NONDESTRUCTIVE EVALUATION OF CONCRETE USING WIDEBAND MICROWAVE TECHNIQUES

by

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Abstract

Demand for the development of reliable nondestructive evaluation (NDE) techniques for structural systems is ever increasing with a growing concern about the deteriorating condition of infrastructure worldwide. Effective nondestructive evaluation techniques are needed in order to accurately assess the condition of existing structures prior to any replacement or rehabilitation action. The research work presented focuses on the study of microwave techniques for nondestructive evaluation of concrete using a wideband imaging radar. Both the theoretical and the experimental aspects of the method are studied.

The research work includes i) establishment of a data base for electromagnetic properties of concrete as a function of frequency, moisture level, and density over a wide frequency range from 100 MHz to 20 GHz using an open-ended coaxial probe method, ii) computer simulation of radar measurements through numerical modeling of wave propagation and scattering through and by various concrete targets using a finite difference-time domain (FD-TD) method, and iii) radar measurements of laboratory size concrete specimens with various inside configurations using a wideband inverse synthetic aperture radar (ISAR). Signal processing algorithms are implemented to obtain imagery of concrete targets from radar measurements and numerical modeling.

A parametric study has been performed to identify optimum combination of measurement parameters to be used in solving real problems using a radar. The measurement parameters investigated includes center frequency, frequency bandwidth, incident angle, and polarization of incident waves, and geometric and material (electromagnetic) properties of concrete targets. As results, for the concrete specimens and measurement setup used in this study, 2 ~ 3.4 GHz waveforms are found to be good for concrete thickness measurement, 3.4 ~ 5.8 GHz waveforms for monitoring of condition change inside concrete, and 8 ~ 12 GHz waveforms for detection of inclusions embedded inside concrete. Appropriate use of polarization of the wave can improve the detectability of inclusions with respect to their orientation. For the specimens studied, transmitting waves at an oblique incident angle did not improve the detectability of inclusions due to the increased edge effect. The effects of other measurement parameters are quantitatively determined.

Thesis Supervisor: Dr. Oral Büyüköztürk
Title: Professor of Civil and Environmental Engineering
Dedicated to

My dear wife Jae Hyo

and my parents
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Notation

(Vectors are indicated by upper score - for example, $\vec{B}$)

1 in. = 1" = 25.4 mm
1 ft. = 1' = 12" = 304.8 mm

$B = \text{bandwidth (GHz)}$

$\vec{B} = \text{magnetic flux density (webers/m}^2, \text{ teslas)}$

$c = \text{velocity of light in free space} = 3 \times 10^8 \text{ m/sec}$

$\vec{D} = \text{electric flux density (coulombs/m}^2)$

decibel, $\text{dB} = 10 \log_{10} \left( \frac{\text{Power}_2}{\text{Power}_1} \right)$

$\text{dBm} = \text{a decibel relative to 1 milliwatt}$

$\text{dBsm} = \text{a decibel relative to 1 square meter of radar cross section}$

$\vec{E} = \text{electric field strength (volts/m)}$

$\varepsilon^* = \text{complex permittivity}$

$\varepsilon' = \text{the real part of complex permittivity}$

$\varepsilon'' = \text{the imaginary part of complex permittivity}$

$\varepsilon_0 = \text{permittivity of air} = 8.854 \times 10^{-12} \text{ Farad/m}$

$\varepsilon_r = \text{relative permittivity to air = dielectric constant}$

$f = \text{oscillation frequency (Hz)}$

$\text{gigahertz, GHz} = 10^9 \text{ Hz} = 10^9 \text{ cycles/sec}$

$\vec{H} = \text{magnetic field strength (amperes/m)}$

$j = \sqrt{-1}$

$k^* = \text{complex wavenumber in lossy media}$

$k' = \text{the real part of complex wavenumber}$

$k'' = \text{the imaginary part of complex wavenumber}$

$\text{megahertz, MHz} = 10^6 \text{ Hz} = 10^6 \text{ cycles/sec}$
\( m = \text{meter} \)
\( \mu^* = \text{complex permeability} \)
\( \mu' = \text{the real part of complex permeability} \)
\( \mu'' = \text{the imaginary part of complex permeability} \)
\( \mu_0 = \text{permeability of air} = 4\pi \times 10^{-7} \text{Henry/m} \)
\( \text{nano second, ns} = 10^{-9} \text{sec} \)
\( \text{power ratio} = 10^{dB/10} \)
\( \text{sec} = \text{second} \)
\( \sigma = \text{radar cross section (dBsm)} \)
\( \sigma_e = \text{electric conductivity (mhos/m)} \)
\( \tan \delta = \text{loss tangent} = \frac{\varepsilon''}{\varepsilon'} \)
\( \tau = \text{pulsewidth (ns)} \)
\( \omega = \text{angular frequency (rad/sec)} \)
Chapter 1

Introduction

Structures deteriorate over time. The deterioration process can be either slow over the service life of a structure or can be sudden as damage done by earthquake. In either case, proper inspection and evaluation is an absolute necessity prior to rehabilitation, retrofit, maintenance, repair, or replacement. With a growing number of aging infrastructure worldwide, there is an increasing need to develop reliable nondestructive evaluation (NDE) techniques for constructed facilities. In this research work, efforts have been focused on the development of an NDE technique for concrete systems using a wideband radar at microwave frequencies.

In Chapter 1, the deterioration mechanism of concrete systems and the review of currently available NDE techniques are provided as background. The objectives of the research and research approach taken are outlined.

