NEAR ZONE RADAR IMAGING AND FEATURE CAPTURE OF BUILDING INTERIORS

A Thesis

Presented in Partial Fulfillment of the Requirements for
the Degree Master of Science in the Graduate
School of The Ohio State University

By

Paul Chinling Chang, BSEE

*****

The Ohio State University
2008

Master Examination Committee:                                        Approved by

Professor John L. Volakis

Dr. Robert J. Burkholder

________________________________________

Electrical Engineering Graduate Program
ABSTRACT

As the target of detection becomes more and more complex in nature, the challenge in radar technology and signal processing capability deepens accordingly. Due to the increasing importance on homeland security and urban counter-terrorism, through-wall radar imaging has become a hot research topic in recent times. The signal attenuation and distortion through the wall is quite significant which can lead to false interior imagery. This thesis is developed to study and demonstrate the capability of EM and signal processing for through-wall building imaging and feature identification. The imaging algorithm employed here has a model-based filtering function built up on top of the conventional FFT method to extract specific features. The theoretical background of using a high frequency EM technique in modeling building scattering is discussed thoroughly. Upon validating with RCS measurement of a building target, the NEC-BSC ray-tracing code is used to study feature capturing, polarization effect, bistatic synthetic aperture radar (SAR), and the through-wall image improvement techniques. An innovative feature identification method has been proposed based largely on the scattering mechanisms of the building features. In addition, it is shown how polarization and bistatic SAR is useful in detecting or avoiding certain building features and hidden objects. Finally, the CLEAN algorithm with a pre-computed wall model is employed to remove exterior wall returns, which leads to better image of the building interiors.
Dedicated to my family
ACKNOWLEDGMENTS

I would like to thank my adviser, Professor John Volakis, for his continuous guidance, understanding, and encouragement in the completion of this work and the topic assignment for my research. I would also like to thank Dr. Robert Burkholder for his technical advises that really push me into the next level.
VITA

September, 2001 – August, 2005…………………………………………………..B.S.E.E
The Ohio State University
Columbus, OH

September, 2005 – September, 2006………………….Harris Fellowship Appointment
ElectroScience Laboratory
The Ohio State University
Columbus, OH

September, 2006 – September, 2007…………………...Graduate Research Associate
ElectroScience Laboratory
The Ohio State University
Columbus, OH

FIELDS OF STUDY

Major Field: Electrical Engineering
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapters</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Dedication</td>
<td>iii</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>iv</td>
</tr>
<tr>
<td>Vita</td>
<td>v</td>
</tr>
<tr>
<td>List of Tables</td>
<td>ix</td>
</tr>
<tr>
<td>List of Figures</td>
<td>x</td>
</tr>
<tr>
<td>Chapters:</td>
<td></td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Radar History and Advancements</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Radar Imaging and Through-Wall Applications</td>
<td>4</td>
</tr>
<tr>
<td>1.4 High Frequency Electromagnetic Modeling Methods</td>
<td>6</td>
</tr>
<tr>
<td>1.5 Thesis Organization</td>
<td>7</td>
</tr>
<tr>
<td>2. Imaging Techniques and Its Physics</td>
<td>8</td>
</tr>
<tr>
<td>2.1 Conventional Imaging Theory</td>
<td>9</td>
</tr>
<tr>
<td>2.1.1 Tomographic Imaging Theory</td>
<td>9</td>
</tr>
<tr>
<td>2.1.1.1 Direct Fourier Reconstruction in Tomographic Imaging</td>
<td>10</td>
</tr>
<tr>
<td>2.1.1.2 Filtered Backprojection in Tomographic Imaging</td>
<td>12</td>
</tr>
<tr>
<td>2.1.2 Tomographic Imaging Theory of Synthetic Aperture Radar</td>
<td>15</td>
</tr>
<tr>
<td>2.1.2.1 Direct Fourier SAR Imaging</td>
<td>15</td>
</tr>
<tr>
<td>2.1.2.2 Filtered Back-Projected SAR Imaging</td>
<td>17</td>
</tr>
<tr>
<td>2.2 Model Based Imaging Approach</td>
<td>18</td>
</tr>
</tbody>
</table>
4.3.3 Monostatic vs. Bistatic Scan for Hidden Object Detection........80

5. Through-Wall Microwave Image Enhancement via CLEAN Algorithm ..........82
   5.1 Conventional CLEAN Algorithm for Microwave Imaging .....................83
   5.2 Model Based CLEAN Algorithm....................................................85
   5.3 Numerical Results........................................................................86

6. Summary and Conclusion........................................................................93

Bibliography...............................................................................................96
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I  Collected data sets in building RCS measurement</td>
<td>44</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>General X-ray CT problem geometry</td>
</tr>
<tr>
<td>2.2</td>
<td>Projection slice in frequency image domain</td>
</tr>
<tr>
<td>2.3</td>
<td>Plane wave illumination of an unknown target</td>
</tr>
<tr>
<td>2.4</td>
<td>Radar target scenario example</td>
</tr>
<tr>
<td>2.5</td>
<td>Far-field scattering from a point scattering center</td>
</tr>
<tr>
<td>2.6</td>
<td>Near-field scattering from a point scattering center</td>
</tr>
<tr>
<td>2.7</td>
<td>Far-field radar scan of a point scatterer</td>
</tr>
<tr>
<td>2.8</td>
<td>Near-field spot-light circular scan of a point scatterer</td>
</tr>
<tr>
<td>2.9</td>
<td>Near-field spot-light circular scan of a point scatterer with diameter 2D</td>
</tr>
<tr>
<td>2.10</td>
<td>Ninety degree angular scanning setup of a dihedral corner</td>
</tr>
<tr>
<td>2.11</td>
<td>Images generated for different angular step size</td>
</tr>
<tr>
<td>2.12</td>
<td>Images generated for different frequency bands</td>
</tr>
<tr>
<td>2.13</td>
<td>Simulation setup for radar illumination of a square room</td>
</tr>
<tr>
<td>2.14</td>
<td>Downrange comparison for 2MHz step vs. 5MHz step</td>
</tr>
<tr>
<td>3.1</td>
<td>Multi-layered slab and its transmission-line equivalence</td>
</tr>
<tr>
<td>3.2</td>
<td>Geometry of wedge diffraction</td>
</tr>
<tr>
<td>3.3</td>
<td>Corner diffraction geometry</td>
</tr>
</tbody>
</table>
3.4 Scale down building model .................................................................41
3.5 Near-field measurement setup scenario.............................................42
3.6 Near-field measurement setup at ESL compact range .........................43
3.7 Spatial pattern comparison (10GHz, H-polarization).............................44
3.8 Building models with wall labeled in blue (top view)..........................45
3.9 Range profile comparison for Plywood Building (6-10GHz, H-polarized) ..46
3.10 (a) H-pol measured images of the Plywood Building Model
     (b) H-pol NEC-BSC images of the Plywood Building Model.................48
3.11 (a) V-pol measured images of the Plywood Building Model
     (b) V-pol NEC-BSC images of the Plywood Building Model..................49
3.12 (a) H-pol measured images of the Plywood Building Model with PEC box
     (b) H-pol NEC-BSC images of the Plywood Building Model with PEC box ....50
3.13 Linear SAR image formation of an one-story room .............................51
3.14 Spot-light SAR image formation of an one-story room .......................52
4.1 Fly-by simulation setup of a T-shaped target ...................................55
4.2 Sector image formation of the T-shaped target .................................55
4.3 Reduced sector image formation of the T-shaped target.......................56
4.4 Proposed Building Feature Identification Method ..............................57
4.5 Circular side-by scan of a complex one-story building .....................58
4.6 Original image formation of the target building in the z = 0 plane........59
4.7 Oblique scan images of the target building ....................................60
4.8 Corner capture of the target building ............................................60
4.9 Trihedral orientation capture via oblique scans of target building ..........61
4.10 Trihedral combination for the target building ..................................61
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.11</td>
<td>Broadside images of the target building</td>
<td>62</td>
</tr>
<tr>
<td>4.12</td>
<td>Original image vs. deduced building features</td>
<td>63</td>
</tr>
<tr>
<td>4.13</td>
<td>Simulation setup of a T-shaped target</td>
<td>64</td>
</tr>
<tr>
<td>4.14</td>
<td>Polarized image formation of a trihedral scatterer</td>
<td>65</td>
</tr>
<tr>
<td>4.15</td>
<td>Local and global coordinate systems of an arbitrary scatterer</td>
<td>66</td>
</tr>
<tr>
<td>4.16</td>
<td>Wave scattering geometry of a dihedral corner</td>
<td>67</td>
</tr>
<tr>
<td>4.17</td>
<td>Wave scattering geometry of a Trihedral corner</td>
<td>70</td>
</tr>
<tr>
<td>4.18</td>
<td>Two-dimensional view of the target building</td>
<td>73</td>
</tr>
<tr>
<td>4.19</td>
<td>Polarized image formation of the target building</td>
<td>74</td>
</tr>
<tr>
<td>4.20</td>
<td>Two-dimensional view of the target building with spheres</td>
<td>75</td>
</tr>
<tr>
<td>4.21</td>
<td>Polarized image formation of target building with spheres</td>
<td>75</td>
</tr>
<tr>
<td>4.22</td>
<td>Near-field bistatic scan of a point scattering center</td>
<td>77</td>
</tr>
<tr>
<td>4.23</td>
<td>Monostatic vs. bistatic scan of three spheres in free space</td>
<td>78</td>
</tr>
<tr>
<td>4.24</td>
<td>Monostatic vs. bistatic image formation of three spheres in freespace</td>
<td>78</td>
</tr>
<tr>
<td>4.25</td>
<td>Bistatic scan setups for different receiver locations</td>
<td>79</td>
</tr>
<tr>
<td>4.26</td>
<td>Bistatic images for different receiver locations</td>
<td>80</td>
</tr>
<tr>
<td>4.27</td>
<td>Monostatic vs. bistatic scan of a T-shaped wall with a hidden sphere</td>
<td>81</td>
</tr>
<tr>
<td>4.28</td>
<td>Monostatic vs. bistatic image formation of a T-shaped wall with a hidden sphere</td>
<td>81</td>
</tr>
<tr>
<td>5.1</td>
<td>Microwave CLEAN Procedure</td>
<td>84</td>
</tr>
<tr>
<td>5.2</td>
<td>Through-wall scanning (Example 1)</td>
<td>87</td>
</tr>
<tr>
<td>5.3</td>
<td>Point spread function vs. model spread function (Example 1)</td>
<td>87</td>
</tr>
<tr>
<td>5.4</td>
<td>Conventional CLEAN image vs. model-based CLEAN image (Example 1)</td>
<td>88</td>
</tr>
</tbody>
</table>
5.5 Through-wall scanning (Example 2)………………………………………………..89
5.6 Point spread function vs. model spread function (Example 2)………………..89
5.7 Conventional CLEAN image vs. model-based CLEAN image (Example 2)…..90
5.8 Drive-by scanning setup of an one-story room (Example 3)…………………..91
5.9 Superimposed images of an one-story room (Example 3)…………………..92
CHAPTER 1

INTRODUCTION

1.1 Motivation

Due to the advancements in both radar technology and signal processing capability, it is of great interest for scientists and engineers to further extend the use of radar in target detection and identification. Basically radar sensing involves transmitting electromagnetic energy by means of an antenna which concentrates the waves into a particular desired direction. The receiver collects and delivers the echo signals for processing and visual display on the computer screen [1]. Due to the increasing importance on homeland security and urban counter-terrorism, through-wall radar imaging has become a hot research topic in recent times [2, 3, 4]. Through-wall radar systems present significant challenges such as the following: A typical building wall can provide significant signal attenuation and distortions; in addition, the propagation is very much dependent on the sensor locations as well as the internal building structure. In order to develop a UAV-mounted or portable device, the antenna size has to be small enough while having to maintain angular resolution. Both the hardware and software system have to be implemented under the above constraints. Motivated by these practical considerations, this thesis is developed to study and demonstrate the electromagnetic
phenomenology for through-wall building imaging and feature identification. In the rest of this chapter, a brief background will be given of radar advancements as well as some signal processing capability that has been developed. Furthermore, high frequency methods and previous efforts in through-wall radar imaging will be briefly discussed. The focus and organization of this thesis will be presented at the end of this chapter.

1.2 Radar History and Advancements

A brief overview of modern radar technology and its applications are given in [1]. The first radar was claimed to be invented by Christian Hulsmeyer for use in vessel traffic supervision. Between 1920 and 1930, large effort was put into developing systems that can capture some useful information from the received echoes. In 1924, Edward Appleton used radio to determine the height of the ionosphere and ever since that, substantial developments of radars for both military and civilian applications have gradually emerged. With incorporation of solid-state electronics, versatile antennas, and powerful signal processing algorithm, the target location and recognition capability of modern radars have been greatly enhanced.

Modern radars are capable of accurately detecting the following physical parameters of the targets: range, relative velocity, target size, and target shape etc. Based on the time delay of the received echoes, the range information of the target can be obtained. The maximum detectable range is limited by the radar cross-section of the target and noise; the longer the transmitted radar signal propagates through the environment, the more signal attenuation is likely to result. Once the signal level is too low with respect to the noise level, the target signals are no longer detectable. Target
velocity can also be detected via Doppler radar. The velocity can be determined through successive time delay measurements or from the associated Doppler frequency shift induced by the target motion. If the radar resolution is small compared to the target geometry then it is possible to determine the approximated size and shape of the target. Depending on the geometrical size, the frequency variation of the received signals will be different. It is expected that as the target size and complexity increases, the frequency variation for any particular viewing aspect will be greater. In order to avoid aliasing, it will require small enough frequency and spatial steps. Sometimes material property can also be determined by the radar. In certain specific cases after accounting for the propagation loss, the amplitude information of the received echoes might be used to estimate the target’s reflection coefficients for which the associated dielectric property can be inferred.

