COMPARATIVE ANALYSIS OF ISAR AND TOMOGRAPHIC RADAR

IMAGING AT W-BAND FREQUENCIES

Thesis

Submitted to

The School of Engineering of the

UNIVERSITY OF DAYTON

In Partial Fulfillment of the Requirements for

The Degree of

Master of Science in Electrical Engineering

By

Nicholas Christian Hopkins

UNIVERSITY OF DAYTON

Dayton, Ohio

May 2017
COMPARATIVE ANALYSIS OF ISAR AND TOMOGRAPHIC RADAR IMAGING AT W-BAND FREQUENCIES

NAME: Hopkins, Nicholas Christian

APPROVED BY:

__________________________  __________________________
Michael Wicks, Ph.D.          Lorenzo Lo Monte, Ph.D.
Advisor Committee Chairman   Committee Member
Professor, Electrical        Associate Professor, Electrical
Engineering                 Engineering

__________________________  __________________________
Robert Penno, Ph.D.          Andrew Bogle, Ph.D.
Committee Member             Committee Member
Professor, Electrical        Adjunct Professor, Electrical
Engineering                 Engineering

__________________________  __________________________
Howard E. Evans II, Ph.D.    Eddy M. Rojas, Ph.D., M.A., P.E.
Committee Member             Dean
Adjunct Professor, Electrical
Engineering                 School of Engineering
ABSTRACT

COMPARATIVE ANALYSIS OF ISAR AND TOMOGRAPHIC RADAR IMAGING AT W-BAND FREQUENCIES

Name: Hopkins, Nicholas Christian
University of Dayton

Advisor: Dr. Michael Wicks

As radar technology development advances and more devices are employed in traditional frequency allocation bands, such as the microwave portion of the frequency spectrum, users are increasingly struggling to operate amidst this spectrum congestion. With spectrum congestion on the rise, application performance degradation is progressively being realized due to scarce available bandwidth. Therefore, users, such as the 5G wireless community and the automotive industry, are exploring applications at higher portions of the frequency spectrum with such efforts being focused in the millimeter wave (MMW) frequency bands. A number of novel applications, such as full-body imaging and automotive collision avoidance systems, have been improved on or realized with the aid of MMW frequencies and their associated phenomenology. However, this portion of the spectrum lags, in some cases by orders of magnitude, far behind in research and development in comparison to other bands such as those found in the microwave region. Therefore, a clear need to aid the knowledge base and investigate MMW radar phenomenology has been undertaken in this thesis. The research this thesis documents concerns designing, building and, fielding a distributed
aperture array W-band (MMW) radar system. This thesis details incrementing the current fielded radar system capability from mono-static to bi-static imaging configurations. An improved method for calibrating the radar system resulting in higher quality imagery is also documented. The defined radar system was designed with the goal of performing multi-static Tomographic imaging. The research covered in this thesis is the first step toward incrementing the fielded system to full maturity.
This thesis is dedicated to the United States Air Force without whom, I wouldn’t be an engineer today.
ACKNOWLEDGMENTS

First and foremost, I would like to thank God for offering up his only son, Jesus Christ, as the sacrifice for my sins that, through repentance, righteousness and, charity, I may achieve salvation. It is upon this faith that arduous endeavors such as this thesis become more feasible and enjoyable. I wish to acknowledge my family and friends, specifically my mother Shannon, my sister Melissa and, my brother Matthew for their loving care and enduring support throughout this research and all of my professional education. I take great joy in explaining some of the finer points I’ve learned in engineering to my mother and I thank her so much for indulging me in these conversations. My sister has provided me, on numerous occasions, a voice of reason in stark contrast to the doubt I experience in being able to accomplish certain tasks in an effort to progress my education. Her ability to ask the right questions has provided me much needed clarity during the most turbulent of times. My brother has never failed to encourage and build up my confidence that I can accomplish all that has been placed before me. I am most grateful for his unwavering support.

This research would not have been possible without the guidance, mentorship and instruction of Dr. Lorenzo Lo Monte and Dr. Michael Wicks. Dr. Lo Monte is, without a doubt, one of the best engineers I will ever have the pleasure of working with and I am honored to have helped bring one of his designs to fruition. Dr. Wicks’ vision and brilliance is still on a level that I’ve yet to fully grasp which, I suppose, is what a Ph.D. will allow me to accomplish! Dr. Wicks’ unyielding confidence and encouragement to see this research through was immensely motivating. I want to thank you both for your efforts in building the Mumma Radar Laboratory at The University of Dayton from
the ground up and the diligent efforts you both spend in the development of your students. Both of you are sure to leave a lasting legacy behind you.

It is with the utmost appreciation that I thank and acknowledge Mr. Taylor Thullen, radar engineer at Brilliant Solutions Inc., for his immense knowledge pertaining to Tomography and for sharing the expertise he has developed with the use of the W-Band radar system and deriving imagery with its employment. My thesis would have gotten accomplished without Taylor, it just would have taken two more years! Mr. Thullen, I can’t thank you enough for the personal time you expended in working with me and helping bring me up to speed on your accomplishments that preceded my research. I hope to one day repay you for the time you’ve spent helping make my research a success.

In addition to Dr. Wicks and Dr. Lo Monte, I would also like to thank the other members of my thesis committee namely, Dr. Andrew Bogle, Dr. Robert Penno and, Dr. Howard Evans, for their time in answering my questions and providing me encouragement and guidance throughout my research.

It is with sincere thanks and appreciation that I acknowledge the members of the Mumma Radar Laboratory. The members of this laboratory have been invaluable in my development as an engineer and I am just as thankful for the professional relationships I have with many of them as I am for their personal friendships. Of specific mention are Mr. James Reed and Mr. Nihad Al-Faisali. Mr. Reed was instrumental in building the RF Sub-System as well as in mounting the four mono-static radars implemented from the design. His knowledge of experiment setup and location of necessary materials has been invaluable. Mr. Al-Faisali managed ordering many parts for the radar system and his timeliness with getting parts on order and conveying their arrival status alleviated many headaches. I would also like to thank Mr. Daryl Osterloh and Mr. Aaron Brandewie for helping me
understand how to run the algorithms implemented to move the robots in the laboratory as well as discussing finer points pertaining to the radar system and the experiments to be performed.

The University of Dayton electrical engineering department deserves my enduring appreciation for the opportunities the department affords to its students as well as its seamless ability to function administratively. Special thanks goes to Dr. Guru Subramanyam, chair of the electrical engineering department, and Mrs. Nancy Striebich, department secretary. I am thankful for Dr. Guru’s inherent kindness and support as well as fostering a true engineer’s mentality of always finding a solution. Without Mrs. Striebich, I most certainly would not be graduating so I may have chosen poorly by not acknowledging her shortly after my praise for the Lord.

Lastly, I would like to give my most ardent gratitude to the United State Air Force and the Palace Acquire Program. It is through these entities that I was enabled to return to graduate school to complete my Master’s degree. I am sincerely indebted to the United States Air Force for the investment they have made in me. I would also like to thank the personnel of the Air Force Life Cycle Management Center Engineering Home Office, and specifically, Mr. David Owen, Ms. Jacquie Rosenlieb, Mr. Jeff Day and Mrs. Robin Napier. As technical experts in the Home Office, Ms. Rosenlieb, Mr. Day and Mrs. Napier have been instrumental in my development as an engineer and my ability to serve the United States Air Force in its acquisition endeavors. Mr. Owen has functioned as my direct supervisor for the past three years and up till now, Mr. Owen is easily the best boss I have ever had. His ability to care about his employees and yet remain steadfastly professional in all respects is an attribute that only the best leaders are capable of developing. Mr. Owen, I thank you for your personal involvement in my professional development and for giving me the necessary resources I needed to finish this thesis. I would also like to thank the F-22 System Program Office and specifically, my new supervisor, Mr. Marvin Most, for affording me the much needed time to
hammer out the last portions of my thesis. The F-22 SPO will learn that I pay continued dividends on such investments.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>v</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xv</td>
</tr>
<tr>
<td>CHAPTERS:</td>
<td></td>
</tr>
<tr>
<td>I.  INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. PROBLEM STATEMENT</td>
<td>15</td>
</tr>
<tr>
<td>III. SAR/ISAR RADAR IMAGING PHENOMENOLOGY</td>
<td>20</td>
</tr>
<tr>
<td>IV.  TOMOGRAPHIC IMAGING PHENOMENOLOGY</td>
<td>33</td>
</tr>
<tr>
<td>V.  W-BAND DISTRIBUTED APERTURE ARRAY DESIGN</td>
<td>45</td>
</tr>
<tr>
<td>VI. EXPERIMENT SETUP</td>
<td>56</td>
</tr>
<tr>
<td>VII. DATA COLLECTION, PROCESSING AND, POST-PROCESSING ALGORITHMS</td>
<td>63</td>
</tr>
<tr>
<td>VIII. DATA CALIBRATION ERRORS AND CONSIDERATIONS</td>
<td>66</td>
</tr>
<tr>
<td>IX.  COMPARATIVE ANALYSIS OF ISAR AND TOMOGRAPHIC IMAGING</td>
<td>71</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>1.1</td>
<td>Spotlight SAR Vs. Stripmap SAR.</td>
</tr>
<tr>
<td>3.1</td>
<td>Range and cross-range definitions with respect to an airborne platform.</td>
</tr>
<tr>
<td>3.2</td>
<td>Formulation of a synthetic aperture.</td>
</tr>
<tr>
<td>3.3</td>
<td>Stripmap SAR image of Washington D.C.</td>
</tr>
<tr>
<td>3.4</td>
<td>Geometry of airborne platform in Spotlight mode.</td>
</tr>
<tr>
<td>3.5</td>
<td>Spotlight SAR image of a reapplication yard at Kirtland AFB.</td>
</tr>
<tr>
<td>3.6</td>
<td>Geometry of an ISAR radar system imaging a rotating target.</td>
</tr>
<tr>
<td>3.7</td>
<td>ISAR imagery of differing aircraft at arbitrary aspect angles.</td>
</tr>
</tbody>
</table>
4.3 Time domain signal representations. *Image courtesy of www.electronicdesign.com.*


4.5 Image in spatial domain transformed and represented in Fourier domain. *Image courtesy of The Academic Resource Center.*


4.7 Radar sensor geometry and Fourier space relationship. *Image, used with permission, from M. Wicks’ Intro to Radar Course.*

4.8 Fourier space relationship based on differing sensor geometries. *Image, used with permission, from M. Wicks’ Intro to Radar Course.*

5.1 Instrumentation Sub-System block diagram.

5.2 RF Sub-System block diagram.

5.3 Cabling Sub-System block diagram.

5.4 MMW Sub-System block diagram.

5.5 MMW Sub-System.

5.6 View from the right of the MMW Sub-System.

5.7 View from the left of the MMW Sub-System.

5.8 View from the front of the MMW Sub-System.

6.1 Copper plumbing pipe targets.

6.2 Laboratory experiment setup.

6.3 Mono-static ISAR experiment setup.

6.4 Bi-static Tomographic experiment setup.
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Stimson Radar Frequency Band Designation Table</td>
<td>9</td>
</tr>
<tr>
<td>1.2</td>
<td>POM Radar Frequency Band Designation Table</td>
<td>9</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

The use of radar systems and their applications has undergone considerable research and exponential advancement since the first radar systems were fielded prior to World War II. During the course of my research for my thesis’s selected topic, it seemed necessary to provide a brief overview of radar system development from first discoveries to modern day system applications. The overview certainly is not exhaustive however, it is hoped the reader will gain a firmer appreciation for the thousands of individuals who developed and incremented radar technology over the last 100 years.

The generation and detection of radio waves by German physicist Heinrich Hertz in the late 1880s [1] created a fuse that would later be lit by engineers and physicists less than a half century later leading to an explosion of research and development into radar system applications driven by the need for protection, security and technological supremacy sought by nations and their citizens caught in the raptures of war. Though World War II would usher in necessity for incrementing radar technology, eight countries of note, namely: France, Germany, Italy, Japan, the Netherlands, the Soviet Union, the United Kingdom, and the United States were quite engaged in radar relevant research and development well before the onset of the war [2].