1.1 Background

1.1.1 Deterioration Mechanisms of Concrete

Deterioration in concrete severely affects the service lives, safety, and maintenance costs of concrete structures. Cracking in concrete is one of the major contributing factors to the deterioration of concrete. In concrete, cracking due to shrinkage occurs even before the structure is subjected to any external loading. Excessive water-cement ratio, improper curing, high temperature during hardening process may result in shrinkage which is the direct cause of cracking. This is especially critical for large concrete structures such as dams due to the placement of massive concrete during construction. Those cracks, which exist in concrete at early stages, later expand and widen during service conditions. Contributing to the crack propagation, after hardening, is the intrusion of moisture. The deterioration is further accelerated by freeze and thaw cycles and hydraulic fracture due to the presence of water.

Another major cause of cracking in concrete is due to excessive tensile stresses that arise from corrosion of steel reinforcement. A widely accepted explanation for this is that infiltration of saline water through pores and hairline cracks destroys the thin protective
iron-oxide layer on the surface of the steel bars. The electric potential of the reinforcing steel changes, as anodic-cathodic cells form due to variations in chloride concentration along the bars, and the anodic areas begin to rust. Rust approximately doubles the volume of the original steel and applies pressure to the surrounding material, several times the tensile strength of concrete. As a result, concrete fractures. Deterioration mechanisms in concrete systems also include failure of interfaces between the concrete and other materials.

1.1.2 Need for Nondestructive Evaluation (NDE)

Demand for the development of reliable NDE techniques for concrete structures is ever increasing with the growing concern about the deteriorating condition of the nation's infrastructure [Chong, Scalzi, and Dillon, 1990]. Effective NDE techniques are needed in order to accurately assess the condition of existing concrete structures prior to any replacement or rehabilitation actions to be taken.

For example, there are more than 578,000 highway bridges in the United States and more than 40 percent of them are structurally deficient or functionally obsolete [FHWA, 1990]. These conditions limit bridge utility, and, if they are not properly monitored and maintained, can pose a threat to the bridge users safety. The bridge deck and its wearing surface are the most vulnerable parts of a bridge to damage from routine service. The deck has a shorter average service life (35 years) than the bridge itself (68 years), and they are particularly well suited for NDE inspection using a vehicle mounted inspection system.

The other example is 1989 Loma Prieta Earthquake in San Francisco. Due to the earthquake, both commercial and residential buildings as well as highway bridges were suddenly damaged. Rapid and reliable inspection of numerous building structures was needed in order to allow occupants to return to their buildings or to use highways. However, a visual or destructive method was the only available means to examine the possibly damaged structures, which would have been much faster and easier if there was a reliable NDE technique available.

The objective of nondestructive inspection for concrete systems is to detect incipient delamination, to determine the extent of damage, or to determine the exact location of steel reinforcing bars and other embedded objects, prior to carrying out appropriate maintenance and repair operations in a timely and effective way.
1.1.3 Overview of Nondestructive Evaluation Techniques

A brief review of currently available nondestructive evaluation methods for concrete is given here to examine their principles, applications, advantages, and limitations. Unlike in the inspection of metals and metal-based materials, the use of nondestructive testing in the inspection of concrete is relatively new. There are two categories of NDE methods for concrete. The first category includes the methods to estimate strength. The surface hardness, penetration, pullout, breakoff, and maturity techniques belong to this category. These methods are compared to the typical destructive testing method of core drilling. The second type includes stress wave, radar, infrared thermography, and x-ray techniques which are to measure moisture content, density, thickness, and dynamic elastic modulus, and to locate delaminations, voids, cracks, and steel reinforcing bars in concrete. Detailed discussion of NDE methods for concrete can be found in the references [Malhotra and Carino, 1991; ACI, 1993].

The stress wave methods include techniques of pulse-echo, impact-echo, ultrasonic, acoustic emission, and spectral analysis of surface waves (SASW). The methods differ in the source of the stress waves, the testing configuration, instrumentation, the characteristics of the measured response, and the signal processing techniques that are used [Sansalone and Carino, 1991]. In principle, the stress wave methods are based on elastic wave propagation in solids. When a stress is applied suddenly to a solid, the disturbance which is generated travels through the solid as stress waves. There are three primary modes of stress wave propagation through isotropic, elastic media: dilatational, distortional, and Rayleigh waves. The three modes are commonly referred to as compression (P-), shear (S-), and surface (R-) waves. The propagation of the waves depend on the dynamic Young's modulus, Poisson's ratio, and density of concrete. By measuring the time of flight, amplitude, and frequency content of the waves, presence of defects or interfaces are indicated. The echo methods (pulse-echo, impact-echo, and ultrasonic) are being used for thickness measurements, flaw detection and integrity testing of piles. The acoustic emission method is used to monitor structure to detect impending failure. The SASW method is being used to determine the thickness of pavements and elastic moduli of layered pavement systems. In this category, the equipments used are relatively inexpensive and portable. Concrete strength can be estimated by correlating compressive strength of cores and wave velocity. Disadvantages include difficulties in the interpretation of results, existence of several paths through the same component or specimen [Hillger, 1987], and required intimate contact between the test equipment and the
object under testing. The methods also suffer from the limitations that sounding becomes less reliable as the depth of delaminations increases or when asphalt overlays are present.

Radar is the electromagnetic analog of sonic and ultrasonic stress wave methods. It is governed by the processes involved in the propagation of electromagnetic energy through materials of different dielectric constants [Clemeña, 1991]. The principle of the radar method is to generate and transmit electromagnetic impulse signals into a concrete element. Reflection of the pulse from the material is monitored and interpreted to detect voids and delaminations. The radar has been applied for quality assessment, detection of substratum voids, delaminations, and embedments, and measurement of thickness of concrete pavements. Advantages of the method include remote sensing capability without contacting the object under testing, measurement at high speed, sensitivity to metallic steel reinforcing bars, and flexibility in adjusting resolution and penetration depth. The limitations are due to expensive equipment and measurement procedure still under development [ACI, 1993].

