4.26. The spectrums of the linearly swept VCO are spread to around 5 bins, and the peak location is shifted downwards. In the predistorted spectrums, the peak level is restored and the spread is narrowed to 3 bins like in the ideal case.

Also measurements of single target between frequency bins are given in Figures 4.17, 4.18,4.21, 4.22 and 4.23, 4.24. With predistortion applied, these spectrums also restored their spectral spread to lower bins, and their peak bins became closer to the correct distance, and the error level was reduced under 0.25m.

The response from multiple reflections also becomes narrower, and their spectral purity performance is increased. This can also help us understand the behaviors of the targets at further distances and performance improvements of predistortion at these distances.

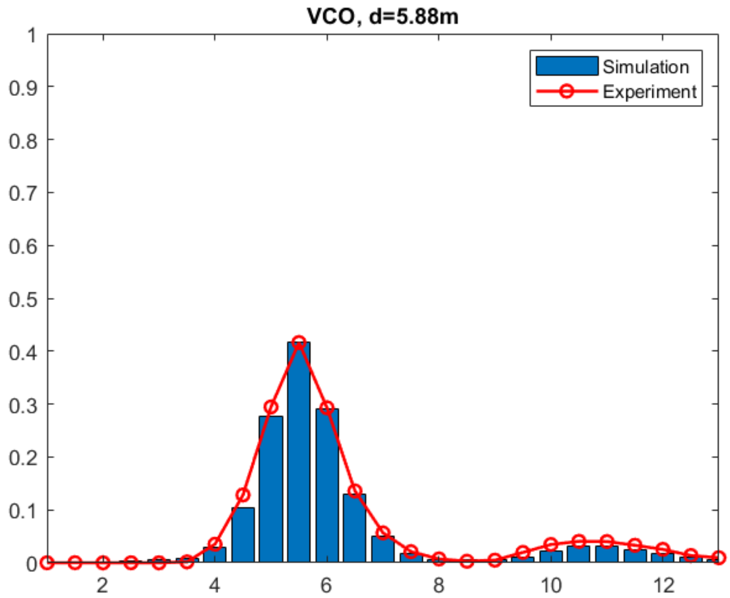

Figure 4.17: Linearly Swept VCO Results @5.88m, red-exp., blue-sim.

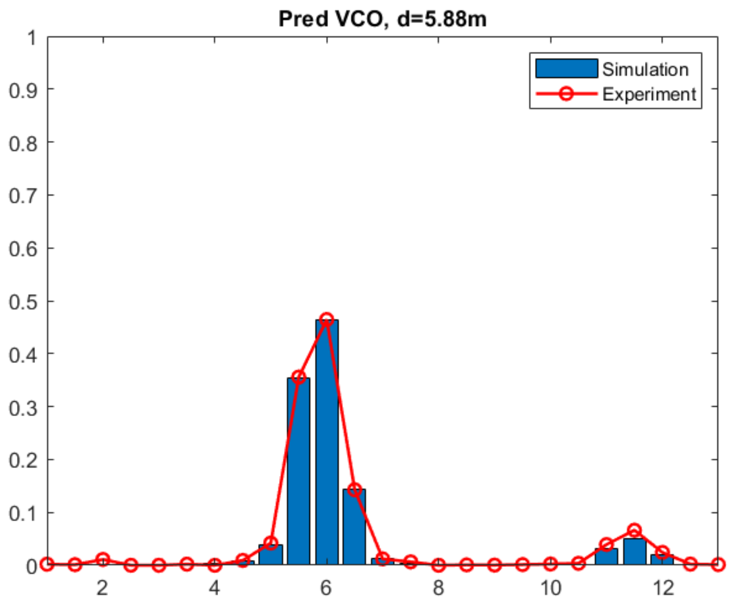

Figure 4.18: Predistortion applied VCO Results @5.88m, red-exp., blue-sim.