Following Hertz’s discovery, Russian scientist, Alexander Popov, observed interference in a wireless transmission experiment he conducted in the Baltic Sea in 1897 [2]. The interference was
due to a Russian warship crossing in between the transmission link Popov had established between two other ships and is noted as the first mention of a means for object detection due to radio wave transmission [2] [3]. The beginning of the 20th century saw the deployment of the first operating device for object detection, the telemobiloscope, which was built in 1904 by the German Christian Hülsmeyer. Operating at 650 MHz, this device was capable of detecting the presence of ships (but not their distance or movement) at sea within 2 miles in dense fog [2]. By 1914, Nikola Tesla had introduced the idea of radar to the United States [2]. In 1922, Guglielmo Marconi, notable for his immense contributions to radio communications, delivered a lecture on the principle of radar at the Institute of Radio Engineers Conference [2]. Eleven years later in 1933, Marconi approached the Italian Warfare Ministry and presented the Ministry his ideas on radar in order to gain financial support [2]. The financial support garnered by Marconi allowed Ugo Tiberio to start a systematic research program in 1935, achieving the main theoretical results such as the radar equation [2]. Tiberio’s research program also led to the first experimental tests with a 200-MHz continuous wave frequency-modulated device, the Radio Detector Telemetro, which took place the following year [2]. Led by Emile Girardeau in 1934, the French were among the first to build and install shipborne radar systems [2]. In 1932 military engineer, Piotr Oshchepkov, proposed radar as a means for aircraft detection to leaders of the Soviet Union who actively supported Oshchepkov’s proposal [3]. By 1934, Oshchepkov had built and demonstrated an experimental radar apparatus capable of detecting an aircraft 3 km away [2] [3]. In December 1934, American Robert M. Page tested an experimental 60-MHz pulse-modulated radar and demonstrated tracking a plane 1.6 km away [2]. A year later, Page received a federal grant of US $100,000 to support radar research [2]. By 1936, Page’s group had developed a 28.6-MHz device that could detect planes as far as 40 km away [2]. During the 1930’s, as mentioned above, a number of countries were actively pursuing radar research.
and fielding operational systems but only those of Germany, the United Kingdom, and the United States had major operational impact [1].

Around the same time Robert Page was developing and testing his pulse-modulated radar, Great Britain had appointed scientists to investigate electromagnetic wave energy of which they concluded that it was possible to use electromagnetic waves for aircraft detection and ranging [2]. This investigation led to the Daventry Experiment in 1935, led by Robert Watson-Watt, which demonstrated beyond doubt that aircraft could be detected by radio waves [4]. The success of this demonstration ushered in vigorous research in Great Britain that culminated in the development and deployment of an aircraft early warning radar system along the eastern British coastline now known as Chain Home [2] [4]. Chain Home, or known at the time as RDF for radio direction finding, consisted of twenty radar stations that went operational in April 1939, had a detection range of 200 kilometers, is considered the first radar system to achieve extensive operational use, was largely credited with winning the Battle of Britain, and was operational throughout World War II [1] [2] [4].

As the 1930’s continued with radar development, most fielded systems relied upon widespread adaptation and extension of existing technology therefore, technological advancement was stagnant most of the decade [1]. This stagnation kept most operational radar systems of the time period at operating frequencies in the very high frequency (VHF) band of 30 MHz to 300 MHz [5]. An exception to the lack of technological advancement of this period can be noted in the United States in 1936-1937 during which the cavity magnetron circuit, the klystron electron tube, and coaxial and waveguide transmission lines and components were developed [1]. These developments aided British scientists, John T. Randall and Henry A.H. Boot, in the development of the cavity magnetron in 1940 [1] [2]. The cavity magnetron was a major breakthrough in radar technology, having the capacity to operate at much higher power and frequencies (3.3 GHz) and allowing much shorter
wavelengths (9.1 cm) which were suitable for small antennas of airborne radars [2]. The development of the cavity magnetron enabled radar systems to escape some of the constraints found in the VHF frequency band and push radar system applications into the microwave (3 to 30 GHz) region of the frequency spectrum [5]. A major benefit from the cavity magnetron was derived in increased detection range without the need for ever increasing antenna size due to the magnified power output derived from the cavity magnetron at S-band (2-4 GHz), and later, X-band (8-12 GHz) frequencies [2]. The year 1940 also saw the institution of the acronym RADAR, for RA dio Detection And Ranging, by the United States Navy [2].

By the end of World War II, researchers and scientists had found a number of ways to implement radar in a means to aid the war effort. Radar was used to steer searchlights and eventually anti-aircraft guns [6]. On ships, it was used to navigate at night and through fog, to locate enemy ships and aircraft and, to direct gunfire [6]. Radars had moved from bi-static to mono-static configurations reducing the size of their platforms [3]. Airplanes utilized radar to locate hostile aircraft and ships, for navigation, and to locate targets designated to be bombed [6]. Storm tracking with radar was implemented by military meteorologists before the end of the war [6]. Non-coherent pulsed radar systems reached maturity during the war and for years afterward, would be used for a number of important applications [7]. Immediately following the war, radar technological development diminished and the latter half of the 1940s was spent refining radar technologies that were initiated during the war such as monopulse tracking radar and moving-target indication (MTI) [5].

The 1950s brought the principle of coherency into practice for radar systems. A coherent radar employs a stable, coherent oscillator to transmit and receive signals and by doing so, the radar is able to keep track of the phase of the received signal over time [7]. A time-varying phase leads to a frequency shift in the receive signal that is well-known as the Doppler frequency shift [7]. With
the development of coherent radars, the 1950s saw serious application of the Doppler frequency shift principle to radar and the ability to take advantage of information derived from a target’s Doppler shift was considered revolutionary [5] [7]. Continuous wave (CW), MTI and pulse Doppler radars depend heavily on the use of the Doppler frequency shift principle as do modern day police radar guns and images derived from synthetic aperture radar (SAR) and inverse-SAR (ISAR) radar applications [5]. Another important contribution from the Doppler frequency shift principle is its application to weather radars in the detection of severe storms and dangerous wind shear [5]. The invention of SAR radar during this period made all-weather terrain and stationary target mapping possible [7]. The development of the airborne pulse Doppler radar provided the radar with additional information on target motion and enabled a mechanism to better separate target returns from those of background clutter due to reflections from Earth’s surface or even from weather phenomenon [7]. It should also be mentioned that a number of significant publications of important theoretical concepts such as matched filter theory, the Woodward ambiguity diagram, the statistical theory of detection of signals in noise, and the basic methods for Doppler filtering in MTI radars were noted during the 1950s [5].

The first large electronically steered phased-array radars were put into operation in the 1960s [5]. Airborne MTI radar for aircraft detection was developed for the U.S. Navy’s Grumman E-2 airborne-early-warning (AEW) aircraft at this time [5]. Many of the attributes of high frequency (HF, 3 to 30 MHz) over-the-horizon radar were demonstrated during the 1960s, as were the first radars designed for detecting ballistic missiles and satellites [5].

The 1970s brought forth major advances in signal and data processing that modern radar is based on [5]. Airborne pulse Doppler radar also advanced to be able to detect aircraft in the midst of heavy ground clutter (undesired signal returns) and the 1970s also initiated the use of radar on spacecraft
for remote sensing of Earth’s environment [5]. An example of a space-borne remote sensing radar platform during this time would be Seasat. Seasat was launched in 1978 by the United States as an experimental ocean surveillance satellite which provided data on a wide array of oceanographic conditions and features including: wave height, water temperature, currents, winds, icebergs, and coastal characteristics [8]. Seasat is noted for being the first ever civilian satellite to carry a SAR radar [9].

Also of special note during the 1970s is the demonstration and rapid implementation of Computerized Tomography to medical imaging [10]. The Tomographic principles utilized for medical imaging in devices that perform Computerized Tomography scans, or more commonly known as CT scans, would be applied later to radar systems which is one area of special interest in this thesis. Tomographic imaging phenomenology and techniques will be covered in Chapter IV.

The 1980s ushered in advances in target identification where radars became able to distinguish one type of target from another [5]. Phased array radars began to see mass production with implementations such as the Patriot and Aegis systems for air defense, the B-1B airborne bomber radar, and the Pave Paws ballistic missile detection system [5]. Building on successes from spacecraft such as Seasat, advances in remote sensing made it possible to measure winds blowing over the sea, the geoid (or mean sea level), ocean roughness, ice conditions, and other environmental effects [5]. Tomographic imaging techniques were utilized in SAR applications during this time period as well.

Continued advances in computer technology in the 1990s and the beginning of the 21st century allowed increased information about the nature of targets and the environment to be obtained from radar echoes [5]. The introduction of Doppler weather radar systems (as, for example, Nexrad), which measure the radial component of wind speed as well as the rate of precipitation, provided new hazardous-weather warning capability [5]. Terminal Doppler weather radars (TDWR) were
installed at or near major airports to warn of dangerous wind shear during takeoff and landing [5]. Unattended radar operation with little downtime for repairs was demanded of manufacturers for such applications as air traffic control [5]. HF over-the-horizon radar systems were operated by several countries, primarily for the detection of aircraft at very long ranges (out to 2,000 nautical miles [3,700 km]) [5]. Space-based radars continued to gather information about the Earth’s land and sea surfaces on a global basis [5].

Advances in digital technology in the first decade of the 21st century sparked further improvement in signal and data processing, with the goal of developing (almost) all-digital phased-array radars [5]. Digital technology improvements have made digital beamforming (DBF) and space-time adaptive processing (STAP) possible [7]. DBF and STAP are key elements in radar electronic protection, superior clutter mitigation techniques and advanced concepts such as passive radar where DBF makes ”pulse chasing” feasible [7]. High-power transmitters became available for radar applications in the millimeter-wave (MMW, approx. 30 to 300 GHz [7]) portion of the spectrum (typically 94 GHz), with average powers 100 to 1,000 times greater than previously available [5]. MMW radars have multiple applications including: seeking radars in precision guided munitions, intruder detection and tracking, full-body imaging systems for medical and security applications, automotive collision avoidance, automated landing guidance for aircraft, atmospheric sensing, military active protection systems, terrain following and avoidance, wireless communications and combat identification [7]. Of particular interest to this thesis is the application of MMW, (specifically W-band, i.e. 75 to 110 GHz), for advanced imaging technology research.

It is well at this point to illustrate to the reader standard frequency band designations, their corresponding frequency ranges and, of special note, frequencies attributed to MMW bands. Table
1 details part of the radar frequency band designation table located on the back cover of the well-known textbook, Stimson’s Introduction to Airborne Radar [11]. This table corresponds to the IEEE radar frequency band designation standard outlined in the Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition [12]. However, this handbook also notes that the designation ”mm” in Table 1 is derived from millimeter wave radar and is also used to refer to V-band, W-band, and, part of Ka-band when general information relating to the region above 30 GHz is to be conveyed [12]. That being said, the reader should be aware that other texts may include a different frequency range for the MMW band as is shown in the SciTech textbook, Principles of Modern Radar (POM): Radar Applications, and reproduced for the reader in Table 2 [7]. Identifying this nuance is important because the advantages of MMW systems may apply to some frequency bands not readily identified as falling into the IEEE defined millimeter wave frequency band. It also helps categorize systems in a more comparable way by differentiating between those systems that operate in the microwave, millimeter wave, or electro-optical frequency spectrums. To further this point, some advantages to MMW radar systems in comparison to microwave radar or electro-optical systems are: the ability to directly measure range, azimuth and elevation angles and, to penetrate nonmetallic surfaces, high spatial resolution (as compared to microwaves) and extension to 3-D with controlled geometry changes, and low resolution (with respect to electro-optical) which means less scanning is required to fill a given search volume [7]. Further evaluation of MMW and, more importantly, W-band center frequency selection will be elucidated in Chapters II and V.