The method of infrared thermography is based on the principle that a delamination introduces an air gap in the slab, acting as an insulator and restricting heat flow into or out of slab. The variations of the surface temperature, resulting from the changes in heat transfer characteristics, are then interpreted to detect delaminations in the slab. The drawback with this method is that data interpretation is complicated by varying weather conditions and surface temperature variations related to the surface properties. The method, presently, is limited to weather conditions with bright sunshine and is in the development phase [de Vekey, 1990].

In x-ray transmission radiography, a beam of radiation passes through the component and exposes a film in a light-tight packet. The method is completely analogous to medical x-ray methods and has the advantage of producing output of photograph that is easily interpreted. It is useful for locating and sizing of voids and reinforcement, however, limitations are imposed by the requirement to access both sides of the object, the necessity for long exposure times, and the demand for safety precautions required to protect both the operators and the public [Malhotra, 1976].

1.1.4 The Radar Method

Up to the present, the radar method has been applied generally to NDE of bridge decks and pavements in the infrastructure [Chung et al., 1992; Halabe et al., 1989; Maser and Roddis, 1990]. However, the technology is still premature for the radar method to be used for massive concrete structures such as large dams or for the structural elements of concrete systems such as beams, columns, slabs, and walls. Probing of various elements of
concrete systems requires a high performance radar system and more sophisticated problem solving approaches than those for the bridge decks and pavements. The radar method is shown to have a potential of being an effective and practical tool for NDE of the structural elements of concrete structures [Büyüköztürk et al., 1993; Bungey et al., 1993]. The success of the radar method as an NDE technique for concrete structures depends on the development of proper hardware and software systems which are suitable for concrete. It is also essential to understand concrete as a material with electromagnetic properties.

Examples of the hardware requirements include the capability of transmitting radar signals i) over a wideband of frequencies for good resolution and adequate penetration depth, ii) with different polarizations to be sensitive to the orientation and backscatter characteristics of the objects, and iii) at multiple angles to maximize the cross range resolution and to provide imagery at different aspect angles for multi-look processing. Software requirements include implementation of appropriate signal processing techniques that can construct high resolution images of objects embedded in lossy dielectric media, such as concrete. Imaging of buried targets is restricted by the large attenuation rate of electromagnetic waves propagating in a highly conducting medium. The ability to detect low level scattering objects in concrete, such as steel reinforcing bars (rebars) and delaminations requires very sensitive detection algorithms.

The electromagnetic properties of concrete affect various aspects of radar measurements by determining the velocity and wavelength of the electromagnetic wave inside concrete, and the amount of reflection from concrete. The properties also determine the attenuation of the wave as it propagates through concrete, which gives the penetration depth of the wave in concrete. Accurate measurements and proper use of electromagnetic properties of concrete can provide valuable information for constructing an effective radar imaging system.

1.2 Objectives of the Research

The general objective of the research performed in this research is to develop both the theoretical and the experimental bases of the microwave technique as an NDE of concrete systems. Specifically, the purpose of this research work was to develop a methodology to investigate a radar method as a tool for NDE of concrete system in a systematic way so that suggestions could be made to solve real problems using the radar. The overall research consists of the following tasks:

I. Development of a data base for electromagnetic properties of concrete,
II. Radar measurements of laboratory size concrete specimens with inclusions such
delaminations and steel bars embedded inside,
III. Computer simulation through numerical modeling of wave propagation and
scattering through and by various concrete targets, and
IV. Implementation of signal processing techniques to generate one- and two-
dimensional images of the specimens.
It is expected that the results of this work will form a basis for further advancement of
microwave techniques and the development of effective hardware systems for civil
engineering applications.

1.3 Research Approach

Use of the radar method for NDE of concrete systems requires understanding of
fundamentals derived from disciplines of electrical engineering, computer science,
mathematics, physics, and radar technology. The research work is motivated by the need
for the development of NDE techniques for civil engineering applications and based on the
theories from the electromagnetism and advanced radar technology in addition to the
knowledge developed for concrete technology from civil engineering background.

Figure 1-1 shows the research approach taken for this work. The research work is
divided into three major areas. The establishment of electromagnetic properties of concrete
provides the understanding of the characteristics of concrete in its interaction with
electromagnetic waves. The data base of the electromagnetic properties of concrete is used
for the numerical modeling, radar measurements, and imaging. Actual radar measurements
are conducted on laboratory size concrete specimens to explore response of concrete
specimens to incoming radar waves. Numerical modeling results are used to simulate radar
measurements.

1.4 Thesis Organization

The organization of the thesis is as follows:

Chapter 1 provides the general background and the motivation for this work. The
objectives of the research and the organization are presented.

Chapter 2 reviews the principles of the electromagnetic wave theory and the basics
and terminology of a radar system. Fundamentals of the signal processing scheme is also
given.
Chapter 3 describes the experimental work performed in the establishment of a data base for the electromagnetic properties of concrete as a function of frequency, moisture level, and density. Significance of those properties in the nondestructive evaluation is discussed.

Chapter 4 presents the finite difference-time domain (FD-TD) method used for the numerical modeling of wave scattering and propagation and the results of the modeling for various concrete specimens. Chapter 4 provides a description about signal processing schemes implemented for computer simulation of wideband radar measurements. Simulation results with a variation of measurement parameters are given.