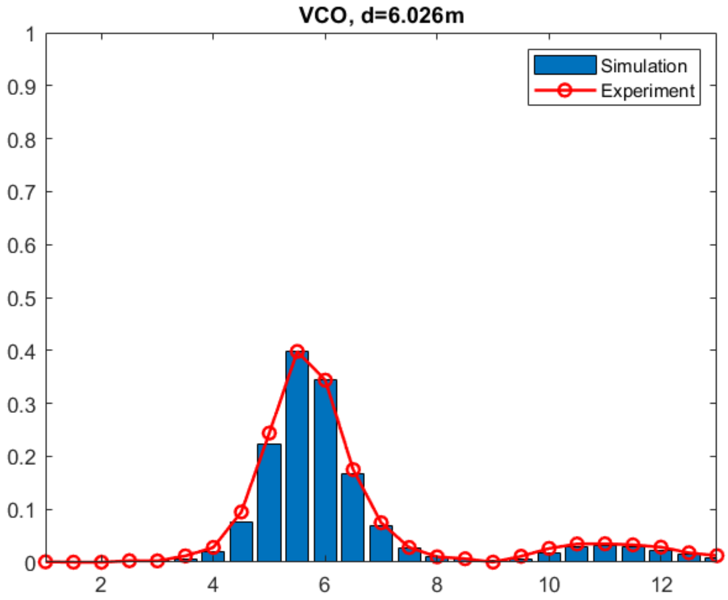

Figure 4.19: Linearly Swept VCO Results @6.026m, red-exp., blue-sim.

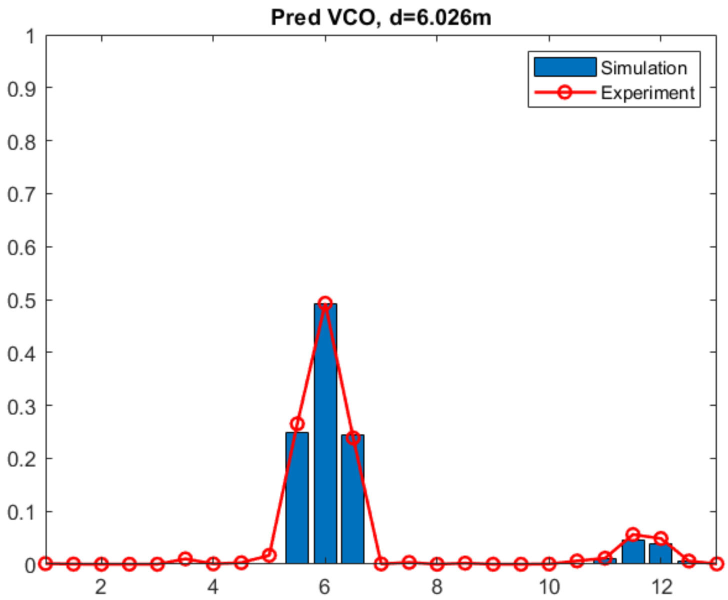

Figure 4.20: Predistortion applied VCO Results @6.026m, red-exp., blue-sim.

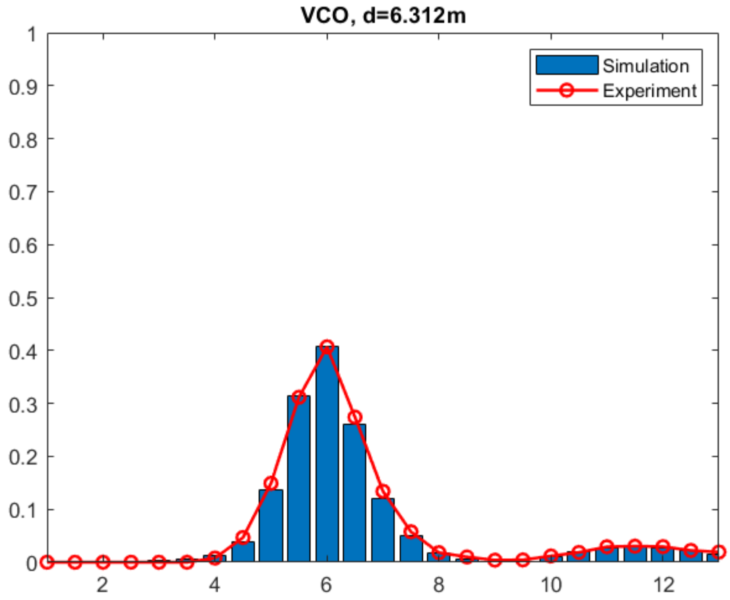

Figure 4.21: Linearly Swept VCO Results @6.312m, red-exp., blue-sim.

