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escola superior de tecnologia e gestão
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Development of a Dual-Mode SAR Radar System for Non-Destructive Testing

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Master's Degree in Electrical and Electronic Engineering

Leiria, July 2026

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Dissertation

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Preparation of this work was facilitated by the use of the *IPLeiria-Thesis* template.

Acknowledgements

I would like to express my gratitude to my supervisors, Prof. Luís Duarte, Prof. Rafael Caldeirinha, and Prof. Telmo Fernandes, for their guidance, expertise, and continuous support throughout the development of this dissertation. Their knowledge, constructive feedback, and encouragement were fundamental to the successful completion of this work.

I would also like to thank the Instituto de Telecomunicações (IT) and the School of Technology and Management of Leiria (ESTG), Polytechnic University of Leiria, for providing access to the facilities, equipment, and research environment that made the experimental work presented in this dissertation possible.

My gratitude extends to my colleagues who contributed through technical discussions, suggestions, and assistance during the development and testing phases of the project.

Finally, I would like to thank my family for their continuous support, understanding, and encouragement throughout my academic journey. This accomplishment is as much theirs as it is mine.

Resumo

Esta dissertação propõe e avalia uma arquitetura para sistemas de imagem por radar de abertura sintética (SAR), tendo em vista aplicações de ensaio não destrutivo. O trabalho centra-se no desenvolvimento de uma plataforma de teste SAR capaz de realizar medições radar recorrendo a uma abertura sintética e, posteriormente, reconstruir imagens utilizando diferentes tecnologias de sensorização.

Foi proposta uma plataforma modular de medição, integrando um sistema robótico de posicionamento com múltiplas configurações de radar. Foram implementadas e avaliadas três abordagens, nomeadamente um radar comercial de onda contínua modulada em frequência (FMCW) baseado no sensor Texas Instruments AWR1843, uma configuração baseada num analisador vetorial de redes (VNA) e, posteriormente, a mesma configuração VNA a operar na banda milimétrica através da utilização de extensores de frequência. A plataforma desenvolvida permite a aquisição automática de dados, o processamento de sinal e a reconstrução de imagem através de algoritmos de retroprojeção SAR.

Foram realizados ensaios de validação para avaliar a influência da amostragem espacial, da frequência de operação e da largura de banda do sinal na qualidade das imagens reconstruídas. Os resultados demonstram que a largura de banda e a frequência de operação desempenham papéis complementares na formação de imagem SAR. Embora a configuração VNA tenha melhorado a resolução teórica em distância, devido à maior largura de banda disponível, a sua frequência inferior de operação resultou numa degradação da resolução transversal e numa redução da capacidade de caracterização dos alvos. Por outro lado, a configuração com extensores de frequência melhorou a qualidade das reconstruções ao combinar elevada largura de banda com comprimentos de onda mais reduzidos, à custa de um aumento da complexidade do sistema.

A plataforma proposta constitui uma bancada de ensaio flexível para investigação em SAR, permitindo a comparação direta entre sensores radar comerciais de baixo custo e instrumentação laboratorial de elevado desempenho sob condições equivalentes. Esta capacidade contribui para a compreensão dos compromissos existentes entre desempenho de imagiologia, complexidade do sistema e custo de implementação, estabelecendo simultaneamente uma base para futuros desenvolvimentos na área dos sistemas de imagem radar aplicados a ensaios não destrutivos.

Palavras-Chave: Radar de Abertura Sintética (SAR), Ensaios Não Destrutivos (END), Imagiologia Radar, Radar FMCW, Analisador Vetorial de Redes (VNA), Radar de Ondas Milimétricas, Reconstrução de Imagem, Inspeção Robótica.

Abstract

This dissertation proposes and evaluates an architecture for synthetic aperture radar (SAR) imaging systems with non-destructive testing applications in mind. The work focuses on the development of a SAR testbench platform capable of performing radar measurements with a synthetic aperture and then reconstructing images using different sensing technologies.

A modular measurement platform was proposed, integrating a robotic positioning system with multiple radar configurations. Three approaches were implemented and evaluated, namely a commercial frequency-modulated continuous-wave (FMCW) radar based on the Texas Instruments AWR1843 sensor, a vector network analyser (VNA)-based configuration, and then the same VNA with a millimetre-wave band through the use of frequency extenders. The developed platform enables automated data acquisition, signal processing, and image reconstruction using SAR backprojection algorithms.

Validation experiments were conducted to evaluate the influence of spatial sampling, operating frequency, and signal bandwidth on the quality of the reconstructed images. The results demonstrate that bandwidth and operating frequency play complementary roles in SAR image formation. Although the VNA configuration improved theoretical range resolution due to the larger available bandwidth, its lower operating frequency resulted in degraded cross-range resolution and reduced target characterisation capability. On the other hand, the frequency extender configuration improved reconstruction quality by combining large bandwidth with shorter wavelengths, at the expense of increased system complexity.

The proposed platform provides a flexible testbench for SAR research, enabling the direct comparison of low-cost commercial radar sensors and laboratory-grade instrumentation under equivalent experimental conditions. This capability contributes to the understanding of the trade-offs between imaging performance, system complexity, and implementation cost, while establishing a foundation for future developments in radar imaging systems for non-destructive testing applications.

Keywords: Synthetic Aperture Radar (SAR), Non-Destructive Testing (NDT), Radar Imaging, Frequency-Modulated Continuous-Wave (FMCW) Radar, Vector

Network Analyser (VNA), Millimetre-Wave Radar, Image Reconstruction, Robotic Inspection.

AI Acknowledgement

I acknowledge the use of Artificial Intelligence to refine the academic tone and improve the linguistic accuracy of this work, including aspects of grammar, punctuation, and vocabulary.

Contents

<i>List of Figures</i>	xi
<i>List of Tables</i>	xiii
<i>Acronyms</i>	1
1 Introduction	3
1.1 Motivation and Context	3
1.2 Research Objectives	5
1.3 Main Contributions	5
1.4 Scientific Dissemination	5
1.5 Dissertation Structure	6
2 State of the Art and Theoretical Background	7
2.1 Radar Fundamentals	7
2.1.1 Pulsed Radar	8
2.1.2 Continuous Wave Radar	9
2.1.3 Frequency-Modulated Continuous Wave Radar	10
2.1.4 Stepped-Frequency Continuous Wave Radar	11
2.1.5 Comparison of Radar Waveforms	13
2.1.6 Performance Metrics	13
2.2 Synthetic Aperture Radar Principles	14
2.2.1 Geometry and Signal Model	15
2.2.2 Coherent Integration and Image Formation	15
2.2.3 Two-Dimensional Planar SAR	16
2.2.4 Resolution Characteristics	16
2.2.5 Spatial Sampling Requirements	17
2.2.6 SAR Reconstruction Algorithms	17
2.3 SAR for Non-Destructive Testing	19
2.3.1 Near-Field and Far-Field Imaging	20
2.3.2 SAR Imaging Architectures	21
2.4 Chapter Summary	22

3	System Architecture	25
3.1	General System Overview	25
3.2	SAR Image Reconstruction Algorithm	26
3.2.1	Algorithm Development	27
3.2.2	Pre-Processing	28
3.2.3	Backprojection Reconstruction	28
3.3	SAR Scanning Geometry	29
3.3.1	Aperture Size and Resolution	30
3.4	Hardware and Sensor Configurations	30
3.4.1	FMCW Radar Instrumentation	31
3.4.2	VNA-Based Instrumentation	33
3.4.3	Robotic Scanning Platform	39
3.5	Chapter Summary	40
4	Experimental Results	43
4.1	FMCW Radar Configuration	43
4.1.1	Experimental Setup	44
4.1.2	System Validation	45
4.1.3	Image Reconstruction Results	48
4.1.4	Discussion	55
4.2	VNA Configuration	55
4.2.1	Experimental Setup	56
4.2.2	Validation Experiments	57
4.2.3	Image Reconstruction Results	61
4.2.4	Discussion	62
4.3	VNA Configuration with Range Extenders	63
4.3.1	Experimental Setup	63
4.3.2	System Validation	63
4.3.3	Image Reconstruction Results	67
4.3.4	Phase Centre Evaluation	71
4.4	Comparative Analysis	72
4.4.1	Reconstruction Performance Comparison	73
5	Conclusions and Future Work	75
5.1	Future Work	76
	<i>References</i>	77

List of Figures

2.1	2D-plane of spherical trajectory where the same distance R results in different positions.	8
2.2	Representation of generic pulsed radar signal waveform.	8
2.3	Representation of generic continuous-wave radar signal waveform. . . .	10
2.4	Representation of frequency-modulated continuous wave radar sawtooth modulation signal waveform.	11
2.5	Representation of generic stepped-frequency continuous wave radar signal waveform.	11
2.6	One-dimensional SAR acquisition geometry.	15
2.7	Two-dimensional planar SAR acquisition geometry.	17
3.1	General system architecture block diagram.	26
3.2	Conceptual representation of the SAR acquisition data cube.	27
3.3	SAR Image Reconstruction Algorithm Block Diagram.	27
3.4	Planar SAR acquisition geometry and scanning trajectory.	29
3.5	Texas Instruments AWR1843BOOST evaluation module [26].	31
3.6	Copper Mountain Technologies C4420 [27].	34
3.7	FEV-12 frequency extension module.	35
3.8	RF SPIN QRH0140 quad-ridged horn antenna [29].	36
3.9	Standard gain horn antennas covering the W-band (75–110 GHz) with 24 dBi gain.	37
3.10	WR-12 to WR-10 waveguide transition adapter.	37
3.11	Copper Mountain S2611 coaxial SOLT calibration kit.	38
3.12	Farran FEK-12-0006 WR-12 precision waveguide calibration kit.	38
3.13	Dial test indicator setup used for robotic arm positioning accuracy characterisation.	40
4.1	FMCW radar experimental setup.	44
4.2	Effect of spatial sampling step size on SAR image quality. Reconstructed images of a pentagonal target for step sizes of (a) 1 mm, (b) 2 mm, (c) 4 mm, and (d) 8 mm.	46
4.3	Experimental evaluation of the AWR1843 range resolution.	47

4.4	Comparison between the target with circular, rectangular and triangular cut-outs and its reconstructed SAR image.	48
4.5	Comparison between the enclosed target sample and its reconstructed SAR image.	49
4.6	Comparison between the large pentagon target and its reconstructed SAR image.	50
4.7	Comparison between the small pentagon target and its reconstructed SAR image.	50
4.8	Comparison between the physical multi-geometry target and its reconstructed SAR image.	51
4.9	Comparison between the target containing the IT logo and its reconstructed SAR image.	52
4.10	Comparison between the target containing multiple inscriptions and its reconstructed SAR image.	52
4.11	Three-dimensional target and reconstructed SAR images obtained at different reconstruction depths.	54
4.12	VNA-based radar experimental setup.	56
4.13	VNA-based radar range resolution analysis.	58
4.14	One-dimensional synthetic aperture experiment with 160 mm aperture size.	59
4.15	One-dimensional synthetic aperture experiment with 400 mm aperture size.	60
4.16	Power delay profiles of all four S-parameters for a single aperture position.	60
4.17	Reconstructed image obtained using the large pentagonal PCB target with the VNA-based sensing configuration.	61
4.18	VNA-based radar with range extenders experimental setup.	64
4.19	Effect of spatial sampling step size on VNA-based SAR with frequency extenders image quality. Reconstructed images of a pentagonal target for step sizes of (a) 1 mm, (b) 4 mm, (c) 8 mm, and (d) 16 mm.	65
4.20	VNA-based radar range resolution analysis.	66
4.21	Reconstructed image obtained using the large pentagonal PCB target with the VNA-based sensing configuration with range extenders.	67
4.22	Reconstructed image obtained using the small pentagonal PCB target with the VNA-based sensing configuration with range extenders.	68
4.23	Reconstructed image obtained using the “30 Years Instituto de Telecomunicações” target with the VNA-based sensing configuration with range extenders.	69
4.24	Horizontal intensity profile extracted through the reconstructed image of the “30 Years Instituto de Telecomunicações” target.	70
4.25	Experimental setup to analyse the influence of phase centre variation.	71

List of Tables

2.1	Comparison of common radar waveforms.	13
3.1	Principal acquisition parameters used for the AWR1843 radar configuration.	32
3.2	RF SPIN QRH0140 antenna electrical specifications [29].	37
3.3	Principal acquisition parameters for the VNA-based sensing configurations.	39
3.4	Principal specifications of the Kinova Gen3 7-DoF robotic arm [31]. . .	39
4.1	Acquisition parameters used for automated SAR evaluation experiments using COTS radar.	45
4.2	Dimensional accuracy of the reconstructed pentagonal targets using the FMCW configuration.	50
4.3	Acquisition parameters used for automated SAR evaluation experiments using VNA-based radar.	57
4.4	Acquisition parameters used for automated SAR evaluation experiments using VNA-based radar with frequency extenders.	64
4.5	Dimensional accuracy of the reconstructed pentagonal targets using the VNA configuration with frequency extenders.	69
4.6	Comparison of dimensional errors obtained using the FMCW and VNA frequency extender configurations.	73

Acronyms

COTS	Commercial Off-The-Shelf. (p. 1, 15)
CW	Continuous Wave. (p. 4, 5)
FFT	Fast Fourier Transform. (p. 13)
FMCW	Frequency-Modulated Continuous Wave. (p. 1, 2, 5–9, 13, 15, 16)
MIMO	Multiple-Input and Multiple-Output. (p. 13)
NDT	Non-Destructive Testing. (p. 1, 10, 13, 14, 16)
RF	Radio Frequency. (p. 1)
RMA	Range Migration Algorithm. (p. 13–15)
SAR	Synthetic Aperture Radar. (p. 1–3, 7, 8, 10–16)
SFCW	Stepped-Frequency Continuous Wave Radar. (p. 6–8, 15, 16)
ToF	Time-of-Flight. (p. 3)
VNA	Vector Network Analyser. (p. 1, 2, 6, 15, 16)

1

Introduction

This chapter introduces the motivation, objectives, and contributions of the present work. It begins by discussing the role of radar-based imaging techniques in non-destructive testing and the challenges associated with the selection of suitable sensing architectures for SAR applications. The research objectives and main contributions are then presented, followed by a summary of the scientific dissemination activities and the overall structure of the work.

1.1 Motivation and Context

Non-Destructive Testing (NDT) plays a fundamental role in the inspection of structures and industrial components. In sectors such as aerospace [1], energy production [2, 3], and advanced manufacturing [4], the ability to detect defects without damaging the inspected object is of great importance for ensuring safety, reliability, and efficient resource utilisation. As engineering systems become increasingly complex, there is a growing demand for inspection techniques capable of providing detailed information about both the internal and external condition of components while minimising downtime and operational costs.

Traditional NDT techniques such as visual inspection, ultrasonic testing, radiography, and computed tomography remain widely used throughout industry. However, each method presents specific limitations. Visual inspection is restricted to surface-accessible defects, ultrasonic techniques often require direct contact and coupling media, while radiographic methods involve safety considerations, high equipment costs, and limited portability. Consequently, there is continued interest in alternative sensing technologies capable of providing rapid, non-contact inspection while maintaining sufficient spatial resolution for defect detection and material characterisation.

Among the various sensing technologies employed in NDT, Radio Frequency (RF) techniques offer several advantages, including non-contact operation, rapid measurements, and the ability to inspect structures that may be inaccessible to

conventional methods. In particular, radar-based imaging has attracted significant attention due to its capability to detect features hidden and generate spatial representations of inspected samples.

Synthetic Aperture Radar (SAR) is a radar imaging technique capable of producing high-resolution images by coherently combining measurements acquired at multiple spatial positions. Originally developed for airborne and spaceborne remote sensing applications, **SAR** has increasingly been adopted in close-range imaging scenarios, including non-destructive testing. By synthesising a large virtual aperture through controlled sensor motion, **SAR** systems can achieve spatial resolutions that would otherwise require physically impractical antenna dimensions.

Conventional radar systems often suffer from limited spatial resolution, particularly when compact antennas are employed. For non-destructive testing applications, where small structural features and defects may be of interest, this limitation can significantly reduce the usefulness of the acquired measurements. Synthetic aperture techniques overcome this constraint by exploiting controlled sensor motion to synthesise a larger effective aperture, enabling substantially improved image resolution without requiring physically large antennas.

Recent advances in millimetre-wave electronics have enabled the development of compact and affordable radar sensors suitable for **SAR** imaging. **Commercial Off-The-Shelf (COTS)** sensors based on **Frequency-Modulated Continuous Wave (FMCW)** radar provide an attractive solution due to their low cost, compact form factor, and ease of integration, albeit with limited signal bandwidth. Alternatively, **Vector Network Analyser (VNA)**-based systems can provide substantially larger bandwidths and superior measurement fidelity, potentially enabling higher-resolution imaging at the expense of increased system complexity and cost. The selection of an appropriate sensing architecture therefore involves balancing imaging performance, acquisition speed, portability, implementation complexity, and cost.

Although both **FMCW** and **VNA**-based sensing approaches have been successfully employed in **SAR** imaging, direct experimental comparisons are relatively uncommon because they are typically developed on different hardware platforms and evaluated under different acquisition conditions. As a result, it is often difficult to isolate the individual influence of operating frequency, signal bandwidth, and sensing architecture on the resulting image quality.

This work was developed within the INOV.AM project, which aims to promote innovation and digital transformation in advanced manufacturing through the integration of emerging technologies, automation, and intelligent inspection solutions. Within this context, radar-based non-destructive testing represents a promising approach for the inspection and characterisation of manufactured components.

1.2 Research Objectives

The main objective of this dissertation is to develop and validate a modular SAR imaging platform capable of operating with different sensing technologies under a common acquisition and processing framework. In particular, the work seeks to evaluate the feasibility of combining commercial low-cost radar sensors and laboratory-grade instrumentation within the same experimental platform, enabling direct performance comparisons under equivalent acquisition conditions.

To achieve this objective, the following research goals were defined:

- Develop an automated robotic SAR acquisition platform;
- Integrate multiple sensing modalities within a common acquisition and reconstruction framework;
- Evaluate the imaging performance of FMCW and VNA-based sensing configurations;
- Investigate the influence of signal bandwidth and operating frequency on SAR image quality;
- Assess the suitability of the proposed platform for radar-based NDT applications.

1.3 Main Contributions

The main contributions of this work are threefold. First, a modular and unified SAR architecture is proposed, integrating robotic positioning, automated acquisition, signal processing, and image reconstruction. Second, the developed platform enables the direct comparison of multiple radar sensing configurations, including FMCW and VNA-based systems. Finally, the experimental results provide insight into the influence of signal bandwidth and operating frequency on SAR image quality, contributing to the understanding of the trade-offs associated with different sensing architectures for non-destructive testing applications.

1.4 Scientific Dissemination

Part of the work developed within this dissertation was disseminated through the conference paper:

F. Lopes, T. Frade, L. Duarte, J. R. Reis, and R. F. S. Caldeirinha, “Automated Shape Classification for Non-Destructive Testing Using mmWave Synthetic Aperture Radar,” in Proceedings of the European Conference on Antennas and Propagation (EuCAP), Accepted for publication, Dublin, Ireland, Apr. 2026.

Additionally, a journal paper based on the work presented in this dissertation is currently under development for submission to an IEEE journal, under the provisional title “A Unified Robotic SAR Testbed for Comparative Evaluation of VNA and COTS Radar Systems for Non-Destructive Testing.”

1.5 Dissertation Structure

The remainder of this dissertation is organised as follows. Chapter 2 presents the theoretical background and reviews the state of the art related to radar systems, SAR imaging principles, and VNA-based sensing approaches. Chapter 3 describes the developed SAR platform, including the acquisition framework, hardware configurations, and image reconstruction methodology. Chapter 4 presents the experimental procedures and discusses the results obtained with the different sensing configurations. Finally, Chapter 5 summarises the main findings of this work and outlines directions for future research.

2

State of the Art and Theoretical Background

This chapter presents the theoretical foundations of [Synthetic Aperture Radar \(SAR\)](#) systems while integrating a review of the current state of the art. The discussion will cover radar fundamentals, [SAR](#) signal modelling, reconstruction techniques, system architectures, and sampling constraints, establishing the basis for the system architecture developed in this work.

2.1 Radar Fundamentals

An active radar system transmits an electromagnetic wave into space and receives the reflected echo from targets after a time delay (Δt). By measuring this delay between the transmitted and received signals, also known as [Time-of-Flight \(ToF\)](#), it becomes possible to determine the target's distance [5]. This distance, denoted as R , is calculated according to Eq. 2.1.

$$R = \frac{c\Delta t}{2}, \quad (2.1)$$

where c represents the wave propagation speed assuming free space. The factor of two accounts for the round-trip path between the radar and target [5].

Since R represents only the target radial distance, it does not contain sufficient information to determine its spatial position. Consequently, any target located at the same distance from the radar will result in the same measurement, as illustrated in Fig. 2.1.

Therefore, it is appropriate to describe the target's position using spherical coordinates. Its location can be represented by the radial distance to the radar and two angles, the azimuthal angle (θ), defined in the horizontal plane, and the zenith angle (ϕ), in the vertical plane [5].

Radar systems can be classified according to the waveform used for signal

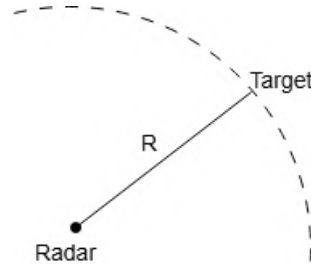


Figure 2.1: 2D-plane of spherical trajectory where the same distance R results in different positions.

transmission. Different waveforms are suited to different operational requirements and applications. Among the most common approaches are pulsed and continuous-wave architectures, the latter including techniques such as [Frequency-Modulated Continuous Wave \(FMCW\)](#) and [Stepped-Frequency Continuous Wave Radar \(SFCW\)](#) radar. The operating principles of these approaches are reviewed in the following sections.