Chapter 5 describes the inverse synthetic aperture radar (ISAR) measurement method and the results of the ISAR measurements of laboratory size concrete specimens with various inside configurations. Chapter 5 presents the analysis and discussion with three cases for applications identified: concrete thickness measurement, monitoring of concrete deterioration, and detection of inclusions involving steel reinforcing bars.

Chapter 6 summarizes the research work performed and presents conclusions.

In the Appendices, radar measurement results are provided followed by brief descriptions of computer programs implemented.
Chapter 2
Principles of the Radar Method

In this chapter, fundamental and theoretical aspects of the radar method is discussed, and definitions and terminologies are given. First, the basics of electromagnetic (EM) wave theory are described. Maxwell’s equations and constitutive equations are introduced. Second, the fundamental features of a radar system are discussed for its use in nondestructive evaluation. Third, mathematics of signal processing schemes is outlined. Throughout the chapter, emphasis is placed on microwaves with respect to their use in NDE.

2.1 Electromagnetic Wave Theory

2.1.1 Fundamentals

The term *microwave* is used to define all electromagnetic radiation waves whose frequencies lie between 0.3 and 300 gigahertz (GHz) [McIntire, 1986]. These frequencies correspond to a range of free-space wavelengths in vacuum from one meter to one millimeter, respectively. In vacuum or air, microwaves travel at the velocity of light, \( c \).

\[
c = 2.997 \times 10^8 \text{ m/sec}
\]  \hspace{1cm} (2-1)

The known spectrum of electromagnetic waves covers a wide range of frequencies. As seen in Figure 2-1, microwaves occupy that portion of the electromagnetic spectrum between radio waves and infrared radiation. Microwaves are commonly used for communications, radio and television signals, radar (radio detecting and ranging), microwave ovens, and to a much lesser degree, nondestructive testing.

The microwave frequency range is subdivided into bands, which are designated with letters. The designations from the Institute of Electrical and Electronics Engineers (IEEE) Standard 521-1976 are shown in Table 2-1.
Figure 2-1. Electromagnetic spectrum wavelengths and frequencies; microwaves are located between infrared and radio waves [McIntire, 1986, p. 463].

Table 2-1. Radar frequency band designations.

<table>
<thead>
<tr>
<th>Band Designation</th>
<th>Frequency Range (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>3-30</td>
</tr>
<tr>
<td>VHF</td>
<td>30-300</td>
</tr>
<tr>
<td>UHF</td>
<td>300-1,000</td>
</tr>
<tr>
<td>L</td>
<td>1,000-2,000</td>
</tr>
<tr>
<td>S</td>
<td>2,000-4,000</td>
</tr>
<tr>
<td>C</td>
<td>4,000-8,000</td>
</tr>
<tr>
<td>X</td>
<td>8,000-12,000</td>
</tr>
<tr>
<td>K_u</td>
<td>12,000-18,000</td>
</tr>
<tr>
<td>K</td>
<td>18,000-27,000</td>
</tr>
<tr>
<td>K_a</td>
<td>27,000-40,000</td>
</tr>
<tr>
<td>millimeter</td>
<td>40,000-300,000</td>
</tr>
</tbody>
</table>

The electromagnetic waves emitted by radars are harmonic in time. The large class of physical quantities that vary periodically with time are called time-harmonic. The electric and magnetic field strengths of an electromagnetic (EM) wave vary sinusoidally with time \( t \) and distance; if the frequency of the source is denoted \( f \), they have the forms

\[
E_x = E_0 \cos(\omega t - kR)
\]  

(2-2)
\[ H_y = H_0 \cos(\omega t - kR) \]  \hspace{1cm} (2-3)

where \( E_x \) = electric field in volts per meter, \( H_y \) = magnetic field in amperes per meter, \( E_0 \) = maximum amplitude of the electric field, \( H_0 \) = maximum amplitude of the magnetic field, \( \omega = 2\pi f \) = the angular frequency of the wave, \( k = 2\pi / \lambda \) = the wave number of the wave, \( \lambda \) = the wavelength of the wave, and \( R \) = distance measured from some origin. Thus, the dependence on time and space is explicit. Although there is nothing imaginary about an EM wave, it is mathematically convenient to use a complex representation, such as

\[ E_x = E_0 e^{j(\omega t - kR)} \]  \hspace{1cm} (2-4)

\[ H_y = H_0 e^{j(\omega t - kR)} \]  \hspace{1cm} (2-5)

where \( j = \sqrt{-1} \). The representation in Eq. (2-2) and Eq. (2-3) are the real parts of Eq. (2-4) and Eq. (2-5). The negative sign of the second term in the exponents of Eq. (2-4) and Eq. (2-5) is interpreted as a positive phase angle.

The electric and magnetic fields of an EM wave are at right angles to each other and to the direction of propagation, as shown in Figure 2-2. The fields are vector quantities having direction as well as intensity.

Figure 2-2. A "snapshot" of the electric and magnetic field intensities at a particular moment in time [Eaves and Reedy, 1987, p. 33].
The ratio of transverse electric to transverse magnetic field strength is an impedance that is characteristic of the medium in which the wave is propagating. For free space, this ratio is about 377 ohms.