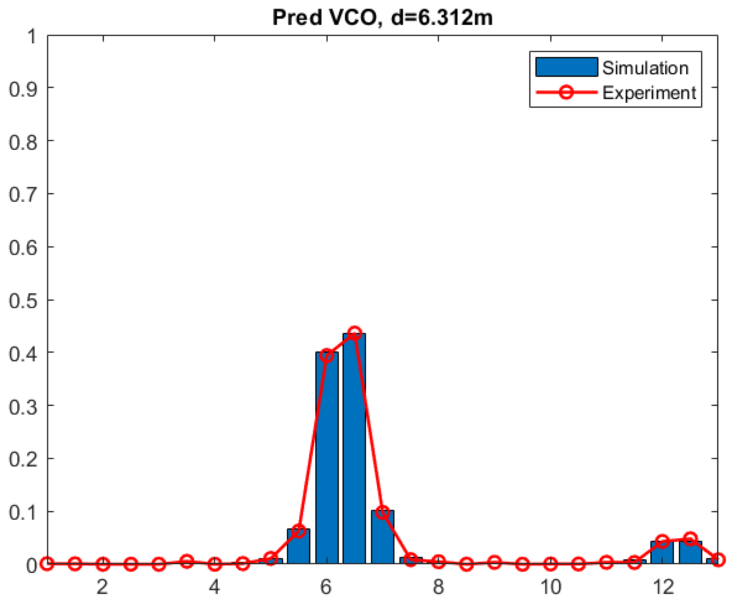

Figure 4.22: Predistortion applied VCO Results @6.312m, red-exp., blue-sim.

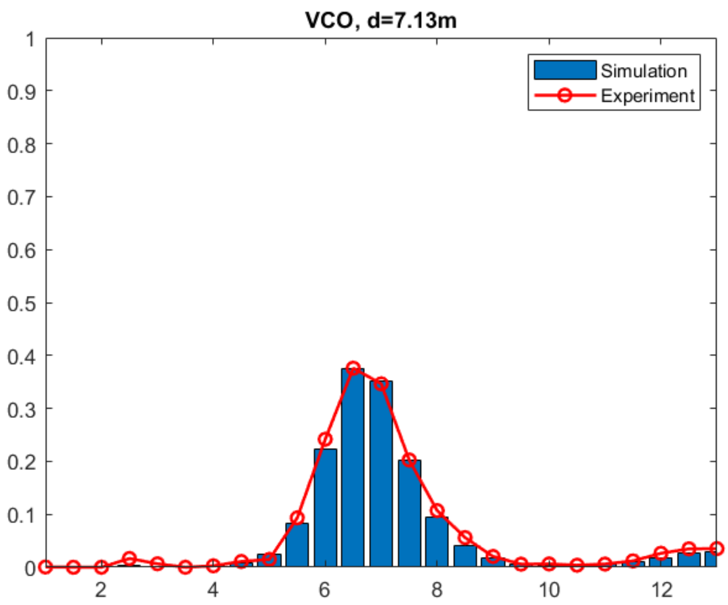

Figure 4.23: Linearly Swept VCO Results @7.13m, red-exp., blue-sim.