As can be seen from the brief radar historical overview that has just been covered, radar systems research and development has been a constant area of exploration and discovery for a multitude of engineers and scientists since the 1930s. Radar systems research and development continues to be
### Table 1.1: Stimson Radar Frequency Band Designation Table

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Frequency (HF)</td>
<td>3-30MHz</td>
</tr>
<tr>
<td>Very High Frequency (VHF)</td>
<td>30-300 MHz</td>
</tr>
<tr>
<td>Ultra High Frequency (UHF)</td>
<td>300 MHz-1GHz</td>
</tr>
<tr>
<td>L</td>
<td>1-2 GHz</td>
</tr>
<tr>
<td>S</td>
<td>2-4 GHz</td>
</tr>
<tr>
<td>C</td>
<td>4-8 GHz</td>
</tr>
<tr>
<td>X</td>
<td>8-12 GHz</td>
</tr>
<tr>
<td>Ku (&quot;under&quot; K-band)</td>
<td>12-18 GHz</td>
</tr>
<tr>
<td>K</td>
<td>18-27 GHz</td>
</tr>
<tr>
<td>Ka (&quot;above&quot; K-band)</td>
<td>27-40 GHz</td>
</tr>
<tr>
<td>V</td>
<td>40-75 GHz</td>
</tr>
<tr>
<td>W</td>
<td>75-110 GHz</td>
</tr>
<tr>
<td>mm</td>
<td>100-300 GHz</td>
</tr>
</tbody>
</table>

### Table 1.2: POM Radar Frequency Band Designation Table

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Frequency (HF)</td>
<td>3-30MHz</td>
</tr>
<tr>
<td>Very High Frequency (VHF)</td>
<td>30-300 MHz</td>
</tr>
<tr>
<td>Ultra High Frequency (UHF)</td>
<td>300 MHz-1GHz</td>
</tr>
<tr>
<td>L</td>
<td>1-2 GHz</td>
</tr>
<tr>
<td>S</td>
<td>2-4 GHz</td>
</tr>
<tr>
<td>C</td>
<td>4-8 GHz</td>
</tr>
<tr>
<td>X</td>
<td>8-12 GHz</td>
</tr>
<tr>
<td>Ku (&quot;under&quot; K-band)</td>
<td>12-18 GHz</td>
</tr>
<tr>
<td>K</td>
<td>18-27 GHz</td>
</tr>
<tr>
<td>Ka (&quot;above&quot; K-band)</td>
<td>27-40 GHz</td>
</tr>
<tr>
<td>Millimeter Wave (mmw)</td>
<td>40-300 GHz</td>
</tr>
</tbody>
</table>
a robust and well-funded industry through which radar technologies continue to be invented, improved, refined and implemented such that radar systems impact the lives of virtually every citizen of industrialized nations. Radar provides roadway safety via the ever unfortunate speeding ticket derived by the unlucky motorist due to police radar. Vehicles are now rolling off assembly lines with radar collision avoidance systems and adaptive cruise control as standard equipment. Ground penetrating radar is used for detection of buried utilities as well as for archaeological site exploration. Weather radar provides storm tracking, severe weather indication and weather prediction capabilities. Space-based radar systems provide terrain maps for various purposes, measure changes to the environment such as sea ice extent or coastal water inundation, and provide data sets that encapsulate the environment at specific times to compare to future data collections. Air traffic control radar safely guides aircraft to and from airport terminals and expedites flight execution providing safety and efficiency to travelers. Radar is even being utilized to replace button and knob functionality on electronic devices with radar systems. These radar systems detect the motion of your hand and fingers where the knob or button would normally be triggering execution of device actions accordingly [13]! Radar systems have seen a myriad of commercial applications however, from my research, military and intelligence gathering applications maintain dominance in radar system development as well as the direction new sensors take in the applications they are designed for. Radars even communicate to other radars. Consider the following example: A pilot on a fighter aircraft initiates a weapons release command executed through an aircraft fire control radar system based on airborne pulse Doppler radar system information that then allows a MMW seeker radar on a guided munition to impact its intended target. As a radar engineer, it will be quite interesting to see the direction radar technology progresses over the next 5, 10 and 15 years!
Radar system advancements have covered a wide array of applications and addressed and solved numerous problems in an effort to gain information about objects of interest as well as one’s surroundings and environment. Of particular interest to this thesis is the comparative analysis of ISAR and Tomographic imaging of a cooperative target of interest at selected W-band frequencies.

Inverse synthetic aperture radar, or ISAR, is a radar technique used to produce images based on SAR principles. For SAR applications, the radar platform is in motion and in general, the target or scene being imaged is considered stationary. Some examples of SAR applications are Spotlight SAR and Stripmap SAR. In Spotlight SAR, the radar focuses on the target of interest, during the whole data integration period, as the radar platform moves along its course. For Stripmap SAR, the radar focuses on a fixed look direction as the radar platform moves along its course. Figure 1.1 illustrates the geometries of Spotlight SAR and Stripmap SAR. The figure details a radar platform carried on an aircraft that is imaging a terrain scene. The reader will note that the terrain highlighted in the left of the figure illustrates Spotlight SAR where the radar platform is fixed on a specific location on the terrain as the aircraft moves along its flight path. The parallel dotted lines in the figure illustrates the Stripmap SAR area the radar platform images with the radar focused with a fixed specific look angle at the terrain. One can picture the highlighted area in the bottom right of the figure moving within the dotted line boundary as the plane flies along its flight path thus deriving a Stripmap SAR image. The inverse to the SAR application would be a radar platform that is stationary that is imaging a moving target and thus, the name categorizing this system is inverse SAR, or ISAR. ISAR theory is developed from Spotlight SAR principles. The term cooperative or non-cooperative, as it pertains to a target, refers to a target of interest an ISAR system attempts to image where the target motion is known a priori (cooperative) or the target motion is unknown (non-cooperative) and
must be estimated. A portion of this thesis will focus on ISAR imaging based on Spotlight SAR principles applied to cooperative targets of interest.

As stated previously, Tomography is an imaging technique that has enjoyed great success in the medical community over the last 40 years due to its non-invasive ability to image the human body with ever increasing resolution. Such an implementation is truly a marvel when one contemplates the impact this technology has had on thousands, if not millions of people. Computerized Tomography was first implemented in devices in the 1970s and, in the medical field, is a technology that is utilized to scan a human body to define and evaluate medical issues within the body. Computerized Tomography takes slice images of the body without superimposition, as if individual sections had been taken out of the body [10]. In advanced systems, these slices are just 0.5 to 1 millimeter thick, allowing doctors to see even the tiniest changes in tissue [10]. However, a paper by Munson et al. in 1983 sought to compare Computerized Tomography principles to SAR principles, specifically
Spotlight SAR principles, in order to show that the two imaging techniques are quite similar in concept [14]. This topic will be explored further in Chapter IV.

Radar system operating frequency selection plays a key role in the design of the system and the application the system shall be utilized for. The phenomenology of the target information derived by the radar system varies with frequency [7] and therefore, certain frequencies will provide more pertinent information for certain targets. With the proliferation of devices which utilize the frequency spectrum, it becomes an ever increasing challenge to operate in specific frequency bands due to the congestion and interference posed by overcrowding the spectrum with multiple devices. Since high resolution requires wider waveform bandwidth [7], operating a device in an uncongested band can be advantageous at increasing resolution capabilities. Signal propagation attenuation through the atmosphere and environment is another consideration as some frequency bands provide less attenuation than others given the conditions the signal must propagate through.

The following shall summarize the remaining chapters of this thesis. Chapter II shall illustrate the problem to be investigated via the comparative analysis of ISAR and Tomographic imaging of a cooperative target of interest. Chapters III and IV shall provide the reader with the requisite background knowledge to ISAR and Tomographic theory, respectively, that is pertinent to the analysis of this problem. Chapter V shall detail the W-band distributed aperture array designed by Dr. Lorenzo Lo Monte, associate professor in electrical engineering at the University of Dayton. This radar system was built and implemented by the writer of this thesis in conjunction with University of Dayton staff, most notably Mr. Jim Reed of the University of Dayton Electrical and Computer Engineering (UDECE) department, members of the Mumma Radar Laboratory at the University of Dayton and, radar engineer, Mr. Taylor Thullen, of Brilliant Solutions Inc. Chapter VI shall define the experiment to be performed and the supporting equipment necessary to conduct the experiment.
Chapter VII shall explain the data collection, processing and, post-processing algorithms employed to perform the comparative analysis. Chapter VIII shall serve to document the data calibration errors inherent to the design as well as those uncovered while performing experiments with the hope that future users of the radar system will develop novel approaches to mitigate these errors and improve the system’s imaging capability. Chapter IX shall provide the awaited comparative analysis of ISAR and Tomographic imaging of cooperative targets of interest at W-band frequencies. Lastly, Chapter X shall summarize the results obtained and provide concluding remarks on the experiments as well as future research considerations employing the designed radar system’s capabilities.
CHAPTER II

PROBLEM STATEMENT

As stated in Chapter I, the goal of this thesis is to perform a comparative analysis of ISAR and Tomographic imaging of cooperative targets of interest at selected W-band frequencies. The literature is rich with investigation and results derived from ISAR/Spotlight SAR (since the theory behind the two modes are analogous) imaging applications as well as applications involving Tomography. References [7] [15] [16] [17] [18] [19] [20] [16] [21] [22] [23] detail a few examples of applications pertaining to ISAR and Tomographic imaging techniques and phenomenology. However, a number of examples in the literature for ISAR/Spotlight SAR applications utilize microwave frequencies such as X-band. Alternatively, much has been written of Tomography applications such as Computerized Tomography with the use of X-rays, microwave band applications to investigate phenomenology such as rotating structures and, HF band ground penetrating radar applications. In researching the topic to be investigated in this thesis, I noted that research into MMW imaging techniques is robust however, few experimental results and setups have been realized and published relative to the copious amount of literature covering such techniques in the microwave bands. This thesis seeks to aid the knowledge base with respect to imaging results and analysis conducted on cooperative targets of interest utilizing ISAR and Tomographic imaging techniques at W-band frequencies.
As one shall note from Chapter I, radar system development has historically progressed from low to high frequency as new electronic devices, as well as ever improving signal processing methods, enable the investigation of radar phenomenology at higher and higher frequencies. Alternatively, development of electro-optic and infrared (EO/IR) remote sensing platforms at the much higher infrared/optical frequency spectrums has recently begun to trickle down innovation and improvements to lower bands encompassing terahertz and MMW applications [24]. It would seem that MMW applications and research may, in the near future, undergo rapid advancement as technologies from the microwave and EO/IR spectrums find new utility and application in the MMW spectrum.

However, there are still a number of issues limiting robust exploitation of MMW phenomenology. EO/IR sensors rely on photon interactions interpreted by analog to digital (A/D) converters where antennas used for MMW rely on converting voltages to currents that are then interpreted by A/D converters. The physics of these interactions limit the technology transfer between these two spectrums. Advances in electronic device capability has yielded massive proliferation of devices that operate in the microwave spectrum however, a number of these devices are not capable of being utilized as frequency increases in the MMW spectrum. As an example, transmit/receive (T/R) modules, which are essential to operate multifunctional radar over a broad spectrum, are increasingly being developed for high output, wide-band applications but this technology is struggling to break out of the microwave band and become more applicable to MMW system designs [25]. Input/output signal losses in the terminal portion of T/R modules as frequency increases limits this device’s applications at MMW frequencies [25]. Advances in the development of sources and detectors are only recently making some applications viable at MMW frequencies and there will surely be a need to further improve these devices [24]. Waveform generation and upconversion of electronically
generated arbitrary baseband signals for the MMW spectrum has also been a strong limiting factor [26]. Another major limiting factor to research and development in the MMW spectrum has been the prohibitive cost of electronic devices needed to realize useful MMW systems. The microwave spectrum has seen huge investment and because of this, billions of devices have been developed to operate within this frequency range. Just think of how many cell phones alone are currently being operated around the world! The proliferation of devices has driven hardware costs lower and lower thus making it advantageous to continue operating in the microwave spectrum and delay expensive research and development at MMW frequencies. However, the proliferation of devices in the microwave frequency range continues to increasingly congest that spectrum and severely limits broadband applications. It should be noted though that it is exactly these kinds of constraints that drive innovation and the search for novel ways of implementing technology in differing frequency bands.