2.1.2 Maxwell's Equations and Constitutive Relationships

In the study of electromagnetics, four vector quantities of electromagnetic fields are concerned:

\[
\begin{align*}
\vec{E} &= \text{electric field strength (volts/meter)} \\
\vec{D} &= \text{electric flux density (coulombs/meter}^2) \\
\vec{H} &= \text{magnetic field strength (amperes/meter)} \\
\vec{B} &= \text{magnetic flux density (webers/meter}^2 \text{ or teslas)}
\end{align*}
\]

These are vectors, and they are functions of space and time. The fundamental theory of electromagnetic fields is based on Maxwell's equations. These equations govern the electromagnetic fields \(\vec{E}, \vec{D}, \vec{H},\) and \(\vec{B}\):

Faraday's Law of Induction
\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{2-6}
\]

Generalized Ampere's Law
\[
\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \tag{2-7}
\]

Gauss' Magnetic Field Law
\[
\nabla \cdot \vec{B} = 0 \tag{2-8}
\]

Gauss' Electric Field Law
\[
\nabla \cdot \vec{D} = \rho_v \tag{2-9}
\]

where \(\vec{J}\) = electric current density (amperes/meter\(^2\))
\[\rho_v = \text{electric charge density (coulombs/meter}^3)\]

For a number of scalar equations in Maxwell's equations, there are three scalar equations for each curl equation Eq. (2-6) and Eq. (2-7), and one for each divergence equation Eq. (2-8) and Eq. (2-9). However, the divergence equations are derivable from the curl equations [Shen and Kong, 1987]. Thus, there are a total of six independent equations.
For a number of independent scalar-field variables in Maxwell's equations, there are 12 unknowns, one for each component of $\overline{E}$, $\overline{D}$, $\overline{H}$, and $\overline{B}$ in $x$, $y$, and $z$, for example, $E_x$, $E_y$, and $E_z$ for $\overline{E}$. Therefore, the six independent equations from the set of Maxwell's equations is not sufficient to solve for the 12 unknowns. Six more equations are needed, called the constitutive relations.

Physically, the constitutive relations provide information about the environment in which electromagnetic fields occur - for example, free space, water, or plasma media. Mathematically, a simple medium can be characterized as follows with a permittivity $\varepsilon$ and a permeability $\mu$:

$$\overline{D} = \varepsilon \overline{E}$$

$$\overline{B} = \mu \overline{H}$$

Eq. (2-10) and Eq. (2-11) are the constitutive relations for the simple medium. There are three independent equations obtained from Eq. (2-10) and the other three independent equations obtained from Eq. (2-11). For free space, $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m, and $\varepsilon = \varepsilon_0 = 8.85 \times 10^{-12}$ F/m. In general, $\varepsilon$ and $\mu$ can be functions of many parameters. When $\varepsilon$ or $\mu$ is a function of the frequency, the medium is called dispersive.

2.2 Radar

2.2.1 Basics of Radar

The acronym radar was coined during World War II. It stands for "radio detecting and ranging." Radar was initially developed to replace visual target detection for several reasons. Radio waves suffer much less attenuation through the atmosphere than light waves, and signals in the lower frequency ranges actually propagate over the visible horizon. This makes it possible to detect targets long before they are visible optically. Radars also work well at night when there is little or no ambient light to illuminate the target.

There are four basic elements in any functional radar: a transmitter, an antenna, a receiver, and an indicator. The basic configuration is illustrated in Figure 2-3. The transmitter generates a desired radio frequency (RF) waveform at some required power level. The waveform generated by the transmitter is determined by the particular
requirements of the system and can range from an unmodulated continuous wave (CW) to a complex frequency, phase, and time code modulated wave for advanced radars. The basic function of the radar antenna is to couple RF energy from the radar transmission line into the propagation medium and vice versa. The antenna also provides beam directivity and gain for both transmission and reception of the EM energy. The gain is a measure of the ability to concentrate in a particular direction the power accepted by the antenna. The receiver accepts weak target signals, amplify them to a usable level, and translate the information contained therein from RF to baseband. The indicator conveys target information to the user. Various types of radar systems are presented and discussed by Eaves and Reedy [1987].

![Diagram of a radar system](image)

Figure 2-3. Radar principle and basic system elements [Eaves and Reedy, 1987, p. 2].

### 2.2.2 Center Frequency, Bandwidth, and Pulse width

The waveforms generated by a radar has a pulse width $\tau$, in time and a bandwidth $B$, in frequency. The achievable pulse width is related to the swept bandwidth by [Cook and Bernfeld, 1967]:

$$\tau = \frac{1}{(f_2 - f_1)} = \frac{1}{B} \quad (2-12)$$

where $f_1$ is starting and $f_2$ is ending frequency, respectively. Center frequency $f_c$, is defined as:
\[ f_c = f_1 + \frac{B}{2} \]  

Figure 2-4 illustrates a waveform with bandwidth and pulse width specified.

![Waveform Diagram](image)

Figure 2-4. A frequency modulated pulse.

### 2.2.3 Range and Cross-range Resolutions

Range and cross range resolutions achievable by an inverse synthetic aperture radar (ISAR) are determined by:

\[ \rho_r = \frac{c}{2B} \]  

\[ \rho_{sr} = \frac{\lambda_c}{2(\Delta \theta_{rad})} \]
where $\rho_r$ is range resolution, $\rho_{xr}$ is cross range resolution, $\lambda_c$ is the wavelength of center frequency, and $\Delta \theta_{rad}$ is the angular rotation of a target in radian during measurement. The resolutions in Eq. (2-14) and Eq. (2-15) are for air. Resolution for concrete is affected by the dielectric constant of concrete as:

$$\rho_r = \left( \frac{c}{\sqrt{\varepsilon_r}} \right) \frac{1}{2B} \text{ in concrete}$$  \hspace{1cm} (2-16)$$

$$\rho_{xr} = \left( \frac{c}{f_c \sqrt{\varepsilon_r}} \right) \frac{1}{2(\Delta \theta_{rad})} \text{ in concrete}$$  \hspace{1cm} (2-17)$$

### 2.2.4 Polarization

The term polarization refers to the direction of the electric field and how it changes with respect to time. Figure 2-5 is a sketch illustrating linear, elliptical, and circular polarization. As shown in Figure 2-5a, a linearly polarized electromagnetic wave has its electric field oriented at all times in the same direction (along the y axis in Figure 2-5). The direction of wave propagation is the z-direction in the figure. Polarization can play an important role in microwave NDE tests of anisotropic test materials whose properties or configuration vary as a function of direction.