Additionally, other properties may be of interest, such as velocity or geometric characteristics, which can be determined in various ways based on the type of radar operating mode utilised.

2.1.1 Pulsed Radar

Pulsed radar is the basis of many long-range surveillance and tracking systems. In this approach, the radar transmits short bursts of electromagnetic energy separated by intervals during which the receiver listens for echoes returning from the illuminated targets [5].

Figure 2.2 illustrates the basic operating principle of a pulsed radar. The transmitted signal consists of pulses with duration τ repeated every pulse repetition interval T . During the interval between transmitted pulses, the receiver monitors the scene for returning echoes. The time delay between a transmitted pulse and its corresponding echo is directly related to the target distance.

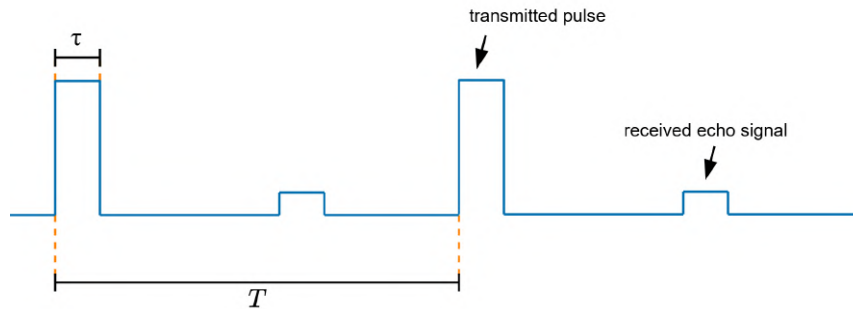


Figure 2.2: Representation of generic pulsed radar signal waveform.

The target range is determined directly from the measured round-trip propagation time between the transmitted pulse and the received echo according to Equation 2.1. Since transmission and reception occur at different times, pulsed

radar systems can estimate target distance without requiring frequency modulation.

The pulse repetition interval T determines the maximum unambiguous range of the radar, since echoes must return before the next pulse is transmitted. The corresponding maximum unambiguous range is given by Eq. 2.2 [5].

$$R_{\max} = \frac{cT}{2}, \quad (2.2)$$

where c is the speed of light.

The achievable range resolution depends primarily on the pulse duration τ . Two targets can only be distinguished if their echoes do not significantly overlap in time. Consequently, the range resolution of a pulsed radar is given by Eq. 2.2 [5].

$$\Delta R = \frac{c\tau}{2}, \quad (2.3)$$

indicating that shorter pulses provide finer range resolution. However, reducing τ requires larger signal bandwidths and more demanding transmitter hardware.

Pulsed radar systems also benefit from high peak transmit power, enabling long detection ranges while maintaining moderate average power consumption.

A limitation of pulsed radar systems is the existence of a blind range. During pulse transmission, the receiver is typically unable to detect incoming echoes, preventing the observation of targets located at short distances from the antenna. Furthermore, the hardware required to generate short high-power pulses can increase system complexity and cost compared to continuous-wave alternatives.

2.1.2 Continuous Wave Radar

Continuous Wave (CW) radar transmits a continuous signal at a constant carrier frequency, without interruption. Unlike pulsed radar systems, there is no temporal reference associated with individual transmissions. Consequently, the propagation delay cannot be measured directly, making it impossible to determine the absolute target distance from a single continuous-wave measurement.

Figure 2.3 illustrates the operating principle of a **CW** radar. The transmitted signal propagates towards a target located at a distance R and is reflected back to the receiver. Due to the propagation path, the received signal exhibits a phase shift φ relative to the transmitted waveform. The signal wavelength is denoted by λ .

Although the phase shift is related to the propagation distance, it is periodic with 2π . As a result, multiple target ranges separated by integer multiples of the wavelength produce the same measured phase, creating an ambiguity that prevents unique range estimation.

On the other hand, **CW** radar is frequently used to estimate the radial velocity of a target by exploiting the Doppler effect. When the transmitted signal is reflected by a target in relative motion, the received frequency (f_r) differs slightly

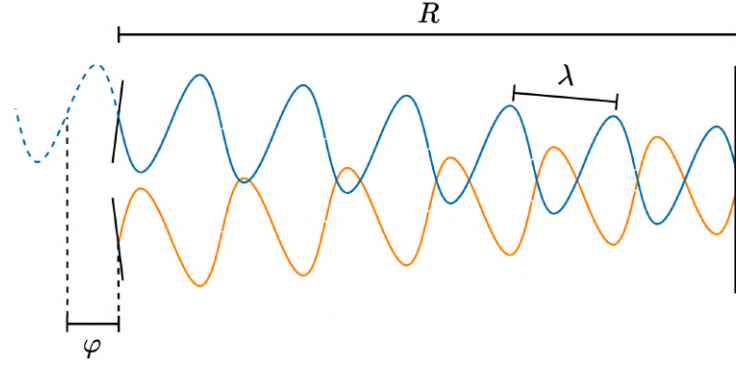


Figure 2.3: Representation of generic continuous-wave radar signal waveform.

from the transmitted frequency (f_t). The difference between these frequencies is known as the Doppler frequency (f_d), which is directly proportional to the target radial velocity (v) [5]. The relationship is given by Eq. 2.4.

$$f_d = f_r - f_t = \frac{2v f_t}{c} \quad (2.4)$$

Therefore, while conventional CW radar cannot determine the absolute range of a target, it provides an efficient and accurate means of measuring radial velocity.

2.1.3 Frequency-Modulated Continuous Wave Radar

Frequency-Modulated Continuous Wave (FMCW) radar emerged as an evolution of conventional CW radar, allowing for the simultaneous measurement of both target distance and velocity. To overcome the lack of a temporal reference in the CW signal, FMCW radar varies the transmitted signal frequency over time through a process known as modulation.

The most common method is linear modulation, where the frequency increases or decreases linearly, creating a signal known as a chirp [5]. This signal is defined by a bandwidth (B) and a sweep time (T_{chirp}), which determines the slope of the frequency ramp (S), calculated using Eq. 2.5.

$$S = \frac{B}{T_{chirp}} \quad (2.5)$$

Operating Principle

In an FMCW radar system, the signal reflected by the target is received with a time delay (Δt) relative to the signal currently being transmitted. Since the transmission frequency is constantly varying, the received signal has a different frequency from the transmitter's current frequency. By mixing both signals, a new signal known as the beat frequency (f_{IF}), or intermediate frequency, is obtained. Figure 2.4 illustrates the relationship between a transmitted chirp signal (in blue)

and the received signal (in orange) using sawtooth modulation in the time-frequency domain.

For a linear frequency modulation, the beat frequency is directly proportional to the time delay and, consequently, to the target's distance R . The relationship is described by Eq. 2.6 [5].

$$f_{IF} = S \cdot \Delta t = S \cdot \frac{2R}{c} \quad (2.6)$$

By rearranging Eq. 2.6, the distance to the target can be calculated as shown in Eq. 2.7.

$$R = \frac{c \cdot f_{IF}}{2S} \quad (2.7)$$

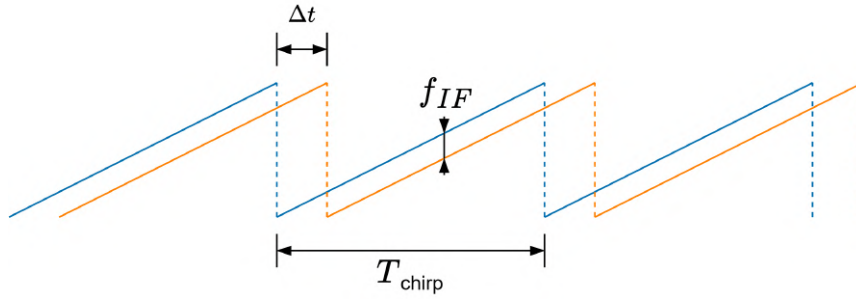


Figure 2.4: Representation of frequency-modulated continuous wave radar sawtooth modulation signal waveform.

2.1.4 Stepped-Frequency Continuous Wave Radar

Stepped-Frequency Continuous Wave Radar (SFCW) radar is an alternative ranging technique that combines characteristics of both continuous-wave and wideband radar systems. Instead of transmitting a continuously varying frequency chirp, the radar sequentially transmits a set of discrete continuous-wave tones distributed across a predefined bandwidth, as illustrated in Figure 2.5 [6].

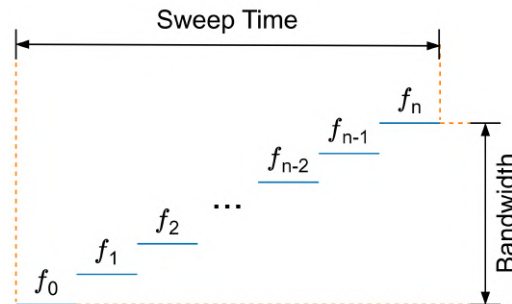


Figure 2.5: Representation of generic stepped-frequency continuous wave radar signal waveform.

Unlike FMCW radar, where range information is obtained from the frequency difference between transmitted and received signals, SFCW radar extracts target

information from the amplitude and phase response measured at each transmitted frequency. By synthesizing a wide bandwidth from a sequence of narrowband measurements, the technique is capable of achieving high range resolution while maintaining relatively simple hardware requirements.

Since each frequency component is measured individually, **SFCW** systems can achieve high frequency accuracy and offer flexible bandwidth configuration. These characteristics make **SFCW** particularly attractive for laboratory instrumentation, precision measurements, and high-resolution imaging applications.

However, the sequential acquisition process generally results in longer measurement duration compared to **FMCW** systems, making **SFCW** less suitable for rapidly changing scenes. Furthermore, target motion during the frequency sweep may introduce phase inconsistencies that degrade the reconstructed response.

SFCW principles are commonly employed in radar systems based on **Vector Network Analyser (VNA)**, where the complex frequency response of the scene is measured directly and subsequently can be used for range profiling and **SAR** image reconstruction.

Operating Principle

In an **SFCW** radar system, the scene is illuminated sequentially using a set of discrete frequencies f_k . At each frequency step, the complex response of the target is measured, preserving both amplitude and phase information.

For a point target located at a distance R , the received signal at frequency f_k can be expressed as shown in Eq. 2.8 [6].

$$s(f_k) = A e^{-j \frac{4\pi f_k R}{c}}, \quad (2.8)$$

where A represents the target reflectivity and propagation losses, and c is the speed of light. The exponential term corresponds to the round-trip propagation delay experienced by the electromagnetic wave. As the transmitted frequency changes, the phase of the received signal evolves proportionally to the target distance.

After all frequency steps have been acquired, the resulting frequency-domain response is transformed into the range domain using an inverse Fourier transform. This operation coherently combines the phase information measured at each frequency, producing a range profile in which peaks correspond to targets located at different distances. Therefore, while **FMCW** radar estimates range from the beat frequency generated by a frequency-modulated chirp, **SFCW** radar determines range from the phase progression measured across the frequency sweep.

2.1.5 Comparison of Radar Waveforms

The waveform employed by a radar system directly influences its ranging capability, resolution, hardware complexity, and acquisition speed. Pulsed, FMCW, and SFCW radar systems each present distinct advantages and limitations, making them suitable for different applications. Table 2.1 summarises the main characteristics of the three approaches discussed in this chapter.

Table 2.1: Comparison of common radar waveforms.

Characteristic	Pulsed	FMCW	SFCW
Range measurement	TOF	Beat frequency	IDFT
Range resolution	High BW dependent	High BW dependent	High BW dependent
Energy Consumption	Moderate	Low	Low
Blind range	Present	Negligible	Negligible
Dynamic range	Moderate	Moderate	High
Acquisition speed	High	High	Low
Hardware complexity	High	Moderate	High

The choice of waveform depends strongly on the intended application. Pulsed radar systems are the preferred solution for long-range surveillance due to their ability to transmit high peak power and achieve large detection ranges. However, the generation of short high-power pulses often increases hardware complexity and cost.

FMCW radar has become the dominant approach in modern short-range sensing applications. By continuously transmitting low-power chirps, FMCW radar systems provide simultaneous range and velocity estimation while benefiting from compact and highly integrated hardware implementations.

SFCW radar offers an alternative approach in which the frequency response of the scene is measured directly. Although acquisition times are generally longer, SFCW systems can achieve higher dynamic range and flexible bandwidth configurations, making them particularly attractive for high-resolution imaging and laboratory-based measurements.

Among the waveforms discussed, FMCW and SFCW are particularly attractive for close-range imaging applications due to their ability to achieve high range resolution while operating with relatively low transmit power.

2.1.6 Performance Metrics

Range Resolution

One of the fundamental characteristics of a radar system, particularly relevant for SAR applications, is its range resolution (ΔR). This represents the radar's ability to distinguish between two targets that are close to each other. The resolution is inversely proportional to the bandwidth of the signal [5, 7], as shown in Eq. 2.9.

$$\Delta R \approx \frac{c}{2B}, \quad (2.9)$$

where B is the bandwidth in Hz.

Angular Resolution

Angular resolution defines the radar's ability to distinguish between two targets located at the same range but separated in angular domain. It is determined by the antenna beamwidth, which is in turn determined by the physical aperture of the antenna. For an antenna of length L_a operating at wavelength λ , the half-power beamwidth in the corresponding plane is approximately given by Eq. 2.10 [8].

$$\theta_{3dB} \approx \frac{\lambda}{L_a} \quad (2.10)$$

The corresponding cross-range resolution at a distance R from the radar is given by Eq. 2.11 [8, 9].

$$\Delta_x = R \cdot \theta_{3dB} \approx \frac{R\lambda}{L_a}, \quad (2.11)$$

Unambiguous Range

The unambiguous range defines the maximum distance at which a target can be correctly identified without ambiguity. In **FMCW** radar systems, this limitation is associated with the chirp repetition period, as echoes from distant targets may overlap with subsequent transmitted signals if the round-trip delay exceeds the sweep duration [5].

Dynamic Range

Dynamic range refers to the radar system's ability to detect weak reflections in the presence of strong signals. It is defined as the ratio between the maximum and minimum detectable signal levels, typically limited by receiver sensitivity and noise floor for the lower boundary, and saturation point or compression point for upper boundary [5].

2.2 Synthetic Aperture Radar Principles

Synthetic Aperture Radar is an imaging technique that achieves high spatial resolution by synthesizing a large virtual aperture through the coherent combination of measurements acquired at multiple spatial positions. By moving the radar along a predefined trajectory and recording the backscattered signal at each position, it is possible to emulate a physically large antenna, thereby

improving the cross-range resolution beyond the limitations imposed by the antenna size and radar resolution [9].

2.2.1 Geometry and Signal Model

A radar platform is assumed to translate along the x -axis (azimuth direction), occupying discrete positions x_n , as illustrated in Figure 2.6. At each position, the system transmits and receives a signal. A stationary point target located at (x_t, y_t, z_t) is observed from each radar position $(x_n, 0, 0)$, resulting in an instantaneous slant range given by Eq. 2.12 [10].

$$R(x_n) = \sqrt{(x_n - x_t)^2 + y_t^2 + z_t^2} \quad (2.12)$$

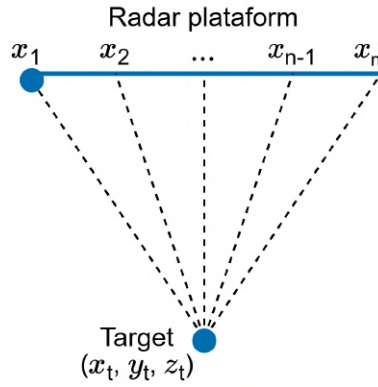


Figure 2.6: One-dimensional SAR acquisition geometry.

The received signal can be represented in complex form, where both amplitude and phase information are preserved. Assuming a narrowband response at frequency f , the received signal at position x_n can be expressed by Eq. 2.13 [7].

$$s(x_n, f) = A e^{-j \frac{4\pi f}{c} R(x_n)}, \quad (2.13)$$

where A represents the target reflectivity and propagation losses, c is the speed of light, and the phase term accounts for the round-trip propagation distance. The factor of 4π arises from the two-way propagation between the radar and the target.

In a bistatic configuration, the phase depends on the sum of the transmitter–target and target–receiver distances. However, when the separation between antennas is small compared to the target range, the system can be accurately approximated as monostatic, allowing the phase to be expressed using an effective round-trip distance [11].

2.2.2 Coherent Integration and Image Formation

SAR image reconstruction is based on the coherent integration of the received signals across the synthetic aperture. For a given reconstruction point (x, y, z_0) ,

the phase associated with each acquisition position is compensated, and the contributions are summed to achieve constructive interference at the true target location.

This process can be expressed by Eq. 2.14 [12].

$$I(x, y; z_0) = \sum_n S(x_n, f) e^{-j \frac{4\pi}{\lambda} R_n(x, y, z_0)}, \quad (2.14)$$

where $I(x, y; z_0)$ represents the reconstructed image intensity at each pixel location (x, y) in the reconstruction plane located at depth z_0 , $S(f, x_n)$ is the measured frequency-domain signal at position x_n , λ is the wavelength, and $R_n(x, y, z_0)$ is the distance between the acquisition point and the reconstruction point. This coherent summation aligns the phase of signals originating from the same spatial location, resulting in a focused reflectivity map of the scene.

2.2.3 Two-Dimensional Planar SAR

In practical close-range NDT applications, the radar is scanned over a two-dimensional rectangular grid in the xy plane, as illustrated in Figure 2.7, collecting measurements at positions (x_m, y_n) for $m = 1, \dots, M$ and $n = 1, \dots, N$. The received signal model of Equation 2.13 extends to this configuration as shown in Eq. 2.15 [13].

$$s(x_m, y_n, f) = A(x_t, y_t) e^{-j \frac{4\pi f}{c} R(x_m, y_n, x_t, y_t)}, \quad (2.15)$$

where $R(x_m, y_n, x_t, y_t)$ results from Eq. 2.16.

$$R(x_m, y_n, x_t, y_t) = \sqrt{(x_m - x_t)^2 + (y_n - y_t)^2 + z_t^2}, \quad (2.16)$$

which represents the range from each antenna position to the target. The ensemble of measurements forms a three-dimensional data cube $s(x_m, y_n, f)$, from which the focused reflectivity image is reconstructed by extending Eq 2.14 in both spatial dimensions.

2.2.4 Resolution Characteristics

The performance of a SAR system is primarily determined by its range and cross-range resolution.

The range resolution depends on the signal bandwidth B and is given by [14]

$$\Delta R = \frac{c}{2B}, \quad (2.17)$$

indicating that larger bandwidths enable finer resolution along the radial direction.

The cross-range resolution is governed by the synthetic aperture extent, the distance to the target. For a planar aperture of dimensions $D_x \times D_y$ at a distance R ,

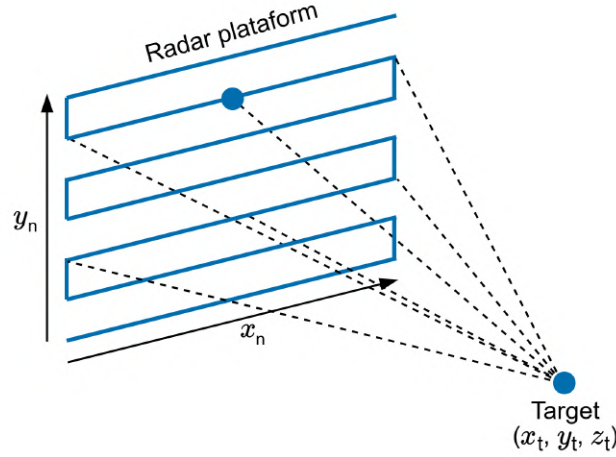


Figure 2.7: Two-dimensional planar SAR acquisition geometry.

the cross-range resolution in each lateral dimension can be approximated by [15]

$$\delta_x \approx \frac{\lambda R}{2D_x}, \quad \delta_y \approx \frac{\lambda R}{2D_y}. \quad (2.18)$$

These expressions show that resolution improves by increasing the aperture extent in the corresponding dimension or by operating at shorter wavelengths. Importantly, the two lateral dimensions are governed independently, meaning the aperture can be designed asymmetrically.

2.2.5 Spatial Sampling Requirements

To ensure accurate image reconstruction, the synthetic aperture must be sampled with sufficient density. The spatial sampling interval must satisfy the Nyquist criterion to avoid aliasing in the aperture domain [16].

The maximum allowable spacing between consecutive measurement positions is given by

$$\Delta x \leq \frac{\lambda R}{2L}, \quad (2.19)$$

where λ is the wavelength, R is the range to the target, and L is the synthetic aperture length. If this condition is not satisfied, spatial under-sampling occurs, leading to defocusing and artefacts in the reconstructed SAR image.

These principles form the theoretical basis for the SAR processing chain adopted in this work, where frequency-domain measurements are coherently combined to generate high-resolution reflectivity maps of the inspected scene.

2.2.6 SAR Reconstruction Algorithms

Several reconstruction techniques have been proposed in the literature for SAR image formation [17]. Although they differ in implementation complexity and

computational requirements, most approaches are based on the principle of matched filtering, where the measured signal is correlated with the expected response of a target at a given location. Through coherent integration across the synthetic aperture, energy originating from the true target position is constructively combined while contributions from other locations are suppressed.