Modern radars are of two main types, the pulse radar and the continuous-wave radar. Pulse radars transmit a RF impulse follow by a long period of hold during which the echoes can be received. The transmitter for the pulse radar is operated as on and off whereas the receiver is only active when the transmitter is off. The pulse radar has very good range resolution but the tradeoff is the instability problem caused by the high peak power. In order to mitigate the limitations seen in pulse radar, pulse compression radar was invented. The peak power problem can be reduced by stretching the transmitted signal in time at the expense of deteriorated range resolution. Range resolution can be maintained by using a matched filter (or a windowing function) to time-limit the received echoes. In other words, the physical peak-power problem seen in pulse radar can be transferred into a signal processing problem in pulse compression radar. The resolving
capability is expected to be the same between the short pulse radar and the pulse compression radar.

The continuous-wave (CW) radar transmits continuously a single frequency signal while the echo signal is continuously measured. There are two classes for the continuous-wave radar, the unmodulated CW and the modulated CW. In unmodulated CW radar, a single frequency is sent and the receiver is listening continuously. It can be used to identify a moving target and its associated velocity via the induced Doppler frequency shift. Because of the fact it is single frequency, it is literally not useful in measuring the range. In frequency modulated CW radar, the transmitted signal can be modulated onto different frequencies and retrieved the returned echoes at different tunes. The frequency diversity in the frequency modulated CW radar can be used to extract target range information.

1.3 Radar Imaging and Through-Wall Applications

Several references in the past [5, 6, 7] have discussed the various synthetic aperture radar (SAR) imaging methods. Synthetic aperture radar is a technique that utilizes narrow beam radars to produce high resolution imagery. The term, “synthetic aperture”, can be thought of as using an antenna with an aperture as wide as the scan path. The methods can be either parametric or non-parametric. In the parametric techniques, an underlying model is assumed in the formulation of the problem and thereby reduces the problem to that of estimating the parameters in the assumed model. Non-parametric methods are classical approaches which solve the spectral estimation problem without assuming any particular model. Parametric methods can offer more
accurate estimates when the data of interest does satisfy the assumed model, but it is not always the case. The conventional Fourier transform method is a nonparametric spectral estimation method that is quite computationally efficient. However, due to the nature of Fourier transform, high sidelobes will often result in the images. Most often a windowing function will be used before applying the FFT (Fast Fourier Transform) to reduce the sidelobe level, but this will increase the mainlobe width which decreases the resolution. There are several other non-parametric methods such as the adaptive FIR (Finite Impulse Response) sidelobe reduction technique [8], and the matched-filterbank complex spectral estimation method [9]. However due to the nonparametric nature, these methods do not result in significant resolution improvement over the conventional FFT methods.

Parametric spectral estimation methods are based on certain parametric data models and the models are usually an approximation to some physical scattering phenomenon. When dealing with SAR imaging, parametric techniques are often used to extract certain target features based on the scattering data; the extracted target features are then combined with the images generated via the FFT-based methods to produce the best overall reconstruction. There are several classes of these “super-resolution” parametric algorithms such as the autoregressive-model-based methods [5, 10], eigendecomposition-based methods [11], rotational invariance methods [12], and the non-linear least square fit methods [13, 14]. A robust parametric method can offer significant improvement in resolution and accuracy over typical FFT methods, but of course at the expense of more computational resources.

Through wall radar sensing has become a hot research topic in scientific
and engineering community. Propagating electromagnetic wave is seen capable of providing useful information behind the wall where optical rays will get blocked out totally. Previous efforts in [2, 3, 4] have employed full-wave computational techniques to invest object imaging inside a multilayered medium. Full wave solvers although relatively accurate are not efficient for generating large building scattering data, which makes high frequency asymptotic methods worthy of investigation. Several references [43, 44] have also proposed the methods of image refocusing and phase correction to account for refractive phase delay and multiple internal reflections resulting from the through-wall propagation. In a typical modern wall, the cinder block is often used as the constructing element. The analytical model developed in [28] can be used to simulate realistic wall penetration more properly. In addition, recent efforts [48] have considered object imaging behind random media. The main interest in through-wall imaging lies on how one can improve detection and recognition of objects behind an unknown wall.

1.4 High Frequency Electromagnetic Modeling Methods

A high frequency asymptotic model refers to a geometry varying little over an interval on the order of a wavelength, which is normally valid at microwave frequencies or above for vehicle or building-sized structures. To obtain a high frequency field solution, asymptotic methods are applied directly or indirectly [32]. The direct approaches apply asymptotic assumptions directly to Maxwell equations at the beginning of the solution process, whereas the indirect approaches employ asymptotic techniques after the exact solutions are obtained. The Geometric Theory of Diffraction (GTD) by Keller [33] originated from geometric optics, which is based on the direct use of the
asymptotic methods. In order to ensure a continuous and bounded total field, the uniform theory of diffraction (UTD) has been developed [34, 35]. UTD has the advantage of handling large-sized scattering targets in a relatively efficient way, which makes it a suitable choice for simulating through-wall building scans. Due to its ray-tracing nature and asymptotic assumptions, one disadvantage of the high frequency UTD method is the possibility of overlooking some important scattering terms when dealing with complex geometries.

1.5 Thesis Organization

In this thesis, through-wall building imaging and feature identification will be studied thoroughly using the high frequency UTD technique. The main objective is to investigate how different EM parameters, scanning setups, and signal processing methods can be used and combined to improve through-wall interior imaging. In Chapter 2, the conventional imaging theory for both tomography and synthetic aperture radar is discussed; the model based imaging approach is then introduced subsequently. In Chapter 3, the capability of using a high frequency method in studying through-wall building imaging is demonstrated both theoretically and experimentally. The high frequency code, NEC-BSC, will be validated against the radar measurement of a building target. In Chapter 4, it will be shown how oblique and broadside scans, polarizations, and bistatic setups can be intelligently used to improve detection of building features as well as hidden objects. In Chapter 5, a model-based CLEAN approach is introduced which is specifically adapted to remove the strongest wall scattering signatures from the image without affecting the much weaker scattering features inside the building.
CHAPTER 2

IMAGING TECHNIQUES AND ITS PHYSICS

In this chapter, the synthetic aperture radar (SAR) imaging technique and its associated phenomenology are discussed along with the background theoretical formulation originated from X-ray computer tomography. Computer-aided Tomography (CAT) has been used extensively in medical examination of internal organs whereas SAR has most of its applications in target identification and remote sensing. It has been shown in the past that the spotlight-mode SAR problem can be treated as a tomographic reconstruction problem and analyzed using the projection-slice theorem from computer tomography [15, 16]. The chapter will start out with a general theoretical overview for tomographic imaging as well as showing how the same theoretical approaches are extended to SAR imaging; it will then move on to the proposed SAR imaging method that will be used throughout this thesis in the study of through wall building imaging for both far field and near field setups. The chapter will close with some discussions and evaluations on spatial and frequency sampling criteria as well as the associated requirements for resolution and operating frequency band.
2.1 Conventional Imaging Theory

2.1.1 Tomographic Imaging Theory

Computer-aided tomography can provide two-dimensional imaging of an unknown object in two-dimensional space by collecting and processing enough projection data in the two-dimensional space where the object belongs. Similarly, if the object has three-dimensional information, the theory still applies and the object can still be reconstructed with enough projection data collection in the three-dimensional space. The underlying theory is based on the projection-slice theorem [16, 17, 18]. For simplicity reasons, let us consider a two-dimensional object of arbitrary shape as shown in Figure 2.1. It is assumed that the target shape and position are the unknowns to be determined as they might well correspond to the internal infrastructure of the body. The available tools are two linear arrays that will be used for the data collection process.

Figure 2.1: General X-ray CT problem geometry
As depicted in Figure 2.1, the transmitting array sends X-ray fields into the unknown target which is then scattered and diffracted before retrieving by the receiver array at the other end. Physically the received field at the receivers can be thought as collapsing the two-dimensional object information into one-dimensional space and this is done for all $\phi$. The projection for any $\phi$ direction, $P_{\phi}(x')$, can be mathematically represented as the following integration in Equation 2-1 where $\delta(\cdot)$ is the Dirac delta function and $f(x,y)$ is the unknown object description to be determined.

$$P_{\phi}(x') = \int \int \delta(x \cos \phi + y \sin \phi - x') f(x,y) dx dy \quad 2-1$$

The object information is collapsing into the $y'$ direction and further algebraic manipulation will lead to the following expression for the projection,

$$P_{\phi}(x') = \int_{-\infty}^{\infty} f(x' \cos \phi - y' \sin \phi, x' \sin \phi + y' \cos \phi) dy' \quad 2-2$$

The integrand in Equation 2-2 is nothing but the unknown object description in the $x', y'$ coordinates. It is expected that for every different $\phi$, there will be a different projection $P_{\phi}(x')$ associated with it. In other words, different $\phi$ will provide different information for the same object from a different perspective and together the information can be combined to reconstruct the object.

2.1.1.1 Direct Fourier Reconstruction in Tomographic Imaging

Let $f'(x', y') = f(x' \cos \phi - y' \sin \phi, x' \sin \phi + y' \cos \phi)$ be the same unknown object description based on the primed coordinate system in Figure 2.1. In speaking of object reconstruction, it should be noted that the object description is independent of
coordinate system for both spatial and frequency domain and will lead the following,

\[ x = x' \cos \phi - y' \sin \phi \; ; \; y = x' \sin \phi + y' \cos \phi \]

\[ x' = x \cos \phi + y \sin \phi \; ; \; y' = -x \sin \phi + y \cos \phi \]

\[ f(x, y) = f'(x', y') \]

\[ F(w_x, w_y) = F'(w'_x, w'_y) \]

The Fourier Transform of the unknown object description is manipulated as following,

\[ F'(w'_x, w'_y) = \iint f'(x', y') e^{-j(x'_w + y'_w)} dx' dy' \]

\[ = \iint f(x, y) e^{-j(xw_x \cos \phi + yw_y \sin \phi - xw_x \sin \phi - yw_y \cos \phi)} dx' dy' \]

\[ = \iint f(x, y) e^{-j(xw'_x \cos \phi - yw'_y \sin \phi + yw'_y \cos \phi)} dx dy \]

\[ F'(w'_x, w'_y) = F(w_x, w_y) = \iint f(x, y) e^{-j(xw_x + yw_y)} dx dy \]

\[ \Rightarrow w'_x = w_x \cos \phi - w_y \sin \phi \; ; \; w'_y = w_x \sin \phi + w_y \cos \phi \]

The derived expression in 2-4 demonstrates that an axis rotation of \( \phi \)

counterclockwise in the spatial domain will correspond to the same axis rotation in the
frequency domain as shown in Figure 2.2. By making \( w'_y \rightarrow 0 \), Equation 2-3 becomes,

\[ F'(w'_x, 0) = \iint f'(x', y') e^{-jw'_x} dx' dy' \]

\[ = \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} f'(x', y') dy' \right] e^{-jw'_x} dx' \]

\[ = \int_{-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} f(x' \cos \phi - y' \sin \phi, x' \sin \phi + y' \cos \phi) dy' \right] e^{-jw'_x} dx' \]

\[ = \int_{-\infty}^{\infty} P_\phi(x') e^{-jw'_x} dx' = F_{1D} \{P_\phi(x')\} \]
The expression in 2-5 is the projection-slice theorem. The equation shows that the Fourier Transform of each projection can be used to populate one slice centered at the origin in the two-dimensional frequency domain. Figure 2.2 pictorially illustrates how projections are used to populate slice by slice in the frequency domain. The object description in the original spatial domain can be obtained via a two-dimensional inverse Fourier Transform of the populated data in the frequency domain. This is the conventional Imaging theory behind X-ray CT using direct inverse Fourier Transform.

2.1.1.2 Filter Backprojected Reconstruction in Tomographic Imaging

Filtered Backprojection Algorithm is also a very powerful reconstruction technique commonly used in Computer-Aided Tomography [16, 17]. Let us again consider the geometrical setup as depicted in Figure 2.1 where the object description in Cartesian coordinates is \( f(x, y) \) and the projection for angle \( \phi \) is \( P_\phi(x') \). The object description can be written as an inverse two-dimensional Fourier Transform of the following,
\[ f(x, y) = (2\pi)^{-2} \iiint F(w_x', w_y') e^{jwx'} e^{jwy'} dw_x' dw_y' \]  

The expression in Equation 2-6 can be converted into polar frequency domain if we let \( w_x' = r \cos \phi, \ w_y' = r \sin \phi \) and \( r \) being a two-sided version of radial component,

\[
f(x, y) = (2\pi)^{-2} \int_{0}^{\pi} \int_{-\infty}^{\infty} F(r, \phi) \exp[jr(x\cos\phi + y\sin\phi)] \mid r \mid dr d\phi \tag{2-7}
\]

If a change of variable \( r = w_x' \) is applied, Equation 2-7 becomes,

\[
f(x, y) = (2\pi)^{-2} \int_{0}^{\pi} \int_{-\infty}^{\infty} F(w_x', \phi) \mid w_x' \mid \exp[jw_x'(x\cos\phi + y\sin\phi)] dw_x' d\phi \tag{2-8}
\]

Using the expression of \( x' = x \cos \phi + y \sin \phi \), the inside integrand becomes nothing but an inverse Fourier Transform of \( F(w_x', \phi) \mid w_x' \mid \)

\[
f(x, y) = (2\pi)^{-2} \int_{0}^{\pi} \{ \int_{-\infty}^{\infty} F(w_x', \phi) \mid w_x' \mid \exp[jw_x'(x'w_x')]} dw_x' \} d\phi \tag{2-9}
\]

From Equation 2-5, Equation 2-9 can be re-substituted as

\[
f(x, y) = (2\pi)^{-2} \int_{0}^{\pi} \{ F^{-1}[F_{1D}\{ P_{\phi}(x') \} \mid w_x' \}]} \} d\phi \tag{2-10}
\]

In fundamental system theory, the multiplication in the frequency domain is same as convolution in the image domain; therefore Equation 2-10 can be rewritten as

\[
f(x, y) = (2\pi)^{-2} \int_{0}^{\pi} \{ F^{-1}[F_{1D}\{ P_{\phi}(x') \} \mid w_x' \}]} \} d\phi \tag{2-11}
\]

\[
= (2\pi)^{-2} \int_{0}^{\pi} \{ P_{\phi}(x') \otimes F^{-1}[|w_x'|]} \} d\phi
\]
In Equation 2-11, there is still an integration over the aspect $\phi$ remaining for evaluation. Due to the fact that projection data are collected at discrete aspect angles, the integration can be approximated by summation assuming the aspect spacing is small enough.

$$f(x, y) = (2\pi)^{-2} \int \{P_\phi(x') \otimes F^{-1}[|w_x'|]\} d\phi$$

$$= (2\pi)^{-2} \sum_\phi P_\phi(x') \otimes F^{-1}[|w_x'|]$$

Equation 2-12

It can be seen from Equation 2-12 that the integrand is nothing but a filtered version of the projection. The filter is characterized by the transfer function $F^{-1}[|w_x'|]$. In the frequency domain for each aspect angle $\phi$, this filter serves the purpose of weighting each projection slice differently in the sense that sensors around the origin will be weighted less than sensors far away from the origin. The idea also matches the physical intuition of equalization because the domain around the origin is already sampled more densely to begin with, which makes it logical to deemphasize their contribution in the image reconstruction. In other words, this filter can be thought as a windowing function for the projection data in order to weigh the contributions equally in the image domain.