![Diagram of polarization](image)

**Figure 2-5.** Linear, elliptical, and circular polarization of microwaves [McIntire, 1986, p. 467].
2.2.5 Decibel (dB)

The decibel (dB) is a logarithmic unit devised to express power ratios. Being logarithmic, it greatly compresses the numbers needed to express values having a wide dynamic range.

\[
Power \ ratio \ in \ dB = 10 \log_{10} \left( \frac{Power_2}{Power_1} \right) \tag{2-18}
\]

Positive decibels correspond to ratios > 1; zero decibels to a ratio of 1; negative decibels, to ratios < 1. Table 2-2 shows power ratios to selected dB values.

Table 2-2. Equivalent Ratios.

<table>
<thead>
<tr>
<th>Power Ratio</th>
<th>dB</th>
<th>Power Ratio</th>
<th>dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>-30</td>
<td>3.2</td>
<td>5</td>
</tr>
<tr>
<td>0.01</td>
<td>-20</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>0.1</td>
<td>-10</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>6.3</td>
<td>8</td>
</tr>
<tr>
<td>1.26</td>
<td>1</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>1.6</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>2.5</td>
<td>4</td>
<td>1000</td>
<td>30</td>
</tr>
</tbody>
</table>

where \( \text{power ratio} = \frac{P_2}{P_1} \).

To convert from decibels to a power ratio, divide the number of decibels by 10 to get the power of 10; then, raise 10 to that power to get the power ratio.

\[
power \ ratio = 10^{\frac{dB}{10}} \tag{2-19}
\]

Another common reference unit is 1 milliwatt. A decibel relative to 1 milliwatt is called a dBm. The dBm is widely used for expressing small signal powers, such as powers of radar echoes.
2.2.6 Radar Cross Section (RCS)

Radar cross section (RCS) is a measure of the power that is returned or scattered in a given direction, normalized with respect to the power density of the incident field. This scattered power is further normalized so that the decay due to spherical spreading of the scattered wave is not a factor in computing the RCS, \( \sigma \). The purpose of this normalization is to remove the effect of the range, \( R \), and thereby arrive at a signature description that is independent of the distance between the target and radar. Formally, the radar cross section is

\[
\sigma = 4\pi \lim_{R \to \infty} R^2 \frac{\left| \vec{E}^s \right|^2}{\left| \vec{E}^i \right|^2} = 4\pi \lim_{R \to \infty} R^2 \frac{\left| \vec{H}^s \right|^2}{\left| \vec{H}^i \right|^2}
\]  

(2-20)

where \( \vec{E}^s \), \( \vec{H}^s \) are the scattered electric and magnetic fields, respectively, and \( \vec{E}^i \), \( \vec{H}^i \) are the incident fields [Knott et al, 1985].

Radar cross section is usually given in square meters and is often expressed in logarithmic form as dB relative to a square meter,

\[
\sigma_{dBsm} = 10 \log_{10} \sigma
\]  

(2-21)

where the reference is one square meter. A decibel relative to 1 square meter of radar cross section is called a dBsm.

2.2.7 Near and Far Fields

The shape of the antenna pattern in general varies with distance \( R \) from the antenna. The pattern shape over a sphere of constant radius is independent of \( R \) if \( R \) is large enough. The pattern variation with \( R \) can be quantified using \( D \), the diameter of the smallest sphere that completely contains the antenna (usually \( D \) is the diameter of the antenna) [Eaves and Reedy, 1987]. Although the boundary is somewhat arbitrary, the usually accepted criterion is that the pattern is independent of range when

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

(2-22)
where $\lambda$ is the shortest wavelength of the transmitted wave. Values of $R$ larger than this value are said to be in the far field or Fraunhofer region of the antenna. Smaller values of $R$ are said to be in the near field or Fresnel region of the antenna, in which case the pattern shape changes with distance. The pattern varies more rapidly with the distance as $R$ gets smaller. The thesis work considers only the far field of the antenna.

The far field criterion also can be used for a target where $D$ is the maximum dimension of the target and $\lambda$ is the shortest wavelength of the wave [Knott et al, 1985]. The criterion requires that the phase of the incident wave at the center of the target is different from the phase at the extremes of the target less than $\pi/8$ radians (22.5°). This limiting process essentially requires that the target be illuminated by a nearly plane wave.

### 2.3 Signal Processing

#### 2.3.1 Fourier Transform

A very large class of important computational problems falls under the general rubric of "Fourier transform methods." A physical process can be described in the time domain, by the values of some quantity $h$ as a function of time $t$, e.g. $h(t)$, or else in the frequency domain, where the process is specified by giving its amplitude $H$ (generally a complex number indicating phase also) as a function of frequency $f$, that $H(f)$, with $-\infty < f < \infty$. For many purposes it is useful to think of $h(t)$ and $H(f)$ as being two different representations of the same function. One goes back and forth between these two representations by means of the Fourier transform equations,

\[
H(f) = \int_{-\infty}^{\infty} h(t)e^{2\pi jft} \, dt \tag{2-23}
\]

\[
h(t) = \int_{-\infty}^{\infty} H(f)e^{-2\pi jft} \, df \tag{2-24}
\]