In order to conduct the comparative imaging analysis which is the main subject of this thesis, a radar system had to be employed to perform the required imaging. Due to size constraints and the need to explore imaging at MMW frequencies, a W-band distributed aperture array radar system was designed and built with the purpose of performing multi-static Tomography as well as being utilized to perform other radar modes as experiments and customers require. This system design is covered in detail in Chapter V. The radar system design consists of four mono-static W-band radars that, at full capability, shall be utilized in a distributed aperture array. The design of the radar itself isn’t novel however, the way in which the radar system shall be deployed is unique. This thesis shall detail the deployment of the W-band radar systems onto industrial Yaskawa Motoman robots in order to form the distributed aperture array. Current research in the Mumma Radar Laboratory at The University of Dayton has utilized one of the four mono-static radars in conjunction with one of
the aforementioned robots to perform imaging of selected targets. This thesis shall focus on an ISAR imaging case utilizing one of the mono-static radars and then incrementing to a bi-static case in an effort to aid incrementing the design to fully deployed maturity. The full capability of the design is set to achieve robust multi-static Tomographic imaging once the design is fully implemented. Our imaging analysis goal is to replicate the mono-static case that has already been implemented in the Mumma Radar Laboratory by performing ISAR imaging and then incrementing to the bi-static case in order to develop the Tomographic imaging framework needed to perform imaging with the data sets derived from both radars. The development of this framework is necessary to achieve the full capability of the W-band radar design.

As previously mentioned, another major driver of this thesis’ research is the need for broadband imaging capabilities. Users such as the 5G wireless communications industry as well as the automotive industry have been employing technologies at MMW frequencies, specifically at the 34 and 39 GHz as well as the 77 and 94 GHz portions of the MMW spectrum, respectively. Congestion in the microwave frequency spectrum is pushing technology applications outside of that band. It should be noted that the applications within the aforementioned industries are proliferating and the need for bandwidth and/or novel ways of sharing the frequency spectrum will increase in proportion to the number of devices fielded for these applications. With users who’ve traditionally relied upon the robust radar imaging capabilities found at microwave frequencies being squeezed out of that spectrum to make room for other applications, other portions of the spectrum must be utilized to provide imaging capabilities. The MMW spectrum offers wide bandwidth that is un-molested due to the lack of users occupying that part of the spectrum. This thesis seeks to leverage imaging capabilities and techniques at microwave frequencies in order to investigate the pertinence of utilizing
these techniques in the MMW spectrum, specifically at W-band frequencies. By performing a comparative analysis of ISAR and Tomographic imaging of targets at W-band frequencies, the utility and value of images derived at W-band from targets of interest will help establish new ways of performing imaging, innovation in system design and, improvements in data processing that meet the needs of users who are increasingly limited in their abilities to provide imaging due to decreasing spectrum availability and bandwidth constraints.

This thesis is experimental in nature and includes MMW radar designs, measurements for performance demonstration and, imaging to demonstrate hardware capabilities.
CHAPTER III

SAR/ISAR RADAR IMAGING PHENOMENOLOGY

In order to better illustrate the methodologies that will be employed to evaluate the imaging analysis this thesis wishes to accomplish, it is necessary to detail some of the fundamental theory behind synthetic aperture radar (SAR) imaging. We will then explain a few of the finer points pertaining to Spotlight SAR. Spotlight SAR fundamentals are what ties inverse synthetic aperture radar (ISAR) and Tomographic imaging together. The relationship between Spotlight SAR and ISAR will then be explained leading into a brief overview of ISAR imaging techniques.

As stated in Chapter I, SAR principles were developed in the 1950’s with the original concept credited to Carl Wiley. Since then SAR has seen a myriad of airborne and space based applications. One of the main applications for SAR deals with terrain imaging. In other radar applications, echoes received by the radar system from the ground are categorized as clutter and are undesirable because they can mask target detections that would otherwise be present and available for the radar to discriminate. However, SAR seeks to exploit this clutter in order to form an image of the terrain or area the radar is obtaining surveillance over. A challenge in SAR imaging has been the resolution achievable by the radar system performing the imaging. Resolution refers to how well the radar system can resolve two objects from one another. In order to form a quality two-dimensional (2-D) image, the SAR radar must provide high resolution in both range and cross-range. Figure 3.1 gives a simple illustration defining range and cross-range with respect to an airborne platform. Figure 3.1
shows that range is parallel to the radar look direction and cross-range is parallel to the direction the airborne platform is traveling. Resolution in range, denoted by $\delta_R$, is dependent on the signal bandwidth, $BW$, and is defined as

$$\delta_R = \frac{c}{2BW} \quad (3.1)$$

where $c$ is the speed of light. Consequently, high range resolution may be achieved with a short-duration pulse or by a coded wide-bandwidth signal that utilizes pulse compression processing [27]. SAR applications seek to provide high cross-range resolution as well. In traditional radar systems, cross-range resolution, denoted by $\delta_{CR}$, is approximately defined as

$$\delta_{CR} \approx R\theta_{3dB} \quad (3.2)$$

where $R$ is the range to the target and $\theta_{3dB}$ is the 3 dB azimuthal beamwidth in radians. Furthermore, the 3 dB azimuthal beamwidth can be approximated by

$$\theta_{3dB} \approx \frac{\lambda}{D_{ant}} \quad (3.3)$$
where $\lambda$ is the signal wavelength and $D_{ant}$ is the length of the antenna in meters. By combining Equations 3.2 and 3.3, we yield

$$\delta_{CR} \approx \frac{R\lambda}{D_{ant}}. \quad (3.4)$$

Equation 3.4 demonstrates that in order to achieve good cross-range resolution at long distances, antennas with large dimensions must be employed. For example in order to achieve cross-range resolutions of 10 meters or better at distances of 10 kilometers with a radar system employing a C-band frequency of 5 GHz, the largest dimension of the antenna must be at least 60 meters. Clearly this is an issue if one seeks to employ this radar on an airborne platform. In order to overcome this obstacle, a novel approach was employed that gives SAR its namesake; the development of the synthetic aperture.

To begin formulating a synthetic aperture, a smaller physical antenna is utilized with a wide beamwidth. In the case of Stripmap SAR, this small antenna is then moved along a flight path and images a scene of interest. Once the scene enters the radar’s beamwidth, the echoes from the scene are coherently combined until the scene that is being imaged exits the radar’s beamwidth. Figure 3.2 helps illustrate this point. The figure details a tank being imaged by a radar platform with beamwidth $\theta_{az}$. As the tank comes into the beamwidth, the echoes received by the radar system begin to be coherently combined and continue to do so until the tank exits the beamwidth. The distance, $D_{SAR}$, the aircraft flies while the radar platform is receiving echoes contained in $\theta_{az}$ simulates an aperture size that is equal to $D_{SAR}$. This simulated aperture is what gives rise to the term synthetic aperture. Based off of the echo collection distance $D_{SAR}$, the beamwidth, $\theta_{SAR}$, that applies to the synthetic aperture can be defined as

$$\theta_{SAR} \approx \frac{\lambda}{2D_{SAR}}. \quad (3.5)$$

22
The reader will note the factor of 2 located in the denominator of Equation 3.5. This factor arises from the fact that a real physical antenna has an antenna pattern for transmission and reception while a synthetic aperture only has an antenna pattern related to the collection of the echoes. Stimsons Introduction to Airborne Radar explains that this is analogous to saying that the two-way pattern of the synthetic array has the same shape as the one-way pattern of a real physical array of twice the length and thus, the factor of 2 [11].

From the geometry illustrated in Figure 3.2, we can deduce that

\[ D_{SAR} \approx \frac{R \cos \theta_{az}}{\lambda} \approx \frac{R \theta_{az}}{2} \]

(3.6)

and given

\[ \theta_{az} \approx \frac{\lambda}{D_{az}} \]

(3.7)

we are able to combine Equations 3.5, 3.6 and 3.7 to arrive at

\[ \theta_{SAR} \approx \frac{D_{az}}{2R} \]

(3.8)
With the result obtained in Equation 3.8, Equation 3.2 can be utilized again to yield the Stripmap SAR cross-range resolution as

$$\delta_{CR} \approx \frac{D_{az}}{2}. \quad (3.9)$$

This tells us that SAR performing in a Stripmap mode has cross-range resolution that gets finer with smaller physical apertures (although there are limits as to how small) and is independent of range. By employing a radar system with the proper signal bandwidth, coherent signal processing and, real antenna apertures, imaging techniques such as Doppler Beam Sharpening (DBS) can be utilized to form high resolution Stripmap SAR images. Figure 3.3 details the fine resolution imaging capable by a Stripmap SAR radar.

However, SAR is a flexible methodology and Stripmap SAR methods is just one area where SAR has found robust utility. Another area is Spotlight SAR and the methodology behind this mode is of greater importance to this thesis.
Spotlight SAR is capable of imaging areas and targets of interest with higher resolution than Stripmap SAR. A Spotlight SAR radar is able to perform finer image resolution due to the radar beam being fixed on a particular location. Because of this, a much longer synthetic aperture can be realized generating higher cross-range resolution. However, as with all things pertaining to radar, a tradeoff exists between the amount of area the radar can image and the increase in image resolution. Stimsons Introduction to Airborne Radar points out three distinct ways in which Spotlight SAR differs from Stripmap SAR:

1. By having the beam focused on one area, the length of the synthetic array is not limited by the azimuthal beamwidth of the real antenna.

2. Since the size of the real antenna does not limit the length of the synthetic aperture, a larger real antenna may be employed thus increasing gain and improving the signal-to-noise ratio (SNR) at the cost of a smaller imaging area due to a decrease in the mainlobe beamwidth.

3. Focusing the radar in a particular location increases the ability to receive returns from more of a target’s main scattering centers thus filling gaps in the backscatter the radar collects about the target.

The third point listed above is a main advantage at using Spotlight SAR. Spotlight SAR increases the geometric diversity of the viewing angles of the target and this leads to more of a target’s main scattering centers providing information about the target thus providing a more comprehensive target image [11].
Range resolution for Spotlight SAR is analogous to that of the Stripmap mode however, cross-range resolution for the Spotlight mode found in the literature is defined as

\[ \delta_{CR} \approx \frac{\lambda}{2\theta_{int}} \]  \hspace{1cm} (3.10)

where \( \theta_{int} \) is the angle of integration over which the received target echoes are coherently processed. It should be noted that Equation 3.10 holds for all SAR modes as long as \( \theta_{int} \) is interpreted as the relative rotation between the radar and the target [28]. Figure 3.4 illustrates some simple geometry of an airborne platform operating in Spotlight mode. The angle \( \Omega \) in Figure 3.4 is analogous to the angle \( \theta_{int} \) in Equation 3.10.

With the resolutions defined, the Spotlight SAR system can focus on accomplishing its main objective; image reconstruction based on the echoes received from the area illuminated by the system. It is at this point that we will begin to develop the connection between Tomography and Spotlight
SAR. As mentioned in Chapter I, Munson et al. were the first to make this connection by publishing, in 1983, their paper: A Tomographic Formulation of Spotlight-Mode Synthetic Aperture Radar. This paper demonstrates that the reconstruction of images derived from Spotlight SAR can be interpreted as a Tomographic reconstruction problem supported by signal processing theory that has as a foundation the Projection Slice Theorem [14]. Currently, the most common algorithm implemented in Spotlight SAR applications for image reconstruction is the Polar Format Algorithm (PFA) [28].