In the filtered backprojection technique, each projected data slice is backprojected into the original image space along the $y'$ direction after passing through the weighting filter; the final object description at any given position can be reconstructed by summing up all the backprojected contributions at that given point.

In comparison with the direct Fourier Transform, the filtered backprojection method does offer a few advantages. Filtered backprojection method does not perform
any Fourier Transform higher than one-dimension, which might be more computationally expensive in certain situations. In addition, Filtered backprojection allows image formation before all the collected data are processed whereas in direct Fourier Transform method, no image can be seen before applying the two-dimensional inverse Fourier Transform in the final step. This summarizes the filtered backprojection algorithm used in Computer-Aided Tomography. The next section discusses the radar applications.

### 2.1.2 Tomographic Imaging Theory for Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) has been widely used in applications involving detection, target identification, and remote sensing. The radar system is commonly placed on a moving platform to scan relatively immobile objects. In a typical SAR scenario, radar pulses are sent from an aircraft or vehicle while the return pulses are measured. The collected SAR data will have both frequency and spatial diversity. Several references in the past have demonstrated how target images can be formed from the collected frequency and aspect data [20, 21]. SAR imaging techniques, although diversified, are all based on similar theoretical ideas originated from tomographic imaging. This section will discuss the theories and how tomographic imaging methods are extended into Synthetic Aperture Radar Imaging.

#### 2.1.2.1 Direct Fourier SAR Imaging

Several references in the past have used the Fourier-based technique in radar imaging applications [19, 20]. Direct Fourier Transform is the most fundamental reconstruction method in SAR imaging. Let us consider a two-dimensional target geometry illuminated by an incident plane wave shown in Figure 2.3 where the
scattered data are collected for large enough frequency band and over the entire aspect.

![Diagram of a plane wave illumination of an unknown target](image)

**Figure 2.3: Plane wave illumination of an unknown target**

If the target can be described by a group of non-dispersive point scattering centers, the backscattered field will have the form of the following in Equation 2-13. Let $k_x$ and $k_y$ be the variables in Cartesian frequency grid and are defined by $k_x = k \cos \phi$ and $k_y = k \sin \phi$, the object description, $S(x, y)$, can then be reconstructed by applying a two-dimensional Fourier Transform on $S(k_x, k_y)$ as in Equation 2-14, which may be evaluated via 2D FFT algorithm with appropriate polar to Cartesian grid interpolation.

$$S(k_x, k_y) = \sum_j A_j e^{-j 2 k (x_j \cos \phi + y_j \sin \phi)} \quad 2-13$$

$$S(x, y) = \iint S(k_x, k_y) \exp j(xk_x + yk_y) \, dk_x \, dk_y \quad 2-14$$

The direct inverse Fourier Transform technique is expected to work best with the plane wave illumination because the $\exp j(xk_x + yk_y)$ in the Fourier Transform integrand can serve as a phase conjugated filter for plane wave incidence. When the
scattered data is available over a large frequency band and aspect region, direct inverse Fourier technique will be good in providing high resolution radar imaging.

A lot of similarities are observed between the direct Fourier-based reconstruction used in X-ray tomography and the one used in synthetic aperture radar imaging. Both cases involve interpolation from frequency polar space to frequency Cartesian space. In addition, both cases use two-dimensional inverse Fourier Transform at the end to obtain object description. The only difference is that in Computer Tomography, projection data are collected via an array of sensors at different positions for the same transmitted frequency (X-ray) while synthetic aperture radar collects the scattered field in the same location for a band of frequencies. In other words, frequency diversity in radar imaging is used to compensate one extra degree of spatial diversity in tomographic imaging.

2.1.2.2 Filter Back-Projected SAR Imaging

Several references in the past have shown the capability of generating SAR imaging using the inverse backprojection algorithm [21]. Let’s consider a radar target scenario as in Figure 2.4. If the target can be represented as a set of N point scatters

![Figure 2.4: Radar target scenario example](image-url)
at a distance $r_m$ away from the antenna, the received field can be written as the following form for any given aspect $\phi$. $c$ is the speed of propagating wave. $A(f, \phi)$

$$S(k, \phi) = \frac{1}{r^2} \sum_{m=1}^{N} A(k, \phi) e^{-j2k r_m(\phi)}$$

2-15

is the reflection intensity which varies slowly as a function of frequency and aspect. Let us consider a two-dimensional image space (x-y plane). The frequency and aspect domain scattered data can be mapped into image space using the following relationship

$$I(x, y) = \int_{\phi_0}^{\phi_1} G(\phi, r(\phi)) d\phi$$

2-16

where $I(x, y)$ is the complex-valued image intensity at coordinates x and y, and

$$G(\phi, r(\phi)) = \int_{k_i}^{k_f} \tilde{S}(k, \phi) e^{+j2k r(\phi)} dk$$

2-17

$$\tilde{S}(k, \phi) = k S(k, \phi) w(k, \phi)$$

$\phi_0 < \phi < \phi_1$ describes the spanned aspect region of the radar and $k_i < k < k_f$ is the available frequency band. $w(k, \phi)$ is a window function, and the extra $k$ factor results from Cartesian to polar transformation. The integration in 2-17 can be evaluated using FFT algorithm, then $r(\phi)$ is interpolated to the x-y grid for each $\phi$ in 2-16. This summarized the SAR imaging technique which utilizes the filtered backprojection algorithm for image reconstruction

2.2 Model Based Imaging Approach

An imaging method has been proposed which further extends the
existing ones based on Filtered Backprojected Reconstruction [22]. The technique is called the Model-Based Imaging which is used throughout the later part of this thesis to study through-wall radar imaging. Unlike most conventional imaging techniques which involve Fourier Transform at some point, model-based imaging is a more general approach utilizing a scattering model based on the physical phenomenology. The use of model-based imaging for point scatterers in both far-field and near field setups will be presented subsequently in the next two subsections. The imaging function used here for the far-field scenario will assume plane wave incidence coming at different aspect angle \( \phi \) while a more general form will be presented for scenarios involving near zone sensors.

2.2.1 Model-Based Imaging for Far-Field Scan

In general, the scanning radar is in the far field if the following criterion is met,

\[
R > \frac{4D^2}{\lambda}
\]  

2-18

where \( R \) is the distance from the antenna to object center, \( D \) is the maximum dimension of the object in the image domain, and \( \lambda \) is the wavelength associated with the maximum frequency used in the collected data. Let us consider a far field scattering setup shown in Figure 2.5 where a point scattering center is illuminated by an incident plane coming circularly at different aspect angle \( \phi \).

The backscattered electric field relative to the origin has the following form,

\[
S(k, \phi, \theta) = \sum_p A_p(k, \phi, \theta)e^{-j2k(x_p \cos \phi + y_p \sin \phi \sin \theta + z_p \cos \theta)}
\]  

2-19

where \( \theta \) is the conical angle measured from the z-axis.
The complex amplitude $A_p(k, \phi, \theta)$ is assumed to be a slow varying function of wavenumber and angles. In the model based imaging approach, a phase-conjugate matching filter is purposely included in the imaging function to cancel out the fast phase variation of the received backscattered fields as shown in Equation 2-20

$$I(x, y, z) = \left| \int \int S(k, \phi, \theta) w(k, \phi) e^{j2k(x \cos \phi \sin \theta + y \sin \phi \sin \theta + z \cos \theta)} dk \, d\phi \right|^2 \tag{2-20}$$

In order to produce a 2D image of a three-dimensional target, a value of $z$ can be chosen from the beginning so that all the target information is projected onto the selected $z$ plane. This however might be not as desirable if the target of interest is very complex in nature and has significant variation along the $z$ direction. A three-dimensional image can be produced if an additional integration over the elevation angle $\theta$ is included in Equation 2-20 provided that enough 3D data is collected. It is not a necessity in the model based imaging technique to perform any Fourier Transforms. The object description can simply be obtained through numerical integration of Equation 2-20. While looping the backscattered field through the entire image domain pixel by
pixel, the phase conjugate matching filter serves to maximize the magnitude of $I$ whenever the point scatterer is located. The windowing function $w(k,\phi)$ can be used to lower the sidelobes (while widening the main lobe).

### 2.2.2 Model Based Imaging for Near-field Scan

If the criterion specified in Equation 2-18 is not satisfied, the scan antenna is no longer in the far zone. An alternative model will be needed for the near zone model based technique. The near zone imaging function presented here is a very general form which is applicable to arbitrary SAR scan movement in scattering data collection. Let us consider a near field scanning setup shown in Figure 2.6 where the sensor location is $\vec{r}' = \hat{x}'x' + \hat{y}'y' + \hat{z}'z'$ and the location of the point scatter is $\vec{r}_p = \hat{x}_p x_p + \hat{y}_p y_p + \hat{z}_p z_p$.

![Figure 2.6: Near-field scattering from a point scattering center](image)

The near field backscattered electric field relative to the origin will have the following form in Equation 2-21. The complex amplitude $A_p(k,\vec{r}',\vec{r}_p)$ is again assumed to be a slow varying function of wavenumber and positions. A near field phase conjugate...
matching filter is introduced in the imaging function to isolate the assumed behavior via fast phase cancellation as shown in Equation 2-22.

\[
I_{nf}(\vec{r}) = \left| \int \int \int S(k, \vec{r}') w(k, \vec{r}') e^{j2k|\vec{r}' - \vec{r}|} dk \, dz' \, dy' \, dx' \right|^2
\]

It should be noted that model based imaging techniques can be further extended to deal with more complicated physical scenarios. The approach presented here for both near-field and far-field scans are all based on a point scattering model. If the target of interest is instead some more specialized feature such as dihedral, trihedral, or corner diffraction; new scattering models can be designed and incorporated into the imaging function to isolate certain special scattering behavior.

### 2.3 Data Sampling and Resolution

In Section 2.2, various SAR imaging methods have been discussed from a theoretical perspective and shown how the principles are originated from tomographic imaging. However in order to successfully reconstruct the target object imagery, scattering data must be collected properly. The collected scattering data in synthetic aperture radar applications will have both frequency and spatial diversity. The discussion here will focus on both frequency and spatial domain sampling as well as showing how they are closely related to scan distance and the frequency of operation. In addition, the required resolution to distinguish closely-spaced scattering objects in through-wall building applications will be considered.
2.3.1 Spatial Sampling Criteria

Based on the Nyquist-Shannon Sampling Theorem, a signal can be successfully reconstructed from its sampled version if and only if the sampling frequency is at least twice the maximum signal frequency. In other words, there is a minimum sampling requirement in order to avoid ambiguity that could result in false representation of the true signal. This idea can be further applied to radar imaging applications. In Mensa [19], the Nyquist sampling criterion is satisfied when the angular increment is sufficiently small so that the phase of signals reflected from points at the object periphery varies less than $\pi$ radians between samples. Let us consider the following monostatic far-field scan geometry of a point scatterer shown in Figure 2.7. The phase difference between two

![Figure 2.7: Far-field radar scan of a point scatterer](image)

far-field antennas is a product of the wave number and the difference in propagating distance which cannot exceed $\pi$ in order to be aliased-free.

$$\Delta \varsigma = 2k \cdot r \sin(\Delta \theta) \leq \pi$$

2-23
If the maximum dimension of the target is $D$, we have the following,

$$\Delta \zeta = 2k \cdot D \cdot \sin(\Delta \theta) \leq \pi$$

$$= 2 \left( \frac{2\pi}{\lambda} \right) \cdot D \cdot \sin(\Delta \theta) \leq \pi$$

Equation 2-24

The approximation $\sin(x) \approx x$ can be used because the angular step is very small in the far field scanning setup. Therefore it will lead to the far-field angular step requirement.

$$\Delta \theta \leq \frac{\lambda}{4D}$$

Equation 2-25

Let us consider a near-field spotlight circular scanning setup shown in Figure 2.8 where the target is a point scatter. The scan radius is $a$, and the distance from the point target to the sensor locations are $r_1$ and $r_2$, respectively.

Figure 2.8: Near-field spot-light circular scan of a point scatterer

The absolute target independent criteria $\Delta \theta$ has to satisfy to provide aliasing-free condition can be derived based on the triangular inequality as following in Equation 2-26.
\[ \Delta l = \sqrt{a^2 + a^2 - 2a^2 \cos(\Delta \theta)} \]

\[ r_1 - r_2 < \Delta l \quad \text{(Triangle inequality)} \]

\[ 2k(r_1 - r_2) < 2k \Delta l \]

\[ \max(\Delta \zeta) \leq 2k \Delta l = 2k \sqrt{a^2 + a^2 - 2a^2 \cos(\Delta \theta)} \leq \pi \]

\[ \Delta \theta \leq \cos^{-1} \left(1 - \frac{\pi^2}{8k^2 a^2}\right), \quad 0 \leq \Delta \theta \leq \frac{\pi}{2} \quad 2-26 \]

In Equation 2-26, the spatial step appears to be radius and frequency dependent. As shown in the formula, a smaller spatial step corresponding to more collected data will be in demand as the frequency or scan radius increases.