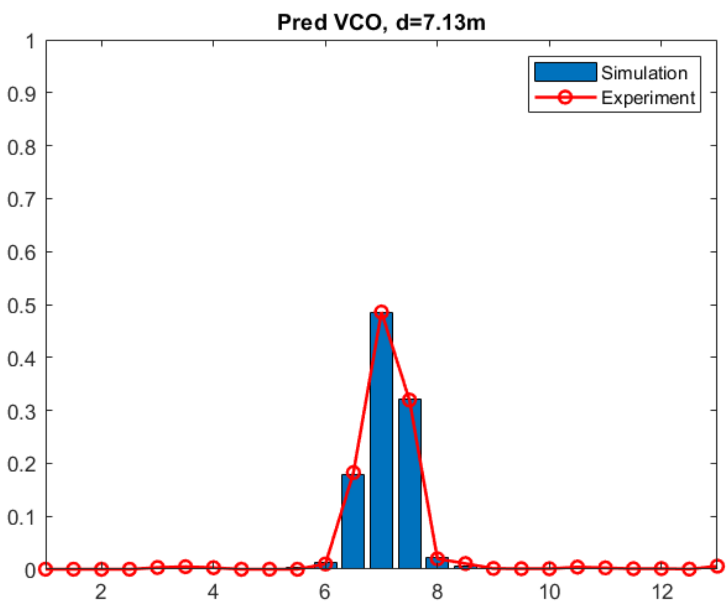

Figure 4.24: Predistortion applied VCO Results @7.13m, red-exp., blue-sim.

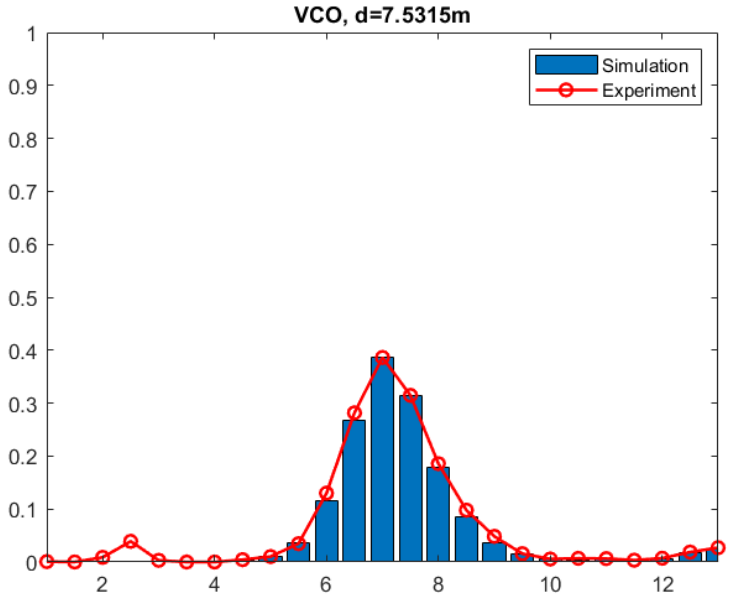

Figure 4.25: Linearly Swept VCO Results @7.53m, red-exp., blue-sim.

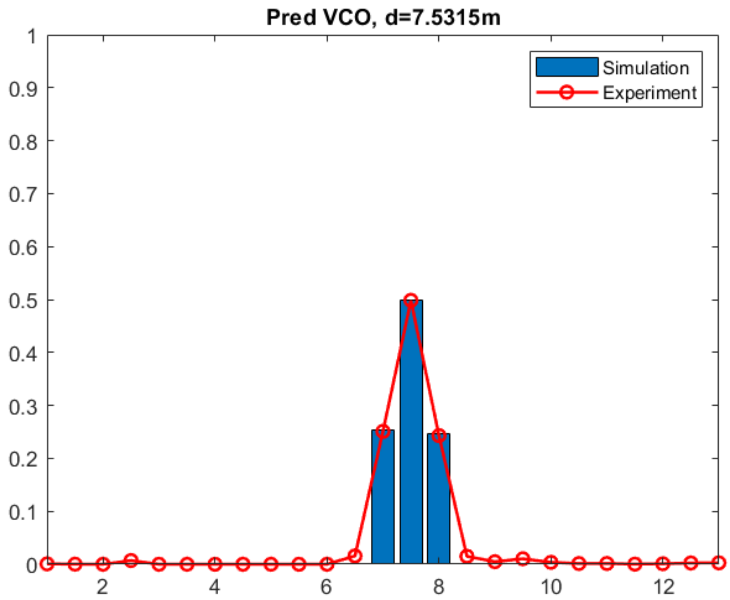

Figure 4.26: Predistortion applied VCO Results @7.53m, red-exp., blue-sim.

4.4 Evaluation

This chapter presents an evaluation of the experiment setups for VCO characterization and a comparison of the predistorted and distorted tune signals.

In the experiment setup, various methods for VCO characterization for predistortion were provided and compared. Using the oscilloscope in the setup that meets the radar's frequency requirements can provide more accurate results. This is because it takes into account other non-idealities in the radar during operation, enabling the preparation of a more precise predistortion signal.