Matched Filtering Principle

Matched filtering constitutes the theoretical foundation of most SAR image reconstruction algorithms. For each candidate image location, the received signal is compared with a reference signal corresponding to the expected propagation path between the radar and that location. When the measured and reference signals are aligned in phase, constructive interference occurs, producing a focused response at the target position [7].

This process maximises the signal-to-noise ratio and enables the coherent integration of measurements acquired from multiple aperture positions, forming the basis of SAR image formation [9].

Time-Domain Reconstruction Methods

Time-domain reconstruction methods perform matched filtering directly by evaluating the propagation model for each image pixel. Among these techniques, backprojection is one of the most widely adopted approaches due to its reconstruction accuracy and geometric flexibility.

In Liu et al. [18], a backprojection-based reconstruction algorithm was employed for airborne SAR imaging. The method reconstructs the image by explicitly calculating the propagation distance between each image pixel and the radar position, followed by coherent integration of the phase-compensated measurements. The authors highlight the flexibility of backprojection in accommodating complex acquisition geometries and its high reconstruction accuracy.

A similar reconstruction principle was employed by Dass et al. [19] for intrawall and throughwall object detection. The proposed system generates a synthetic aperture by scanning a radar along the wall surface and reconstructs two-dimensional and three-dimensional images using a backprojection algorithm. The authors demonstrated the detection of concealed wall substructures, including metallic pipes, wooden beams and calibration targets, highlighting the suitability of backprojection methods for near-field SAR imaging and non-destructive inspection applications.

The principal advantage of backprojection is its ability to work with different acquisition geometries, bistatic configurations and near-field propagation models. However, these advantages are obtained at the expense of increased

computational complexity, since the reconstruction process must be repeated individually for every image pixel.

Frequency-Domain Reconstruction Methods

Frequency-domain reconstruction techniques aim to reduce computational complexity by exploiting Fourier-transform relationships between the measured data and the spatial reflectivity distribution of the scene. Rather than performing pixel-by-pixel propagation calculations, these methods reconstruct the image through operations in the spatial-frequency domain [7], [9].

One of the most widely used frequency-domain approaches is the [Range Migration Algorithm \(RMA\)](#). Cuong Bui et al. [15] presented a near-field SAR imaging approach based on [RMA](#), in which the received [FMCW](#) measurements are represented in the wavenumber domain and reconstructed through matched filtering and Fourier-domain processing. The method incorporates the exact transmitter-target-receiver geometry through the propagation model, allowing near-field effects to be considered during image formation while maintaining computational efficiency.

Another example is provided by Skouroliakou et al. [20], who investigated a Fourier-based image reconstruction approach for near-field millimetre-wave imaging using sparse multistatic [Multiple-Input and Multiple-Output \(MIMO\)](#) apertures. The proposed method employs phase-centre approximation and multistatic-to-monostatic data conversion to transform the acquired measurements into a form compatible with [Fast Fourier Transform \(FFT\)](#) processing.

Compared with time-domain methods, frequency-domain techniques generally provide significantly faster image reconstruction and are therefore attractive for real-time imaging systems. However, they often require more restrictive assumptions regarding sampling uniformity, aperture geometry and signal representation.

2.3 SAR for Non-Destructive Testing

The use of radar for [NDT](#) has received increasing attention due to the ability of electromagnetic waves to penetrate dielectric materials and reveal internal structural features. Nevertheless, the spatial resolution achievable with conventional radar measurements is fundamentally constrained by the physical antenna aperture and the signal bandwidth. As discussed in Section 2.1.6, while range resolution can be improved by increasing the signal bandwidth, angular and cross-range resolution remain dependent on the antenna aperture.

[Synthetic Aperture Radar](#) overcomes this limitation by synthesising a larger effective aperture through the coherent combination of measurements acquired at

multiple spatial locations. By increasing the synthetic aperture extent while satisfying the spatial sampling requirements presented in Section 2.2.5, significantly finer cross-range resolution can be achieved than would be possible with a single antenna position, as described in Section 2.2.4. This capability enables the reconstruction of high-resolution two-dimensional and three-dimensional reflectivity maps, allowing the visualisation of internal features and defects that may not be distinguishable using conventional radar measurements.

As a result, SAR has emerged as a promising framework for non-destructive inspection, combining the penetration capability of microwave and millimetre-wave sensing with high-resolution image formation. The performance of a SAR-based NDT system depends on several factors, including the imaging geometry, the image reconstruction method, and the radar architecture employed. These aspects are reviewed in the following sections, covering near-field and far-field imaging, SAR reconstruction algorithms, and representative SAR system implementations reported in the literature.

2.3.1 Near-Field and Far-Field Imaging

The imaging geometry has a significant influence on the formulation of SAR reconstruction algorithms. Depending on the relationship between the target distance and the dimensions of the synthetic aperture, imaging systems may operate in either the far-field or near-field region.

In far-field imaging, the target is located sufficiently far from the radar such that the incident wavefront can be approximated as planar [8]. Under this assumption, the propagation distance varies approximately linearly across the aperture, simplifying both the signal model and the image reconstruction process. These conditions are commonly encountered in airborne and spaceborne SAR systems, where efficient frequency-domain algorithms such as the Range Migration Algorithm (RMA) can be employed [7], [9].

The transition between the near-field and far-field regions is commonly defined using the Fraunhofer distance [8]

$$R_{FF} = \frac{2D^2}{\lambda}, \quad (2.20)$$

where D is the largest physical dimension of the antenna aperture and λ is the operating wavelength. For target distances greater than R_{FF} , the incident wavefront can be approximated as planar and far-field assumptions are generally valid. At shorter distances, spherical-wave effects must be considered in the signal model and image reconstruction process.

In contrast, near-field imaging occurs when the target is located at a distance where the curvature of the wavefront cannot be neglected. In this case, the received signal must be modelled using the exact spherical propagation distance

between each antenna position and each reconstruction point [10], [13]. Although this increases the complexity of the reconstruction process, the shorter propagation distances result in stronger received signals while also enabling a more accurate representation of the acquisition geometry through spherical-wave modelling.

Near-field operation is particularly common in millimetre-wave imaging and non-destructive testing applications, where the radar is typically positioned at distances ranging from a few centimetres to a few metres from the inspected object.

2.3.2 SAR Imaging Architectures

SAR imaging systems can be classified according to the radar waveform employed. Among the most common approaches for close-range imaging and non-destructive testing are FMCW and SFCW systems.

FMCW-based SAR Systems

The integration of FMCW radar with SAR techniques has enabled compact and cost-effective close-range imaging systems, particularly through the adoption of Commercial Off-The-Shelf (COTS) millimetre-wave sensors. These devices integrate the complete radar transceiver chain into a single chip, operating on FMCW principles and directly outputting range profiles, which can be accumulated across a scanning trajectory to form the raw data cube required for image reconstruction [21].

Yanik and Torlak [13, 21, 22] demonstrated the feasibility of close-range SAR imaging using a Texas Instruments IWR1443 sensor mounted on a two-dimensional scanning platform, showing that focused images of concealed metallic targets could be obtained using Fourier-based reconstruction, provided the spatial sampling interval satisfies the Nyquist criterion.

More recently, Cuong Bui et al. [15] developed a compact near-field SAR imaging system based on a Texas Instruments AWR1843 mmWave radar and a rail-mounted scanning mechanism for automated internal defect detection. The system exploits the low cost, small size, and high mobility of modern FMCW radar sensors to generate high-resolution SAR images of dielectric test samples. Image reconstruction was performed using a RMA, while additional signal processing techniques were employed to improve image quality and automate defect localisation. Experimental results demonstrated the successful detection of internal defects with varying sizes, depths, and material properties, highlighting the potential of compact FMCW-based SAR systems for non-destructive testing applications.

SFCW-based SAR Systems

While FMCW-based systems offer portability and low cost, VNA-based SAR systems can be used as the laboratory benchmark for close-range millimetre-wave imaging, owing to their larger bandwidth.

SFCW-based SAR systems are widely employed in laboratory and research environments due to their ability to exploit large bandwidths and accurately measure the complex frequency response of the scene. In practice, these systems are commonly implemented using a VNA, which provides high dynamic range and flexible frequency configuration.

Duarte et al. demonstrated a VNA-based planar SAR system for the inspection of 3D-printed dielectric components, using a robotic arm to scan with millimetre-level spacing over a 15 GHz bandwidth [23]. The wide bandwidth enabled sub-centimetre range resolution, indicating potential for resolving internal features of additively manufactured parts.

Kumar et al. presented a three-dimensional SAR imaging system at microwave frequencies, using VNA-acquired data and a Fourier-based reconstruction algorithm to generate volumetric images [24]. Their results experimentally validate the capability of the system to reconstruct three-dimensional reflectivity maps, including in concealed target scenarios.

Similarly, Ruiz Benítez et al. [25] developed a ground-based SAR demonstrator based on a Copper Mountain VNA, horn antennas, and a linear scanning rail. The system operates using an SFCW waveform and employs a Frequency-Domain Backprojection algorithm for image formation. Experimental results demonstrated the generation of high-resolution SAR images and validated the feasibility of implementing complete VNA-based imaging systems using commercially available instrumentation and software-defined processing chains.

2.4 Chapter Summary

This chapter presented the theoretical foundations for radar and synthetic aperture radar imaging, together with a review of representative SAR architectures and reconstruction approaches reported in the literature. The discussion covered the operating principles of FMCW and SFCW radar systems, the formation of synthetic apertures through coherent integration, the factors governing SAR resolution and spatial sampling, and the principal image reconstruction techniques used in near-field imaging applications.

The reviewed literature demonstrates that both FMCW-based and VNA-based SAR systems are capable of producing images for NDT applications. FMCW systems offer compactness, low cost, and ease of deployment, whereas VNA-based systems provide greater measurement flexibility and larger bandwidths. Similarly, reconstruction algorithms present different trade-offs

between computational efficiency and geometric flexibility, with frequency-domain approaches generally favouring processing speed and time-domain methods favouring reconstruction accuracy.

These observations provide the basis for the design choices adopted in the present work. The following chapter describes the architecture of the developed experimental platform, including the selected sensing modalities, mechanical scanning system, acquisition geometry, and image reconstruction pipeline.

3

System Architecture

This chapter describes the proposed architecture of a close-range [Synthetic Aperture Radar](#) for [Non-Destructive Testing](#) experimental platform developed in this work. The system was designed to perform automated, spatially coherent electromagnetic measurements suitable for [SAR](#) image reconstruction, and supports two sensing modalities: a [Frequency-Modulated Continuous Wave](#) radar and a [Stepped-Frequency Continuous Wave Radar](#) VNA-based configuration. Both share a common mechanical scanning subsystem and a unified software acquisition framework, allowing the platform to be reconfigured between modalities without changes to the core data collection and processing pipelines.

Section [3.1](#) presents the overall architecture of the developed platform and the interaction between its principal subsystems. Section [3.3](#) introduces the acquisition geometry, coordinate system, and spatial sampling requirements governing the measurement process. Finally, Section [3.2](#) describes the signal processing and image reconstruction pipeline employed to generate focused [SAR](#) images from the acquired measurement data.

3.1 General System Overview

The platform was designed around three core requirements: precise mechanical positioning of the sensor along a predefined planar trajectory, synchronised triggering of measurements at each aperture position, and structured storage of the acquired data for subsequent [SAR](#) processing. Figure [3.1](#) illustrates the overall system architecture, organised into three main subsystems: the host computer, the mechanical scanner, and the sensing unit.

The host computer runs the custom control and acquisition framework, which handles device communication, scanning parameter configuration, acquisition triggering, data management, and system monitoring through a unified custom software environment. This framework was implemented in Python using a modular architecture to support both sensing modalities under a common

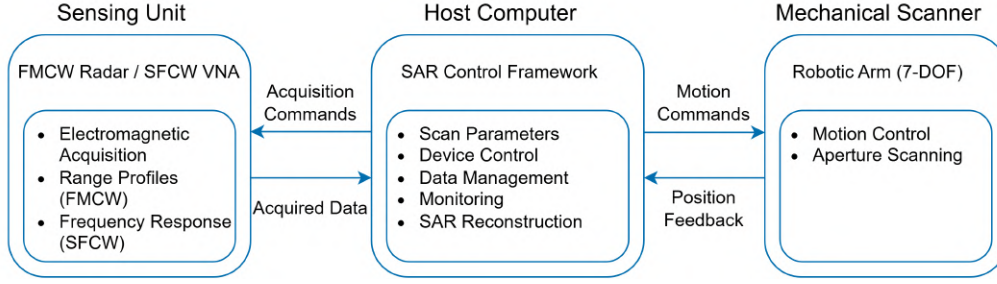


Figure 3.1: General system architecture block diagram.

acquisition workflow, enabling flexible experimentation with different scanning configurations.

The mechanical scanner consists of a 7 **Degrees of Freedom (DoF)** robotic arm responsible for sensor positioning and trajectory execution during the synthetic aperture acquisition. At each point along the scanning trajectory, the arm comes to rest and sends a position feedback signal to the host computer, which then issues an acquisition trigger to the active sensing unit. The principal advantage of employing a robotic manipulator is the flexibility it provides in defining the acquisition geometry. While the present work focuses on planar synthetic apertures, the system can readily be extended to other scanning trajectories without requiring modifications to the sensing hardware.

The sensing unit is responsible for electromagnetic data acquisition and can operate in either of the two sensing configurations. In the **FMCW** radar configuration, the AWR1843 module transmits and receives frequency-modulated chirps, internally processing the received signals to generate range profiles, as described in Section 2.1.3. In the **VNA**-based configuration, the instrument performs a stepped-frequency sweep and records the complex frequency response of the scene at each frequency point, implementing the **SFCW** sensing principle described in Section 2.1.4.

Together, these three subsystems form a closed loop where the host computer issues motion commands to the robotic arm, waits for positional confirmation, triggers the sensor, and stores the returned measurement before advancing to the next position. This process repeats until the full planar aperture has been sampled, producing the three-dimensional data cube $s(x_m, y_n, f)$, illustrated in Figure 3.2 introduced in Equation 2.15.

3.2 SAR Image Reconstruction Algorithm

Regardless of the sensing modality, the acquired three-dimensional data cube $s(x_m, y_n, f)$ is processed through a common reconstruction pipeline to produce a focused **SAR** image. The processing chain consists of two main stages: a pre-processing stage that conditions the acquired frequency-domain measurements, and a reconstruction stage that coherently combines the

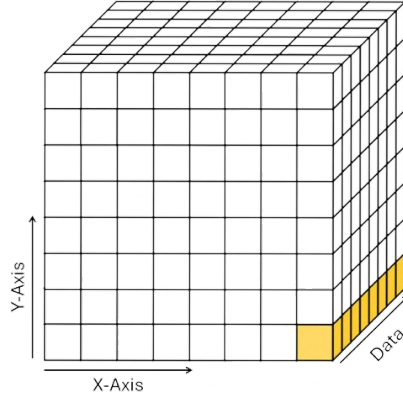


Figure 3.2: Conceptual representation of the SAR acquisition data cube.

conditioned data into a spatial reflectivity map. The complete processing workflow is illustrated in Figure 3.3.

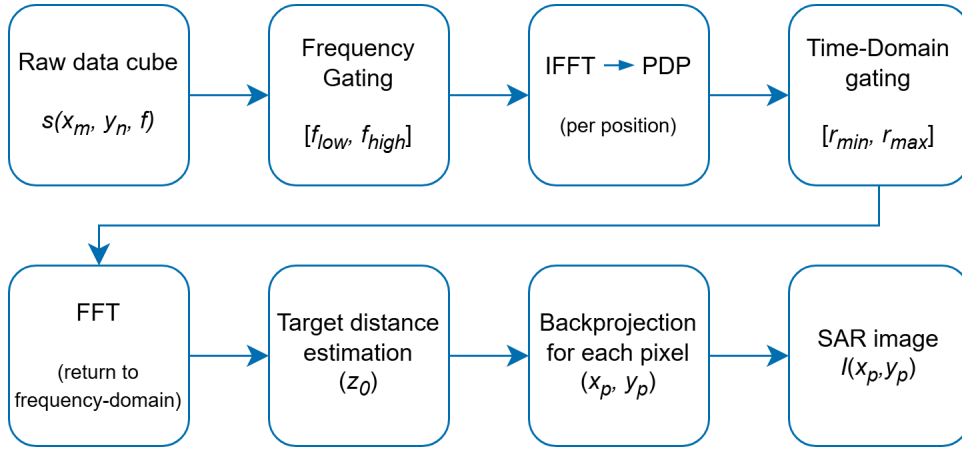


Figure 3.3: SAR Image Reconstruction Algorithm Block Diagram.

3.2.1 Algorithm Development

The reconstruction methodology proposed in this work was developed progressively throughout the experimental evaluation of the platform. Initial reconstruction experiments were inspired by the literature, where image formation is performed using the amplitude associated with a single range bin extracted from the range profile. This strategy effectively applies matched filtering to a selected target range and can provide satisfactory results when the target response is concentrated within a single range bin.

Such approaches are particularly attractive for compact FMCW radar sensors, where the available bandwidth typically results in range resolutions of a few centimetres. Under these conditions, the target response is often represented by a limited number of range bins, making single-bin image formation a computationally efficient solution.

However, during the development of the present platform, it became evident

that this approach does not fully exploit the information available in the acquired measurements. In particular, when operating with VNA-based SFCW acquisitions providing range resolutions close to 1 cm, the target response may extend across multiple range bins. Restricting the reconstruction process to a single bin therefore discards useful information.

For this reason, the reconstruction methodology evolved towards an approach that preserves the complete response of the measured signal. Following frequency-domain conditioning and range gating, image formation is performed through a backprojection-based reconstruction algorithm.

Backprojection was selected for its geometric flexibility and direct correspondence with the fundamental SAR imaging model. By explicitly evaluating the propagation distance between each acquisition position and each image pixel, it accommodates different synthetic apertures without structural modification. While the computational cost is higher than that of Fourier-based alternatives, reconstruction accuracy and algorithmic flexibility were prioritised over processing velocity.

3.2.2 Pre-Processing

The acquired frequency-domain data cube is first refined passing through a pre-processing stage intended to isolate the target response and suppress undesired reflections outside the region of interest. This conditioning process reduces the impact of environmental clutter and multipath reflections.

Initially, frequency gating is applied by restricting the acquired spectrum to the frequency interval $[f_{low}, f_{high}]$, allowing the removal of invalid or undesired frequency components located near the sweep boundaries. This operation also enables the evaluation of different frequency sub-bands and their influence on the reconstructed SAR image. The gated frequency-domain signal is then transformed into the range domain through an Inverse Fast Fourier Transform (IFFT), producing a range-domain response for each spatial acquisition position.

A time-domain gating operation is subsequently applied within the interval $[r_{min}, r_{max}]$ in order to isolate the target reflections located within its expected distance. This step suppresses reflections originating from surrounding objects, antenna coupling, and background structures outside the region of interest.

Finally, the gated signal is transformed back into the frequency domain through a Fast Fourier Transform (FFT), producing the conditioned data cube used during the subsequent SAR image reconstruction stage.

3.2.3 Backprojection Reconstruction

Following pre-processing, the conditioned frequency-domain data cube is reconstructed into a two-dimensional reflectivity image using a backprojection-based reconstruction approach derived from the coherent

integration principles introduced in Section 2.2. The reconstruction process evaluates each image pixel individually by coherently combining the contributions from all aperture positions.

For each pixel location (x_p, y_p) , the propagation distance between the pixel and every sensor position is estimated according to the acquisition geometry. This distance defines the expected phase contribution associated with the reflected signal at each measurement position.

The corresponding phase-compensated signals are then coherently summed across the full synthetic aperture, producing the reconstructed pixel intensity. Repeating this operation for all image pixels generates the final focused SAR image $I(x_p, y_p)$.

3.3 SAR Scanning Geometry

The developed system employs a planar synthetic aperture acquisition geometry in which the sensing element is mechanically moved across the defined scanning area. During acquisition, measurements are collected at discrete spatial positions Δx or Δy , enabling the synthesis of a larger effective aperture for SAR image reconstruction.

A Cartesian coordinate system was adopted to define the measurement geometry, as illustrated in Figure 3.4. The scanning plane is defined along the x - and y -axis, while the target scene is positioned along the range direction represented by the z -axis. The distance between the sensor plane and the target region is defined as the stand-off distance R .

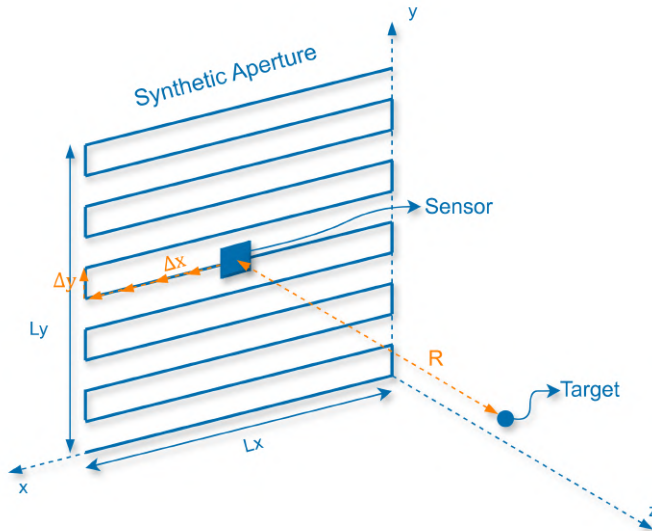


Figure 3.4: Planar SAR acquisition geometry and scanning trajectory.