The condition derived in Equation 2-26 is independent of the target size. Let us now derive the target dependent condition in spot-light radar scan shown in Figure 2.9

**Figure 2.9**: Near-field Spot-light circular scan of a point scatterer with diameter 2D
From the geometry configuration, the phase difference in both Scenario 1 and Scenario 2 will be zero. Under the assumption, $\Delta \ell << D$, the maximum phase change can be approximated well by Scenario 3 leading to the following target dependent condition.

$$2k\left(\sqrt{a^2 + D^2 - 2aD\cos\left(90^\circ + \frac{\Delta \theta}{2}\right)} - \sqrt{a^2 + D^2 - 2aD\cos\left(90^\circ - \frac{\Delta \theta}{2}\right)}\right) \leq \pi \quad 2-27$$

Using small argument approximation, $\sin(x) \approx x$, Equation 2-27 can be further simplified into the following expression in Equation 2-28,

$$\Delta \theta \leq \frac{16k^2a^2 + 16k^2D^2 - (4k^2aD - \pi)^2}{16k^2aD} \quad \& \quad \frac{4k^2aD - \pi}{k} \geq 0 \quad 2-28$$

This target dependent condition in Equation 2-27 is expected to be less strict than the one proposed in Equation 2-26. Target dependent condition can be very useful when scanning a relatively small target with a big scan radius at a high frequency because it looses the data requirement without giving much compromise to the aliasing condition.

The conditions derived from Equation 2-26 and 2-27 are now verified with the following simulation example shown in Figure 2.10. The target is a two connected

Figure 2.10: Ninety degree angular scanning setup of a dihedral corner
trihedrals made up of material plates \((\varepsilon_r = 3.1 - j0.372)\) with maximum dimension 6m.

The operating frequency band goes from 1.0GHz to 1.3GHz. The scanning radar runs through a 90 degree angular sector at a distance of 5m. Based on Equation 2-26, the condition is expected to be \(\Delta \theta < 0.6611^\circ\) while target dependent condition is \(\Delta \theta < 1.28497^\circ\). Three different angular stepsizes 0.5 \(^\circ\), 1.0 \(^\circ\), and 1.5 \(^\circ\) are simulated; the difference in image quality is quite significant as shown in Figure 2.11.

![Images generated for different angular step size](image)

**Figure 2.11:** Images generated for different angular step size

When the strict condition is met, the image appears to be very clear. The image also appears very well acceptable if it instead satisfies the target dependent condition. If neither condition is satisfied, the image will have aliasing which makes it unacceptable.

Based on Equation 2-26, higher frequency will demand smaller spatial step size. In the geometry shown in Figure 2.10, let us instead fix the angular step size \(\Delta \theta = 1^\circ\). The scan radius is again 5m while simulating for three different frequency bands, 500MHz to 800MHz, 1.0GHz to 1.3GHz, and 1.7GHz to 2.0GHz. The generated images are shown below in Figure 2.12. According to Equation 2-26, \(f < 859.45MHz\) is the strict criterion while \(f < 1.6704GHz\) is the target dependent condition. The
images shown in Figure 2.12 again agree with what the conditions predict.

![Figure 2.12: Images generated for different frequency bands](image)

When choosing the desired operating frequency band in through-wall radar scan, signal level should also be in consideration. It is important to select a frequency band that can result in both sufficient signal penetration and reflection for some typical walls.

### 2.3.2 Frequency Sampling Criteria

Let $x(t)$ be a periodic signal with fundamental period $T$. Based on the Fourier series representation, $x(t)$ can be expressed as a sum of complex exponentials as in Equation 2-29 where $w_o = 2\pi / T$, refers to the fundamental frequency in rad/s.

$$
x(t) = \sum_{k=-\infty}^{\infty} c_k e^{jkw_o t}
$$

It should be noted that all frequencies associated with $x(t)$ are integer multiples of the fundamental frequency, therefore the frequency spacing is the fundamental frequency itself. In other words, a periodic signal with period $T$ will have corresponding Fourier representation with spacing $2\pi / T$ (rad/s) or equivalently $1 / T$ (Hz). This idea can be
further extended to imaging by multiplying the time variable with \( c = 3 \times 10^8 (m/s) \) to get the downrange distance. In order to obtain an aliased-free image, period \( T \) must be sufficiently large such that it can accommodate all wave interactions starting from the time it is sent to the time it is received. This sufficiently large \( T \) will correspond to frequency step size being sufficiently small. Let us now consider an example shown in Figure 2.13 where two different frequency step sizes, 2MHz and 5MHz, are used. 2MHz step size can allow 150m of total wave propagation where 5MHz can allow for only 60m. Both setups have 151 collected data points. Figure 2.14 shows the associated range profile generated for each step size.

There is no aliasing when using 2MHz step size; the peak locations correspond correctly to the actual locations of the walls. On the other hand, the downrange profile for 5MHz step size will have aliasing. Due to the insufficient range domain, the second peak which corresponds to actual physical location at 80m aliases onto 40m resulting in false representation.

In general, frequency step should meet the following criterion to be aliase-free,

\[
\Delta f \leq \frac{c}{2D}
\]

where \( c \) is the speed of light and \( D \) is the maximum one-way downrange distance needed to get to the target.
Figure 2.13: Simulation setup for radar illumination of a square room

Figure 2.14: Downrange comparison for 2MHz step vs. 5MHz step
2.3.3 Resolution

In through-wall building applications, the resolution plays an important role in the image quality since the target complexity is very high. Literature in the past [19, 23] has shown that downrange resolution depends only on the operating bandwidth while crossrange resolution is a function of both center frequency and look angles as illustrated below where $B$ is the bandwidth; $f_c$ is the center frequency and $\theta$ is the angular span.

\[
\Delta R_{\text{downrange}} = \frac{c}{2B} \quad 2.31
\]

\[
\Delta R_{\text{crossrange}} = \frac{c}{2f_c \theta} \quad 2.32
\]

In general, wider bandwidth and angle span will increase the resolution. Operating center frequency is however not a so straightforward parameter to be selected. Based on Equation 2-32, higher frequency will produce better resolution at the expense of more spatial sampling points based on Equations 2-25 and 2-26. In choosing operating center frequency, the tradeoffs between resolution and spatial sampling need to be weighed accordingly in order to generate good quality images.
CHAPTER 3

HIGH FREQUENCY EM CHARACTERIZATION FOR THROUGH-WALL BUILDING IMAGING

In this chapter, a high frequency electromagnetic modeling technique based on the Uniform Geometric Theory of Diffraction (UTD) will be used to study through-wall building interior imaging. The ray-tracing nature along with incorporated diffraction coefficients make the high frequency method very fast and computationally efficient to account for multiple scattering interactions in a large structure. A model-based imaging algorithm as presented in Section 2.2 will be used for the image formation. The employed imaging algorithm has a devised model filtering function built up on top of the conventional FFT-based method to extract specific features. The high frequency computational tool, NEC-BSC, is validated against the near-field RCS measurement of a scaled down building model. The reconstructed images demonstrate the capability of using high frequency techniques in capturing important building features through the walls for various scanning schemes.

3.1 Numerical Electromagnetic Code – Basic Scattering Code

Numerical Electromagnetic Code – Basic Scattering Code (NEC-BSC) is a high frequency ray-tracing code that utilizes uniform geometric theory of diffraction.
In this section, the theoretical background and practical uses of NEC-BSC in generating building scattering data will be presented.

### 3.1.1 NEC-BSC Overview

NEC-BSC is a computer code with graphical interface for electromagnetic analysis at high frequency. The ray-tracing prediction code has been used for various applications such as antenna pattern prediction in the presence of complex structures, indoor wave propagation, and EMI/EMC coupling between antennas. It serves to give engineers and EM researchers an understanding of what the engineering problems are and how designs can be optimized before being built. When dealing with scattering problems, the code allows complex geometries to be built from several primitive elements such as plates, cylinders, ellipsoids, frustums, and wires whose scattering fields are known analytically. The dimension for each element can be assigned accordingly. Both far-zone and near-zone scanning setups can be configured. In near-zone scan, the code allows antenna movement for both transmitters and receivers, which is particular useful for generating large sets of radar scan data.

Unlike most full wave computational methods, NEC-BSC utilizes uniform asymptotic techniques formulated in terms of the Uniform Geometrical Theory of Diffraction (UTD). The UTD analysis is under the high frequency asymptotic assumption where the electromagnetic waves can be treated as rays. Instead of solving the wave equations in a defined numerical domain, NEC-BSC models waves as rays propagating, reflecting, and diffracting off scattering objects. The analytical form of the coefficient is incorporated upon each interaction, and the final received fields are
obtained by summing up all the contributions from individual rays. The user also has a choice of manually select the scattering terms to be included in the computation which makes it very suitable for feature extraction.

The target of interest in through-wall radar imaging is the building which is constructed from a set of dielectric material plates for both exterior and interior walls. The dielectric plates will form junctions with one another resulting in a wedge shell. Therefore, wave propagation through the material slab as well as the corner and edge diffractions of material wedge shells are the pre-dominant contributions in building scattering. Their theory will be discussed in the subsequent subsections

3.1.2 Propagation Through Material Slab

![Diagram of multi-layered slab and its transmission line equivalence](image)

Figure 3.1: Multi-layered slab and its transmission line equivalence

In NEC-BSC when a ray penetrates through the transparent multi-layered material slab, the equivalent transmission and reflection coefficients are incorporated to compute
the corresponding ray and slab interaction. Let us consider a multi-layered slab shown in Figure 3.1. The boundary value problem can be translated into its transmission line equivalent problem. In doing so, the propagation constant and characteristic impedance of the transmission line can be expressed as the following in Equation 3-1 in terms of wave number and dielectric property of the slab. Each transmission line section can be

\[ \beta_m^{TL} = k_m \cos \theta_m \quad Z_m^{TL} = \frac{\eta_m}{\cos \theta_m} (TE) \quad Z_m^{TM} = \eta_m \cos \theta_m (TM) \]  

3-1

\[
\begin{bmatrix}
V_t \\
I_t
\end{bmatrix}
= \begin{bmatrix}
A_1 & B_1 \\
C_1 & D_1
\end{bmatrix} \cdots \begin{bmatrix}
A_m & B_m \\
C_m & D_m
\end{bmatrix} \cdots \begin{bmatrix}
A_N & B_N \\
C_N & D_N
\end{bmatrix}
\begin{bmatrix}
V_t \\
I_t
\end{bmatrix}
\]

3-2

characterized via the ABCD matrix as in Equation 3-2. The matrix element for each section can be expressed using its T-line parameters,

\[ A_m = D_m = \cos (\beta_m^{TL} \ell) \quad B_m = j Z_m^{TL} \sin (\beta_m^{TL} \ell) \quad C_m = \frac{j \sin (\beta_m^{TL} \ell)}{Z_m^{TL}} \]  

3-3

The resulting transmission and reflection coefficients for the multilayered slab are,

\[ T = \frac{2}{A_{total} + \frac{B_{total}}{Z_t} + Z_i \left( C_{total} + \frac{D_{total}}{Z_t} \right)} \]  

3-4

\[ R = \frac{A_{total} + \frac{B_{total}}{Z_t} + Z_i \left( C_{total} + \frac{D_{total}}{Z_t} \right)}{A_{total} + \frac{B_{total}}{Z_t} + Z_i \left( C_{total} + \frac{D_{total}}{Z_t} \right)} \]  

3-5
An alternative way of obtaining Fresnel coefficients for each individual layer is based on recursive summation of infinite bouncing rays [36, 37]. This however might be too computationally inefficient as it contradicts the goal of high frequency methods.

3.1.3 Edge Diffraction for Material Wedge Shell

The UTD edge diffraction coefficient for a perfectly conducting wedge was developed by Kouyoumjian and Pathak [34]. As shown in Figure 3.2, the dyadic diffraction coefficients for a two-dimensional PEC wedge can be written as the following,

\[ \hat{\phi}' = \hat{\beta}' \times \hat{s}' \]
\[ \hat{\phi} = \hat{\beta} \times \hat{s} \]

Figure 3.2: Geometry of wedge diffraction

\[
\overline{D} = - D_s \hat{\beta}' \hat{\beta} - D_h \hat{\phi}' \hat{\phi}
\]

\( D_s \) and \( D_h \) are the associated soft and hard diffraction coefficients. Soft coefficient corresponds to the E-field component parallel to the edge whereas the hard coefficient corresponds to the E-field component perpendicular to the edge. Their forms are
as follows. The subscripts “n, o” refer to the n-face and o-face respectively. The subscripts “i, r” refer to the incident and reflected shadow boundaries.

\[
D_{S,h} = (D_{ni} + D_{oi}) \mp (D_{nr} + D_{or})
\]

\[
= -\exp(-j\pi/4) \frac{1}{2n\sqrt{2\pi k \sin \beta}} 
\times \left[ \cot\left(\frac{\pi + (\phi - \phi')}{2n}\right) F[kLa^+ (\phi - \phi')] 
+ \cot\left(\frac{\pi + (\phi + \phi')}{2n}\right) F[kLa^- (\phi + \phi')] 
\mp \left\{ \cot\left(\frac{\pi + (\phi - \phi')}{'2n}\right) F[kLa^+ (\phi + \phi')] 
+ \cot\left(\frac{\pi + (\phi + \phi')}{2n}\right) F[kLa^- (\phi + \phi')] \right\} \right]
\]

\[
a^\pm (\phi \pm \phi') = 2 \cos^2 \left(\frac{2n \pi N^\pm - (\phi \pm \phi')}{2} \right)
\]

\[
L = \begin{cases} ss' \sin^2 \beta & \text{plane-wave inc.} \\ ss'/(s + s') & \text{cylindrical-wave inc.} \\ ss' \sin^2 \beta/(s + s') & \text{conical and spherical-wave inc.} \end{cases}
\]

\[
F(x) = 2j \sqrt{|x|} e^{j|z|} \int_{|z|}^\infty e^{-j\tau z} \, d\tau
\]

The diffracted field can be expressed in dyadic form as in Equation 3-8 or its equivalent matrix representation as in Equation 3-9.

\[
\bar{E}^d \sim \bar{E}^i \cdot \bar{D} A(s) e^{-jks}
\]
Extending upon Burnside and Burgener’s [37] heuristic diffraction coefficients for a material half plane, an approximate UTD coefficient is developed for a material wedge shell by Aktas [38]. The corresponding shadow boundary dependent modification terms are incorporated into Equation 3-7 as the following,

\[
D_{s,h} = C_{ni} D_{ni} + C_{oi} D_{oi} \mp C_{nr} D_{nr} + C_{or} D_{or}
\]

3-10

The value of C terms depends on the wedge angle and can be expressed in terms of transmission and reflection coefficients of the o-face and n-face. When dealing with three-dimensional wedge diffraction problem, the dyadic must be generalized to account for the cross-polarized components,

\[
\overline{D} = - D_{ss} \hat{\phi}'\hat{\beta}' - D_{sh} \hat{\phi}'\hat{\beta} - D_{hs} \hat{\beta}'\hat{\phi} - D_{hh} \hat{\phi}'\hat{\phi}
\]

3-11

The coefficients in Equation 3-11 can be expressed in terms of polarization transform dyads. To ensure the total UTD field is continuous at shadow boundaries, the incident field in edge fixed coordinate system needs to be transformed into ray fixed coordinate system, add the transmitting and reflecting effect, then transform back to edge-fixed system. This will result in the following expression in Equation 3-12,
\[
\mathbf{D} = -\mathbf{\bar{T}}^{-1}(\alpha) \cdot \mathbf{C}_{ni} \cdot \mathbf{\bar{T}}(\alpha) \mathbf{D}_{ni} \\
= -\mathbf{\bar{T}}^{-1}(-\alpha) \cdot \mathbf{C}_{oi} \cdot \mathbf{\bar{T}}(-\alpha) \mathbf{D}_{oi} \\
= -\mathbf{\bar{T}}^{-1}(\alpha) \cdot \mathbf{C}_{nr} \cdot \mathbf{\bar{T}}(-\alpha) \mathbf{D}_{nr} \\
= -\mathbf{\bar{T}}^{-1}(-\alpha) \cdot \mathbf{C}_{or} \cdot \mathbf{\bar{T}}(\alpha) \mathbf{D}_{or} 
\]

\(\alpha\) is the angle between the two coordinate systems and \(\mathbf{\bar{T}}\) is the polarization transform matrix. NEC-BSC has incorporated the 3D material edge diffraction for wedge shell with arbitrary angle whose geometry resembles the wall junction in various modern buildings.