If $t$ is measured in seconds, then $f$ in Eq. (2-23) and Eq. (2-24) is in cycles per second, or Hertz (the unit of frequency). Using angular frequency $\omega$, which is given in radians per sec. The relation between $\omega$ and $f$, $H(\omega)$ and $H(f)$ is

\[
\omega \equiv 2\pi f, \quad H(\omega) \equiv [H(f)]_{f = \omega/2\pi} \tag{2-25}
\]
and Eq. (2-23) and Eq. (2-24) look like these

\[ H(\omega) = \int_{-\infty}^{\infty} h(t) e^{j\omega t} dt \]  \hspace{1cm} (2-26)

\[ h(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} H(\omega) e^{-j\omega t} d\omega \]  \hspace{1cm} (2-27)

### 2.3.2 Discrete Fourier Transform

The Fourier transform of a function from a finite number of its sampled points is now estimated. Suppose that there are \( N \) consecutive sampled values

\[ h_k \equiv h(t_k), \quad t_k \equiv k\Delta, \quad k = 0, 1, 2, ..., N - 1 \]  \hspace{1cm} (2-28)

so that the sampling interval is \( \Delta \). To make things simpler, it is supposed that \( N \) is even. If the function \( h(t) \) is non zero only in a finite interval of time, then that whole interval of time is supposed to be contained in the range of the \( N \) points given. Alternatively, if the function \( h(t) \) goes on forever, then the sampled points are supposed to be at least "typical" of what \( h(t) \) looks like at all other times.

With \( N \) numbers of input, no more than \( N \) independent numbers of output can be produced. So, instead of trying to estimate the Fourier transform \( H(f) \) at all values of \( f \) in the range \(-f_c\) to \( f_c\), let us seek estimates only at the discrete values

\[ f_n \equiv \frac{n}{N\Delta}, \quad n = -\frac{N}{2}, ..., \frac{N}{2} \]  \hspace{1cm} (2-29)

where \( f_c \) is the Nyquist critical frequency, given by

\[ f_c \equiv \frac{1}{2\Delta} \]  \hspace{1cm} (2-30)

The extreme values of \( n \) in Eq. (2-29) correspond exactly to the lower and upper limits of the Nyquist critical frequency range.

The remaining step is to approximate the integral in Eq. (2-23) and Eq. (2-24) by a discrete sum:
\[ H(f_n) = \int_{-\infty}^{\infty} h(t) e^{2\pi j f \Delta t} dt = \sum_{k=0}^{N-1} h_k e^{2\pi j f \Delta t} \Delta = \Delta \sum_{k=0}^{N-1} h_k e^{2\pi j k n / N} \] (2-31)

The final summation in Eq. (2-31) is called the discrete Fourier transform of the \( N \) points \( h_k \). Let us denote it by \( H_n \),

\[ H_n = \sum_{k=0}^{N-1} h_k e^{2\pi j k n / N} \] (2-32)

The discrete Fourier transform maps \( N \) complex numbers (the \( h_k \)'s) into \( N \) complex number the \( H_n \)'s).

The formula for the discrete inverse Fourier transform, which recovers the set of \( h_k \)'s exactly from the \( H_n \)'s is:

\[ h_k = \frac{1}{N} \sum_{n=0}^{N-1} H_n e^{-2\pi j k n / N} \] (2-33)

### 2.3.3 Two-dimensional Discrete Fourier Transform

Given a complex function \( h(k_1, k_2) \) defined over the two-dimensional grid \( 0 \leq k_1 \leq N_1 - 1, \ 0 \leq k_2 \leq N_2 - 1 \), we can define its two-dimensional discrete Fourier transform as a complex function \( H(n_1, n_2) \), defined over the same grid,

\[ H(n_1, n_2) = \sum_{k_2=0}^{N_2-1} \sum_{k_1=0}^{N_1-1} \exp(2\pi j k_2 n_2 / N_2) \exp(2\pi j k_1 n_1 / N_1) h(k_1, k_2) \] (2-34)

By pulling the 'subscript 2' exponential outside of the sum over \( k_2 \), or by reversing the order of summation and pulling the 'subscripts 1' outside of the sum over \( k_1 \), we can see instantly that the two-dimensional FFT can be computed by taking one-dimensional FFTs sequentially on each index of the original function. Symbolically,

\[ H(n_1, n_2) = \text{FFT} - \text{on} - \text{index} - 1 \ (\text{FFT} - \text{on} - \text{index} - 2 \ h(k_1, k_2)) \]

\[ = \text{FFT} - \text{on} - \text{index} - 2 \ (\text{FFT} - \text{on} - \text{index} - 1 \ h(k_1, k_2)) \] (2-35)
2.3.4 Data Windowing

When we select a run of $N$ sampled points of periodogram spectral estimation, we are in effect multiplying an infinite run of sampled data $c_j$ by a window function in time, one which is zero except during the total sampling time $N\Delta$, and is unity during that time. In other words, the data are windowed by a square window function.

As the square window function turns on and off so rapidly, there is a leakage at high frequencies. To remedy this situation, we can multiply the input data $c_j$, $j = 0, \ldots, N - 1$ by a window function $w_j$ that changes more gradually from zero to a maximum and the back to zero as $j$ ranges from 0 to N-1. Figure 2-6 shows few windows as examples.

![Window Functions](image)

Figure 2-6. Window functions commonly used in FFT power spectral estimations. The data segment, here of length 256 is multiplied by the window function before the FFT is computed [Press et al., 1988, p. 443].