The sensor follows a planar zig-zag trajectory across the defined scanning area, as illustrated in Figure 3.4. This pattern ensures complete coverage of the aperture

while minimising the total mechanical movement of the robotic arm. The sensor advances along the x -axis at a constant step Δx , incrementing along the y -axis at the end of each row and reversing direction for the next pass. The sample under inspection remains stationary throughout the acquisition.

Since the relative motion between sensor and target is what governs the synthetic aperture formation, whether the sensor moves over a stationary target or the target moves over a stationary sensor is physically equivalent. Both configurations were therefore considered during system development, with the choice driven primarily by practical integration constraints.

3.3.1 Aperture Size and Resolution

The total synthetic aperture (L) is defined by the number of measurement positions and the step size in each lateral dimension:

$$L_x = (M - 1) \Delta x, \quad L_y = (N - 1) \Delta y, \quad (3.1)$$

where M and N are the number of positions along the x - and y -axes respectively.

The achievable cross-range resolution in each dimension follows directly from Equation 2.18. These expressions highlight two key design parameters under the operator's control: the aperture extent L_x, L_y and the standoff distance R . Increasing the aperture or reducing the standoff distance both improve cross-range resolution, independently of the sensing modality used. Range resolution, on the other hand, is governed exclusively by the signal bandwidth as expressed in Equation 2.17, and therefore differs between the [FMCW](#) and [VNA](#) configurations.

The selection of step size, aperture dimensions, and standoff distance involves a practical trade-off where finer spatial sampling and larger apertures improve resolution but increase the total number of measurement positions and, consequently, acquisition time.

3.4 Hardware and Sensor Configurations

This section describes the physical components that constitute the developed [SAR](#) platform. The system is built around three main hardware elements: a [FMCW](#) radar module for direct range-profile acquisition, a [VNA](#)-based sensing chain for stepped-frequency bistatic measurements, and a [7-DoF](#) robotic arm that provides the mechanical scanning motion. Each sensing modality presents distinct characteristics in terms of operating frequency, bandwidth, and integration constraints, which are detailed in the following subsections alongside the relevant acquisition parameters and hardware specifications.

3.4.1 FMCW Radar Instrumentation

One of the sensing modalities employed in the developed platform is based on the Texas Instruments AWR1843BOOST evaluation module operating in the 77–81 GHz frequency band, shown in figure 3.5. The device integrates a complete FMCW radar front-end together with on-board digital processing capabilities, enabling compact and low-cost radar acquisition suitable for close-range SAR imaging applications [26].

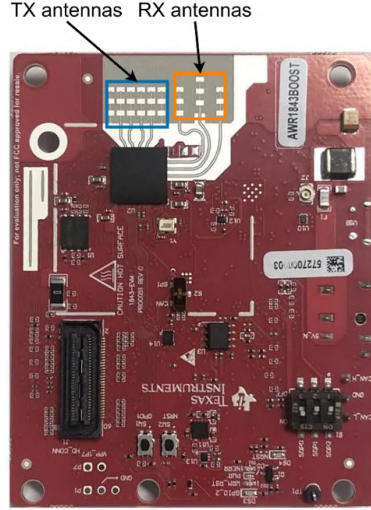


Figure 3.5: Texas Instruments AWR1843BOOST evaluation module [26].

This module was selected because it represents a commercially available and highly integrated millimetre-wave FMCW radar platform that aligns closely with the sensing architectures reported in the recent SAR imaging literature. As discussed in Chapter 2, several close-range SAR systems for NDT applications have been successfully implemented using radar sensors from the same Texas Instruments mmWave family [13, 15, 21, 22]. The availability of a fully integrated transceiver, operating in the 77–81 GHz band, provides a practical compromise between system complexity, cost, portability, and imaging performance, making it an appropriate platform for evaluating FMCW-based SAR imaging within the scope of this work.

Operating Principle

The AWR1843 operates according to the FMCW principle described in Section 2.1.3, transmitting a sequence of linearly frequency-modulated chirps and processing the received echoes to estimate target range. The principal parameters governing the radar performance are the chirp slope (S) and chirp duration (T_c), which together define the effective swept bandwidth, as shown in Eq. 3.2.

$$B = S \cdot T_c. \quad (3.2)$$

As shown in Equation 2.17, the achievable range resolution is inversely proportional to the transmitted bandwidth. Consequently, increasing either the chirp slope or chirp duration improves the radar's ability to distinguish between closely spaced targets in range. In practice, the maximum usable bandwidth is constrained by the ADC sampling rate and the radars processing limitations.

Unlike conventional FMCW SAR systems that rely on raw ADC data, the implementation developed in this work uses the processed range profile generated internally by the radar firmware. The received signal is transformed into the range domain through an internal range FFT, and the resulting range profile is transmitted to the host computer through the Type-Length-Value (TLV) interface. These range profiles are subsequently organised into the acquisition data cube used for SAR image reconstruction.

Radar Configuration and Control

The radar was operated using the standard Texas Instruments mmWave demo firmware provided as part of the official mmWave SDK distribution. The firmware image was loaded into the device during initialization and was responsible for low-level radar operation, chirp generation, signal acquisition, and internal processing.

Radar operation was configured through a dedicated mmWave configuration file containing the acquisition and signal generation parameters. This configuration defines the radar operating frequency, chirp slope, sampling rate, frame structure, antenna activation, and acquisition timing used during the experiments.

Table 3.1 summarises the principal radar acquisition parameters employed throughout this work.

Table 3.1: *Principal acquisition parameters used for the AWR1843 radar configuration.*

Parameter	Value
Start frequency	77 GHz
Chirp slope	63.343 MHz/ μ s
ADC samples per chirp	512
ADC sampling rate	9.121 MSps
Chirps per frame	10
Frame periodicity	500 ms

The radar configuration employed a single transmit and single receive antenna channel during acquisition, simplifying the processing chain and enabling direct integration with the developed SAR reconstruction framework. Based on the selected chirp slope, ADC sampling rate, and number of ADC samples, the effective swept bandwidth is approximately 3.55 GHz. According to Equation 2.17, this corresponds to a theoretical range resolution of approximately 42.2 mm.

Radar Data Output and TLV Structure

The proposed architecture does not rely on the DCA1000 raw data capture board for data acquisition. This board is an external high-speed data capture interface commonly used together with Texas Instruments mmWave radar devices, allowing the stream of raw ADC samples directly to the host computer. However, this work proposes SAR processing based on the Texas Instruments TLV data protocol instead, reducing the overall system complexity and cost. This approach takes advantage of the Cortex-R4F processor embedded in the radar device, which outputs post-processed range profile data in the TLV format.

This approach significantly simplifies the acquisition setup by eliminating the need for external high-speed raw ADC capture hardware while still providing access to the range-domain information required for the implemented SAR reconstruction pipeline.

The radar data is transmitted through a serial communication interface using a TLV message structure. Each transmitted frame contains a packet header followed by one or more TLV blocks containing processed radar information generated internally by the radar firmware.

Each TLV structure consists of three components:

- **Type:** identifies the content of the transmitted data block;
- **Length:** specifies the size of the data payload;
- **Value:** contains the actual radar measurement data.

The implemented acquisition framework extracts the range profile TLV from each radar frame. This structure contains the range-domain response obtained internally by the radar processing chain after the range FFT computation. The extracted data is subsequently reorganized into the three-dimensional acquisition cube $s(x_m, y_n, f)$ used during SAR image reconstruction.

3.4.2 VNA-Based Instrumentation

The second sensing modality employed in the developed platform is based on the Copper Mountain Technologies C4420 Vector Network Analyser, shown in Figure 3.6. The instrument is used to implement a SFCW radar architecture by measuring the complex frequency response of the scene over a user-defined bandwidth.

A VNA-based approach was selected because it provides direct access to the signal information required for coherent SAR image reconstruction, while offering precise frequency control and flexible bandwidth configuration. These characteristics make VNA-based systems a widely adopted reference platform for laboratory SAR research and high-resolution SFCW imaging [23, 24, 25]. Consequently, the C4420 was considered a suitable instrument both for



Figure 3.6: Copper Mountain Technologies C4420 [27].

implementing the proposed **SFCW** sensing modality and for providing a benchmark against which the **FMCW**-based configuration could be evaluated.

Operating Principle

The **VNA**-based sensing modality implements the **SFCW** radar principle described in Section 2.1.4. Rather than transmitting a frequency-modulated chirp, the instrument performs a stepped-frequency sweep over a predefined bandwidth, measuring the complex response of the scene at each discrete frequency point. For every step, both the amplitude and phase of the selected scattering parameter are recorded, providing direct access to the frequency-domain representation of the target response and the information required for coherent **SAR** image reconstruction.

Two **VNA** settings are particularly important for **SFCW** operation: the number of frequency points N_f and the **Intermediate Frequency Bandwidth (IFBW)**. The number of frequency points determines the spacing between consecutive frequency samples, which in turn governs the maximum unambiguous range of the reconstructed range profile. This quantity is given by Eq. 3.3 [28]

$$R_{max} = \frac{c}{2\Delta f}, \quad (3.3)$$

where Δf denotes the frequency step size. Since the frequency samples are uniformly distributed over the measurement bandwidth B , the frequency spacing is given by Eq. 3.4.

$$\Delta f = \frac{B}{N_f - 1} \quad (3.4)$$

Substituting Eq. 3.4 into Eq. 3.3 yields in the maximum unambiguous range being directly related to the measurement bandwidth and the number of acquired frequency points, shown in Eq. 3.5.

$$R_{max} = \frac{c(N_f - 1)}{2B}, \quad (3.5)$$

The **IFBW** defines the bandwidth of the receiver filter applied at each frequency point and establishes a trade-off between measurement sensitivity and acquisition speed. Narrower **IFBW** settings improve dynamic range by reducing measurement noise, while wider settings reduce sweep duration at the expense of increased noise.

Instrument Native Frequency Range

The C4420 operates natively over a frequency range of 100 MHz to 20 GHz. While this bandwidth is sufficient for many laboratory measurement tasks, it presents a fundamental limitation for **SAR** imaging applications. As established in Equation 2.18, cross-range resolution is directly proportional to the operating wavelength λ . At lower frequencies the wavelength is considerably larger, resulting in coarser lateral resolution for a given aperture size and standoff distance. For example, at 10 GHz ($\lambda \approx 30$ mm), the theoretical cross-range resolution for a 200×200 mm aperture at 80 cm standoff is approximately given by Eq. 3.6.

$$\delta_x \approx \frac{\lambda R}{2D_x} = \frac{30 \times 10^{-3} \times 0.8}{2 \times 0.2} = 60 \text{ mm}, \quad (3.6)$$

whereas operating at 80 GHz ($\lambda \approx 3.75$ mm) under the same geometry reduces this to approximately 7.5 mm, an order of magnitude improvement. This analysis directly motivates the adoption of millimetre-wave frequency extension modules to access the E-band (60 GHz to 90 GHz), where better cross-range resolution is achievable.

Frequency Extension Modules

To extend the operating frequency into the millimetre-wave band, the C4420 was equipped with a pair of FEV-12 frequency extension modules, shown in figure 3.7. Each extender connects to the instrument through four coaxial cables responsible for signal routing and a fifth power cable.



Figure 3.7: FEV-12 frequency extension module.

The **Radio Frequency (RF)** source cable delivers a low-frequency stimulus signal from the **VNA** to the extender, where an internal frequency multiplier chain upconverts it to the target W-band frequency. This upconverted signal is then radiated through the connected antenna as the measurement stimulus. On the receive side, the **Local Oscillator (LO)** cable provides a reference oscillator signal used by the extender's internal mixer to downconvert the received high-frequency signal back to an intermediate frequency within the **VNA**'s native receiver range. The reference receiver cable (Ref) returns a sample of the outgoing signal to the **VNA**, providing the known incident signal against which the received measurement is normalised. The measurement receiver cable (IF Test) carries the downconverted received signal back to the **VNA**, from which the complex transmission coefficients are computed as the ratio of the received to the incident signal. Finally the DC cable supplies the operating voltage to the extenders.

Due to their size and the number of cables, the extender modules cannot be attached to the robotic arm. As discussed in Section 3.3, this constraint requires that the target-motion acquisition configuration for this setup be switched, meaning the sample is moved while the extenders and antennas remain fixed.

Antenna Configuration

Two antenna configurations were employed depending on the operating frequency range, one for the native **VNA** setup and one for the extender setup.

For measurements using the native **VNA** configuration, a pair of RF SPIN QRH0140 quad-ridged horn antennas (Figure 3.8) were used [29]. These antennas are specified for operation over the 1–40 GHz frequency range and support dual linear polarisation through two independent ports with a port isolation of 30 dB. Their wide bandwidth and well-characterised radiation pattern make them suitable for broadband radar measurements.



Figure 3.8: RF SPIN QRH0140 quad-ridged horn antenna [29].

Although the antennas are nominally specified down to 1 GHz, preliminary measurements indicated reduced performance below approximately 5 GHz. Consequently, the native **VNA** configuration was operated over the 5–20 GHz frequency range, providing a usable bandwidth of 15 GHz. Table 3.2 summarises the principal electrical characteristics of the antenna.

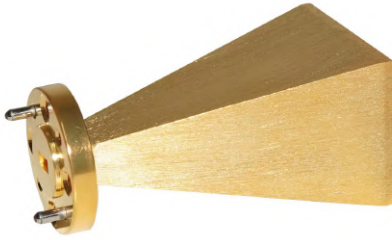
For the configuration using the FEV-12 extenders, no matched antenna was

Table 3.2: RF SPIN QRH0140 antenna electrical specifications [29].

Parameter	Value
Model	RF SPIN QRH0140
Type	Quad-ridged horn
Frequency range	1–40 GHz
Gain	–20 to 15 dBi
VSWR (avg)	1.6
Port isolation	30 dB
Polarisation	Dual linear
Impedance	50 Ω

available for the extender’s operating range. Standard gain horn antennas covering the W-band (75–110 GHz) with 24 dBi gain were therefore selected, as shown in Figure 3.9. The FEV-12 extenders have a WR-12 waveguide output port, corresponding to the 60–90 GHz band, while the selected antennas are designed for the 75–110 GHz range and require a WR-10 waveguide connection. Consequently, a WR-12 to WR-10 transition adapter was required at each port to interface the extender output with the antenna, shown in figure 3.10. This mismatch inherently restricts the usable frequency range to the overlap between both bands, yielding an operational bandwidth of 75–90 GHz. The resulting 15 GHz usable bandwidth gives a theoretical range resolution of 10 mm, as shown by Eq. 3.7.

$$\Delta R = \frac{c}{2B} = \frac{3 \times 10^8}{2 \times 15 \times 10^9} = 10 \text{ mm} \quad (3.7)$$

**Figure 3.9:** Standard gain horn antennas covering the W-band (75–110 GHz) with 24 dBi gain.**Figure 3.10:** WR-12 to WR-10 waveguide transition adapter.

Calibration Procedure

Prior to each measurement campaign, the VNA setup was calibrated to remove errors introduced by cables, connectors, adapters, and antenna transitions. Calibration is performed at the point closest to the antenna, ensuring the measured S-parameters reflect only the propagation channel between the antennas and not instrumentation artefacts.

For the **VNA** configuration, a standard **Short-Open-Load-Thru (SOLT)** calibration was performed at the cables coaxial ports using the Copper Mountain S2611 calibration kit, shown in Figure 3.11, which provides the Short, Open, Load, and Thru standards required for full 2-port error correction.

For the frequency extender configuration, a **SOLT** calibration was performed at the waveguide output port of each FEV-12 extender module using the Farran FEK-12-0006 precision waveguide calibration kit [30], shown in Figure 3.12. This kit provides precision waveguide standards for the 60–90 GHz band and enables full 12-term error correction at millimetre-wave frequencies. Calibrating at the extender output port moves the measurement reference plane to the waveguide interface, effectively removing the electrical contribution of all cables and internal extender signal paths from the measured data.



Figure 3.11: Copper Mountain S2611 coaxial **SOLT** calibration kit.



Figure 3.12: Farran FEK-12-0006 WR-12 precision waveguide calibration kit.

Data Acquisition

During acquisition, the **VNA** performs a stepped-frequency sweep over the selected frequency range, recording the complex frequency response at each frequency point. For every aperture position (x_m, y_n) , a complete frequency sweep is acquired and stored as a complex vector of length N_f . Once the full planar scan is complete, these measurements are assembled into the three-dimensional data cube $s(x_m, y_n, f)$, which serves as the input to the reconstruction pipeline described in Section 3.2.

A value of $N_f = 501$ frequency points was selected for both **VNA** configurations. Given the adopted measurement bandwidth of 15 GHz, this corresponds to a frequency spacing of approximately 30 MHz and a maximum unambiguous range of approximately 5 m according to Equation 3.5. Since all

experimental measurements were performed at standoff distances well below this limit, range ambiguity does not occur.

An [IFBW](#) of 10 kHz was selected for both configurations as a compromise between measurement sensitivity and acquisition time. The selected value provided sufficient sensitivity for the experimental scenarios while maintaining practical acquisition times for the complete synthetic aperture scan.

Table 3.3 summarises the principal acquisition parameters employed throughout this work.

Table 3.3: *Principal acquisition parameters for the VNA-based sensing configurations.*

Parameter	Native VNA	E-band (Extenders)
Instrument range	100 MHz–20 GHz	60–90 GHz
Used range	5–20 GHz	75–90 GHz
Bandwidth	15 GHz	15 GHz
Theoretical ΔR	10 mm	10 mm
Frequency points N_f	501	501
IFBW	10 kHz	10 kHz

3.4.3 Robotic Scanning Platform

The mechanical scanning subsystem is based on the Kinova Gen3 robotic arm configured with 7 [DoF](#) [31]. The robotic platform was selected due to its positioning repeatability, programmable motion control, and geometric flexibility. Unlike dedicated linear scanning rails commonly employed in [SAR](#) systems, the robotic manipulator enables the implementation of different acquisition trajectories without requiring hardware modifications. Although only planar apertures are considered in the present work, the platform provides the possibility of extending the system to non-planar, cylindrical, or arbitrary synthetic apertures in future developments.

The arm is interfaced with the host computer through the Kinova Kortex API, which provides programmatic control of trajectories, maximum speed and acceleration. Motion commands are issued by the acquisition framework, which drives the arm sequentially through the predefined set of aperture positions and waits for a positional confirmation signal before issuing the measurement trigger to the active sensing unit.

Table 3.4 summarises the principal specifications of the Kinova Gen3 7-DoF arm.

Table 3.4: *Principal specifications of the Kinova Gen3 7-DoF robotic arm [31].*

Parameter	Value
Degrees of freedom	7
Maximum reach	902 mm
Continuous payload	4 kg
Arm weight	8.2 kg

Positioning Accuracy Characterisation

To assess the positional repeatability of the robotic arm at the step sizes relevant to SAR acquisition, a mechanical validation test was performed using a [Dial Test Indicator \(DTI\)](#) placed in contact with the end-effector. The experimental setup is shown in Figure 3.13.



Figure 3.13: *Dial test indicator setup used for robotic arm positioning accuracy characterisation.*

The arm was commanded to perform repeated back-and-forth displacements along the DTI axis for three nominal step sizes: 0.1 mm, 0.5 mm, and 1 mm. In addition, a sequence of successive incremental steps of 0.1 mm was executed along the same axis to evaluate the arm's behaviour at the smallest intended sampling interval.

The tests revealed that for step sizes below 1 mm the arm does not reliably reach the commanded position on every individual move. Nevertheless, the controller was observed to compensate for these deviations over subsequent movements, preventing errors from accumulating persistently across the aperture. At a step size of 1 mm, the arm demonstrated consistent and repeatable positioning suitable for coherent aperture synthesis.

Based on these observations, a minimum spatial sampling interval of $\Delta x = \Delta y = 1$ mm was adopted for all acquisitions performed with the robotic scanning configuration. Sub-millimetre step sizes were considered insufficiently reliable for phase-coherent SAR measurements and were therefore excluded from the experimental work presented in this thesis.

3.5 Chapter Summary

This chapter presented the [SAR NDT](#) testbed and proposed an architecture based on a collaborative robotic platform together with [COTS](#) and [VNA](#)-based radar

solutions that are controlled by a webpage Graphical User Interface. The overall system architecture had special care with the asynchronous interaction between host computer, sensing unit, and synthetic aperture motor subsystem.

The common SAR reconstruction framework adopted for both sensing modalities was described, with special care given on the pre-processing operations and backprojection image reconstruction algorithm. Here, a detailed study of the system requirements in terms of synthetic aperture geometry, spatial sampling and SAR algorithms, as well as their impact on the reconstructed image was conducted.

The hardware implementation was subsequently detailed for both sensing approaches. The FMCW configuration based on the Texas Instruments AWR1843 radar and the SFCW configuration based on the Copper Mountain C4420 VNA were presented together with their respective acquisition parameters, operating constraints, and supporting hardware. Finally, the Kinova Gen3 robotic arm accuracy was characterised and shown to comply with the positioning accuracy required for coherent SAR measurements.

The resulting platform provides a modular experimental framework capable of operating with multiple sensing technologies while maintaining a consistent acquisition and reconstruction methodology. This enables the influence study of bandwidth, operating frequency, and sensing architecture on SAR image quality.

Having established the system architecture and implementation details of the developed platform, the following chapter presents its experimental validation. The performance of different sensing configurations will be evaluated under controlled environment, as well as in more harsh environments. Such section will assess acquisition accuracy, reconstruction quality, and imaging capabilities of the proposed SAR NDT architecture.

4

Experimental Results

This chapter presents the experimental validation of the synthetic aperture radar platform developed throughout this work. The objective is to evaluate the acquisition framework, reconstruction algorithms, and imaging capabilities of the proposed system using three distinct sensing configurations. The first being a commercial off-the-shelf [FMCW](#) radar, then a stepped-frequency [VNA](#)-based system, and lastly a millimetre-wave [VNA](#) configuration employing frequency extenders.