To illustrate what made PFA the algorithm of choice for Spotlight SAR image reconstruction, the reader will recall that range resolution is dependent on signal bandwidth. To achieve 0.1 meter range resolution, the RF bandwidth must be 1.5 GHz. Historically however, analog-to-digital converters (ADCs) have not been able to keep pace with meeting these bandwidth requirements [28]. That’s not to say that ADC technology to digitize such high bandwidth is unavailable; it simply illustrates these devices may be difficult to obtain or simply too costly [28]. To combat the ADC issue, a novel approach called dechirp-on-receive, also known as deramp or stretch processing, is employed when the transmitted waveform is a linear frequency modulated (LFM) chirp with a large time-bandwidth product [28]. A radar receiver that utilizes deramp processing is capable of incorporating an ADC with a sampling rate that is significantly lower than the transmit bandwidth would normally call for [28]. However, the measurements obtained by this receiver are made in a polar coordinate system and the fast Fourier transform (FFT) used in the image reconstruction requires samples of this data in Cartesian coordinates [28]. PFA interpolates the measured data in the frequency domain in order to provide samples from the polar coordinate domain to the Cartesian coordinate domain which allows the FFT to be properly applied to the data in rendering the SAR image [28]. Improvements in signal processing as well as many other areas have allowed Spotlight SAR applications to reach maturity and Figure 3.5 illustrates the fine image resolution inherent to this mode of SAR imaging.
Now that some of the finer points pertaining to Spotlight SAR have been established, we can begin the discussion on inverse synthetic aperture radar or, ISAR. Since both Stripmap SAR and Spotlight SAR principles are derived based off of the radar platform being in motion, a radar platform employing these modes suffers imaging degradation with respect to targets that are moving. In general, targets being imaged by these platforms are assumed to be stationary and targets that are in motion induce phase shifts in the measured data that must be compensated for before image reconstruction. The inverse of a moving radar platform illuminating a stationary target would be a stationary radar platform illuminating a moving target and that is exactly what ISAR does. That is not to say that the radar platform must remain stationary but for our purposes, we shall focus on the
ISAR cross-range resolution is a function of the change in viewing angle between the radar and target [11]. Figure 3.6 illustrates a basic geometry of an ISAR radar system imaging a rotating target. The reader can see that as the target rotates in the counterclockwise direction on the turntable with respect to the radar system, the viewing angle between the radar and the target changes. This change
in viewing angle induces a differential rate of phase change which produces differing Doppler frequencies [11]. Each Doppler frequency specifies a cross-range location on the target. As these target cross-range positions, or scatterers, get farther from the scene center the radar is imaging, the scatterer’s rate of phase change increases and thus differing Doppler frequencies are yielded. Upon further evaluation of this target geometry, it can be shown that the cross-range resolution for an ISAR radar system is

$$\delta_{CR} = \frac{\Delta f_d \lambda}{2\dot{\theta}_{int}}$$

where $\Delta f_d$ is the difference in Doppler frequency, $\lambda$ is the radar system operating wavelength and, $\dot{\theta}_{int}$ is the rate of change of the viewing angle during the timeframe that the aperture is being synthesized. However, the radar system has a minimum difference in Doppler frequency that it can resolve and typically this minimum difference is approximated by the 3 dB bandwidth of the radar system’s Doppler filter bank [11]. Therefore, ISAR cross-range resolution depends on the Doppler resolution and Equation 3.11 becomes

$$\delta_{CR} = \frac{BW_{3dB} \lambda}{2\dot{\theta}_{int}}$$

where $BW_{3dB}$ is the 3 dB bandwidth of the Doppler filter bank.

As we spoke of earlier, there are two cases of ISAR targets: targets that are cooperative, where the target motion is known, and those that are un-cooperative, where the target motion is unknown a priori and must be estimated. In general ISAR typically addresses the latter situation and estimation of the target motion parameters is a major focus of ISAR imaging algorithms. The process of estimating the target’s radial motion and removing the phase term associated with the target’s radial motion is called range alignment or range tracking [29]. After this processing is done, the processed
signal is referred to as motion compensated. Typically motion compensation is not enough to pro-
duce time-invariant Doppler shifts and a phase correction must be implemented [29]. This phase
correction is referred to as phase tracking. Once the motion compensation and phase tracking have
taken place, the signal can be processed via an FFT and the ISAR image is rendered. Another con-
sideration on why these processing corrections are necessary is derived from the implementation of
the FFT. To use the FFT effectively, the scatterers must remain in their range cells during the entire
coherent processing interval (CPI), and their Doppler frequency shift must remain constant [29]. If
the scatterers drift out of their range cells or Doppler frequency bins, the FFT-generated image will
be smeared [29]. Figure 3.7 illustrates ISAR imagery of differing aircraft at arbitrary aspect angles
and details the high resolution capabilities inherent to ISAR imaging applications.

As noted above, there are a number of challenges to address processing of ISAR imagery how-
ever, the experiment to be evaluated in this thesis is being conducted in a controlled setting and thus,
the target motion parameters shall not need estimating. This eliminates the need for such processing
as motion compensation and phase tracking. Therefore, for our purposes we need only to collect the
in-phase and quadrature (I and Q) data and then process this data via an FFT to produce an ISAR
image.
Figure 3.7: ISAR imagery of differing aircraft at arbitrary aspect angles. Image, used with permission via Creative Commons License, from Journal of King Saud University - Computer and Information Sciences.
In Chapter I we briefly mentioned Computerized Tomography with the use of X-rays and how that technology has enjoyed great success for its applications in the field of medical imaging. Computerized Axial Tomography scans, now commonly known as CAT scans, utilize X-rays to provide two-dimensional cross sectional projection imagery of three-dimensional solid objects via digital processing of multiple one-dimensional projectional views received from different look angles [14] [22]. This technology has been widely used for non-invasive medical examination of internal organs and in non-destructive testing of manufactured items [14]. Figure 4.1 illustrates a simple CAT scan geometry of imaging a human head and helps detail the technique of Tomography as applied to medical imaging. As the X-ray source and detector rotate around the object to be imaged, narrow X-ray views of the object are acquired over a full $360^\circ$ [27]. The results obtained due to the various imaging angles provided by the X-ray source/detector rotation are then integrated, via the Projection Slice Theorem, to derive an image [27].

The seminal work on Spotlight SAR and Tomography by Munson et al. does a succinct job of explaining the Projection Slice Theorem which shall be reproduced here for the reader. Let $g(x, y)$ be an unknown signal we wish to reconstruct based on its projections. The Fourier transform of the
Figure 4.1: Simple CAT scan geometry. Image courtesy of Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach, C. Jakowitz.
function $g(x, y)$ is then defined as

$$G(X, Y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y) e^{-j(xX+yY)} dx dy$$  \hspace{1cm} (4.1)$$

Given Equation 4.1, the inverse Fourier transform is then defined as

$$g(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(X, Y) e^{j(xX+yY)} dX dY.$$  \hspace{1cm} (4.2)$$

By employing a $(u, v)$ coordinate system on the unknown signal space of $g(x, y)$ via a counterclockwise rotation from the $x$-axis with respect to an angle, $\theta$, an orthonormal linear transformation is derived for the unknown signal space such that

$$x = u\cos(\theta) - v\sin(\theta)$$

$$y = u\sin(\theta) + v\cos(\theta).$$  \hspace{1cm} (4.3)$$

If we let the unknown signal, $g(x, y)$, be an arbitrary two-dimensional X-ray attenuation function then, Figure 4.2 illustrates the geometry of this arbitrary function with a $(u, v)$ counterclockwise rotation through the $x$-axis via angle $\theta$ [22]. Therefore, utilizing the $(u, v)$ coordinate transformation, the projection of $g(x, y)$ is defined as

$$p_\theta(u) = \int_{-\infty}^{\infty} g(ucos(\theta) - vsin(\theta), usin(\theta) + vcos(\theta)) dv$$  \hspace{1cm} (4.4)$$

One can see from Equation 4.4 and Figure 4.2 that the function $p_\theta(u)$ represents a series of line integrals in the direction of the $v$-axis with respect to each value of $\theta$ [14]. In taking the one-dimensional Fourier transform of $p_\theta(u)$, we yield

$$P_\theta(U) = \int_{-\infty}^{\infty} p_\theta(u) e^{-juU} du.$$  \hspace{1cm} (4.5)$$

With this definition of $P_\theta(U)$, we can restate equation 4.5 as

$$P_\theta(U) = G(Ucos\theta, Usin\theta).$$  \hspace{1cm} (4.6)$$
Figure 4.2: Geometry of \((u, v)\) counterclockwise rotation. Image courtesy of Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach, C. Jakowitz.
Equation 4.6 is the Projection Slice Theorem and this equation demonstrates that the Fourier transform of the projection, $p_{\theta}(u)$, at angle $\theta$ is a one-dimensional “slice” of the two-dimensional transform $G(X, Y)$ taken at angle $\theta$ with respect to the $x$-axis [14]. The Projection Slice Theorem is utilized to define another equation namely, the Radon transform, and the Radon transform is what is used in such algorithmic techniques as Filtered Backprojection (FBP) and Time Domain Correlation (TDC) to produce Tomographic images [27].

In deriving the mathematics behind the Projection Slice Theorem, we defined the Fourier transform and the inverse Fourier transform of an unknown signal, $g(x, y)$. The Fourier transform decomposes a complicated signal into the frequencies and relative amplitudes of its simple component waves [30]. In addition to the frequencies and amplitudes of the component waves, the Fourier transform also provides phase information associated with each wave. This transform follows from mathematical discoveries made by Joseph Fourier in the early 19th century [31]. Fourier proposed that any periodic signal could be represented by an infinite sum of weighted sinusoidal functions, later known as a Fourier series [32]. This proposal went on to form the basis for periodic signal analysis through the use of a Fourier series. A key difference between the use of a Fourier series for signal analysis versus using a Fourier transform for signal analysis is whether the signal being analyzed is periodic or non-periodic. As stated previously, Fourier series is applied to periodic signals where the Fourier transform is applied to non-periodic signals. A common application for a Fourier transform is the interrogation of a signal via the signal’s time/frequency domain relationship. The Fourier transform takes a time domain signal and converts this signal into the frequency domain. Alternatively, the inverse Fourier transform converts a signal specified in the frequency domain back to the time domain. A time domain signal is one where the value of the signal is displayed as a function of time. A prime example of a signal with respect to time are signal outputs on the display
of an oscilloscope. Figure 4.3 illustrates some common time domain signal representations such as sine, square and sawtooth waves as viewed on an arbitrary oscilloscope. However, there is another domain that the Fourier transform is capable of coupling to the frequency domain. This domain is called the spatial domain and it is through this domain, in conjunction with the frequency domain, that the kind of imagery we have been discussing is analyzed and generated.

An image can be represented as a two-dimensional or three-dimensional array of pixels in the spatial domain. Each pixel represents a value of the image’s intensity [33]. There are many different kinds of spatial images and these images can be differentiated by the way pixel intensity is characterized. For example, black and white images are determined by pixel intensities taking on values of either 0 or 1 where a grayscale image has a pixel intensity value scale that goes from 0
Pixels in color images are characterized by each pixel having 3 matrices associated with it and the combination of values from these three matrices determines the intensity and color of each pixel. Figure 4.4 illustrates these three image cases. An image could be described as a collection of information and image transformations, such as those that take place with the use of a Fourier transform, allow us to change the way we view the information that has been collected [33]. By converting images from the spatial domain to the frequency domain, the information of an image’s pixels can be viewed from a spatial frequency, magnitude and, phase perspective. The frequency domain representation of an image is also referred to as viewing the image in Fourier space. Images in Fourier space are represented by frequency components that either consist of high frequencies or low frequencies. The bulk of information in an image is represented in Fourier space by frequency components made up of low frequencies [33]. These low frequencies are analogous to small changes in pixel intensity and are located near the origin in Fourier space [33]. Fourier space frequency components consisting of high frequencies represent large pixel intensity variations. High frequency Fourier space components contain information describing the edges and fine detail of an
image and the component’s distance from the origin in Fourier space is proportional to the component’s frequency value [33]. Figure 4.5 illustrates a simple image in the spatial domain and this image’s representation upon being Fourier transformed into Fourier space.

Tomography, as applied to radar, functions by mapping the radar’s observation of a target into Fourier space and this mapping depends heavily on the target/radar spatial geometry [27]. The observations collected and mapped to the Fourier space constitute a frequency domain data set of the object under observation and this frequency domain data set is equivalent to the image of the object in the spatial domain albeit, with varying degrees of image resolution due to a number of factors. By taking radar observations from varying viewing angles, an attribute known as spatial or geometric diversity is provided to the radar system performing the observations. As noted earlier, generally with any improved attribute of a radar system there is a tradeoff that must take place that reduces the radar’s capability in some way elsewhere in the system. With Tomography, that trade-space is demonstrated via frequency diversity being traded to achieve the spatial diversity just mentioned. Spatial diversity enables more observational data to be mapped to the Fourier space and
with more information about the object, a higher resolution image of the object can be produced in the spatial domain. The process of mapping as much object information as possible to Fourier space is also referred to as filling the K-space. In the literature, Fourier space is commonly referred to as K-space and Figure 4.6 aids in illustrating the geometry associated with mapping a vector in K-space back to the spatial domain and viewing the image the K-space vector is associated with.