When predistorted signals are used, the experimental and simulation results align well with each other. Linearly swept tune signals produce errors in both amplitude and peak locations. The predistortion technique significantly reduces distance measurement errors in both experimental and simulated environments. The consistency between experimental and simulation data validates the robustness of the predistortion approach, showing its potential to improve the precision and reliability of FMCW radar systems.

In the next chapter, the key findings of this research are summarized. The limitations of the study and directions for future research are addressed.

CHAPTER 5

CONCLUSIONS

5.1 Summary

This thesis explored the impact of predistortion on FMCW radar systems, especially addressing the nonlinearities introduced by VCOs. The effects of distortions in VCO frequency characteristics are examined with simulations and experiments. Applied predistortion technique with a lookup table increased radar performance in both cases. Two different methods are provided for characterizing VCOs, and their challenges and results are compared.

This study identified different nonlinear behaviors in VCO frequency characteristics that affect the accuracy and reliability of FMCW radars. These nonlinearities cause deviations in frequency sweeps that lead to inaccuracies in range range and velocity measurements. With both simulation and experimental validation, it is shown that the adverse effects of nonlinear VCO characteristics can be lowered with predistortion techniques by improving the linearity of the frequency sweep.

The simulations conducted in the MATLAB environment showed that applying predistortion to the VCO tune signal improved spectral purity and target detection accuracy. These simulations provided a controlled environment to isolate the impact of the different levels and types of distorted VCO signals and predistorted VCO tune signals on the performance of FMCW radar. The shape and level of distortion are examined. The distortions with different shapes can result in different types of errors in target detection. The level of distortion is mostly proportional to the deterioration of performance.

The real-world experiments showed similar results to simulation results and confirmed that predistorted VCOs performed better than linearly swept VCOs. The practical applicability of the prediction technique with the lookup table showed sufficient improvements in the performance of FMCW radars with design constraints, such as in fast- and short-range applications.

Two different methods for characterizing VCO tune nonlinearity and their results are compared. Both methods can be used to determine predistorted tune signals and increase radar performance. Their practical challenges are mentioned, and their limitations are discussed. The capability of the test equipment in the operation frequency band limits the use of the oscilloscope without additional tools and favors the other method. Measuring with a spectrum analyzer can help characterize VCOs with higher frequencies; however, it can be difficult and time-consuming if the VCO has time-varying frequency characteristics due to changes in the temperature during operation. Even the temperature drift does not affect the performance of FMCW radar during operation; during characterization, this phenomenon makes it harder to take healthy measurements.

5.2 Implications of the Research

Fast and short-range FMCW radars can use this method to increase performance when design requirements lead the designer to low cost, low complexity, and small geometry radar.

5.3 Limitations of the Study

This study primarily focused on nonlinearities in the VCO frequency sweep. Other sources of nonlinearities, such as amplifiers and mixers, are not extensively addressed. The research is done with a single FMCW radar design and a single type of VCO. This approach can affect results and make it difficult to generalize and evaluate other types of designs. Environmental factors like temperature rise are examined only by self-heating the circuit starting from room temperature. This approach can be problematic in radars with operations in various temperatures in different environments. Measuring and finding lookup tables for radars can add complexity to design when characteristics of other types of design are affected by environmental conditions, when wide part-to-part variations occur in VCOs, or when higher accuracy and wider range are required.

5.4 Future Research

Future research could explore other compensation techniques with all sources of non-linearity and distortion in FMCW radar systems.

Adaptive predistortion algorithms can be developed using this approach. Different look-up tables can be used in changing environmental conditions, and this method can be compared to other adaptive and non-adaptive solutions.

Extensive real-world tests can be conducted to evaluate other environmental and non-ideal conditions. Practical applicability can be tested in real operations or similar test setups.

Applicability in other RF systems can evaluated other than FMCW radars. This approach could open new possibilities for advanced radar technologies

To conclude, this thesis demonstrated the potential of predistortion techniques to improve the performance of FMCW radar systems. This practical solution enhances radar accuracy and reliability while providing less complex designs.

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