Although the long-term objective of this research is the development of [SAR](#)-based non-destructive testing solutions for harsh and industrial environments, the experimental campaign combines both controlled and representative operating conditions. Validation experiments intended to verify theoretical performance metrics, such as range resolution and spatial sampling requirements, were conducted under controlled conditions. In contrast, the image reconstruction experiments using the [FMCW](#) radar were conducted in a standard laboratory environment, reflecting its intended operating conditions and providing a more representative assessment of practical system performance.

The experimental evaluation is organised into four stages. First, a set of validation experiments is performed to verify the theoretical assumptions associated with spatial sampling, resolution, and image formation. Subsequently, the imaging performance of the [FMCW](#), native [VNA](#), and frequency-extended [VNA](#) configurations is analysed using a collection of test targets. Finally, the principal findings obtained throughout the experimental campaign are summarised and discussed.

4.1 FMCW Radar Configuration

The first sensing modality tested in this work was based on the Texas Instruments AWR1843 [FMCW](#) radar. This configuration was selected as the initial implementation platform due to its compact form factor, integrated signal

processing capabilities, and lower cost. The radar was integrated with the robotic scanning platform described in Chapter 3, enabling measurements over a planar synthetic aperture.

Unlike conventional SAR systems based on raw intermediate-frequency signal acquisition, the developed implementation relied on the processed range profile data generated internally by the radar firmware. The acquired measurements were subsequently organised into a three-dimensional data cube and processed using the reconstruction pipeline described in Section 3.2.

4.1.1 Experimental Setup

The experimental setup employed for the FMCW radar configuration is illustrated in Figure 4.1. The AWR1843 radar module was mounted on the robotic scanning platform and positioned at a fixed stand-off distance from the Device Under Test (DUT). During acquisition, the radar followed a planar zig-zag trajectory across the predefined scanning area while maintaining a constant orientation towards the target scene.



Figure 4.1: *FMCW radar experimental setup.*

The target was positioned approximately at the centre of the synthetic aperture footprint and aligned normal to the radar boresight. The distance between the radar aperture plane and the target surface was approximately 300 mm. During acquisition, the radar was translated over a 120 mm $\times$ 120 mm planar aperture with a spatial sampling interval of 1 mm.

For each acquisition position, the radar produced a range profile containing the reflected signal power as a function of distance. These range profiles were subsequently combined to form the measurement data cube used for image reconstruction.

The scan area was selected to fully encompass the spatial extent of the target

response within the synthetic aperture. This was verified experimentally by ensuring that no significant target reflections were present at the boundaries of the acquired aperture.

Table 4.1 summarises the principal acquisition parameters adopted throughout the experiments.

Table 4.1: Acquisition parameters used for automated SAR evaluation experiments using COTS radar.

Parameter	Value
Radar model	TI AWR1843BOOST
Operating frequency	77–81 GHz
Effective Bandwidth	3.55 GHz
Theoretical range resolution	~42.2 mm
Scan geometry	Raster (zig-zag) trajectory
Scan area	120 × 120 mm
Spatial sampling interval	1 mm
Target distance	~30 cm

4.1.2 System Validation

Prior to evaluating the imaging capabilities of the developed FMCW SAR platform, a series of validation experiments were conducted under controlled conditions to assess the consistency and repeatability of the acquisition process, as well as to verify system performance against the theoretical expectations presented in Chapter 2. These experiments focused on the influence of spatial sampling, range measurement accuracy, and imaging resolution, providing a baseline for the interpretation of the reconstruction results discussed in the following sections.

Spatial Sampling Interval

As established in Section 2.2, the spatial sampling interval must satisfy the Nyquist criterion in the aperture domain to ensure coherent and alias-free image reconstruction. Violating this condition causes spatial aliasing, which manifests as defocusing artefacts and degraded image quality in the reconstructed SAR image. In practice, the selected spatial sampling interval corresponds to the smallest step size that the robotic scanning subsystem is capable of executing with sufficient positioning precision and repeatability. This approach ensures the highest achievable spatial sampling density while preserving positioning accuracy during acquisition.

Considering the acquisition geometry employed in this work and the radar centre frequency of 79 GHz, with a stand-off distance of approximately 300 mm and a synthetic aperture of 120 mm, the maximum allowable spatial sampling interval predicted by the Nyquist criterion is

$$\Delta x_{\max} = \Delta y_{\max} = \frac{\lambda R}{2D} \approx 4.75 \text{ mm.} \quad (4.1)$$

This result indicates that spatial sampling intervals larger than approximately 5 mm are expected to introduce spatial aliasing and image degradation. To experimentally evaluate this behaviour, the original dataset acquired with a 1 mm spatial sampling interval was progressively downsampled by retaining every second measurement point. This procedure generated equivalent datasets with effective sampling intervals of 2 mm, 4 mm, and 8 mm. The results presented in Figure 4.2 are consistent with the theoretical prediction, showing acceptable image quality for sampling intervals up to 4 mm and a significant loss of reconstruction fidelity for a step size of 8 mm, which severely degrades the reconstructed image.

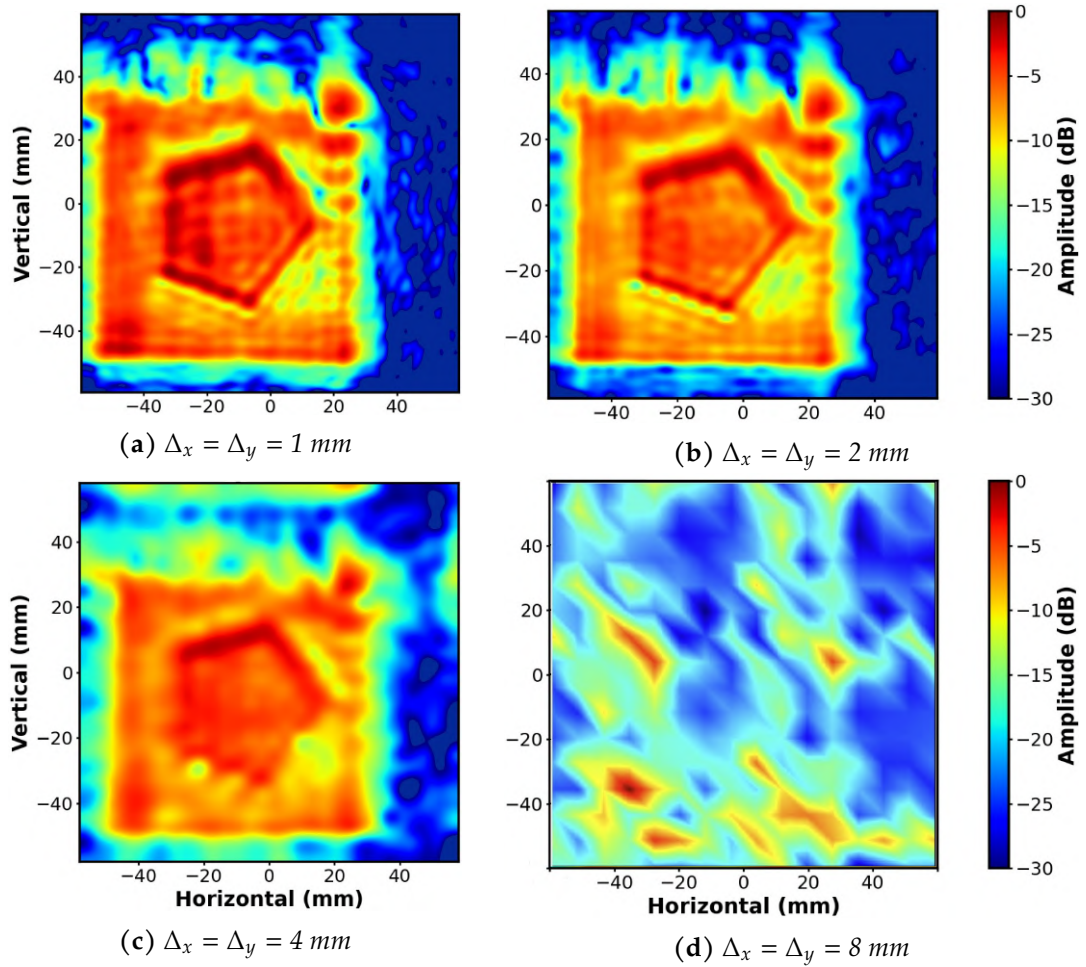


Figure 4.2: Effect of spatial sampling step size on SAR image quality. Reconstructed images of a pentagonal target for step sizes of (a) 1 mm, (b) 2 mm, (c) 4 mm, and (d) 8 mm.

Range Resolution Evaluation

To experimentally evaluate the achievable range resolution of the FMCW radar configuration, a metallic spherical target was translated along the radar line-of-sight while maintaining all other radar settings unchanged. The spherical

geometry was deliberately chosen to ensure a uniform radar cross-section response regardless of the angle of incidence. The target was supported by an expanded polystyrene (EPS) fixture, selected for its negligible electromagnetic reflectivity so as to minimise any spurious contributions to the received signal. The sphere was initially positioned at a stand-off distance of approximately 340 mm and subsequently displaced with 10 mm increments over a range of ± 50 mm relative to this reference position.

For each target position, a radar acquisition was performed and the corresponding range profile was analysed. The distance associated with the dominant reflection peak was extracted and compared with the imposed target displacement.

Figure 4.3 presents the measured target distance as a function of the imposed displacement. The results show that the estimated target position remains constant over discrete intervals before transitioning to the adjacent range bin. This behaviour is characteristic of range-domain quantisation and reflects the finite range resolution of the radar system.

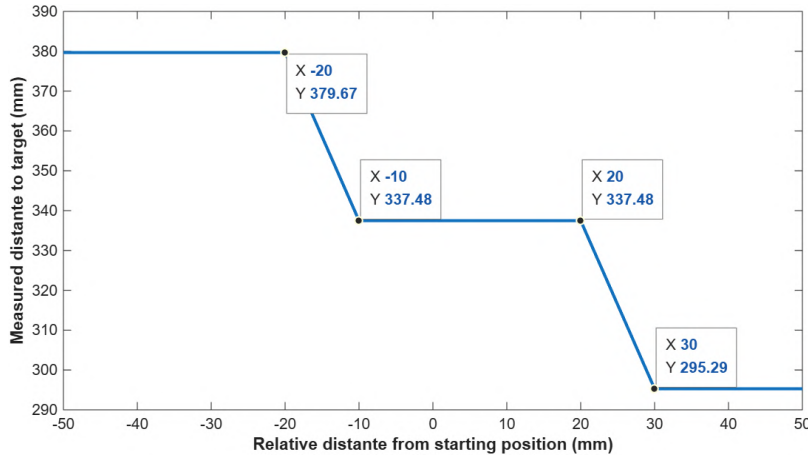


Figure 4.3: Experimental evaluation of the AWR1843 range resolution.

The measured distance changes in increments of approximately 42 mm, corresponding to the spacing between adjacent range bins. As discussed in Section 3.4.1, the selected radar configuration provides an effective swept bandwidth of approximately 3.55 GHz, yielding a theoretical range resolution of

$$\Delta R = \frac{c}{2B} = \frac{3 \times 10^8}{2 \times 3.55 \times 10^9} \approx 42.2 \text{ mm.} \quad (4.2)$$

The experimentally observed range-bin spacing is in agreement with the theoretical prediction, and the measured transitions between adjacent range bins occur at target displacements consistent with the expected 42.2 mm resolution.

4.1.3 Image Reconstruction Results

Following validation of the radar and SAR algorithm, a series of experiments were conducted to evaluate the imaging capabilities of the developed configuration. Unlike the validation experiments, which were performed under controlled conditions, the image reconstruction experiments were conducted in a standard laboratory environment. This choice was motivated by the successful validation of the acquisition and processing framework, as well as by the extensive use of the AWR1843 radar in non-controlled environments reported in the literature. The selected samples were designed to assess different aspects of system performance, including target detection, geometrical reconstruction, material sensitivity, and the ability to resolve increasingly smaller structures.

Detection and Concealed Target Assessment

The initial experiments focused on verifying the ability of the system to distinguish between reflective and non-reflective regions. For this purpose, a copper-clad PCB with dimensions of approximately 120 mm $\times$ 70 mm was manufactured containing three cut-out geometries: a rectangle, a circle, and a triangle, as shown in Figure 4.4a.

The reconstructed image presented in Figure 4.4b successfully reproduces the location and general shape of the three geometrical features. Although some edge blurring is visible, the experiment demonstrates the capability of the system to distinguish between regions of contrasting reflectivity and confirms the correct operation of the acquisition and reconstruction pipeline.

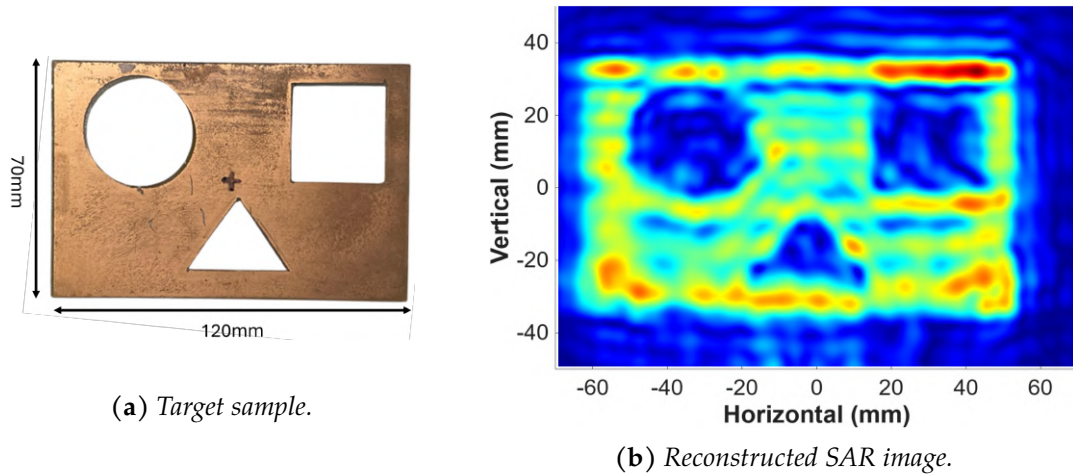


Figure 4.4: Comparison between the target with circular, rectangular and triangular cut-outs and its reconstructed SAR image.

To further evaluate the applicability of the system to non-destructive inspection scenarios, the same target was subsequently placed inside a box, as illustrated in Figure 4.5a. The corresponding reconstruction, shown in Figure 4.5b, indicates that the target remains detectable despite the additional material layer,

providing an initial demonstration of concealed target imaging under controlled laboratory conditions.

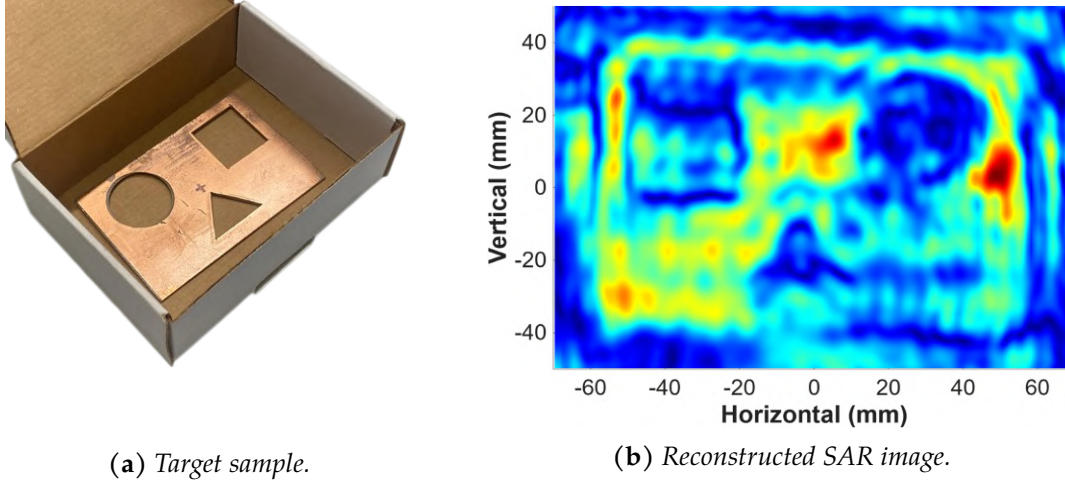


Figure 4.5: Comparison between the enclosed target sample and its reconstructed SAR image.

Geometrical Reconstruction Assessment

Following the initial target detection experiments, a series of geometrical targets with progressively smaller feature sizes were evaluated to assess the reconstruction accuracy and spatial resolution capabilities of the developed FMCW-based SAR system.

The first targets consisted of regular pentagonal geometries fabricated on PCB substrates. Two sizes were considered: a large pentagon with dimensions of approximately $50 \text{ mm} \times 50 \text{ mm}$ and a smaller pentagon with dimensions of approximately $25 \text{ mm} \times 25 \text{ mm}$. The physical samples and their corresponding reconstructed images are presented in Figures 4.6a–4.6b and Figures 4.7a–4.7b, respectively.

The reconstructed images demonstrate that the larger geometry can be accurately identified, whereas the smaller target naturally exhibits increasing shape distortion and edge broadening. Furthermore, both reconstructed images were compared to the original sample target, resulting in the errors presented in table 4.2. The obtained results indicate that the developed FMCW SAR system is capable of reproducing the principal dimensions of the evaluated targets with reasonable accuracy. The large pentagon was reconstructed with dimensional errors below 7%, while the smaller target exhibited a maximum error of 8%.

To further challenge the reconstruction process, a multi-geometry target containing four independent metallic features of different shapes and dimensions was evaluated. The physical sample and corresponding reconstruction are shown in Figures 4.8a–4.8b. Unlike the pentagonal targets, this sample introduces multiple closely spaced scattering regions and a wider range of characteristic feature sizes.

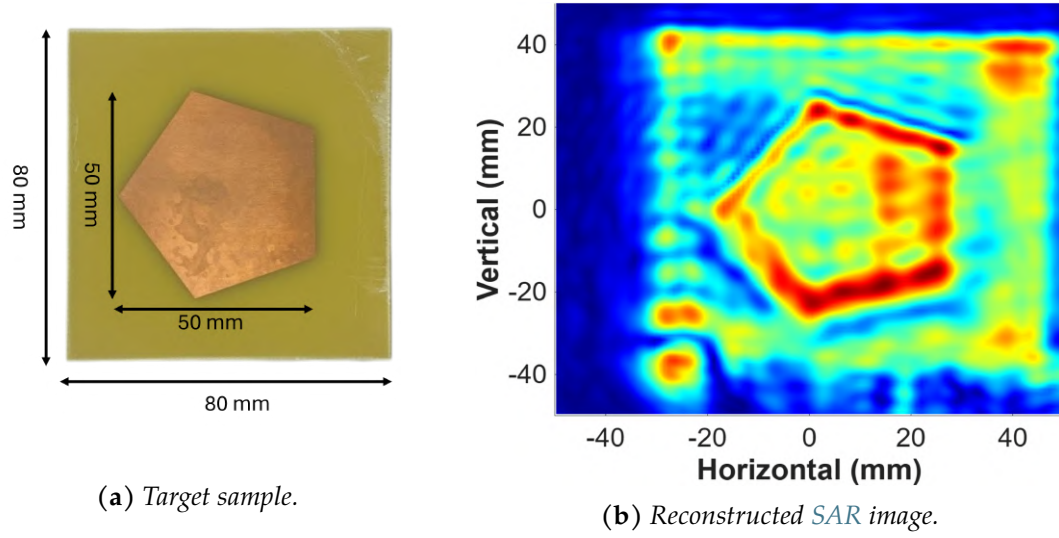


Figure 4.6: Comparison between the large pentagon target and its reconstructed SAR image.

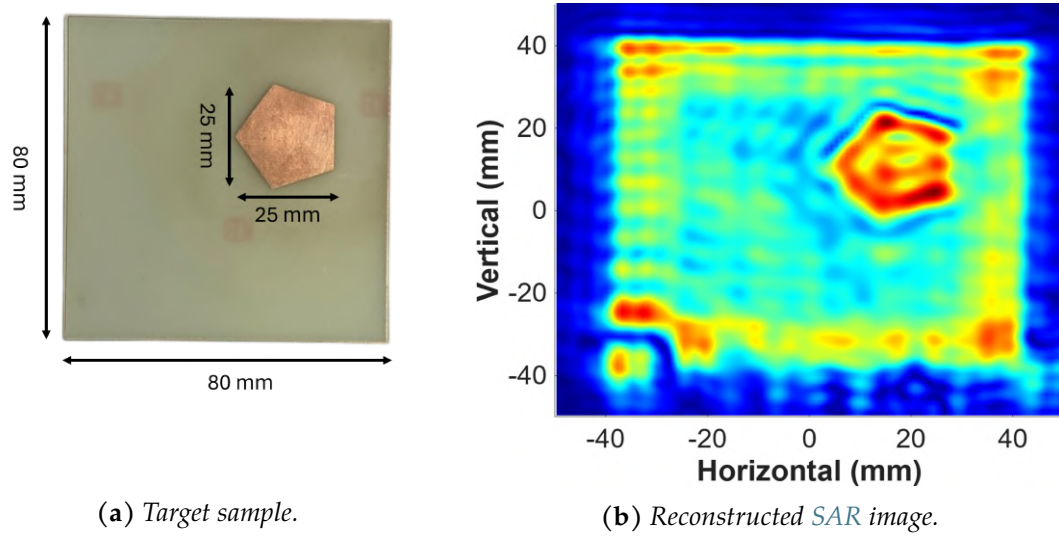


Figure 4.7: Comparison between the small pentagon target and its reconstructed SAR image.