With radar Tomography, the orientation of the radar’s receivers and transmitters with respect to the object being observed defines the way in which the Fourier space is filled and, subsequently, the amount of information available to derive an image of the object upon transforming the collected Fourier space data back to the spatial domain. Figures 4.7 and 4.8 help illustrate these sensor geometries and how they affect the data collected in the Fourier space. In Figure 4.7, the radar’s transmitter (Tx) and receiver (Rx) are located at arbitrary positions in two-dimensional space. Separation of the Tx and Rx sensors generates an angle, $B$, known as the bi-static angle. A unit vector,
\[ F = \frac{4\pi f}{c} \cos\left(\frac{B}{2}\right)U_B \]  

where \( f \) is the transmit frequency, \( c \) is the speed of light and, \( F \) is the Fourier space vector. The reader should note that in the case of a mono-static radar configuration, the \( \cos\left(\frac{B}{2}\right) \) term in Equation 4.7 goes to one since the bi-static angle, \( B \), is zero. From Equation 4.7, one can see that as either the angle \( B \) or the transmit frequency \( f \) change, a new vector \( F \) in Fourier space is generated defining a point in this space. Therefore, the more \( F \) vectors generated, the more information collected from the observations from a target. Figure 4.8 shows four examples of how the Fourier space fills as a result of differing sensor geometries. The first example in Figure 4.8 demonstrates a Tx/Rx geometry where both sensors are stationary however, the sensors employ a wideband waveform utilizing multiple frequencies. The consequence of such an arrangement is a set of linear points mapped into Fourier space that follow the Fourier space vector, \( F \). The second example illustrates
a stationary Tx with moving Rx geometry and a continuous wave (CW) waveform employed by the sensors. In this configuration, the frequency does not change however, the bi-static angle does vary with the Rx sensor movement and thus, a circle of points are traced out in Fourier space. In analyzing the third geometry example, a pattern begins to emerge. Adjustment of the bi-static angle in the spatial domain allows points to be defined in Fourier space that rotate about the Fourier space origin. Adjusting, or stepping, the frequency in the spatial domain corresponds to points being proportionally, with respect to the frequency, closer or further from the origin in Fourier space. In this way, more and more observed information about the target can be mapped to Fourier space and thus, a more representative image of the target can be constructed in the spatial domain.
Figures 4.7 and 4.8 detail the utility of radar Tomography and how spatial diversity and in-band stepped frequencies contribute to providing additional target information in the pursuit of high resolution target imaging.
CHAPTER V

W-BAND DISTRIBUTED APERTURE ARRAY DESIGN

The W-band distributed aperture array radar system that is being utilized in illuminating/imaging the target of interest that is the focus of this thesis was designed by Dr. Lorenzo Lo Monte, associate professor in electrical engineering at the University of Dayton and also, chief scientist of Telephonics Corporation. The motivation behind Dr. Lo Monte’s design concerns two areas. Given the size of the imaging chamber our laboratory possesses, physical target size can be a constraint to the imaging being accomplished. All radar imaging is based on far-field approximation and a larger physical target can limit the imaging range needed to be in the far-field in our chamber. Conversely, targets need to be large with respect to the imaging wavelength otherwise the scattering mechanism can be adversely influenced by the near field. Therefore, utilizing W-band frequencies for imaging eases these constraints. In speaking with Dr. Lo Monte, he provided a comparison example where, given an X-band radar with a wavelength of 3 cm, the best image that we can accomplish in our chamber is probably on the order of 20x20 in pixel size. In using a radar at W-band, the wavelength is on the order of 3 mm therefore, the image could be on the order of 200x200 in pixel size. The second area of motivation for this design isn’t the design of the radar itself but rather, how the system shall be employed to perform the imaging. The radar design details building four monostatic radars and these radars shall be mounted on four industrial Yaskawa Motoman robots. The robots shall be controlled by a Matlab program that details an imaging routine to be accomplished based
on the target geometry that is outlined for the imaging experiment. Therefore, implementing the radar design in this fashion is a unique and novel approach to performing Tomography. This thesis seeks to provide a step forward in implementing the full radar design capability by utilizing two of the four radar systems to perform the ISAR and Tomographic imaging comparative analysis.

The design of each individual radar system can be broken down into four components: Instrumentation Sub-System, Radio Frequency (RF) Sub-System, Cabling Sub-System and, Millimeter Wave (MMW) Sub-System.

The Instrumentation Sub-System consists of an Agilent N5221A Network Analyzer, a Stanford Research Systems FS725 Rubidium Frequency Standard and, a National Instruments Data Acquisition (NI DAQ) module. The Network Analyzer utilizes two ports to connect to the radar system’s transmitting and receiving antennas and this constitutes one channel. This thesis shall utilize two channels, i.e. two radar systems, to perform the required imaging for analysis. The Rubidium Frequency Standard operates as an atomic clock in the radar system which synchronizes the operation of the system. The Frequency Standard outputs a 10 MHz signal upon which all other signals are created. The Frequency Standard signal also interfaces with the Network Analyzer in order to keep the network signals coherent. The NI DAQ commands switches in the RF Sub-Subsystem that allow the local oscillator and transmit signals to continue down their respective signal chains. To be more succinct, the NI DAQ controls whether the radar transmitter is in standby or radiate mode. Figure 5.1 details the Instrumentation Sub-System.

The Instrumentation Sub-System interfaces the RF Sub-System via the Network Analyzer, Rubidium Frequency Standard and, the NI DAQ. The Network Analyzer transmits a 2-12 GHz signal through the RF Sub-System and this signal is used as the intermediate frequency that’s mixed with the operating frequency. Before exiting the RF Sub-System, a bias tee is employed in the transmit
Figure 5.1: Instrumentation Sub-System block diagram.
signal chain to carry -5V down the RF transmission line along with the transmit signal to power other components in the system. The received signal chain also incorporates a bias tee in the RF Sub-System to carry +5V down the RF reception line to power other components in the system. Variable 5V power supplies are utilized as power inputs for the bias tees. Upon entering the RF Sub-System, the Rubidium Frequency Standard, or clock, signal is bandpass filtered because the signal is quite noisy and must be cleaned. The clock signal outputs more power than can be input into components down the line in this signal chain so the signal is attenuated by 4 dB. This signal then interfaces with an 11 GHz Phase Locked Local Oscillator (LO) to synchronize and cohere the LO to the phase of the Frequency Standard’s 10 MHz output. The LO then multiplies the 10 MHz Frequency Standard signal in order to achieve an LO output signal of 11 GHz. The LO output signal contains harmonics and spurious frequencies therefore, the signal passes through a bandpass filter to ensure passing only the 11 GHz signal and proceeds to a power divider. In the design, the power divider shall provide an 11 GHz signal to four channels however, as previously mentioned, this thesis shall be concerned with only two channels. The NI DAQ commands the switches located prior to the bias tee in the transmit signal chain, after the LO downstream bandpass filter and, after the six port power divider. These switches allow the LO and the transmit signal to interface with the MMW Sub-System in order to radiate a signal from the MMW Sub-System upconverter. Figure 5.2 details the RF Sub-System.

The transmitted signal, received signal and LO signal chains exit the RF Sub-System and interface with Micro-Coax Ultra Low-Loss 50 foot cables in the Cabling Sub-System. These cables are necessary to span the distance between the RF Sub-System and the radar mounting locations. Figure 5.3 details the Cabling Sub-System.
Figure 5.2: RF Sub-System block diagram.
Figure 5.3: Cabling Sub-System block diagram.
The 50 foot coax cables terminate into the MMW Sub-System. Upon reaching the MMW Sub-System, the 11 GHz LO signal is bandpass filtered and pushed through a low noise amplifier (LNA) that incorporates a gain of 17 dB. The LO signal then enters an active multiplier chain, powered by a +9V power supply, that multiplies the LO signal eight times to achieve a signal of 88 GHz. Upon exiting the active multiplier chain, this 88 GHz signal is bandpass filtered again and routed through a magic tee hybrid coupler that sends this signal to mixers located in the upconverter utilized for the transmit antenna and the downconverter utilized for the receive antenna. The transmission signal that enters the MMW Sub-System encounters a bias tee that strips off the -5V that was carried to it via the RF transmission line and routes this voltage to supply power to both the upconverter and downconverter. The transmission signal is then routed to the mixer in the upconverter. The receive signal chain also encounters a bias tee to strip off the +5V that was carried to it via the RF reception line and routes this voltage to power the LNA. The upconverter mixer utilizes the transmission signal of 2-12 GHz and mixes this signal with the 88 GHz signal to produce a stepped frequency signal of 90-100 GHz thus providing 10 GHz of bandwidth for the system. Likewise, the downconverter takes the 90-100 GHz received signal and mixes this signal down to 2-12 GHz to be sent back to the Network Analyzer for data processing. The antennas connected to the upconverter and downconverter are scalar horn antennas that provide a nominal beamwidth of 25°. Figure 5.4 details the MMW Sub-System. Figures 5.5, 5.6, 5.7 and, 5.8 illustrate the fielded physical architecture of the MMW Sub-System.
Figure 5.4: MMW Sub-System block diagram.

Figure 5.5: MMW Sub-System.
Figure 5.6: View from the right of the MMW Sub-System.
Figure 5.7: View from the left of the MMW Sub-System.
Figure 5.8: View from the front of the MMW Sub-System.
CHAPTER VI

EXPERIMENT SETUP

In order to conduct the comparative ISAR and Tomographic imaging analysis, imaging experiments must be conducted and measurement data collected about the targets of interest. The targets of interest that have been selected for our primary imaging experiments are copper plumbing pipes and these targets are detailed in Figure 6.1. The copper plumbing pipes are 15.3 cm in length and 1.43 cm in diameter. The copper pipes shall be secured on top of a thick, round, wooden platform with the pipes pointing in the $+z$ direction. One copper pipe is located at the center of the pedestal while the second copper pipe is positioned 7 cm away from the center pipe. The wooden platform is 38 cm in diameter and is secured on top of a thick foam cylinder. This foam cylinder functions as a standoff between the rotating pedestal and the wooden platform. The only purpose of this foam standoff is to position the targets an adequate distance above the floor of the laboratory for ease of illuminating/imaging the targets. Underneath the foam standoff lies the motor driven rotating pedestal.

The rotating pedestal is located at the center of a square whose boundaries are defined by one industrial Yaskawa Motoman robot at each of the four corners of the square. Two of the mono-static radar systems detailed in Chapter V shall be utilized to illuminate/image the targets selected for our experiments. Each of the two radar systems shall be mounted to one of the industrial robots. Figure 6.2 illustrates the radar systems mounted to two of the four robots along with the targets and
Figure 6.1: Copper plumbing pipe targets.
foam standoff located on top of the rotating pedestal in the center of the square boundary the robots define. The choice as to which of the four robots the two radar systems are mounted to depends on the type of experiment to be performed. The following details the experiments to be performed for investigation in this thesis.

The first step in our investigation deals with accomplishing data collection for the stationary mono-static ISAR case. In this experiment, the radar system is fixed at a chosen azimuth and elevation with respect to the target. The rotating pedestal then rotates the target through a full 360° and the collected data is formed into an image of the target scene. A Matlab program has been created which controls the robot’s movements and records the collected data. The execution of
this program will be detailed later in this chapter for the bi-static Tomographic imaging case. Both radars shall perform the stationary mono-static ISAR case. The imagery generated from both radars will be compared in order to ensure the radars are generating similar images with the target/radar geometry taken into account. Figure 6.3 details the mono-static ISAR experiment setup.

Once the mono-static ISAR case is accomplished for both radar systems, the second radar system shall perform a mono-static ISAR experiment that replicates the aforementioned case. However, after each 360° rotation of the rotating pedestal, the radar system shall increment in azimuth to a new position. With each new azimuth position, the rotating pedestal will again rotate through 360°. This process repeats until a pre-determined azimuth position has been reached and data is collected.
from that position. Once all of the azimuth positions have returned their respective data collections, an image of the target scene is generated with the data for analysis.

The aforementioned experiment cases allow us to increment to a bi-static Tomographic imaging case. As stated earlier, the targets shall be secured to the rotating pedestal from which it shall be imaged by the two radar systems. The previously mentioned Matlab program controls the target’s rotation via the robotic pedestal, the position of the two mono-static radar systems located at the ends of the industrial robotic arms and, the collection of the received signal data. As the Matlab program executes, the robotic arms move the radars into their initial positions for illuminating/imaging the targets. Once these positions are achieved, the illuminating/imaging iteration sequence begins. Figure 6.4 details the bi-static experiment setup. From Figure 6.4, let’s consider the radar system mounted on the right robot in the figure as Radar 1 and the radar system mounted on the left robot in the figure as Radar 2. When Radar 1 reaches its initial position, it shall remain fixed in that position throughout the duration of the Matlab program and thus, for the duration of illuminating/imaging
the target. On the other hand, Radar 2 shall be commanded to an initial illuminating/imaging position however, Radar 2 shall increment in azimuth around the target generating multiple bi-static angles between Radar 1 and Radar 2. This pre-determined geometry of the two radar systems shall be used to collect imaging data from the targets. For brevity’s sake, let’s consider the targets on the rotating pedestal as Target 1. The following details the Matlab program execution for movement of Target 1 and Radar 2 as well as the illumination/imaging sequence.