### 3.1.4 Corner Diffraction for Material Wedge Shell

Consider the corner diffraction geometry shown in Figure 3.3. Based on [39, 40], the corner diffracted field associated with one edge and one corner of a three-dimensional PEC wedge for near field spherical wave incidence can be expressed in matrix form as the following in Equation 3-13.
\[
\begin{bmatrix}
E_{\phi}^c \\
E_{\phi}^e
\end{bmatrix} = [AC(\phi - \phi') + BC(\phi - \phi')]
\begin{bmatrix}
E_{\phi}^c (Q_e) \\
E_{\phi}^e (Q_e)
\end{bmatrix}
\times \frac{\exp(-j\pi/4)}{\sqrt{2\pi k} \frac{\sin \beta_c \sin \beta_{oc}}{(\cos \beta_{oc} - \cos \beta_c)}}
\times F[kL_e a(\pi + \beta_{oc} - \beta_c)] \frac{\exp(-jks)}{s}
\]

\[C(x) = \frac{-\exp(-j\pi/4)}{2n\sqrt{2\pi k} \sin \beta_o} \times \left\{ \cot \left( \frac{\pi + x}{2n} \right) F[kLa^+(x)] \right\}
\times \left\{ \cot \left( \frac{\pi - x}{2n} \right) F[kLa^-(x)] \right\} \frac{La^+(x)/\lambda}{kL_e a(\pi + \beta_{oc} - \beta_c)}
\]

\[L = \frac{s^3s'''}{s''+s'''} \sin^2 \beta_o \quad L_c = \frac{s_e s}{s_e + s}
\]

The special functions used in Equation 3-13 are the same as those defined in 3-7. The wedge angle is \((2-n)\pi\). The corner diffraction field can be written as

\[C_{s,b} = C(\phi - \phi') \mp C(\phi + \phi')\]

Comparing Equation 3-14 to Equation 3-7, an extra modification factor is included to avoid abrupt sign change due to shadow boundary. The corner diffraction fields associated with other edges can be treated in a similar manner. The corner diffraction in Equation 3-13 always exists whereas the edge diffraction from each edge may or may not exist depending on the geometry. The total effect from the corner is the summation of individual contributions from each edge. The idea is applied to a number of plate geometries and discussed further by Sikta [41].
When dealing with corner diffraction of the material wedge shell, similar modification terms as in Equation 3-10 can be included. The modification terms are again dependent upon wedge angle as well as the transmission and reflection coefficients of the o-face and n-face. The corner diffraction calculation for the three-dimensional material wedge shell with arbitrary angle has been incorporated into NEC-BSC.

3.2 Near-field RCS measurement of A Building Model

In this section, a small building model made of concrete and plywood has been constructed and used for near-field RCS measurement. The range profiles and the reconstructed images will be compared and validated against the NEC-BSC simulations.

3.2.1 Small Building Model

Let us consider a typical one-story building with dimensions 18m x 12m x 3m made of concrete block with thickness 20cm. The typical frequency band of interest goes from 100MHz to 1GHz. The building size is scaled down eighteen times while the frequency goes up eighteen times. After scaling down, the building has the dimension of

![18:1 scale ratio](image)

**Figure 3.4: Scaled down building model**
1m x 0.67m x 0.1541m with wall thickness of 0.5 inch. Durock cement board which has a measured dielectric constant of 3.1-j0.12 will be used for construction. In addition, a 0.25-inch plywood sheet will be placed as the roof. As demonstrated in Figure 3.4, the Durock cement board does appear to have a similar transmission level as the concrete wall commonly used in modern buildings based on Holloway’s equivalent model [31].

3.2.2 Measurement Setup

The constructed scaled-down building model will be used as the target in a near-field airborne fly-by measurement. The whole scanning scenario is shown in Figure 3.5.

![Figure 3.5: Near-field measurement setup scenario](image)

The target building is placed on a circular rotor while the horn antenna is kept stationary. A network analyzer is placed near and connected to the horn antenna to capture and collect the backscattered signal for frequency band 2-18 GHz. The entire measurement setup in the Ohio State University ElectroScience Lab compact range is shown in Figure 3.6.
Since the measurement is corrupted by many interferences such as cable junctions, floor, pedestal, and platform scattering, a background subtraction with the environment itself is necessary. Placing the horn antenna 5m away from the target center seems reasonable for simulating a scaled-down version of a fly-by radar scan.

![Near-field measurement setup at ESL compact range](image)

**Figure 3.6: Near-field measurement setup at ESL compact range**

In addition to measuring the actual building target, measured data will also be collected for a hemisphere on the ground plane to calibrate the data. Table I summarizes the different sets of data to be collected in the measurement. It is found however that the hemisphere data is too weak for calibration use but useful in locating center of rotation.

### 3.2.3 Measurement vs. NEC-BSC

The model used for measurement is simulated using NEC-BSC for comparison. Instead of using a horn antenna, a dipole is used for the simulations. Figure 3.7 shows
<table>
<thead>
<tr>
<th></th>
<th>Vertical Polarization</th>
<th>Horizontal Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood building</td>
<td>2-18GHz, 0-360 deg</td>
<td>2-18GHz, 0-360 deg</td>
</tr>
<tr>
<td>Plywood building with PEC box</td>
<td>2-18GHz, 0-360 deg</td>
<td>None</td>
</tr>
<tr>
<td>Hemisphere for calibration</td>
<td>2-18GHz, 0 deg</td>
<td>2-18GHz, 0 deg</td>
</tr>
<tr>
<td>Empty Ground</td>
<td>2-18GHz, 0 deg</td>
<td>2-18GHz, 0 deg</td>
</tr>
</tbody>
</table>

Table 1: Collected data sets in building RCS measurement

**NEC-BSC Simulation**

**Measured Data**

Figure 3.7: Spatial pattern comparison (10GHz, H-polarization)
an azimuthal field comparison between NEC-BSC simulation and measurement for the Plywood Building at 10GHz with horizontal polarization. It can be seen that NEC-BSC indeed predicts the dominant trends very well. The radar is expected to capture strong dihedral wall returns around azimuthal angles, 0 deg, 90 deg, 180 deg, and 270 deg due the way the target building is aligned. The diffractions and triple-bounced trihedral returns appear relatively low compared to dihedral returns. The measured data is also seen to have a constant level of noise interference.

Two building models used for measurement is built in NEC-BSC for comparison and their top views are shown in Fig. 3.8.

![Figure 3.8: Building models with wall labeled in blue (top view)](image)

The range profile comparison between NEC-BSC and measurement for the Plywood Building is shown in Figure 3.9. The downrange associated with bandwidth 6 to 10 GHz is obtained for horizontal polarization at two azimuthal angles (0 and 270 deg).
Figure 3.9: Range profile comparison for Plywood Building (6-10GHz, H-polarized)
It can be seen that NEC-BSC predicts the peak locations very well agreed with the measurement. The magnitude at some peak location differ slightly which are probably due to noise and the approximated material index.

### 3.2.4 Measured Images vs. NEC-BSC Images

Two-dimensional images of the measured data and NEC-BSC simulations are formed using the near-field model-based imaging approach. The measured images and NEC-BSC images for H-polarized Plywood Building model are shown in Figure 3.10. It can be seen that NEC-BSC indeed successfully predicts the important building features.

The measured and NEC-BSC images for V-pol Plywood Building model are shown in Figure 3.11. In both cases, trihedrals show up with the highest intensity. Dihedrals formed by exterior walls with the ground also show up quite strong. Dihedrals formed by the interior walls with ground are very clear in certain frequency bands. It can be seen for both NEC-BSC and measured images, dihedrals appear with higher intensity for H-pol than V-pol. Furthermore, the image quality deteriorates with high frequency as it demands finer spatial sampling.

Figure 3.12 displays the V-pol measured and NEC-BSC images of the Plywood Building with PEC box. The PEC box shows up strongly for all frequency bands. Unlike material objects, PEC targets are relatively insensitive to frequency variation because the reflection coefficients are not frequency dependent. NEC-BSC again correctly predicts dominant scattering features and their relative magnitude. Measured images appear to have stronger dihedral return which may be due to the diffraction from the rough edges.
Figure 3.10: (a) H-pol measured images of the Plywood Building Model  
(b) H-pol NEC-BSC images of the Plywood Building Model
Figure 3.11: (a) V-pol measured images of the Plywood Building Model
(b) V-pol NEC-BSC images of the Plywood Building Model
Figure 3.12: (a) V-pol measured images of the Plywood Building with PEC box (b) V-pol NEC-BSC images of the Plywood Building with PEC box
3.3 Through Wall NEC-BSC Simulation Examples

The validity of using a high frequency EM modeling technique to collect building scattering data has been demonstrated in the previous section. In this section, an example room model will be simulated in NEC-BSC for imaging. Linear SAR and spot-light orbital SAR [42] are both legitimate ways for building scan operation. Let us consider image formation of one-story building using linear SAR as shown in Figure 3.13. The dielectric constant for both exterior and interior walls is 3.1-j0.12. The frequency of operation goes from 700MHz to 1GHz. The image is seen to have high clutter level possibly due to imaging sidelobes and multi-bounce. The interior objects don’t appear
discernable due to the spatial limiting nature of linear SAR. Figure 3.14 shows the image formation of the same building room using spot-light orbital SAR for the same bandwidth and number of spatial points. The spot-light scan does clearly reconstruct the two-dimensional layout of the room.

Figure 3.14: Spot-light SAR image formation of one-story room
CHAPTER 4

BUILDING FEATURE CAPTURE AND INTERIOR OBJECT DETECTION

Through-wall radar imaging of buildings can be quite a challenge due to target complexity, strong exterior wall returns, and interior multi-bounce. Target complexity and interior multi-bounced propagation could increase clutter level and possibly lead to false target identifications. Strong exterior wall reflections can also cause the same disasters by introducing unwanted sidelobes in the images that obscure weaker interior details. As a result, image formation of a complex target like a building won’t be very useful in showing the actual layout. The validity of using NEC-BSC in radar building simulations has been demonstrated in the previous chapter. In this chapter, the discussion will focus on utilizing some of the electromagnetic controlling factors to avoid and mitigate some of the above challenges. It will be shown that intelligently processing the collected oblique and broadside scan data can allow better determination of the building features relatively free from undesired interferences. In addition, it will be demonstrated how polarization can be utilized to capture or avoid different types of building features. Lastly, bistatic scans for hidden object detection will be considered.
4.1 Feature Capture via Oblique and Broadside Return

In this section, we focus on building feature capture and identification. A feature capturing and identifying method based on feature scattering mechanisms is proposed. The method will be demonstrated through examples of how it allows better determination of building features relatively free from clutter and sidelobe interferences.

4.1.1 Oblique Radar Return for Dihedral and Trihedral

The radar return from an urban building is largely due to scattering and reflections from the surfaces [24, 25]. In a monostatic building scan, the radar return is dominated by the backscattered field coming from the direct wall reflections, the double bounce effect (dihedral), and the triple bounce effect (trihedral). Let us consider an orbital simulation setup shown in Figure 4.1 involving a T-shaped target on a ground plane where the dimensions are specified in the Figure. The material dielectric is 6.0-j0.72. The frequency of operation goes from 1.0 to 1.3GHz and the scan radius is 10m at 45-degree look down angle. Individual images are formed from the scattering data at four different radar sectors: 0-90 deg, 90-180 deg, 180-270 deg, and 270-360 deg. It can be seen in Figure 4.2 that the dihedrals show up clearly in all the images whereas trihedrals only show up strong in the 0-90 deg and 90-180 deg images. Based on the triple bounce scattering mechanism, whenever the scanning radar runs across the sector where the trihedral opens outward, the trihedral corner will appear focused in that sector image.
Figure 4.1: Fly-by simulation setup of a T-shaped target

Figure 4.2: Sector image formation of the T-shaped target
The dihedral returns associated with the walls can be avoided by reducing the angular sectors at the expense of reduced resolution. This is shown in Figure 4.3 when the angular span for each sector is reduced from 90 degrees to 30 degrees. The resulting images are free from having any undesirable wall returns as well as their associated sidelobes. The trihedrals appear clear in the 30-60 deg and 120-150 deg sector images.