Table 4.2: Dimensional accuracy of the reconstructed pentagonal targets using the FMCW configuration.

Target	Width			Height		
	Nominal (mm)	Reconstructed (mm)	Error (%)	Nominal (mm)	Reconstructed (mm)	Error (%)
Large Pentagon	50.0	51.1	2.2	50.0	53.1	6.2
Small Pentagon	25.0	25.0	0.0	25.0	23.0	8.0

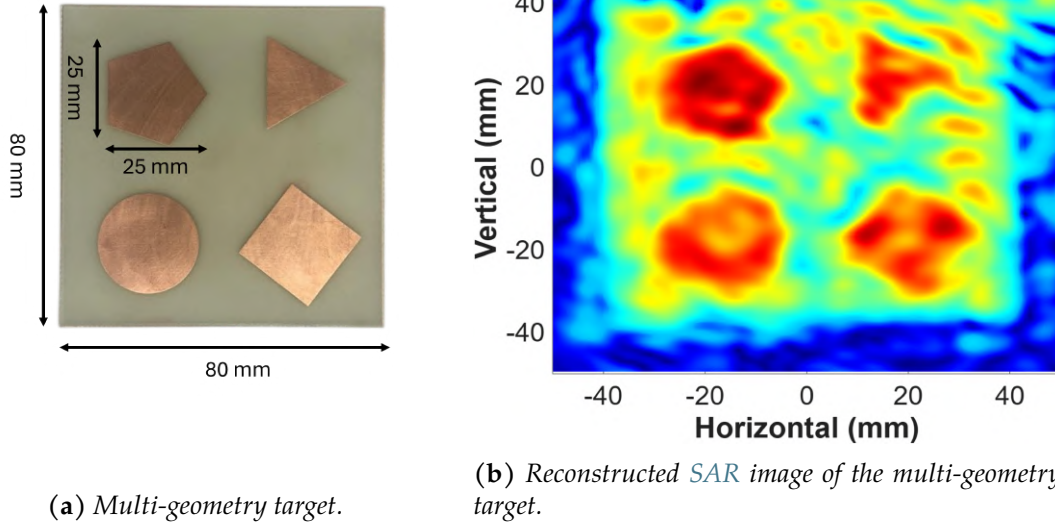


Figure 4.8: Comparison between the physical multi-geometry target and its reconstructed SAR image.

The reconstructed image successfully reveals the presence and approximate location of all geometrical elements. However, the smallest features exhibit increased blurring and partial merging of neighbouring scattering responses. This behaviour illustrates the progressive loss of reconstruction fidelity as the characteristic dimensions of the target approach the theoretical resolution limits.

Overall, the results demonstrate that the developed FMCW SAR platform is capable of accurately reconstructing simple metallic geometries and preserving their principal dimensions. While fine details become increasingly difficult to resolve for smaller structures, the dominant target features remain identifiable throughout all evaluated test cases.

Complex Pattern Reconstruction

Following the evaluation of simple geometrical targets, additional experiments were conducted using more complex patterns containing fine features, disconnected elements, and alphanumeric characters. These targets were designed to assess the practical imaging capabilities of the developed system beyond basic shape reconstruction.

The first target consisted of the Instituto de Telecomunicações (IT) logo fabricated on a PCB substrate with dimensions of approximately 80 mm × 80 mm. The reconstructed image, presented in Figures 4.9a–4.9b, demonstrates that the logo can be successfully identified. The characteristic shape of the IT symbol remain clearly visible, confirming the ability of the system to preserve the overall geometry of the target.

To further challenge the reconstruction process, a second target with dimensions of approximately 160 mm × 80 mm containing the complete “30 Years

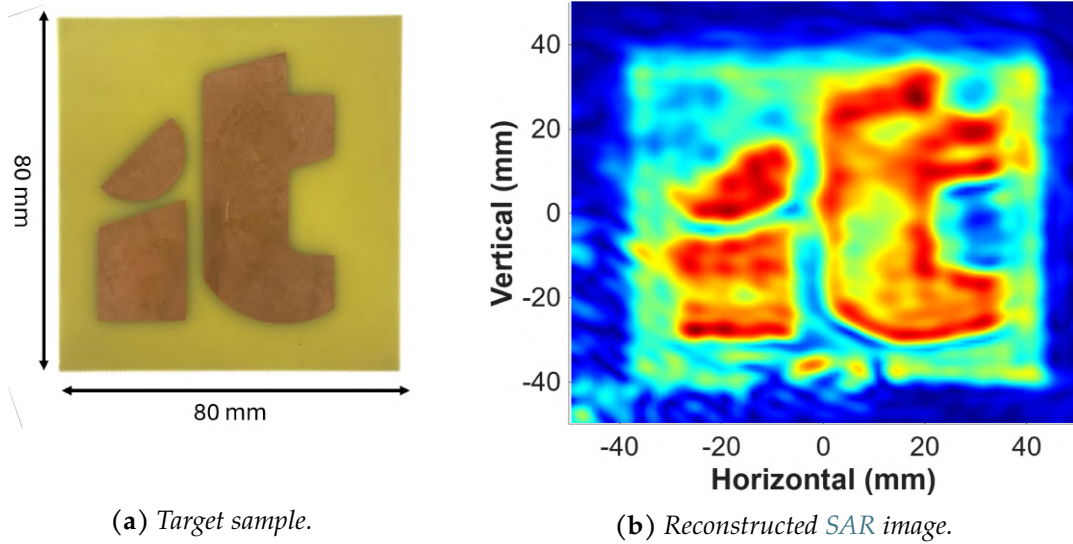


Figure 4.9: Comparison between the target containing the IT logo and its reconstructed SAR image.

Instituto de Telecomunicações” inscription was evaluated. This sample introduces substantially smaller features and narrow character spacing. The physical target and the corresponding reconstructed image are presented in Figures 4.10a–4.10b.

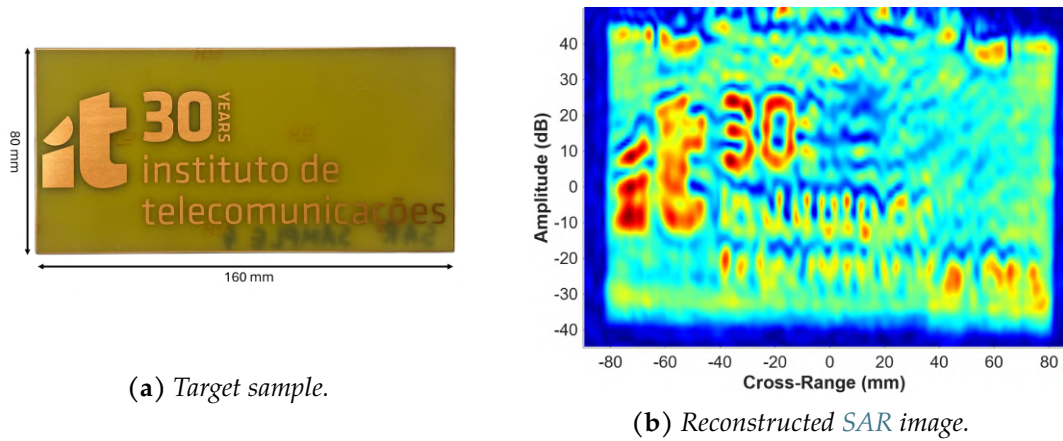


Figure 4.10: Comparison between the target containing multiple inscriptions and its reconstructed SAR image.

Despite the increased complexity, the reconstructed image retains the dominant target features. The large graphical elements and numerical characters remain distinguishable, while portions of the textual content can not be identified with significant blurring observed in the smaller letters.

These results demonstrate that the developed platform is capable of reconstructing simple geometrical objects but also complex patterns containing graphical symbols and text. Although the reconstruction quality decreases as the feature dimensions approach the system resolution limits.

These reconstruction results obtained were subsequently employed as the validation dataset for the development of an automated shape detection and classification framework. By exploiting the geometrical information preserved in

the reconstructed SAR images, a blob-based post-processing algorithm was developed to automatically identify and classify the reconstructed shapes. This work formed the basis of a conference paper submitted to the European Conference on Antennas and Propagation (EuCAP 2026), where the feasibility of combining compact mmWave SAR imaging with automated target recognition was investigated [12].

Three-Dimensional Target Evaluation

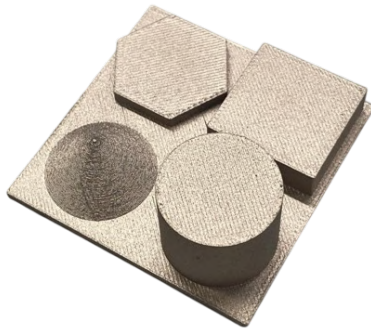
Following the successful reconstruction of two-dimensional targets, an additional experiment was conducted to evaluate the capability of the developed FMCW radar system to image three-dimensional structures. For this purpose, a target containing multiple surface features at different heights was manufactured using additive manufacturing techniques, as shown in Figure 4.11a. The target consists of a square base measuring approximately 60 mm $\times$ 60 mm, onto which four geometric features were incorporated: a cylindrical feature with a height of 22 mm, a conical feature with a height of 15 mm, a rectangular feature with a height of 10 mm, and a pentagonal feature with a height of 5 mm. Due to the low electromagnetic reflectivity of the printing material, a conductive metallic coating was applied to the target surface to increase its radar visibility.

Figure 4.11 presents the reconstructed images obtained by focusing the reconstruction algorithm at three different depth planes corresponding approximately to the upper, intermediate, and lower regions of the target. This approach allows the influence of the reconstruction depth on the recovered target features to be evaluated.

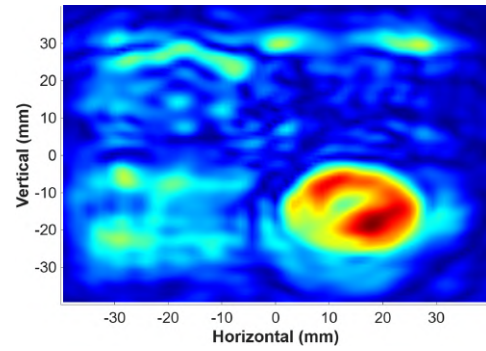
The reconstruction focused on the upper surface successfully highlights the most elevated features of the object. As the reconstruction plane is moved towards the intermediate region, additional structures become visible, however, significant overlap between neighbouring reflections remains apparent. Finally, the reconstruction focused on the lower region of the target reveals only limited additional information, indicating that dominant responses on previous planes are shadowing parts of this region.

These results demonstrate that the developed FMCW radar platform is capable of identifying the presence and approximate location of three-dimensional structures. Nevertheless, the reconstructed images do not provide a faithful representation of the complete surface topology. Features located at different heights cannot be clearly separated and tend to merge into a small number of dominant scattering regions.

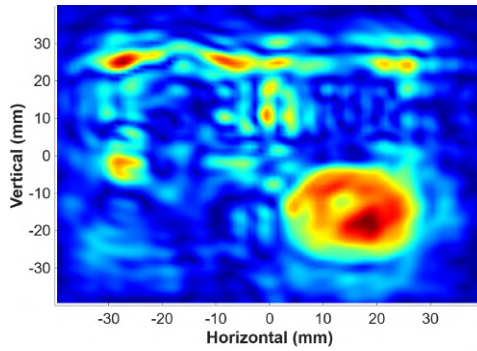
This behaviour is primarily attributed to the limited range resolution of the radar. As discussed in Section 3.4.1, the 3.55 GHz effective signal bandwidth provides a theoretical range resolution of approximately 42.2 mm. The height differences between the target features (5–22 mm) are therefore significantly



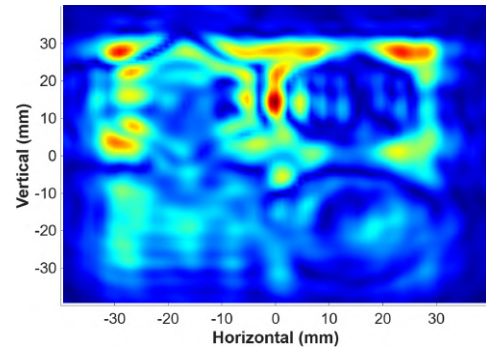
(a) Physical target.



(b) Reconstruction of focus plane at the upper cylinder surface.



(c) Reconstruction of focus plane at the upper rectangular surface.



(d) Reconstruction of focus plane at the base surface.

Figure 4.11: Three-dimensional target and reconstructed SAR images obtained at different reconstruction depths.

smaller than a single range-resolution cell. Consequently, reflections originating from different surfaces occupy the same range bin and cannot be independently resolved. As a result, stronger reflections from elevated regions tend to mask neighbouring features and prevent accurate reconstruction of the target depth profile.

4.1.4 Discussion

Despite the successful reconstruction of the tested targets, the experimental evaluation revealed limitations that constrain the applicability of the developed [FMCW](#) radar configuration to more demanding [NDT](#) scenarios.

The primary limitation is associated with the available signal bandwidth, which results in a theoretical range resolution of about 42.2 mm. While this resolution proved sufficient for the reconstruction of two-dimensional metallic targets and simple geometrical features, it becomes inadequate when imaging objects containing fine depth variations.

In contrast, the operating frequency range of 77–81 GHz provided adequate cross-range performance for the sample dimensions investigated. The successful reconstruction of multiple target geometries demonstrates that the achievable lateral resolution is sufficient to identify the principal characteristics of the inspected objects.

Overall, the obtained results demonstrate that the AWR1843 radar is a viable low-cost platform for close-range [SAR](#) imaging and system prototyping. However, the limited range resolution restricts its suitability for applications requiring the discrimination of small depth variations. These observations motivated the investigation of an alternative sensing modality where significantly larger bandwidths can be employed to improve range resolution.

4.2 VNA Configuration

The second sensing modality investigated in this work was based on a Vector Network Analyser operating within its native frequency range of 100MHz–20 GHz. By employing stepped-frequency measurements over a significantly wider bandwidth, improved range resolution can theoretically be achieved.

Unlike the AWR1843 implementation, where part of the signal processing chain is performed internally by the radar firmware, the [VNA](#)-based configuration required the complete implementation of the acquisition and reconstruction pipeline. All stages, including frequency-domain acquisition, frequency gating, range processing, and image reconstruction, were therefore performed externally using the custom processing framework developed in this work.

4.2.1 Experimental Setup

The experimental setup employed for the native VNA configuration is shown in Figure 4.12. The VNA was connected to a pair of quad-ridged horn antennas described in Section 3.4.2 and operated over the 5–20 GHz frequency range.

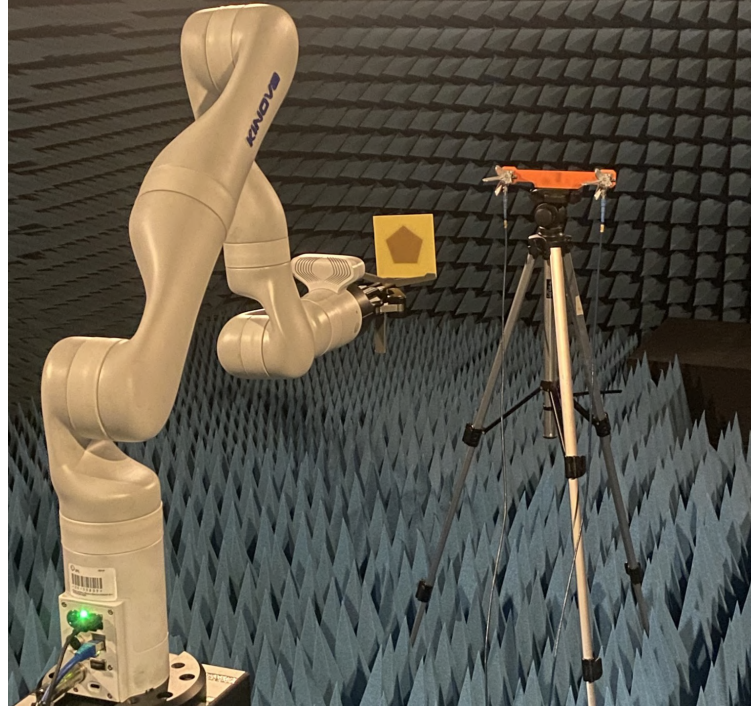


Figure 4.12: VNA-based radar experimental setup.

The target was positioned approximately at the centre of the synthetic aperture and aligned normal to the boresight direction of the antenna pair. The stand-off distance between the antennas and the target was approximately 800 mm. The transmitting and receiving antennas were separated by approximately 110 mm and remained fixed throughout the acquisition, while the target was translated over a 200 mm $\times$ 200 mm synthetic aperture with a spatial sampling interval of 1 mm.

To minimise external electromagnetic interference and unwanted reflections, all measurements were performed in a controlled environment, inside an anechoic chamber. The VNA itself remained outside the chamber, with the antennas connected through high-frequency RF cables.

For this configuration, both antennas were kept stationary to minimise cable movement and maintain measurement repeatability, while the samples were mounted on the robotic scanning platform and translated across the synthetic aperture.

For each aperture position, the VNA performed a stepped-frequency sweep and recorded the complex response across the selected frequency band. The resulting measurements were organised into the three-dimensional data cube

$s(x_m, y_n, f)$ and processed using the reconstruction algorithm described in Section 3.2.

The acquisition parameters used throughout the experiments are summarised in Table 4.3.

Table 4.3: Acquisition parameters used for automated SAR evaluation experiments using VNA-based radar.

Parameter	Value
VNA model	Copper Mountain C4420
Operating frequency	5–20 GHz
Bandwidth	15 GHz
Theoretical range resolution	~1 cm
Scan geometry	Raster (zig-zag) trajectory
Scan area	200 × 200 mm
Spatial sampling interval	1 mm
Target distance	80 cm

The selected stand-off distance of 80 cm ensures operation within the far-field region of the antennas. Using the Fraunhofer criterion of Equation 2.20, and considering the largest antenna dimension ($D = 53.3$ mm) together with the highest operating frequency (20 GHz), corresponding to $\lambda = 15$ mm, the far-field distance is

$$R_{FF} = \frac{2(0.0533)^2}{0.015} \approx 38 \text{ cm.} \quad (4.3)$$

The adopted stand-off distance therefore ensures far-field operation, simplifying the experimental validation by reducing the influence of antenna near-field effects on the acquired measurements.

4.2.2 Validation Experiments

Before evaluating representative targets, a series of validation experiments were conducted to verify the correct operation of the acquisition and processing chain. Since the VNA-based system requires the complete implementation of the acquisition and reconstruction workflow, it was necessary to validate each stage independently before analysing the resulting SAR images.

The validation process focused on three main aspects. First, the achievable range resolution was experimentally evaluated and compared with the theoretical value predicted by the selected bandwidth. Second, preliminary one-dimensional synthetic aperture measurements were performed to determine an appropriate aperture extent for the subsequent two-dimensional acquisitions. Finally, the responses obtained from monostatic and bistatic measurement configurations were compared to justify the use of the complex transmission coefficient S_{21} throughout the remainder of this work.

Range Resolution Evaluation

To experimentally evaluate the achievable range resolution of the developed VNA-based sensing configuration, the same metallic spherical target described in Section 4.1.2 was translated along the radar line-of-sight while maintaining all remaining acquisition parameters unchanged. The sphere was positioned at a nominal stand-off distance of approximately 80 cm and subsequently displaced in 1 mm increments over a range of ± 10 mm relative to this reference position.

For each target position, a frequency sweep was acquired and processed to generate a PDP. The distance associated with the dominant reflection peak was extracted and compared with the imposed target displacement.

Figure 4.13 presents the measured target distance as a function of the imposed displacement. As expected, the estimated distance does not vary continuously with the physical target position but instead remains constant within discrete intervals before transitioning to the adjacent range cell.

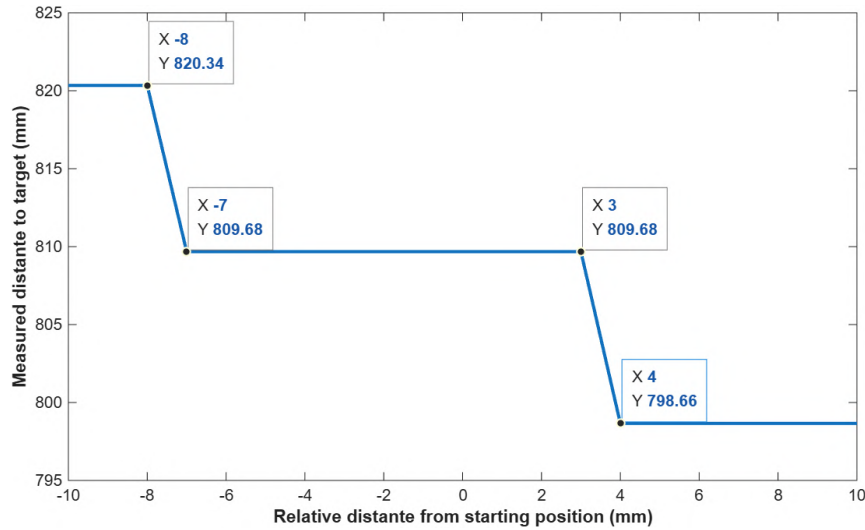


Figure 4.13: VNA-based radar range resolution analysis.