With Radar 1, Radar 2 and, Target 1 in place, the Matlab program begins executing the illumination/imaging sequence. During this sequence, the transmitter on Radar 1 illuminates Target 1 and the receivers on Radar 1 and Radar 2 capture the target image data. This data is recorded by the Network Analyzer via the $S_{21}$ S-parameter. Once the Network Analyzer collects the $S_{21}$ imaging information pertaining to Radar 1’s illumination of the target, Radar 2’s transmitter illuminates the target and Radar 1 and 2’s receivers capture the target image data again. This second dataset is recorded by the Network Analyzer via the $S_{43}$ S-parameter. Next, the Matlab program commands the rotating pedestal to turn a set value of degrees in a counterclockwise manner with respect to the radars imaging the target. Once this rotation is complete, Radar 1 illuminates Target 1 and the receivers on Radar 1 and Radar 2 capture the target image data. Radar 2’s transmitter then illuminates the target and Radar 1 and 2’s receivers again capture the target image data. The aforementioned S-parameters are again utilized to record this data. This process repeats itself until the rotating pedestal has rotated Target 1 through a full $360^\circ$ rotation. Also, the reader should note that during this $360^\circ$ rotation of Target 1, Radar 1 and Radar 2 remain stationary. Upon completion of the $360^\circ$ rotation by Target 1, Radar 2 is moved to its next pre-determined azimuth imaging location. Once Radar 2 is located at its next position to collect data, the aforementioned illumination/imaging sequence starts over. Once Target 1 completes another $360^\circ$ rotation, Radar 2 is again moved to its
next azimuth imaging location and the process repeats. The Matlab program executes this sequence until Radar 2 has covered a $90^\circ$ azimuthal arc around Target 1.

By the geometry of the aforementioned experiment and the methodology employed to illuminate/image the target of interest, the experiment can summarize some of the phenomenology detailed in Chapters III and IV. To begin, let’s consider Radar 1’s and Target 1’s geometry throughout the illumination/imaging sequence. Throughout this sequence, Radar 1 illuminates and images Target 1 from a fixed location. However, Target 1 rotates with respect to Radar 1. This geometry is analogous to ISAR where a fixed radar platform images, or spot-lights (notice this geometry’s inverse would be a Spot-light SAR application), a moving target. The data collected by Radar 1’s receivers is what is used to process the ISAR image in our comparative analysis. It is also well to note that since the Matlab program controls the rotating motion of Target 1, the motion of Target 1 is therefore known a priori and this is what makes Target 1 a cooperative target.

Now let’s consider Radar 2’s geometry with respect to Radar 1 and Target 1. Radar 2 receives data from Target 1 due to the illumination provided by Radar 1. A key difference is that Radar 2 moves with respect to Target 1 and Radar 1. The angle created between Radar 1 and Radar 2 is the bi-static angle we defined in Chapter IV and this angle is what creates the multiple look directions with respect to the target that yields geometric diversity and the foundation for Tomographic image reconstruction. Therefore, the target image data collected by Radar 2 is combined with the data collected by Radar 1 and the combination of this data is the basis for processing the Tomographic image needed for our comparative analysis.
CHAPTER VII

DATA COLLECTION, PROCESSING AND, POST-PROCESSING ALGORITHMS

Data collection and initial processing is managed and accomplished via the same Matlab program declared in Chapter VI that controls the robotic arm movements. An overview of this algorithm’s execution steps, as well as the details of algorithms used for post-processing, shall be provided to the reader here.

The data collection and initial processing Matlab algorithm begins by navigating to the directories containing pertinent robotic control and component interfacing files and adds these directories to the current Matlab working directory. The program then executes a function which interfaces Matlab with a National Instruments (NI) data acquisition (DAQ) module. The NI DAQ module allows the Matlab algorithm to communicate with the Network Analyzer which outputs stepped frequencies from 2-12 GHz for transmission and records the complex-valued received signal data. With the NI DAQ module communicating with Matlab, the program commands the NI DAQ switches to enter radiate mode to prepare the radars for signal transmission.

With the radars in radiate mode, the algorithm engages the robotic servos and places all robots in standby mode. With the robots standing by to be actuated, the robotic arms needed for the experiment are selected. The selected robots are then moved into pre-determined initial positions.
Once the robotic arms are in their respective initial positions, the program communicates to the Network Analyzer the values of required parameters that shall manage the collection of the complex-valued received signal data. The parameters communicated to and established in the Network Analyzer are: an S-Parameter matrix, the Network Analyzer start and stop frequencies, the radar system bandwidth, the number of stepped frequencies within the system bandwidth that shall be utilized as output tones for signal transmission, the intermediate frequency (IF) bandwidth and, the Network Analyzer output power.

With the Network Analyzer parameters set, the span of the image in meters is specified as is a range gate shift value. The range gate shift value places the range gate that encompasses the DC return at the origin of the image span. The angular increments of rotation for the robotic pedestal are established as is the required angular increments and span of azimuthal and elevation movements with respect to the robotic arms. With the motion increments set, the robots are commanded to their respective initial data acquisition positions. The radar system is now ready to perform data collection about the target scene to be observed.

The algorithm then begins executing a double for-loop. This looping procedure is what executes the illumination/imaging sequence detailed in VI. At each iteration of the inner loop, the Network Analyzer records the received signal data for data processing and then outputs two plots to analyze the raw signal data. The plots represent a range profile taken at each iteration of pedestal rotation as well as images of the received signal magnitude, the running sum of the received signal magnitude and, the summed coherent signal magnitude for each pedestal iteration.

Once the illumination/imaging sequence completes, the user is prompted to save the collected data in a specified location for post-processing. With the data saved, the robotic servos are shut off and the program execution ends.
Post-processing of the received signal data involves leveraging a range focusing algorithm developed by Mr. Taylor Thullen, radar engineer with Brilliant Solutions Inc. This algorithm creates a range to target scene center window around an initial estimated target scene center range. The algorithm then processes the received signal data against this range window and finds the maximum non-coherent signal return that falls within the window. The range window then shrinks the difference in maximum and minimum range values of the window and shifts the window to encompass this maximum non-coherent return. The algorithm increases the sample points within this new range window and again searches the maximum non-coherent signal return. Once this signal return is found, the range window again shrinks and shifts and searches for a final maximum non-coherent signal return. The range to target scene center that corresponds to this maximum non-coherent signal return is then output by the algorithm and this range value is utilized for all other imaging experiments that are performed with the specific radar that collected the received signal data.
CHAPTER VIII

DATA CALIBRATION ERRORS AND CONSIDERATIONS

In the course of defining and executing the experiments to be scrutinized in this thesis, a need has arisen to document the numerous sources of error that pervade the collected measurements as well as other considerations that degrade system performance. This chapter shall serve to document the procedures taken to mitigate these measurement errors and considerations as well as detail for future users the errors that are still inherent to the radar system and associated equipment so that attempts to correct these errors and improve the measurement/imaging capability of the system may be facilitated.

To begin elucidating the errors inherent to the design and implementation of the W-Band distributed aperture array, we shall start with the Network Analyzer. As aforementioned in VII, the Network Analyzer is commanded to produce a number of tones within the specified system bandwidth. The maximum and minimum frequency and the number of tones is passed to the Network Analyzer using Matlab. The frequency differential is the same for all tones, creating a linearly spaced stepped FM data collection. Matlab then commands the Network Analyzer to output the tones specified however, we have not tested the frequency accuracy of the tones that Matlab calls for compared to the tones that the Network Analyzer outputs. Any transmit frequency errors may cause problems with generation of coherent imagery. By using a spectrum analyzer, one could measure this frequency accuracy. In addition to this, the accuracy of the W-band frequencies would also
be assessed. However, if the W-band frequencies are outside the frequency range of the spectrum analyzer, then ranging experiments could be used to measure the relative phase change and the relative range change of a target return to estimate the accuracy of the minimum transmit frequency of the W-band radiation according to the following relationship:

\[ \lambda_{max} = 2 \Delta R \Delta \theta \]  

(8.1)

where \( \lambda_{max} \) is the maximum transmit wavelength, \( \Delta R \) is the change in range and, \( \Delta \theta \) is the change in phase. Rearranging Equation 8.1 to show the frequency relationship yields:

\[ f_{min} = \frac{1}{\lambda_{max}} = \frac{1}{2 \Delta R \Delta \theta} \]  

(8.2)

where \( f_{min} \) is the minimum transmit frequency.

By using a series of stepped chirp transmit signals, one could use progressively higher minimum transmit frequencies to assess the frequency accuracy of the W-band system.

Moving into the radar design, it may seem apparent that filters and oscillators are not perfect and that some distortion and spurious signals may prevail despite our best efforts to mitigate such issues. In most cases these types of errors have been foreseen and mitigated to a point that they’re negligible. However, I was surprised by the way in which some components degrade the system’s design and this should be noted to the reader. The designed radar system sends an 11 GHz signal through an active frequency multiplier chain, as described in Chapter V, to achieve a frequency of 88 GHz. What was surprising to me was that the active multiplier chain outputs frequencies between 77 and 86 GHz, as shown from the specifications sheet for this component. Furthermore, the passband on the bandpass filter immediately following the active multiplier chain isn’t specified to start until 88.2 GHz. These frequency mismatches compared to the desired 88 GHz results in the signal being attenuated somewhat. As the system was designed, this attenuation was found to be
negligible, but it should be noted that these types of component imperfections are an important part of the design trade space the radar engineer must evaluate. I’m sure that components with the proper output and passband frequencies could have been sourced however, cost most surely played a factor in deciding on utilizing less robust but more readily available components in the design. One of the niceties of the Network Analyzer is the capability of frequency integration. This integration time was set through Matlab scripts through the IF bandwidth parameter as detailed in Chapter VII. The actual integration time for each tone is the inverse of the IF bandwidth setting. Through frequency integration, it was possible to overcome some of the non-idealities in signal attenuation coming from the components.

Another consideration is the fact that the radars move. All imaging measurements for our experiments were conducted with each robot remaining static throughout the collections. This helped eliminate phase errors associated with coaxial transmission line path length changes as well as the need for range and phase tracking compensation commonly conducted in ISAR image processing.

Imprecise mounting of the radar hardware highly impacts the errors produced in the system. Precise alignment and mounting of components becomes more important as wavelength decreases. A prime example is the slight offset geometries of the antennas which are detailed in Figure 8.1. From the figure, one should be able to discern how the Tx antenna is slightly lower than the Rx antenna. We attempted to rectify this misalignment by placing washers under the standoffs that are used to mount the Tx upconverter the antenna is attached to however, a slight misalignment still exists.

Another error concerning the antennas arises from not knowing the phase center of the radar system. The phase center has been assumed to fall in the middle of the distance separating the antennas and the range to scene center has been calculated based off of this assumption. However,
Figure 8.1: Antenna misalignment.
the system imaging capability could be simplified and most definitely improved if the phase center
de of the system were to be properly determined. Calculating the range to the target scene center
precisely positions the targets in the generated image correctly, mitigates blurring and smearing of
the generated image and, may reduce the complexity of the image post-processing.

A further possible source of error may be derived during the illumination/imaging sequence
detailed in Chapter VI. The Matlab program commands the robots to move/rotate to different po-
sitions however, it is currently unknown what the absolute positioning accuracy of the robots and
angular accuracy of the pedestal are exactly and how closely the commanded movements match up
with where the robots are physically positioned. It would be beneficial to determine the movement
accuracy of the robotic pedestal and robotic arms so that these could be included in a positioning
error budget.