### 4.1.2 Building Feature Identification via Oblique and Broadside Scans

In through-wall building imaging, the radar returns from the exterior walls are somewhat undesirable because they can introduce unwanted sidelobes resulting in unacceptable images. It can be concluded from Section 4.1.1 that oblique scans with
proper angular sector size can be used to successfully avoid wall returns while preserving the important corner features. Moreover, the features associated with each individual corner can be determined collectively based on the data from different scanning sectors; trihedrals will only show up strong in the sector image if the scanning path is on the concave side of the trihedrals. With all these observations, a building feature identification methodology is proposed as follows in Figure 4.4. This method along with some basic decision making can remove a lot of ambiguities resulting in much better estimation of the interior building layout.

![Diagram of proposed building feature identification method]

**Figure 4.4: Proposed Building Feature Identification Method**

The proposed method will begin by processing the oblique scan data to identify the corner locations. The angular size of each oblique scan should be chosen properly so that it is small enough to avoid the return from the exterior walls and big enough to provide tolerable resolution. The oblique scan images are expected to be clear so that all corners can be identified by a simple search of local maxima. Once the corner locations are found, the next step is to determine their associated features. If high intensity is found at a corner location associated with 30-60 deg oblique scan set, then a trihedral
facing towards the 30-60 deg direction can be expected at that location. The same principle applies vice versa for other oblique scans. The feature at each corner location is then determined after combining the information from all the oblique scan sets. Furthermore, broadside images will be obtained to assist corner connection when ambiguities exist.

The usefulness of the proposed method can be demonstrated through the following example. Let’s consider an 8m x 4m x 5m target building with a very complex interior layout as shown in Figure 4.5. The exterior walls are made of lossy material with dielectric index 6-j0.72 while the interior walls have a material index of 3.1-j0.12. A fly-by circular scan around the target is performed at a scan radius of 25m. The frequency band of operation is 0.7-1.0GHz.

![Figure 4.5: Circular side-by scan of a complex one-story building](image)

The complete 360 deg scattering data is used to form a 2D image of the complex room as shown in Figure 4.6. It can be seen that the interior layout does not appear very clear in the image as it is very much distorted by the unwanted clutter and sidelobes.
The proposed feature identification method will now be applied to this scenario. Four oblique scan data sets (15-75 deg, 105-165 deg, 195-255 deg and 285-345 deg) are selected for processing. The size of the oblique scan data is chosen this way to avoid undesired wall returns and provide high enough resolution. The images from all the different oblique scan sets are shown in Figure 4.7. Based on the trihedral scattering mechanism, corners will appear high intensity and are less obscured by interferences.

A reasonable threshold can be applied to filter out the sidelobes resulting from the corner returns. The corner position can then be identified by a simple search of the local maxima as shown in Figure 4.8. It is possible that the corner positions found deviate slightly from the actual locations due to wall transmission phase distortion. This drawback may be mitigated if some prior information about the wall is known. Once the corners are found, each oblique scan image can be used to determine the trihedral orientations as in Figure 4.9. The deduced trihedral orientations from different oblique scans are then combined to show the associated corner features. This is illustrated in Figure 4.10.
Figure 4.7: Oblique scan images of the target building

Figure 4.8: Corner capture of the target building
Figure 4.9: Trihedral orientation capture via oblique scans of target building

Figure 4.10: Trihedral combination for the target building
Figure 4.10 shows the deduced corner features of the target building. Based on
the trihedral orientation, the attempt to connect the corners can be quite automatic under
certain basic assumptions. However in order to more accurately represent the interior
layout, broadside images can be used to assist corner connection. In broadside scans, the
strong wall returns are captured as well as the associated sidelobes. Therefore proper
decision rules need to be implemented to connect the corners. The broadside images for
the target building are shown in Figure 4.11. Notice that certain broadside scans can
capture certain interior walls better than the others, and hopefully as a whole, all the
ambiguities associated with corner connection are removed.

![Figure 4.11: Broadside images of the target building](image)
It can be seen in Figure 4.12 that the oblique scan data can be intelligently processed to give a very true representation of the building features. Upon combining the broadside images with proper decision making, the corners can be connected. The main principle behind this method is to look for certain trihedral orientations which cause the triple bounce scattering effect and combine them together under some estimation procedure. The technique fully employs the ideas of wave scattering phenomenology.

Figure 4.12: Original image vs. deduced building features

4.2 Radar Polarimetry for Feature Capture

In this section, the polarization effect in radar imaging will be studied. It is of great interest to understand the difference in image quality of radars with different polarizations and to discover whether certain polarizations can be used to provide additional information about the target. The effect of polarization on urban features has been studied in the past [26]. Theoretical demonstration and numerical simulations will be done here for different targets to illustrate how polarization is indeed a useful
4.2.1 Polarization Study of a T-Shaped Target

Let us consider a T-shaped target in Figure 4.13. The radar scan runs through 0 to 90 degree aspect angle for four different setups: VV, VH, HH, and HV where the first letter represents the source polarization while the second is the receiver polarization. The resulting images are shown in Figure 4.14. In a monostatic radar scan, the two cross-polarized components in the scattering matrix are expected to be symmetric by reciprocity, which is why the resulting VH and HV images are the same. A few observations are seen here. The trihedrals show up strongly in both co-polarized images.
and cross-polarized images. However, the dihedral wall returns show up in co-polarized images, but not very well in the cross-polarized images. In other words, cross-polarized configurations can be used to capture building trihedrals while avoiding undesired dihedral return from the walls. The idea is demonstrated through the following analysis.

Let us first consider the following coordinate systems of an arbitrary scatterer shown in Figure 4.15. Ray-fixed coordinate systems can be written in terms of the local coordinate system as illustrated in Equation 4-1.
Figure 4.15: Local and global coordinate systems of an arbitrary scatterer

\[
\hat{h} = \sin(\phi_s) \hat{\mathbf{x}} - \cos(\phi_s) \hat{\mathbf{y}}
\]

\[
\hat{e} = -\cos(\phi_s) \cos(\theta_s) \hat{\mathbf{x}} - \sin(\phi_s) \cos(\theta_s) \hat{\mathbf{y}} + \sin(\theta_s) \hat{\mathbf{z}}
\]

\[
\hat{k} = -\cos(\phi_s) \sin(\theta_s) \hat{\mathbf{x}} - \sin(\phi_s) \sin(\theta_s) \hat{\mathbf{y}} - \cos(\theta_s) \hat{\mathbf{z}}
\] 4-1

\[
\hat{h}' = -\sin(\phi_R) \hat{\mathbf{x}} + \cos(\phi_R) \hat{\mathbf{y}}
\]

\[
\hat{e}' = \cos(\phi_R) \cos(\theta_R) \hat{\mathbf{x}} + \sin(\phi_R) \cos(\theta_R) \hat{\mathbf{y}} - \sin(\theta_R) \hat{\mathbf{z}}
\]

\[
\hat{k}' = \cos(\phi_R) \sin(\theta_R) \hat{\mathbf{x}} + \sin(\phi_R) \sin(\theta_R) \hat{\mathbf{y}} + \cos(\theta_R) \hat{\mathbf{z}}
\]
The coordinate systems defined above can be applied to a dihedral corner as shown in Figure 4.16. The directions of the electric and magnetic field can be arbitrary as long as they are perpendicular to each other and the direction of propagation, $\mathbf{k}$. The subscript number, “1, 2, 3” designates either one of the three wave paths shown in the figure. The subscript letter, “S” and “R” denotes “coming from a source” and “going towards a receiver” respectively. Let $\hat{h}_1 = \sin(\phi_{s1})\hat{x}_1 - \cos(\phi_{s1})\hat{y}_1$ be the transmitted field and $\hat{h}_i$ be the return field, we can express each ray-fixed coordinate in terms of its local axes via the following matrix representations,

$$
\begin{align*}
\begin{bmatrix}
\hat{k}_1 \\
\hat{e}_1 \\
\hat{h}_1
\end{bmatrix}
&=
\begin{bmatrix}
-\cos(\phi_{s1})\sin(\theta_{s1}) & -\sin(\phi_{s1})\sin(\theta_{s1}) & -\cos(\theta_{s1}) \\
-\cos(\phi_{s1})\cos(\theta_{s1}) & -\sin(\phi_{s1})\cos(\theta_{s1}) & \sin(\theta_{s1}) \\
\sin(\phi_{s1}) & -\cos(\phi_{s1}) & 0
\end{bmatrix}
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix} \quad 4-2
\end{align*}
$$

$$
\begin{align*}
\begin{bmatrix}
\hat{k}_3 \\
\hat{e}_3 \\
\hat{h}_3
\end{bmatrix}
&=
\begin{bmatrix}
\cos(\phi_{r2})\sin(\theta_{r2}) & \sin(\phi_{r2})\sin(\theta_{r2}) & \cos(\theta_{r2}) \\
\cos(\phi_{r2})\cos(\theta_{r2}) & \sin(\phi_{r2})\cos(\theta_{r2}) & -\sin(\theta_{r2}) \\
-\sin(\phi_{r2}) & \cos(\phi_{r2}) & 0
\end{bmatrix}
\begin{bmatrix}
\hat{x}_2 \\
\hat{y}_2 \\
\hat{z}_2
\end{bmatrix} \quad 4-3
\end{align*}
$$
By law of reflection and the way radar is positioned against the dihedral corner, the following relationships between the azimuthal and elevation angles exist for each plate reflection and can be used to rewrite Equation 4-2 and Equation 4-3. It can be seen

\[ \theta_{s1} = \theta_{r1}, \quad \theta_{s2} = \theta_{r2} \]

\[ \phi_{s1} = \phi_1 + \frac{3}{2} \pi, \quad \phi_{r1} = \phi_1 + \frac{\pi}{2} \]  \quad (4-4)

\[ \phi_{s1} = \phi_1 + \frac{3}{2} \pi, \quad \phi_{r1} = \phi_2 + \frac{\pi}{2} \]

from Figure 4.16 that the two local coordinate systems are related via three axis rotations. One can go from first coordinate system to second coordinate system by rotating \( z_i \) axis counterclockwise for angle \( \phi_1 \), then rotating \( x_i \) axis counterclockwise for 90 degrees, and finally rotating \( z_i \) axis clockwise by angle \( \phi_2 \). This leads to following transformation,

\[
\begin{bmatrix}
\hat{x}_2 \\
\hat{y}_2 \\
\hat{z}_2
\end{bmatrix} = R_{s1}(-\phi_2) R_{s1}(90^\circ) R_{s1}(\phi_1)
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix}
\]

\[
\begin{bmatrix}
\hat{x}_2 \\
\hat{y}_2 \\
\hat{z}_2
\end{bmatrix} = \begin{bmatrix}
\cos(\phi_2) & -\sin(\phi_2) & 0 \\
\sin(\phi_2) & \cos(\phi_2) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & -1 \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
\cos(\phi_1) & \sin(\phi_1) & 0 \\
-\sin(\phi_1) & \cos(\phi_1) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix}
\]

\[
\begin{bmatrix}
\hat{x}_2 \\
\hat{y}_2 \\
\hat{z}_2
\end{bmatrix} = \begin{bmatrix}
\cos(\phi_1)\cos(\phi_2) & \sin(\phi_1)\cos(\phi_2) & -\sin(\phi_2) \\
\cos(\phi_1)\sin(\phi_2) & \sin(\phi_1)\sin(\phi_2) & \cos(\phi_2) \\
\sin(\phi_1) & -\cos(\phi_1) & 0
\end{bmatrix}
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix}
\]  \quad (4-5)

Using the expressions in Equation 4-4 and Equation 4-5, Equation 4-3 can be further rewritten as the following shown in Equation 4-6.
\[
\begin{bmatrix}
\hat{k}_3 \\
\hat{e}_3 \\
\hat{h}_3
\end{bmatrix} = \begin{bmatrix}
\cos(\phi_{r_2}) \sin(\theta_{r_2}) & \sin(\phi_{r_2}) \sin(\theta_{r_2}) & \cos(\theta_{r_2}) \\
\cos(\phi_{r_2}) \cos(\theta_{r_2}) & \sin(\phi_{r_2}) \cos(\theta_{r_2}) & -\sin(\theta_{r_2}) \\
-\sin(\phi_{r_2}) & \cos(\phi_{r_2}) & 0
\end{bmatrix} \begin{bmatrix}
\hat{x}_2 \\
\hat{y}_2 \\
\hat{z}_2
\end{bmatrix}
\]

\[
= \begin{bmatrix}
\cos(\phi_2 + \frac{\pi}{2}) \sin(\theta_{r_2}) & \sin(\phi_2 + \frac{\pi}{2}) \sin(\theta_{r_2}) & \cos(\theta_{r_2}) \\
\cos(\phi_2 + \frac{\pi}{2}) \cos(\theta_{r_2}) & \sin(\phi_2 + \frac{\pi}{2}) \cos(\theta_{r_2}) & -\sin(\theta_{r_2}) \\
-\sin(\phi_2 + \frac{\pi}{2}) & \cos(\phi_2 + \frac{\pi}{2}) & 0
\end{bmatrix} \cdot \begin{bmatrix}
\cos(\phi_1) \cos(\phi_2) & \sin(\phi_1) \cos(\phi_2) & -\sin(\phi_2) \\
\cos(\phi_1) \sin(\phi_2) & \sin(\phi_1) \sin(\phi_2) & \cos(\phi_2) \\
\sin(\phi_1) & -\cos(\phi_1) & 0
\end{bmatrix} \begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix}
\]

\[
A_{33} = -\sin\left(\phi_2 + \frac{\pi}{2}\right) \cdot (-\sin(\phi_2)) + \cos\left(\phi_2 + \frac{\pi}{2}\right) \cdot \cos(\phi_2) = 0
\]

Therefore from Equation 4-6, the backscattered field does not have \( z_1 \) (cross-polarized) component which analytically demonstrates the assertion that cross-polarized configuration can be used in building scan to avoid undesired dihedral return. The polarizations for the transmitted and backscattered signals are actually the same

\[
\hat{h}_3 = -\cos(\phi_1) \hat{x}_1 - \sin(\phi_1) \hat{y}_1
\]

\[
\hat{h}_1 = \sin(\phi_{s_1}) \hat{x}_1 - \cos(\phi_{s_1}) \hat{y}_1 = \sin\left(\phi_1 + \frac{3}{2} \pi\right) \hat{x}_1 - \cos\left(\phi_1 + \frac{3}{2} \pi\right) \hat{y}_1
\]

\[
\hat{h}_1 = -\cos(\phi_1) \hat{x}_1 - \sin(\phi_1) \hat{y}_1
\]