The measured distance changes in increments of approximately 10 mm, corresponding to the spacing between adjacent range bins. As discussed in Section 3.4.2, the selected operating band of 5–20 GHz provides a bandwidth of 15 GHz, yielding a theoretical range resolution of

$$\Delta R = \frac{c}{2B} = \frac{3 \times 10^8}{2 \times 15 \times 10^9} \approx 10 \text{ mm}. \quad (4.4)$$

The experimentally observed range-bin spacing is in agreement with the theoretical prediction, and the measured transitions between adjacent range bins occur at target displacements consistent with the expected 10 mm resolution.

Synthetic Aperture Validation

Before experimental two-dimensional measurements, preliminary one-dimensional synthetic aperture experiments were performed to determine the correct aperture required to capture the dominant spatial information from the target scene. The objective was to identify an aperture size large enough to achieve the maximum practical cross-range resolution while avoiding unnecessary acquisition time.

Initially, measurements were acquired over an aperture extending from -80 mm to 80 mm relative to the centre position. The resulting one-dimensional reconstruction, presented in figure 4.14 showed that significant energy contributions remained present near the aperture boundaries, suggesting that part of the target response was not being fully captured.

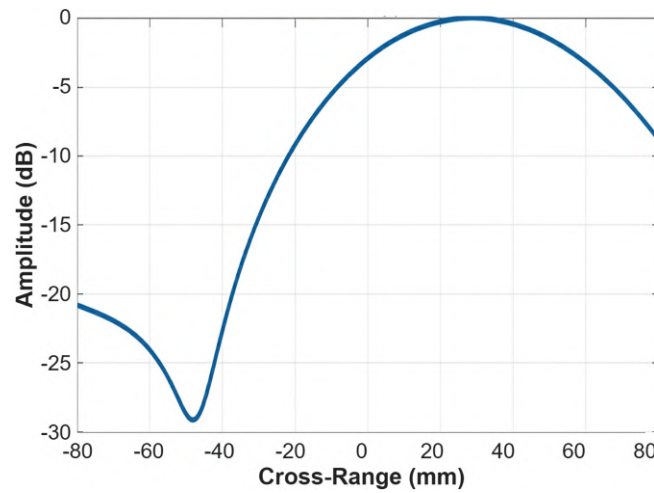


Figure 4.14: One-dimensional synthetic aperture experiment with 160 mm aperture size.

The aperture was subsequently extended to span from -200 mm to 200 mm. The corresponding reconstruction, shown in figure 4.15, revealed that the dominant response was effectively contained within a region extending approximately from -50 mm to 100 mm, beyond which only minor contributions were observed. This offset results from the sample not being perfectly centred with the synthetic aperture.

Based on these observations, a two-dimensional aperture of approximately 200 mm $\times$ 200 mm was selected for the subsequent SAR experiments. This aperture provides sufficient spatial coverage to capture the dominant scattering information while maintaining a reasonable acquisition duration.

Monostatic and Bistatic Configurations Comparison

To evaluate the influence of the measurement configuration on the acquired radar response, the four available scattering parameters of the VNA system were analysed independently. Figure 4.16 presents the resulting power delay profiles obtained

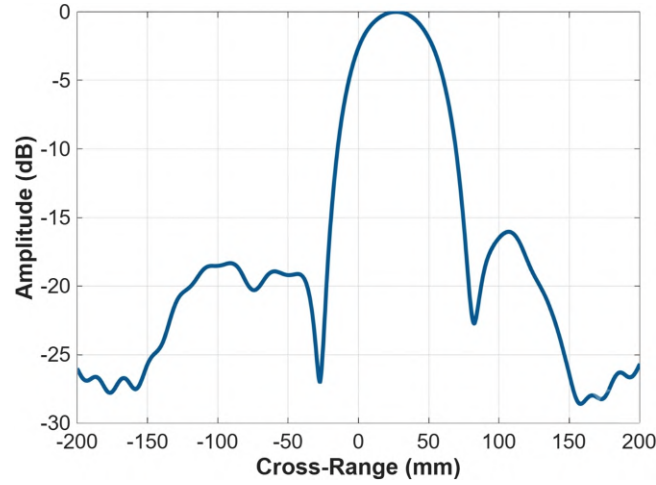


Figure 4.15: One-dimensional synthetic aperture experiment with 400 mm aperture size.

from the reflection coefficients (S_{11} and S_{22}) and transmission coefficients (S_{21} and S_{12}).

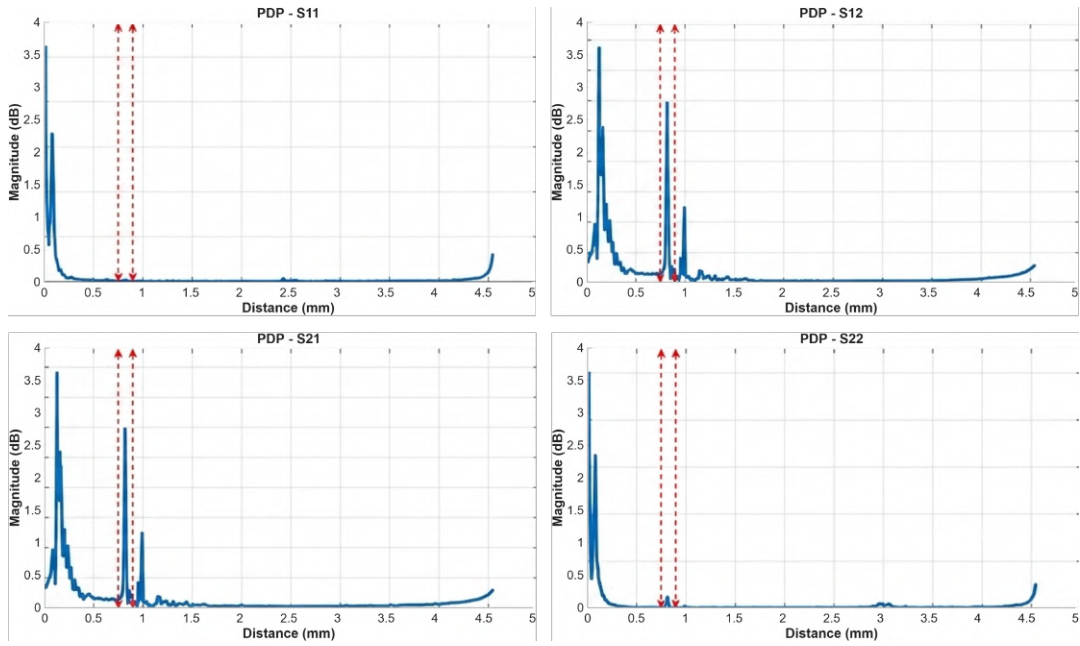


Figure 4.16: Power delay profiles of all four S -parameters for a single aperture position.

The monostatic configurations represented by S_{11} and S_{22} exhibited responses dominated by strong reflections located near the antenna region, together with comparatively weak target reflections. Although the target response remains detectable around the expected stand-off distance, marked with red dashed lines, the corresponding peaks are partially masked by the noise floor. This behaviour demonstrates that the effective dynamic range available for target discrimination with this configuration is insufficient.

In contrast, the bistatic transmission measurements represented by S_{21} and S_{12} produced significantly stronger and clearer distinguishable target responses. The

dominant reflection peak associated with the target is much stronger at the expected distance, with the addition of other weaker reflections not seen with monostatic configuration, associated to the robotic arm itself.

Based on these observations, the bistatic configuration was selected for all subsequent SAR acquisitions presented in this work due to its superior target detectability and improved separation between the desired target response and unwanted reflections.

4.2.3 Image Reconstruction Results

Following validation of the acquisition and processing chain, SAR reconstructions were generated using the same reconstruction methodology previously applied to the FMCW radar configuration. Figure 4.17 presents the reconstructed image obtained for the large pentagonal PCB target.

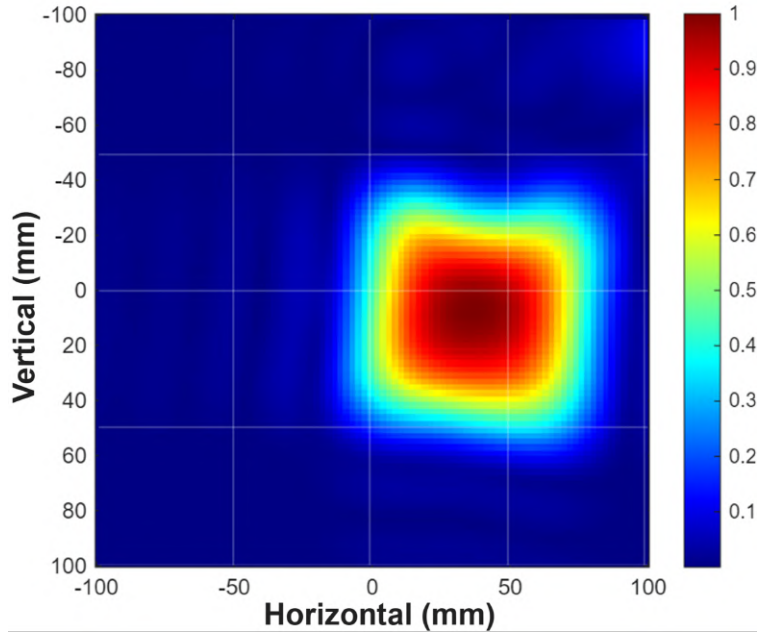


Figure 4.17: Reconstructed image obtained using the large pentagonal PCB target with the VNA-based sensing configuration.

The acquisition was performed using a bistatic configuration in which the transmitting and receiving horn antennas were separated by approximately 110 mm. This separation distance was selected as a compromise between minimising electromagnetic coupling between antennas and ensuring that the target region remained fully illuminated within the overlapping beam region of both antennas.

The reconstructed image successfully identifies the presence and approximate location of the target within the scanned region. The overall extent of the PCB substrate is visible, confirming the correct operation of the acquisition chain and the ability of the reconstruction algorithm to coherently combine the measured

responses across the synthetic aperture.

However, despite the successful detection of the target, the pentagonal metallic geometry itself cannot be clearly distinguished in the reconstructed image. Instead of reproducing the expected polygonal shape, the reconstruction exhibits a broad and diffuse scattering region with significant spatial spreading.

This behaviour is primarily attributed to the relatively large wavelengths associated with the operating frequency range of the native [VNA](#) configuration. Although the 15 GHz bandwidth provides improved theoretical range resolution compared to the [FMCW](#) radar implementation, the lower centre frequency significantly reduces the achievable cross-range resolution. As discussed in Section 3.4.2, the selected acquisition geometry yields a theoretical cross-range resolution of approximately 60 mm. This value is larger than the target features dimensions, limiting the system's ability to accurately reproduce its geometry. As a consequence, the system becomes capable of detecting the presence of the target but remaining unable to accurately resolve its geometrical features.

The obtained results demonstrate that bandwidth and operating frequency must be considered jointly when designing a [SAR](#) imaging system. Although the native [VNA](#) configuration provides substantially improved range resolution, the reduction in operating frequency degrades cross-range performance to the extent that overall image quality deteriorates. These observations motivated the investigation of a higher-frequency sensing configuration based on millimetre-wave frequency extenders, presented in the following section.

4.2.4 Discussion

The results obtained with the native [VNA](#) configuration highlight the trade-off between bandwidth and operating frequency. The stepped-frequency measurements provide significantly greater flexibility and improved theoretical range resolution compared to the [FMCW](#) radar implementation, the relatively low operating frequency limits the achievable cross-range performance for the dimensions considered in this work.

These observations demonstrate that increasing bandwidth alone is insufficient to obtain high-resolution [SAR](#) images. Both range and cross-range resolution must be considered simultaneously when selecting the sensing modality. To address this limitation, a third sensing configuration based on E-band frequency extenders was investigated. By shifting the operating frequency to the 75–90 GHz range, it becomes possible to combine improved range resolution with shorter wavelengths and enhanced cross-range performance.

4.3 VNA Configuration with Range Extenders

To overcome the cross-range limitations identified in the native VNA configuration, the sensing system was upgraded using millimetre-wave frequency extenders operating in the E-band frequency range. This configuration combines the advantages of a larger bandwidth with shorter wavelengths, enabling improved lateral resolution while preserving the increased bandwidth available through the VNA-based acquisition approach.

The frequency extenders translated the operating range of the VNA to approximately 75–90 GHz, corresponding to wavelengths between approximately 4.0 mm and 3.3 mm. This range is comparable to the operating frequency of the AWR1843 FMCW radar while simultaneously providing a significantly larger available bandwidth.

4.3.1 Experimental Setup

The experimental setup employed for this configuration is illustrated in Figure 4.18. The transmitting and receiving extenders were connected to a pair of W-band horn antennas mounted in a bistatic configuration. As in the previous VNA implementation, the antennas remained stationary while the target was translated across the synthetic aperture using the robotic scanning platform.

The target was positioned near the centre of the synthetic aperture and aligned normal to the boresight direction of the antenna pair. The stand-off distance was approximately 900 mm. The transmitting and receiving horn antennas were separated by approximately 140 mm and remained fixed during the measurements, while the target was translated across a 200 mm × 200 mm synthetic aperture using the robotic positioning system.

To minimise environmental reflections and unwanted electromagnetic interference, all measurements were again performed in a controlled environment, inside the anechoic chamber. The acquisition and reconstruction pipeline remained identical to that described for the previous sensing configurations, allowing direct comparison between the obtained results.

The acquisition parameters used throughout the experiments are summarised in Table 4.4.

4.3.2 System Validation

Prior to evaluating the image reconstruction performance of the developed SAR platform, a series of validation experiments were conducted to verify the theoretical assumptions underlying the acquisition and processing framework.

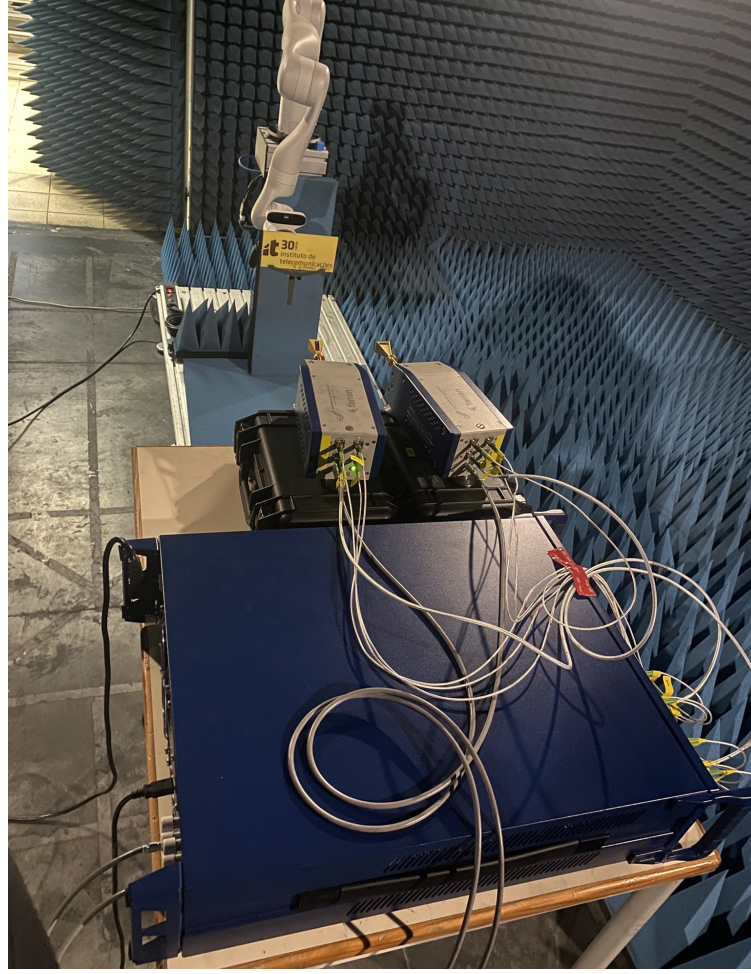


Figure 4.18: VNA-based radar with range extenders experimental setup.

Table 4.4: Acquisition parameters used for automated SAR evaluation experiments using VNA-based radar with frequency extenders.

Parameter	Value
VNA model	Copper Mountain C4420
Frequency extenders	FEV-12
Operating frequency	75–90 GHz
Bandwidth	15 GHz
Theoretical range resolution	~1 cm
Scan geometry	Raster (zig-zag) trajectory
Scan area	200 × 200 mm
Spatial sampling interval	1 mm
Target distance	90 cm
Antenna separation	140 mm

Spatial Sampling Interval

The spatial sampling interval is a critical parameter to avoid aliasing artefacts during SAR reconstruction. As discussed in Section 2.2, the spatial sampling interval must satisfy the Nyquist criterion to ensure coherent image formation.

Considering the acquisition geometry employed in this work and the system centre frequency of 82.5 GHz, with a stand-off distance of approximately 900 mm and a synthetic aperture of 200 mm, the maximum allowable spatial sampling interval predicted by the Nyquist criterion is determined by Eq. 4.5.

$$\Delta x_{\max} = \Delta y_{\max} = \frac{\lambda R}{2D} \approx 8.21 \text{ mm} \quad (4.5)$$

This result indicates that spatial sampling intervals larger than approximately 8 mm are expected to introduce spatial aliasing and image degradation. The experimental results presented in Figure 4.19 are consistent with this prediction, showing acceptable image quality for sampling intervals up to 8 mm, while visible artefacts and loss of reconstruction fidelity appear for a step size of 16 mm.

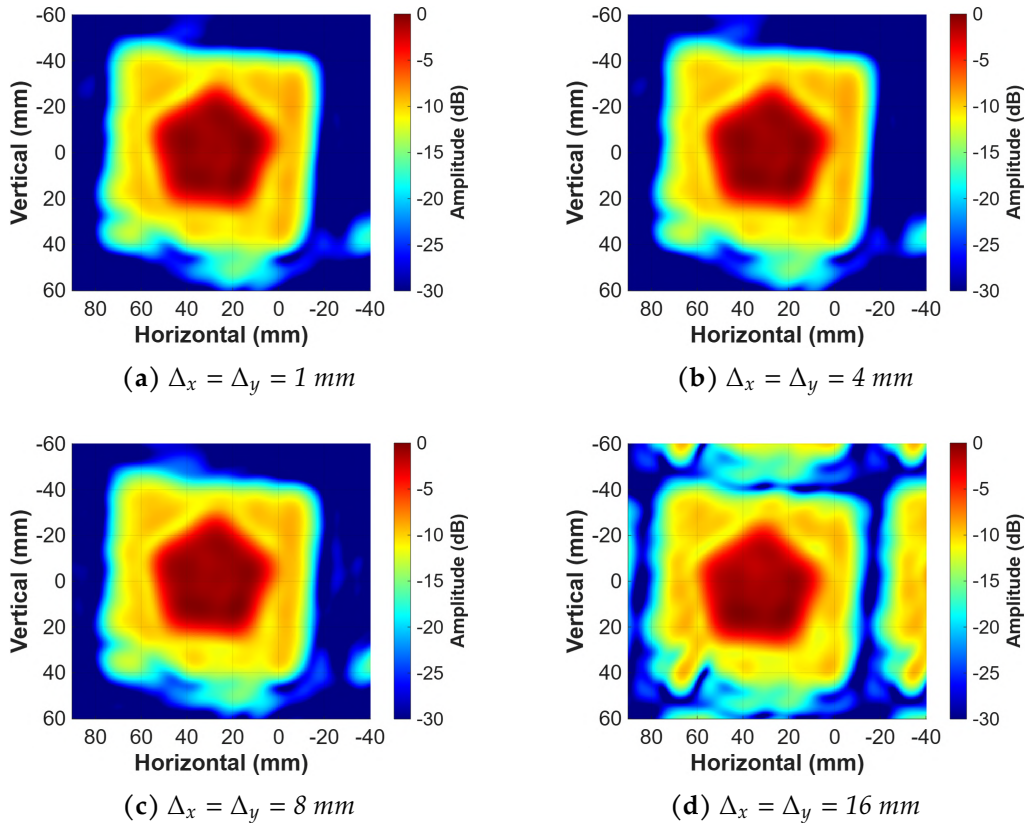


Figure 4.19: Effect of spatial sampling step size on VNA-based SAR with frequency extenders image quality. Reconstructed images of a pentagonal target for step sizes of (a) 1 mm, (b) 4 mm, (c) 8 mm, and (d) 16 mm.

Range Resolution Evaluation

The achievable range resolution of the VNA configuration with frequency extenders was experimentally evaluated using the same methodology previously applied to the native VNA setup. The metallic spherical target described in Section 4.1.2 was displaced along the radar line-of-sight in small increments around a nominal stand-off distance while maintaining all remaining acquisition parameters unchanged.

For each target position, a frequency sweep was acquired and processed to generate a Power Delay Profile (PDP). The distance associated with the dominant reflection peak was extracted and compared with the imposed target displacement.

Figure 4.20 presents the measured target distance as a function of the imposed displacement. As in the previous configurations, the estimated target position remains constant over discrete intervals before transitioning to the adjacent range bin. This behaviour is characteristic of range-domain quantisation and reflects the finite range resolution determined by the signal bandwidth.