The aforementioned possibilities of error certainly do not create an exhaustive list of errors
inherent to the radar system design, laboratory setup and, target scene. This list merely touches on
the errors we’ve encountered and believe have the possibility of skewing the collected data in some
way.
CHAPTER IX

COMPARATIVE ANALYSIS OF ISAR AND TOMOGRAPHIC IMAGING

As noted in Chapter VII, our investigation into detailing the comparative analysis of ISAR and Tomographic imaging involved first performing mono-static ISAR experiments with both radar systems. In order to perform this and subsequent experiments, we utilized calibration spikes mounted to the face of each robot as well as to the rotating pedestal. These spikes are detailed in Figure 9.1. By touching the fine pointed tips of the spikes on each robot to the tip of the spike mounted to the rotating pedestal, we were able to determine, with millimetric precision, global \( x \), \( y \) and, \( z \) coordinates to the target scene center for each robot. Figure 9.2 illustrates the level of spatial precision that bringing the fine pointed spike tips together afforded. Because the precision of the robot positioning system is on the order of one millimeter, we can conclude that this calibration process created a similar level of precision for the scene center coordinates for each robot. However, since the positioning of the spikes was performed manually in order to ensure that no damage was done to the spike tips, there may be error in the scene center coordinates of approximately one millimeter. With these coordinates established, we then mounted the radar systems to the respective robotic arms and imaged the calibration spike that was still mounted to the rotating pedestal. We utilized the second radar system for the initial illumination experiment of the calibration spike. The radar system was located a distance of 1.2 meters from the target scene center and at an azimuth and elevation of 0° with respect to the target scene. The imaging routine commanded the rotating pedestal
Figure 9.1: Mounting of calibration spikes.
Figure 9.2: Spatial precision of calibration spikes.
to rotate the calibration spike at $15^\circ$ azimuthal increments and the Network Analyzer collected 801 frequency samples from 90 GHz to 100 GHz per angle. Figure 9.3 details the non-coherent mono-static ISAR image generated by the calibration spike. The $x$ and $y$-axes in Figure 9.3 refer to the image extent in centimeters in the $x$ - $y$ plane. The strong return of the imaged calibration spike located at the origin of the figure appears as a point target return. The image appears as expected for a non-coherent image formation with resolution limited to 15 mm in each dimension as detailed in Equation 3.1. The location of the target return also corresponds well with the geometry of the experiment. The data received from this imaging experiment of the calibration spike was then post-processed by leveraging the range focusing algorithm written by Mr. Taylor Thullen and detailed in Chapter VII. The algorithm allows us to home in on the dominant scatterer of the target scene to
derive a precise range to target scene center reference point in order to perform subsequent imaging experiments with similar radar positioning. This process of bringing the spike tips together in order to derive global spatial coordinates, imaging the calibration spike mounted to the rotating pedestal and, post-processing the data of the imaged calibration spike with the range focusing algorithm was performed with both radar systems to define specific range to target scene center values that are applicable to each individual radar system.

With range to scene center values derived for each radar system, we proceeded to place our copper two-pipe target on the rotating pedestal and perform a mono-static ISAR measurement of the target with the first radar system. The first radar system was positioned 1.2 meters away from the target scene at $-90^\circ$ azimuth and $10^\circ$ elevation with respect to the target scene center. The rotating pedestal was then commanded to rotate through an azimuth range of $0 - 360^\circ$ at $1^\circ$ azimuthal increments as the first radar system imaged the targets. Figure 9.4 details the mono-static ISAR setup for this experiment. Figure 9.5 illustrates the non-coherent ISAR image derived from the mono-static ISAR experiment performed with the first radar system. Again, the image extent in centimeters in the $x$-$y$ plane forms the $x$ and $y$-axes of the non-coherent ISAR target image in Figure 9.5. One can see that the derived image in the figure shows two strong returns that correspond well with the target’s physical geometry and placement. To better understand the image in Figure 9.5, the reader should imagine standing at the bottom of the figure looking down onto the target scene from the ceiling. The image represents a cross-section of the target scene at the zero $z$-axis location. The first radar is radiating from the top of the image towards the bottom.

This same experiment was then performed with the second radar system however, the second radar was located at a $0^\circ$ azimuth and $10^\circ$ elevation with respect to the target scene and, again with a distance from the target scene center of 1.2 meters. We performed the same experiment with both
Figure 9.4: Mono-static ISAR experiment setup for the first radar system.
Figure 9.5: Mono-static ISAR target image generated with the first radar system.
radar systems, albeit with slightly different sensor geometry with respect to the target scene, in order to compare their images with the anticipation that both radar systems would derive similar imagery. The only difference should be that when the target images are compared the targets will look rotated in angle due to the different look directions of the respective radars. Figure 9.6 details the initial image derived from the second radar system utilizing the aforementioned offset azimuth geometry with respect to the first radar system. From Figure 9.6, one can indeed see that the target returns in the image are rotated in azimuth due to the offset azimuth geometry utilized by the second radar. We proceeded to post-process this image to account for this azimuth offset, and Figure 9.7 details this post-processed image. In comparing the post-processed image in Figure 9.7 with the image derived
Figure 9.7: Post-processed mono-static ISAR target image generated with the second radar system.
from the first radar system in Figure 9.5, one can see that indeed the target returns in both figures correspond well in comparison to one another and with respect to the target physical geometry.

With the mono-static ISAR experiments successfully completed, we transitioned to the bi-static Tomographic experiment case. The Matlab program controlling the robotic arms and pedestal was modified to accommodate moving the second radar system in azimuth around the target scene, as detailed in Chapter VI, in order to generate the spatial diversity inherent to Tomographic imaging. We tested the routine and verified that the robotic arm movement and pedestal rotation sequence accomplished exactly as desired. However, we did not currently have an image processing procedure in place to combine all of the data we would be receiving from the multiple azimuth look angles that the illumination sequence would generate. At this point, the progress of incrementing to the Tomographic experiment case slowed considerably. We realized that further calibration of the bi-static experiment setup would need to be investigated.

We proceeded to utilize the second radar system to re-image the calibration spike mounted to the rotating pedestal. We took measurements of the calibration spike with the second radar system located at $-30^\circ$ azimuth and $0^\circ$ elevation and at a distance from the target scene of 1.2 meters. We then moved the radar system in azimuth to $-40^\circ$, then back to $-30^\circ$ and finally back to $-40^\circ$. This provided us two data sets at each azimuth position in order to determine what the robot arm positioning error was after processing these data sets through the range focusing algorithm. We determined that an effective positioning error in range to scene center of approximately $\pm 0.5$ millimeters exists with respect to each time the robotic arm is re-positioned. This error was larger than we anticipated and indicates that we must accomplish determining range to target scene center values for each radar position the Matlab routine commands the robot to move to in accomplishing the Tomographic imaging sequence. However, we did not have time to accomplish these calibrations.
due to other customers requiring use of the robotic laboratory chamber and the deadline constraints for accomplishing this thesis. Therefore, we proceeded to back-track from the Tomographic imaging case and to perform a bi-static imaging experiment of a 6 inch diameter calibration sphere.

Performing the bi-static experiment was pertinent mainly because a bi-static image of a target scene had not yet been generated with the designed radar system. To accomplish the experiment, we positioned the first radar system at $-90^\circ$ azimuth and $10^\circ$ elevation and the second radar system at $-40^\circ$ azimuth and $10^\circ$ elevation with respect to the target scene. Both radar systems were again located 1.2 meters from the target scene. We then connected the Rx signal cable on the first radar system and the Tx signal cable on the second radar system to provide data to the $S_{43}$ parameter via the Network Analyzer. The Tx signal cable on the first radar and the Rx signal cable on the second radar were connected to the Network Analyzer in a configuration that provided data to the $S_{21}$ parameter. Connecting the signal cables to the Network Analyzer in this way allowed us to effectively shut off the receiver and transmitter on the first and second radar system, respectively. The S-parameter matrix in the Matlab program was also modified to read only the $S_{21}$ parameter. These modifications ensure that only the receiver on the second radar system receives signal returns due to the transmit signal propagating from the transmitter on the first radar system. The data collected from this experiment was processed using the mono-static ISAR image formation routine. Therefore, the bi-static angle was not accounted for in the image formation process as this is a needed further algorithmic development. Figure 9.8 illustrates the bi-static imaging experiment of the calibration sphere.

We initially imaged the calibration sphere with the rotating pedestal rotating the sphere at $15^\circ$ azimuthal increments. Figure 9.9 details the image generated from this experiment. The reader can see from Figure 9.9 that the calibration sphere diameter of approximately 15 centimeters is
Figure 9.8: Bi-static imaging experiment of the 6 inch diameter calibration sphere.
measureable from the image, however, the 15° azimuthal increments utilized by the rotating pedestal failed to adequately sample the sphere. This resulted in a loss of received data on the sphere’s boundary as well as some Doppler aliasing. The necessary subsample angle increment needed is determined by the following equation:

$$\beta_{\text{min}} = \frac{\lambda_{\text{min}}}{2\delta_{CR_{\text{max}}}}$$

(9.1)

where $\beta_{\text{min}}$ is the smallest allowable angular sample spacing (in radians) necessary to avoid Doppler aliasing and $\delta_{CR_{\text{max}}}$ is the maximum cross-range extent of the image.

We reduced the azimuthal increment of the rotating pedestal down to 1° and re-imaged the sphere with the same radar/target geometry. Figure 9.10 illustrates the image generated from this experiment. The reader can see from Figure 9.10 that reducing the azimuthal increment of the
Figure 9.10: Image generated by rotating calibration sphere at 1 degree azimuthal increments.

rotating pedestal allowed much better illumination of the sphere’s scatterers resulting in a more detailed image with no Doppler aliasing.

Due to the aforementioned time constraints and customer demand for use of the robotic chamber, we were unable to perform any further experiments to increment towards performing a full Tomographic imaging data collection with the two copper pipe target setup. However, we were well pleased with the initial fielded capabilities of the radar system configuration we employed. The imagery derived from the experiment setups detailed above demonstrate an initial capability for this setup to potentially collect and process a truly bi-static data collection with multiple bi-static angles.
CHAPTER X

CONCLUSION AND SUMMARY OF RESULTS

The documentation of radar system design, implementation and analysis that this thesis has sought to detail is quite broad in scope and it is hoped that the reader has been provided a succinct synopsis explaining the finer points of research that this thesis encompasses. The radar history detailed in Chapter I was written with the aim of providing the reader with a timeline of radar system development and application that allows one to understand how SAR, ISAR and, Tomographic radar imaging systems fit into the big picture of radar technology. Chapter II illustrates the operating constraints of radar applications in congested spectrums and provides insight into the benefits of leveraging other parts of the spectrum, such as W-band, for these applications. The brief overview of SAR, ISAR and, Tomographic imaging principles provided in Chapters III and IV instructs the reader on the importance of image resolution definitions and the imaging techniques inherent to these radar modes of operation. The W-band distributed aperture array design outlined in Chapter V illustrates in detail the fielded radar system’s theory of operation. Chapter VI provided an overview of the experiments this thesis sought to perform and explained in detail how the robotic assets available in the imaging chamber of our laboratory would be utilized to perform these experiments. The data collection, processing and post-processing algorithms and methods presented in Chapter VII provide the reader a high-level overview of the sequence utilized to provide imagery and exploit the data the performed experiments provided. Chapter VIII sought to begin initial documentation on the
measurement errors inherent to the system design, support equipment and, target scene setup. Future research with the use of this radar system and the ability to increment the radar system’s capabilities will rely heavily on identifying and mitigating these errors. Lastly, the comparative analysis detailed in Chapter IX demonstrated the operation of the fielded system and presented the experimental imagery results of a cooperative target of interest. Though a full-Tomographic imaging experiment was unattainable in the scope of this thesis, this thesis directly facilitated incrementing three key elements of the radar system’s capabilities. An improved method for calibrating the radar system range to target scene was identified culminating in mitigating range errors that were pervasive in the collected measurements. This research also successfully demonstrated producing similar imagery of the same target scene with two separate mono-static radar systems located at different spatial geometries. Finally, this research performed a bi-static measurement of the target scene which had not been previously accomplished.

There is a great deal of work ahead to continue tuning the radar system for optimal performance in an effort to produce a Tomographic radar image however, this thesis demonstrates the utility and potential for this radar system design and its associated support equipment to be a viable Tomographic imaging apparatus.


88


[33] “Relationship between fourier space and image space,”