We will now show analytically how trihedrals indeed scatter cross-polarized
return field. Let us consider a trihedral corner shown in Figure 4.17. Each plate reflection will have its associated elevation and azimuthal angles which are not shown explicitly in the figure. The subscript notations are the same as those defined previously. The local coordinate systems are defined such that the incident wave for each plate comes in at zero azimuthal angle on each local coordinate system. As a consequence, these following conditions in Equation 4-7 automatically result,

\[ \phi_{s1} = -\phi_1, \quad \phi_{s2} = -\phi_2, \quad \phi_{s3} = -\phi_3 \]

\[ \theta_{s1} = \theta_{R1}, \quad \theta_{s2} = \theta_{R2}, \quad \theta_{s3} = \theta_{R3} \]  

\[ \phi_{R1} = \pi - \phi_1, \quad \phi_{R2} = \pi - \phi_2, \quad \phi_{R3} = \pi - \phi_3 \]  

Let \( \hat{h}_1 = \sin(\phi_{s1}) \hat{x}_1 - \cos(\phi_{s1}) \hat{y}_1 \) be the transmitted field and \( \hat{h}_4 \) be the return backscattered field, we can again express each ray-fixed coordinate in terms of its local axes via the following matrix representations shown in Equation 4-8 and 4-9,
\[
\begin{align*}
\begin{bmatrix}
\hat{k}_1 \\
\hat{e}_1 \\
\hat{h}_1
\end{bmatrix}
&=
\begin{bmatrix}
-\cos(\phi_1)\sin(\theta_1) & -\sin(\phi_1)\sin(\theta_1) & -\cos(\theta_1) \\
-\cos(\phi_1)\cos(\theta_1) & -\sin(\phi_1)\cos(\theta_1) & \sin(\theta_1) \\
\sin(\phi_1) & -\cos(\phi_1) & 0
\end{bmatrix}
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix} \\
\hat{k}_4
&=
\begin{bmatrix}
\cos(\phi_3)\sin(\theta_3) & \sin(\phi_3)\sin(\theta_3) & \cos(\theta_3) \\
\cos(\phi_3)\cos(\theta_3) & \sin(\phi_3)\cos(\theta_3) & -\sin(\theta_3) \\
-\sin(\phi_3) & \cos(\phi_3) & 0
\end{bmatrix}
\begin{bmatrix}
\hat{x}_3 \\
\hat{y}_3 \\
\hat{z}_3
\end{bmatrix}
\end{align*}
\]

It can be seen from Figure 4.17 that the first and third local coordinate systems can be interrelated through the following transformation in Equation 4-10.

\[
\begin{align*}
\begin{bmatrix}
\hat{x}_3 \\
\hat{y}_3 \\
\hat{z}_3
\end{bmatrix}
&= R_{z1}(\pi/2 - \phi_3) R_{y1}(90^\circ) R_{x1}(90^\circ) R_{z1}(\phi_1)
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix} \\
\begin{bmatrix}
\hat{x}_3 \\
\hat{y}_3 \\
\hat{z}_3
\end{bmatrix}
&=
\begin{bmatrix}
\cos(\pi/2 - \phi_3) & \sin(\pi/2 - \phi_3) & 0 \\
-\sin(\pi/2 - \phi_3) & \cos(\pi/2 - \phi_3) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
0 & 0 & -1 \\
0 & 1 & 0 \\
1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix} \\
\begin{bmatrix}
\hat{x}_3 \\
\hat{y}_3 \\
\hat{z}_3
\end{bmatrix}
&= \begin{bmatrix}
\cos(\phi_1) & \sin(\phi_1) & 0 \\
-\sin(\phi_1) & \cos(\phi_1) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix} \\
\begin{bmatrix}
\hat{x}_3 \\
\hat{y}_3 \\
\hat{z}_3
\end{bmatrix}
&= \begin{bmatrix}
-\sin(\phi_1)\sin(\phi_3) & \cos(\phi_1)\sin(\phi_3) & \cos(\phi_3) \\
\sin(\phi_1)\cos(\phi_3) & -\cos(\phi_1)\cos(\phi_3) & \sin(\phi_3) \\
\cos(\phi_1) & \sin(\phi_3) & 0
\end{bmatrix}
\begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix}
\end{align*}
\]

Using the expressions in Equation 4-7 and Equation 4-10, Equation 4-9 can be further rewritten as the following shown in Equation 4-11.
\[
\begin{align*}
&\hat{k}_4 = \begin{bmatrix}
\cos(\phi_{R3})\sin(\theta_{R3}) & \sin(\phi_{R3})\sin(\theta_{R3}) & \cos(\theta_{R3}) \\
\cos(\phi_{R3})\cos(\theta_{R3}) & \sin(\phi_{R3})\cos(\theta_{R3}) & -\sin(\theta_{R3}) \\
-\sin(\phi_{R3}) & \cos(\phi_{R3}) & 0
\end{bmatrix} \begin{bmatrix}
\hat{x}_3 \\
\hat{y}_3 \\
\hat{z}_3
\end{bmatrix} \\
&= \begin{bmatrix}
\cos(\pi - \phi_{e})\sin(\theta_{e}) & \sin(\pi - \phi_{e})\sin(\theta_{e}) & \cos(\theta_{e}) \\
\cos(\pi - \phi_{e})\cos(\theta_{e}) & \sin(\pi - \phi_{e})\cos(\theta_{e}) & -\sin(\theta_{e}) \\
-\sin(\phi_{e}) & \cos(\phi_{e}) & 0
\end{bmatrix}. \\
&= \begin{bmatrix}
\cos(\phi_{c})\sin(\phi_{3}) & \cos(\phi_{c})\sin(\phi_{3}) & \cos(\phi_{3}) \\
\sin(\phi_{c})\cos(\phi_{3}) & -\cos(\phi_{c})\cos(\phi_{3}) & \sin(\phi_{3}) \\
\cos(\phi_{c}) & \sin(\phi_{c}) & 0
\end{bmatrix} \begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix}.
\end{align*}
\]

\[
\begin{align*}
\hat{k}_4 &= \begin{bmatrix} B_{11} & B_{12} & B_{13} \\
B_{21} & B_{22} & B_{23} \\
B_{31} & B_{32} & B_{33} \end{bmatrix} \begin{bmatrix}
\hat{x}_1 \\
\hat{y}_1 \\
\hat{z}_1
\end{bmatrix} \\
B_{11} &= \cos(\phi_{1})\cos(\theta_{R3}) + 2\sin(\phi_{1})\sin(\phi_{3})\cos(\phi_{3})\sin(\theta_{R3}) \\
B_{12} &= \sin(\phi_{1})\cos(\theta_{R3}) - 2\cos(\phi_{1})\sin(\phi_{3})\cos(\phi_{3})\sin(\theta_{R3}) \\
B_{13} &= (\sin(\phi_{3}))^2\sin(\theta_{R3}) - (\cos(\phi_{3}))^2\sin(\theta_{R3}) \\
B_{21} &= 2\sin(\phi_{1})\sin(\phi_{3})\cos(\phi_{3})\cos(\theta_{R3}) - \cos(\phi_{1})\sin(\theta_{R3}) \\
B_{22} &= -2\cos(\phi_{1})\sin(\phi_{3})\cos(\phi_{3})\cos(\theta_{R3}) - \sin(\phi_{1})\sin(\theta_{R3}) \\
B_{23} &= (\sin(\phi_{3}))^2\cos(\theta_{R3}) - (\cos(\phi_{3}))^2\cos(\theta_{R3}) \\
B_{31} &= \sin(\phi_{1})\left[1 - 2[\cos(\phi_{3})]^2\right] \\
B_{32} &= \cos(\phi_{1})\left[2[\cos(\phi_{3})]^2 - 1\right] \\
B_{33} &= -2\sin(\phi_{1})\cos(\phi_{3})
\end{align*}
\]
The unit vectors for both transmitted and return signals can be written as following. It

\[ \hat{h}_t = \sin(\phi_x) \hat{x}_t - \cos(\phi_x) \hat{y}_t = -\sin(\phi_x) \hat{x}_t - \cos(\phi_x) \hat{y}_t \]

\[ \hat{h}_r = \sin(\phi_x) \left[ 1 - 2[\cos(\phi_x)]^2 \right] \hat{x}_r + \cos(\phi_x) \left[ 2[\cos(\phi_x)]^2 - 1 \right] \hat{y}_r - 2\sin(\phi_x) \cos(\phi_z) \hat{z}_r \]

has been demonstrated analytically how trihedrals do scatter cross-polarized radar returns. Cross-polarized scan configuration is useful in capturing the trihedrals while avoiding the dihedral returns from the walls. This idea will be demonstrated via numerical simulations in the subsequent section.

### 4.2.2 Radar Polarimetry for Building Simulations

![2D View](image)

**Figure 4.18:** Two-dimensional view of the target building

Let’s now consider a building geometry shown in Figure 4.18 where the exterior and interior walls have the material index of 6-j0.72 and 3.1-j0.372 respectively. The radar scan goes from 0 to 360 degrees from frequency 700MHz to 1.0GHz. The scan radius is 25m with 2.25m elevation above the ground. NEC-BSC has included scattering terms of plate reflections up to four bounces, edge diffraction and vertex diffraction for the simulations. Four different polarization setups (VV, VH, HH, and HV) are studied.
The resulting images are shown in Figure 4.19.

Figure 4.19: Polarized image formation of the target building

It can be seen from Figure 4.19 that the walls actually show up clear in the co-polarized images. In addition, the walls with horizontal polarized (HH) image appear with higher intensity, which makes the corners less observable than the vertical polarized (VV) image. In the cross-polarized images (VH and HV), only the corners show up strong. Let’s now consider the following geometry shown in Figure 4.20 where three PEC spheres with radius 0.5 m are added to the previous building geometry. The fly-by
Figure 4.20: Two-dimensional view of the target building with spheres

circular simulation again goes from frequency 700MHz to 1.0GHz at the elevation 2.25m above the ground with a scan radius of 25m. In addition to having plate reflection, edge diffraction, and corner diffraction, the sphere scattering term is also included. The resulted images for different polarizations are displayed in Figure 4.21.

Figure 4.21: Polarized image formation of target building with spheres
The sidelobe level for the co-polarized images is quite high which prevents successful detection of the interior objects. Because of the fact spheres don’t scatter much cross-pol, the returns from spheres still show up relatively weak in the cross-polarized images. The cross-polarized configuration again avoids dihedral wall return while being able to capture clearly the trihedral corners. This feature of cross-pol scan can be used as an advantage to capture smaller interior trihedrals that would normally get obscured in the co-polarized images.

4.3 **Bistatic Building Scan for Hidden Object Detection**

In this section, bistatic synthetic aperture radar scanning will be studied focusing on how it can be used to provide further target information from on through-wall radar imaging. Based on the physical phenomenology, monostatic imaging has the following characteristics. A monostatic scan is able to capture the direct backscattered field from the objects of interest. When dealing with target like buildings, the monostatic setup serves well to capture the dihedral and trihedral corner returns. In addition, monostatic data collection is more realistic and easy to operate in a typical airborne fly-by operation. However, a monostatic setup has the following limitations for through-wall radar applications. The main objective for through-wall imaging is to obtain building layout and object information behind the wall; therefore the strong broadside exterior wall return captured by the monostatic radar is not very desirable as it can increase sidelobe distortion. Furthermore, it has fewer degrees of freedom in operation because the transmitter and receiver are at the same location. Bounded by this spatial limitation, certain hidden objects may not be detectable.
In contrast, bistatic synthetic aperture radar has less spatial restriction in that the transmitter and the receiver don’t have to be in the same location. Through this extra degree of freedom in data collection, the undesirable signal return from the wall can be purposely avoided. As a result, the sidelobe distortion can be cleaned up and hopefully certain hidden objects can be detected. When considering airborne fly-by scan operation of a building, it is not feasible to have both moving transmitter and receiver. The bistatic simulations considered in this section will have a moving transmitter and a stationary receiver around the target of interest. The phase reference will be placed at the target center. Let us first consider the following near-field bistatic scan geometry of an arbitrary object as shown in Figure 4.22. If it is again under point scattering assumption, the imaging function expressed in Equation 2-21 can be modified as following in 4-12.

$$I_{nf}(\bar{r}) = \left| \int \int \int S(k, \bar{r}_S', \bar{r}_R)w(k, \bar{r}_S')e^{i k |\bar{r}_S - \bar{r}_R|}dk \, dz' \, dy' \, dx' \right|^2$$

Figure 4.22: Near-field bistatic scan of a point scattering center

Several simulations will be done in the following sections to compare monostatic imaging and bistatic imaging.
4.3.1 Monostatic vs. Bistatic Image Formation of Spherical Objects

Let us consider the following fly-by angular scan setup in Figure 4.23 consisting of three spheres in free space. The frequency of operation goes from 1.0GHz to 1.3GHz.

![Monostatic scanning](image1)

![Bistatic scanning](image2)

Figure 4.23: Monostatic vs. bistatic scan of three spheres in free space

The scan radius is 15m and the bistatic receiver is located at (-10.6m, 10.6m).

The images for both monostatic and bistatic setups are shown in Figure 4.24.

![Monostatic image (0 to 90 deg)](image3)

![Bistatic image (0 to 90 deg)](image4)

Figure 4.24: Monostatic vs. bistatic image formation of three spheres in freespace

Even though both monostatic and bistatic images have local maxima corresponding to the correct sphere locations, the bistatic image does appear to have a lot more distortions near the scattering objects. Although a bistatic scan has an extra
degree of freedom in spatial configuration, due to the fact that it has no more direct backscattered return, it is much more dependent on target size and shape. This might serves to be an explanation of why the sidelobes are higher in the bistatic images.