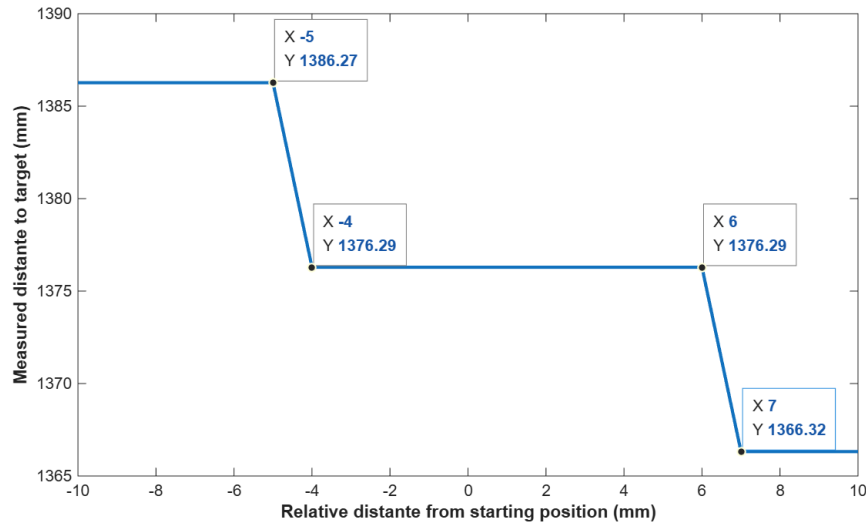


Figure 4.20: VNA-based radar range resolution analysis.

The measured distance changes in increments of approximately 10 mm, corresponding to the spacing between adjacent range bins. As discussed in Section 3.4.2, the selected operating band of 75–90 GHz provides a bandwidth of 15 GHz, yielding a theoretical range resolution of

$$\Delta R = \frac{c}{2B} = \frac{3 \times 10^8}{2 \times 15 \times 10^9} \approx 10 \text{ mm}. \quad (4.6)$$

The experimentally observed range-bin spacing is in agreement with the theoretical prediction, and the measured transitions between adjacent range bins occur at target displacements consistent with the expected 10 mm resolution. Compared with the native VNA configuration, the obtained results are virtually identical, as both systems operate with the same effective bandwidth. This

confirms that the introduction of the frequency extenders primarily affects wavelength-dependent characteristics, such as cross-range resolution, while having negligible influence on range resolution.

4.3.3 Image Reconstruction Results

Following the validation experiments, SAR reconstructions were generated using targets previously employed throughout the experimental evaluation. This way, a direct comparison with the FMCW and native VNA configurations can be done, assessing the improvements introduced by the millimetre-wave frequency extenders.

Unlike the FMCW image reconstruction experiments, all measurements for this configuration were performed inside the anechoic chamber. Maintaining controlled measurement conditions minimised the influence of environmental reflections and external interference, ensuring that any observed reconstruction artefacts could be primarily attributed to the sensing hardware and antenna characteristics rather than the surrounding environment.

Geometrical Target Reconstruction

The first target used was the large pentagonal PCB geometry used previously to evaluate both the FMCW radar and native VNA configurations. The reconstructed image obtained using the frequency extender configuration is presented in Figure 4.21.

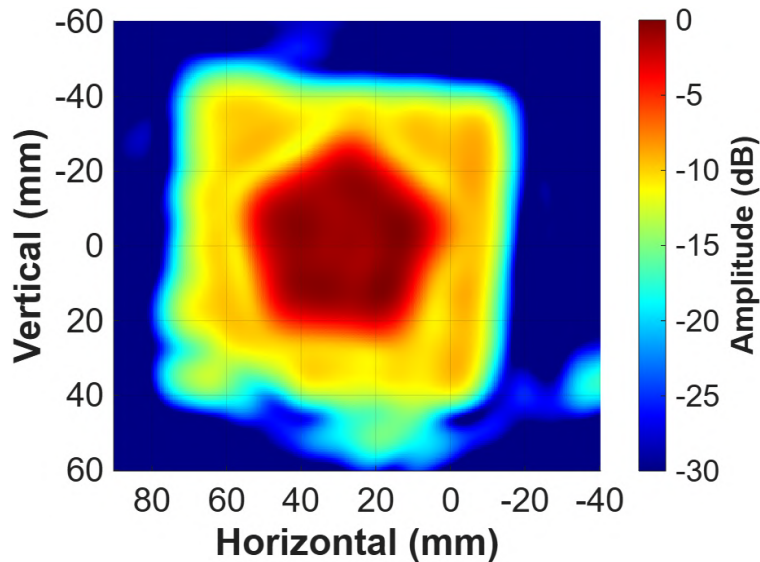


Figure 4.21: Reconstructed image obtained using the large pentagonal PCB target with the VNA-based sensing configuration with range extenders.

Compared with the reconstruction obtained using the native operating band, the resulting image exhibits substantially improved definition. The target boundaries became more distinguishable and the pentagonal geometry can now

be identified. This improvement is attributed to the shorter wavelength associated with the 75–90 GHz operating range, which provide better cross-range resolution while preserving the range resolution enabled by the stepped-frequency acquisition approach.

To further evaluate the reconstruction capabilities of the system, the smaller pentagonal target was also measured. The resulting reconstruction, shown in Figure 4.22, demonstrates that the target remains identifiable despite its reduced dimensions. Although the overall geometry is successfully recovered, a similar degree of edge broadening and spatial spreading is still present.

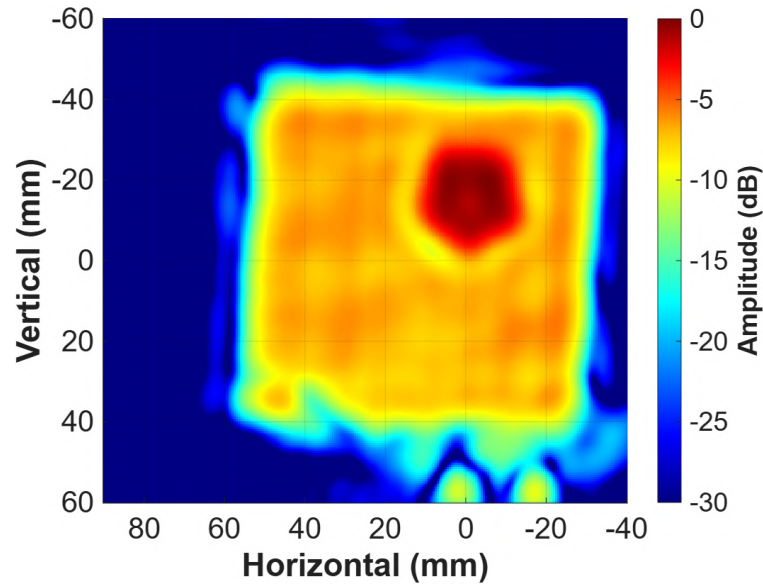


Figure 4.22: Reconstructed image obtained using the small pentagonal PCB target with the VNA-based sensing configuration with range extenders.

To provide a quantitative assessment of the reconstruction accuracy, the dimensions of the reconstructed targets were estimated from the SAR images. Since the reconstructed responses exhibited low-amplitude peripheral regions associated with image blurring, the target boundaries were defined using a threshold of -6 dB relative to the peak image amplitude.

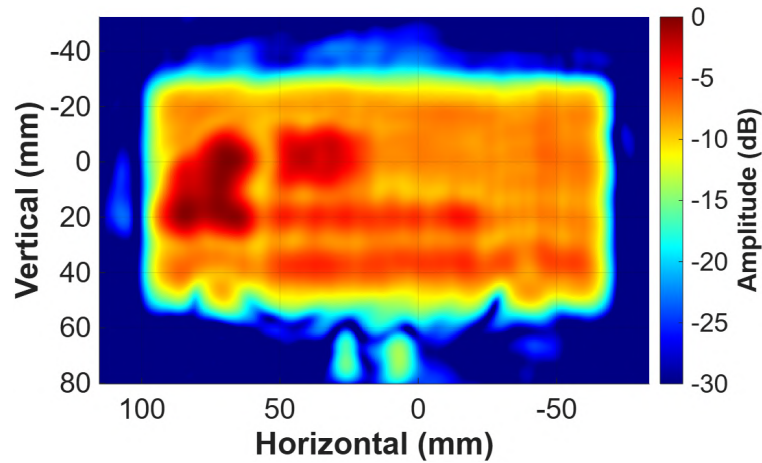
The obtained measurements are summarized in Table 4.5. The large pentagon was reconstructed with dimensions of 51.5 mm $\times$ 52.2 mm, corresponding to errors of 3.0% and 4.4% in width and height, respectively. The smaller pentagon was reconstructed with dimensions of 26.2 mm $\times$ 25.6 mm, resulting in errors of 4.8% and 2.4%. These results confirm that the frequency extender configuration is capable of reproducing the principal geometrical dimensions of the targets with reasonable accuracy while providing a substantial improvement in visual image quality compared with the native VNA configuration.

Table 4.5: Dimensional accuracy of the reconstructed pentagonal targets using the VNA configuration with frequency extenders.

Target	Width			Height		
	Nominal (mm)	Reconstructed (mm)	Error (%)	Nominal (mm)	Reconstructed (mm)	Error (%)
Large Pentagon	50.0	51.5	3.0	50.0	52.2	4.4
Small Pentagon	25.0	26.2	4.8	25.0	25.6	2.4

Complex Pattern Reconstruction

A more challenging assessment was subsequently performed using the “30 Years Instituto de Telecomunicações” target, shown in Figure 4.23. This sample contains a combination of large graphical elements, alphanumeric characters, and fine textual features, providing a more demanding evaluation of the reconstruction process.

**Figure 4.23:** Reconstructed image obtained using the “30 Years Instituto de Telecomunicações” target with the VNA-based sensing configuration with range extenders.

Contrary to the expected behaviour, the resulting reconstruction did not exhibit the improvement anticipated from the higher operating frequency. The reconstructed image is unable to recover the principal features of the target. While the overall dimensions of the PCB remain visible, neither the IT logo nor the textual content can be identified.

Although the reconstructed image does not clearly reproduce the graphical and textual features of the target, inspection of the image intensity distribution reveals that the radar response remains sensitive to the underlying metallic pattern.

Figure 4.24 presents a horizontal intensity profile extracted from the reconstructed image at the coordinate $y = 20$ mm. This profile was selected because it intersects both the highly reflective “IT” logo and the smaller textual features, allowing the response of structures with different dimensions to be analysed.

The profile exhibits a clear increase in response over the metallic region of the target, while the surrounding non-metallic areas produce substantially lower signal

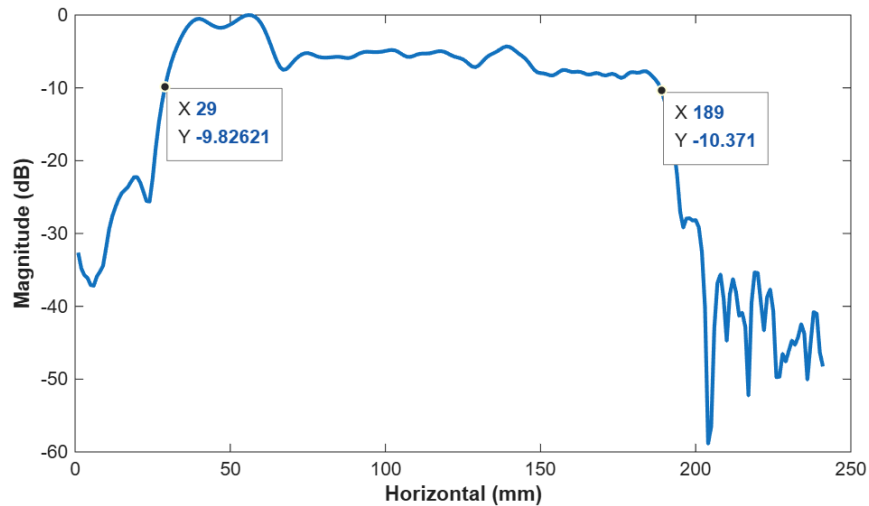


Figure 4.24: Horizontal intensity profile extracted through the reconstructed image of the “30 Years Instituto de Telecomunicações” target.

levels, establishing the system capability to distinguishing between metallic and non-metallic regions.

The markers shown indicate the points at which the signal level decreases by approximately 10 dB relative to the peak response. The distance between these points is 160 mm, which corresponds to the physical width of the sample, validating the systems ability to correctly reconstruct the target overall dimensions.

Although the global extent of the target is accurately recovered, the response associated with individual features remains spatially spread over a relatively large region. As a consequence, neighbouring reflections overlap and merge, preventing the individual letters and graphical elements from being clearly resolved. The profile therefore suggests that the target information is present in the reconstructed image, but that image blurring limits the ability to recover the finer details of the pattern.

A clear distinction can also be observed between the response levels associated with different target features. The region corresponding to the large metallic “IT” logo produces the strongest reflection, while the smaller textual features generate a measurable but lower-amplitude response compared with the surrounding non-metallic areas. This behaviour confirms that the radar is sensitive to the presence of the fine metallic structures and is capable of differentiating them from the PCB substrate.

However, the responses associated with these features extend over a relatively broad spatial region rather than being confined to their physical dimensions. Consequently, neighbouring reflections overlap and merge, causing the individual letters and graphical elements to lose their definition in the reconstructed image. The profile therefore suggests that the information associated with the fine target features is present in the acquired data, but that image blurring prevents its accurate spatial localisation and reconstruction.

The observed behaviour indicates that a source of error is affecting the image formation process. One possible explanation is associated with phase centre variations of the horn antennas across both frequency and angle [8]. Unlike the patch antennas employed in the FMCW radar, whose phase centre can be reasonably approximated as fixed over the operating bandwidth, horn antennas exhibit frequency-dependent phase-centre variation, meaning that the effective radiation origin does not remain fixed at a single spatial location throughout the operating band. Since the implemented reconstruction algorithm assumes a constant antenna phase centre for all frequencies and acquisition positions, these variations may introduce phase errors during coherent integration and consequently degrade the final image focus.

To further investigate this hypothesis, additional experimental tests were conducted to evaluate the influence of antenna phase centre behaviour and acquisition geometry on the reconstruction quality. These investigations are presented in the following subsection.

4.3.4 Phase Centre Evaluation

To further investigate the hypothesis that antenna phase centre variations were contributing to the observed image blurring, an additional experimental procedure was developed, shown in figure 4.25.



Figure 4.25: *Experimental setup to analyse the influence of phase centre variation.*

For this purpose, a target was mounted on a precision linear rail and translated laterally relative to the antenna pair.

The acquired frequency-domain data was subsequently divided into multiple subbands extracted from the original 75–90 GHz operating range. Independent reconstructions were then generated for each subband in order to evaluate whether changes in operating frequency produced measurable shifts in the

apparent target position. Since variations in antenna phase centre are frequency dependent, any significant displacement of the reconstructed target across different subbands could indicate the presence of phase centre movement.

However, the obtained results proved inconclusive. No definitive correlation could be established between operating frequency and apparent target displacement. This is because of one important limitation of this approach associated with the reduction of effective signal bandwidth when dividing the full operating range into smaller frequency subbands.

As discussed previously, range resolution is determined by signal bandwidth. Reducing the bandwidth of each analysed subband, reduces the achievable range resolution. The resulting range-resolution cells become substantially larger than the expected millimetre-scale phase centre variations of the antennas, making such displacements difficult to observe.

The results obtained in this experiment were therefore inconclusive. Further investigation for methods reported in the literature is required to determine whether this effect is responsible for the observed image degradation.

4.4 Comparative Analysis

The experimental results obtained throughout this work reveal the fundamental influence of operating frequency and signal bandwidth on SAR image formation and how their contributions are associated with different dimensions of the reconstructed image, bandwidth determining range resolution, whereas operating frequency influences cross-range resolution.

The FMCW radar operating within the 77–81 GHz frequency range, provides a relatively short wavelength that enabled good cross-range resolution. However, the available bandwidth is limited when compared with the stepped-frequency VNA configuration, resulting in a coarser range resolution. The influence of this limitation was controlled by the use of planar targets throughout the experimental evaluation. Since the targets occupied a narrow range interval, the reconstruction process was primarily dependent on cross-range resolution, allowing the geometrical characteristics of the samples to be accurately recovered.

The range resolution limitation became evident when targets exhibiting depth variation were considered. In these cases, the limited range resolution resulted in scattering contributions from different target depths being mapped into the same range cells, reducing the ability of the reconstruction algorithm to correctly separate individual features. The resulting images exhibited overlap between neighbouring reflections, demonstrating the importance of adequate range resolution when imaging three-dimensional structures.

To improve the achievable range resolution, the acquisition system was then changed to using the native VNA configuration. The significantly larger signal bandwidth provided improved theoretical range resolution compared with the

FMCW radar. However, the lower operating frequency increased the signal wavelength and consequently reduced the achievable cross-range resolution. The experimental results demonstrate that the improvement in range resolution alone is insufficient to compensate for the loss of cross-range resolution, resulting in poor target characterization and degraded image quality.

To address these limitations, the introduction of millimetre-wave frequency extenders enabled operation within the 75–90 GHz frequency range while maintaining the advantages of the native **VNA** configuration. This configuration combined the large bandwidth with a significantly shorter wavelength, improving range and cross-range resolution. As expected, the resulting reconstructions exhibited substantially improved target definition when compared with the native **VNA** configuration.

The experimental results therefore confirm that successful **SAR** imaging requires an appropriate balance between bandwidth and operating frequency rather than the optimisation of a single parameter.

4.4.1 Reconstruction Performance Comparison

The dimensional errors obtained for the reconstructed pentagonal targets are summarised in Table 4.6. Since identical samples were used for both sensing configurations, these results provide a direct comparison of their ability to preserve target geometry during the image reconstruction process.

Table 4.6: Comparison of dimensional errors obtained using the **FMCW** and **VNA** frequency extender configurations.

Target	Width Error (%)		Height Error (%)	
	FMCW	VNA+Ext.	FMCW	VNA+Ext.
Large Pentagon	2.2	3.0	6.2	4.4
Small Pentagon	0.0	4.8	8.0	2.4

For both systems, the reconstructed dimensions remained within 10% of the nominal target dimensions, indicating that the developed **SAR** platform is capable of providing reasonable dimensional estimates for planar geometries.

Although both systems produce comparable dimensional errors, it should be noted that the frequency extender reconstructions remain affected by the image blurring discussed previously. Consequently, the dimensional errors may not represent the maximum achievable performance of the system. A reduction of the observed blurring effects would improve the accuracy of the reconstruction algorithm and further enhance the geometrical fidelity of the resulting images.

This observation is further supported by the reconstructions obtained for the “30 Years Instituto de Telecomunicações” sample (Figures 4.10b and 4.23). Although the reconstruction obtained using the **FMCW** radar makes the larger features of the target more identifiable, the frequency extender configuration appears to better preserve the spatial distribution of the target information.

The experimental results therefore indicate that the frequency extender configuration represents a favourable compromise between bandwidth and operating frequency, combining the high range resolution of the [SFCW](#) approach with the short wavelengths required for improved cross-range resolution. However, this improvement is accompanied by increased system complexity. The bistatic acquisition geometry, horn antenna illumination characteristics, and possible phase-centre variations introduce additional sources of reconstruction error that are not present, or are significantly less pronounced, in the compact [FMCW](#) radar configuration. Consequently, achieving the full theoretical performance of the frequency extender system requires more accurate antenna behaviour modelling within the reconstruction process.

5

Conclusions and Future Work

This dissertation presented the development and experimental evaluation of a robotic SAR imaging platform for non-destructive testing applications. The proposed system was designed to support multiple sensing technologies through a common acquisition and image reconstruction framework, enabling a direct comparison between different radar configurations under equivalent experimental conditions.

Three sensing approaches were implemented and evaluated: i) a COTS FMCW radar based on the Texas Instruments AWR1843 sensor; ii) a stepped-frequency VNA configuration and iii) a VNA-based millimetre-wave configuration employing frequency extenders. Experimental validation was performed using a set of targets with known geometrical characteristics, allowing the influence of spatial sampling, operating frequency, and signal bandwidth on image quality to be investigated.

The obtained results demonstrated that bandwidth and operating frequency play complementary roles in SAR image formation. While the native VNA configuration provided improved theoretical range resolution through its larger bandwidth, the lower operating frequency resulted in reduced cross-range resolution and poor target characterisation. In contrast, the frequency extender configuration successfully combined large bandwidth with millimetre-wave operation, leading to a significant improvement in image quality and target reconstruction capability.

The FMCW radar demonstrated the most consistent overall performance throughout the experimental campaign. Despite its limited bandwidth, the system was capable of reconstructing the evaluated targets while maintaining low hardware complexity. The frequency extender configuration produced improved geometrical fidelity and demonstrated the highest imaging potential, although image blurring effects limited the achievable reconstruction performance.

Overall, the developed platform successfully achieved the objectives established for this work and provided valuable insight into the trade-offs associated with different SAR sensing architectures. The obtained results establish

a solid foundation for future research into radar-based non-destructive testing systems and high-resolution imaging applications.

Part of the work developed throughout this dissertation resulted in the following conference publication:

F. Lopes, T. Frade, L. Duarte, J. R. Reis, and R. F. S. Caldeirinha, "Automated Shape Classification for Non-Destructive Testing Using mmWave Synthetic Aperture Radar," in *Proceedings of the European Conference on Antennas and Propagation (EuCAP)*, Dublin, Ireland, Apr. 2026, accepted for publication.

Additionally, a journal paper based on the work presented in this dissertation is currently under development for submission to an IEEE journal, under the provisional title "A Unified Robotic SAR Testbed for Comparative Evaluation of VNA and COTS Radar Systems for Non-Destructive Testing."

5.1 Future Work

Several opportunities for future work were identified throughout the development and evaluation of the proposed system. The most immediate priority is the investigation of the image blurring observed in the frequency extender configuration. Further studies should focus on antenna characterisation, phase centre modelling, and calibration procedures in order to improve image focusing performance.

Future work should also include the evaluation of additional reconstruction algorithms and signal processing techniques capable of improving image quality and reducing reconstruction artefacts. The implementation of two-dimensional depth imaging and three-dimensional imaging approaches could further expand the capabilities of the developed platform.

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