4.3.2 Bistatic Imaging of A Sphere with Different Antenna Placements

Consider three bistatic scan setups shown in Figure 4.25 where the receiver location varies from one to the others. The source runs a 0 to 90 degree angular scan with radius 4m while the receiver is located respectively at (2.8284, -2.8284), (0,-4), and (-3.4641,2). The resulting bistatic images for each case are shown in Figure 4.26. As shown in the figure, the image distortion around the target object is quite inevitable but as the source and receiver get closer and closer, the target becomes more and more focused due to the fact it becomes less and less target dependent.

Figure 4.25: Bistatic scan setups for different receiver locations
4.3.3 Monostatic vs. Bistatic Scan for Hidden Object Detection

Let us consider the scan geometry consisting of a hidden sphere behind the T-shaped wall as shown in Figure 4.27. The T-shaped wall is assumed to be highly attenuating with material index of 6.0-j0.72. The setup is designated for both monostatic and bistatic scans. The source goes from phi 0 to 90 degree and the bistatic receiver is located at (0,-5). The resulting images are displayed in Figure 4.28. The hidden sphere that is invisible in the monostatic image shows up very clear in the bistatic image. In this monostatic setup, the sphere is not detectable in the presence of strong corner and wall reflections whereas these undesired return signals can be avoided in the bistatic scan.
Monostatic scans in general should provide better overall images than bistatic scans. However if the sensors are set correctly, bistatic scans can do a better job than monostatic ones in highlighting certain less detectable objects. By utilizing the extra degree of spatial freedom, the undesired signals can be avoided and the desired signal can be captured.
In this chapter, we propose a modified CLEAN-like technique that will be used to improve and enhance the interior images in through-wall radar applications. The challenge of through wall sensing comes in when the exterior wall attenuates, distorts, and scatters the propagating waves while introducing unwanted sidelobes to the Fourier reconstructed images. The conventional microwave CLEAN algorithm [30] is proven to be useful in radar signal post-processing as it can remove sidelobes, reduce target break-up, and increase target dynamic range. However one drawback of it has to do with the point-scattering assumption for which the point spread function may be inadequate in accounting for the actual target downrange profiles. Here a model based CLEAN algorithm is employed to enhance the through-wall interior images with the incorporation of a multilayered slab transmission model as it can de-emphasize more properly the exterior wall interference as well as its associated sidelobes. The methodology can indeed be generalized to clean up other undesired signals by incorporating various other scattering feature models. The proposed idea is demonstrated through numerical simulations using the high frequency ray-tracing code, NEC-BSC.
5.1 Conventional CLEAN Algorithm for Microwave Imaging

The CLEAN deconvolution technique has been used in seismic exploration and radio astronomy for decades and more recently its use has been extended to microwave imaging [30]. Let $I(r_i)$ be one-dimensional downrange profile consisting of multiple point targets which can be described by a set of weighted delta functions as shown in Equation 5-1. The subscript, $i$, denotes the $i^{th}$ array scanning position. If we take the Fourier transform of Equation 5-1,

$$I(r_i) = \sum_{m=1}^{M} A_m \delta(r_i - r_m)$$  \hspace{1cm} 5-1

the output expression gives the received radiated fields as a function of wave number, $k$

$$S(k,i) = F[I(r_i)] = \sum_{m=1}^{M} A_m \exp(-jk(r_i - r_m))$$  \hspace{1cm} 5-2

It should be noted that the exponential term in 5-2 gives the phase variation of the propagating wave. In the CLEAN algorithm, the unambiguous removal of the sidelobe energy is the main objective. The algorithm proceeds first by identifying the brightest scattering center in 5-1; it then calculates the associated backscattered field and removes its contribution. The process is repeated for the next brightest scattering center and so on. The procedure is summarized in Figure 5.1. From Equation 5-1 and 5-2, the Dirac delta function and exponential function are actually a Fourier transform pair, therefore the complex amplitude can be extracted exactly in the transition between the spatial and frequency domains. However since the scattering data can only be taken for a limited frequency band, the complex amplitude for each scattering center is obscured by the sibelobes from the adjacent scattering centers; therefore the magnitude extraction
becomes more of an approximation and so one should proceed with caution. Let $S(k, i)$ be the complex signal received at the $i^{th}$ array position over the frequency band. There are $N$ number of array scanning positions and $M$ number of bright scattering centers whose contributions are there to be removed. $G$ is the signal with the brightest scattering contributions subtracted out. The analytical description of the CLEAN

$$
\text{Do } i = 1 \text{ to } N
$$

$$
G_i (i) = S_i (k, i)
$$

$$
\text{Do } m = 1 \text{ to } M
$$

$$
G_{m+1} (i) = G_m (i) - A_m \exp(-jk(r_i - r_m))
$$

$$
\text{ENDDO}
$$

$$
\text{ENDDO}
$$

Figure 5.1: Microwave CLEAN Procedure
algorithm can be summarized in Expression 5-3, and the flowchart is shown in Figure 5.1. To be more computationally efficient in practice, one can attempt to remove several spots in one try; however this runs the risk of false identification as some sidelobes can be brighter than the actual targets of interest.

5.2 Model Based CLEAN Algorithm

The conventional CLEAN algorithm does have its limitations. The procedure successively removes the brightest target points and their sidelobes by subtracting their point spread functions. However in a more realistic environment where scattering targets can’t be well approximated by a set of points, the point spread function might be inadequate for accurately remove the undesirable target contribution. A model based CLEAN algorithm based on the conventional CLEAN is developed in this section and extends its use to through-wall radar imaging. Let us replace the Dirac delta function in 5-2 by a model spread function, \( R \). Equation 5-1 and Equation 5-2 can be rewritten as the following in Equation 5-3 and Equation 5-4. The model spread function associated with each bright target should be pre-determined with a priori knowledge either analytically, computationally, or experimentally. Notice the model spread function itself, \( R \), varies for different scattering features. The complex amplitude can again be extracted

\[
I_R(r_i) = \sum_{m=1}^{M} A_m R_m(r_i - r_m) \quad 5-3
\]

\[
S_R(k,i) = F[I_R(r_i)] = \sum_{m=1}^{M} A_m F[R_m(r_i - r_m)] \quad 5-4
\]
approximately under the relatively low signal-to-sidelobe assumption between adjacent model scatterer. The CLEAN algorithm description illustrated previously can now be re-formulated using the pre-existing model spread functions as the following in 5-5.

The CLEAN algorithm can be used for image enhancement in through-wall sensing by de-emphasizing the exterior wall contribution. It should be obvious that the point spread function assumed in the conventional CLEAN algorithm is inadequate for modeling

\[
\text{Do } \quad i = 1 \text{ to } N \\
G_i(i) = S_i(k, i) \\
\text{Do } \quad m = 1 \text{ to } M \\
G_{m+1}(i) = G_m(i) - F[A_m R_m (r_i - r_m)]  \tag{5-5} \\
\text{ENDDO} \\
\text{ENDDO}
\]

wave reflection from the exterior wall with finite thickness. In order to correctly characterize the model spread function of the wall, transmission and reflection coefficients over the frequency band of interest will need to be known. Here a wave propagation model for the layered slab discussed in Section 3.1.2 will be used as the assumed model. This pre-computed model spread function will be incorporated into the algorithm in the next section to discount the wall for through-wall simulations in NEC-BSC.

5.3  Numerical Results

In this section, several through-wall radar scanning setups will be simulated in NEC-BSC and the proposed model based CLEAN algorithm will be used to de-
emphasize the exterior wall returns. Let us first consider the drive-by scan geometry shown in Figure 5.2. The blue curve in Figure 5.3 shows the downrange profile at the center position. The frequency goes from 1.0GHz to 1.3GHz.

![Figure 5.2: Through-wall scanning (Example 1)](image)

\[ \varepsilon_r = 6 - j0.72 \]

Wall thickness: 15 cm

Figure 5.2: Through-wall scanning (Example 1)

position of the scanning path. It can be seen clearly from the plot the difference between using the point spread function and the model spread function for the wall scattering. By incorporating the pre-computed slab model spread function, the contribution from the wall can be much better de-emphasized as compared to using just the point spread function.

![Figure 5.3: Point spread function vs. model spread function (Example 1)](image)

Figure 5.3: Point spread function vs. model spread function (Example 1)
Figure 5.4: Conventional CLEAN image vs. model-based CLEAN image (Ex.1)

Figure 5.4 compares the image formation between using conventional CLEAN and model-based CLEAN. The model-based CLEAN is seen doing a much better job clearing out the wall to enhance the interior object.

Let us consider now the second through-wall scanning example shown in Figure 5.5 where the sphere is now very close to the wall on the other side. Both conventional CLEAN and model-based CLEAN will again be used for comparison.
The downrange profile is again plotted in Figure 5.6. It can be seen that the target of interest is very much obscured by the wall return. A good model spread function is needed to separate the wall contribution with the target contribution.

Figure 5.7 shows the resulted images for Example 2. Model-based CLEAN again outperforms the conventional CLEAN in clearing out the image.
In the third example, model-based CLEAN algorithm will be applied to remove the associated exterior wall return for a one-story building drive-by scan whose geometry is shown in Figure 5.8. It will be demonstrated how the interior image can indeed be improved significantly through the proposed algorithm. The 15cm thick exterior walls are made of lossy concrete material with dielectric constant of 6-j0.72. The interior walls also have the same thickness but with dielectric constant of 3.1-j0.372 while the spheres are made of PEC. Operating frequency goes from 700MHz to 1GHz. Four drive-by scan cuts will be done separately and the final image will be generated by superimposing
Figure 5.8: Drive-by scanning setup of an one-story room (Example 3)

together all four cuts. The resulted image before and after model-based CLEAN are shown in Figure 5.9. It can be seen in Figure 5.9 that the image before CLEAN shows no useful information about the interior as the target signals are distorted or even totally swallowed by the sidelobes. For each drive-by scan cut, CLEAN is applied to remove the contribution from the first wall. The after CLEAN has no problem of showing the T-shaped interior walls as well as the spheres.

Modern building walls are often made of cinder block with intercrossed rebar reinforcement in which the electromagnetic propagation through this kind of wall is highly complex. However the proposed model based CLEAN technique can still be used as long as we have a reasonably accurate pre-computed model spread function which can be obtained through electromagnetic analysis, computational modeling, or even experimental measurement.
Figure 5.9  Superimposed images of an one-story room (Example 3)
CHAPTER 6

SUMMARY AND CONCLUSION

Through-wall sensing has raised a lot of attention for both military and civilian applications. A typical scenario in through-wall building scan will be either a vehicle drive-by or an aircraft fly-around. This thesis studies intensively the electromagnetic and signal processing capability to generate and improve the building interior images from the outside scan data. It has been demonstrated in Chapter 2 how both tomographic imaging and SAR imaging are actually rooted from the same reconstruction principle; the extra spatial information obtained through a set of projections in tomography can be compensated by the collected frequency information in synthetic aperture radar. A model based SAR imaging technique is introduced, which allows the use of certain analytical functions to highlight specific features in the domain of interest. Furthermore, the spatial and frequency sampling criteria are derived for use in through-wall building scans. In order to meet the Nyquist criteria, the scan radius, center frequency, and bandwidth are all important considerations. The resolution issue is also very important in complex sensing to distinguish certain close-by objects. Wide bandwidth and angle span will in general increase the resolution, but the choice is not so straightforward for operating center frequency. As expected, a high center frequency will increase the crossrange
resolution but the sampling requirement is higher; the transmission and reflection characteristics are also different for different frequencies, and attenuation tends to increase with frequency.

In Chapter 3, the high frequency analytical coefficients for reflection, transmission, and diffraction commonly encountered in building scattering is presented. In addition, the simulation code NEC-BSC is presented and validated with the small scaled building radar measurement done in the compact range of the ElectroScience Laboratory. The resulting images agree very well with the measured images. NEC-BSC demonstrates its validity in predicting the important building features as well as the changes subjected to electromagnetic variation.

In Chapter 4, a feature identification technique is proposed which utilizes smartly the oblique and broadside scan data to look for certain features and orientations. It’s been demonstrated in the simulation examples that the proposed technique can indeed remove a lot of ambiguities seen in the original image.

Polarization is used as another parameter for interior object detection. It has been shown through analysis and simulations that cross-polarized radar configurations do avoid strong dihedral wall returns while preserving the important trihedral features. As demonstrated in the numerical examples, the cross-polarized images capture clearly the building trihedrals free from the wall interference. In addition, bistatic radar scans are set up intelligently to avoid certain radar returns and detect hidden objects that can’t be captured by the monostatic configuration.

One of the biggest challenges in through-wall radar sensing is the wall itself. The radar signal can be attenuated and distorted as it passes through the walls. In addition,
the walls can introduce sidelobes that will interfere with the target objects and increase the possibility of false identification. In chapter 5, the CLEAN algorithm is employed to remove building wall effects. The conventional CLEAN algorithm assumes point scattering model and essentially subtracts out the point spread functions associated with the brightest points in the image. Here a model based CLEAN algorithm employs analytical model spread functions to de-emphasize the wall return more properly. The CLEAN technique has been applied to the building scan simulations to demonstrate how the interior image quality can actually be improved.

There are several extensions to this current research work for the future. First, a better wall modeling tool will be in demand since a lot of modern buildings are made with periodic structures such as cinder blocks. When the frequency is high, the periodic structure will have higher order Floquet modes which will need to be accounted for in the wall model [28]. In addition, more advanced feature extraction methods will be studied and developed to extract and estimate the interior layout of multi-story complex buildings.
BIBLIOGRAPHY


97


diffraction of electromagnetic waves by a smooth convex surface,” IEEE Trans.


[37] W. D. Burnside and K. W. Burgener, “High frequency scattering by a thin lossless

shaped material shell,” M.S. Thesis, The Ohio State University, Columbus, 1997.

compact range chambers,” Ph.D. dissertation, The Ohio State University, Columbus,


and corner diffraction scattering from flat plate surfaces,” IEEE Trans. Antenna and


[43] J. A. Marble and A. O. Hero, “Phase distortion correction for see-through-the-wall
imaging radar ,” IEEE International Conference on Image Processing, October 2006

radar,” 17th International Symposium on Antennas, Propagation & EM Theory,
October 2006

of objects behind obscuring random layers,” Waves In Random and Complex Media,
vol. 00, no. 00. September 2005, 1-15

99