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2.3.5 Processing of Data for Imaging

The numerical schemes discussed are used for the processing of data obtained either from radar measurements or from computer simulation of wave propagation and scattering. The process basically involves transform of data from frequency to time domain or vice versa. A window is applied to data in frequency as discussed in subsection 2.3.4. The diagrams in Figure 2-7 shows the process of data manipulation to obtain an image for both radar measurements and computer simulations.

![Flow chart of signal processing schemes](image)

Figure 2-7. Flow chart of signal processing schemes for (a) radar measurement results and (b) computer simulation.
2.3.6 Definition of Terminologies Used

As shown in Figure 2.7, the signal processing of data obtained from radar measurements and numerical modeling is similar to each other in their basic concepts. However, there are also differences between the two. To clarify each step of signal processing tasks, the following terminologies are defined:

Radar measurements: three-dimensional measurements of three-dimensional concrete targets using an inverse synthetic aperture radar (ISAR). The raw data are obtained in the format of amplitude and phase of returned signals at each frequency swept from an initial frequency to an ending frequency with a given increment (Details of the measurements are described in Chapter 5).

Numerical modeling: two-dimensional finite difference-time domain (FD-TD) modeling of wave propagation and scattering through and by two-dimensional concrete specimens (infinity is assumed in the third direction, which usually corresponds to the height of a specimen) modeled inside a computational domain. The data obtained as a result of modeling are in the format of electric or magnetic field as a function of time. Numerical modeling refers to the process of obtaining reflected signals based on the FD-TD scheme.

Computer simulation: process of data obtained from the numerical modeling to simulate actual radar measurements with the use of the same window and the same number of data points for FFT. Thus, computer simulation has a broader meaning compared to the numerical modeling.

Signal processing: refers to any numerical process to covert raw data to any desired format of the data. Usually, the purpose and result of signal processing is to obtain an image.

Imaging: any signal processing process which results in imagery as an output.

Windowing: application of data window (filter) to obtain smooth plot in time domain. Windowing is always performed in frequency domain.
Chapter 3

Electromagnetic Property Measurements of Concrete

3.1 Objective

A successful application of a radar method to concrete structures for nondestructive testing requires a clear understanding of the electromagnetic properties of concrete. As a building material, mechanical properties of concrete have been well known and widely used for civil engineering applications. Now, it becomes necessary to explore its electromagnetic properties as those are needed for nondestructive evaluation (NDE) purposes using the electromagnetic wave techniques.

Many aspects of electromagnetic wave propagation in a material are dependent on the electromagnetic properties of that material. Generally, the interaction of electromagnetic waves with a given material is frequency-dependent, and furthermore, this interaction at a given frequency strongly depends on the electromagnetic properties of the material. For example, as a wave propagates from free space into the material, an impedance mismatch occurs at the boundary causing part of the energy to be reflected from the material and the rest of the energy to be transmitted through the material. Once inside the material, the wave's velocity and wavelength are decreased based on the electromagnetic properties of the material. If the material is lossy, there will be attenuation through the material.

This necessitates the need to develop a data base for electromagnetic properties of concrete as a function of frequency. In addition to the frequency dependency of the electromagnetic properties of concrete, the inherent characteristics of concrete such as moisture content and density variations further complicate the problem requiring an in-depth study of the material behavior in its interaction with electromagnetic waves.

3.2 Fundamentals of Electromagnetic Properties

3.2.1 Constitutive Relations to Maxwell's Equations
Physically, the constitutive relations provide information about the environment in which electromagnetic fields occur - for example, free space or water. Mathematically, a medium is characterized as follows with a permittivity $\varepsilon^*$ and a permeability $\mu^*$:

\[ \overline{D} = \varepsilon^* \overline{E} \quad (3-1) \]
\[ \overline{B} = \mu^* \overline{H} \quad (3-2) \]

In general, $\varepsilon^*$ and $\mu^*$ can be functions of many parameters. When $\varepsilon^*$ or $\mu^*$ is a function of the frequency, the medium is called dispersive. Concrete is a dispersive medium.

3.2.2 Dielectric Constant and Loss Factor

Every material has a unique set of electromagnetic (EM) properties affecting the way in which the material interacts with the electric and the magnetic fields of the electromagnetic waves. Concrete is a dielectric (nonmetallic) material. A dielectric material can be characterized essentially by two independent electromagnetic properties: the complex permittivity $\varepsilon^*$ and the complex (magnetic) permeability $\mu^*$. In general, four independent measurements are necessary to establish the quantities of both real and imaginary parts of $\varepsilon^*$ and $\mu^*$. However, most common dielectric materials including concrete are nonmagnetic, making the permeability $\mu^*$ very close to the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ Henry/meter). So, the focus of the discussion is on the complex permittivity $\varepsilon^*$ which will be defined as:

\[ \varepsilon^* = \varepsilon' - j\varepsilon'' \quad (3-3) \]

where $\varepsilon^*$ is the complex permittivity, $\varepsilon'$ is the real part of the complex permittivity, $\varepsilon''$ is the imaginary part of the complex permittivity, and $j = \sqrt{-1}$. By dividing Eq. (3-3) by permittivity in free space $\varepsilon_0$, the property becomes unitless and relative to the permittivity of free space:

---

1 Superscripts *, ', and " are used to denote a complex number, the real part of a complex number, and the imaginary part of a complex number, respectively.
\[
\frac{\varepsilon^*}{\varepsilon_0} = \frac{\varepsilon'}{\varepsilon_0} - j\frac{\varepsilon''}{\varepsilon_0}
\] (3-4)

\[
\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r''
\] (3-5)

where \(\varepsilon_r^*\) is the relative complex permittivity, \(\varepsilon_r'\) is the real part of the relative complex permittivity or dielectric constant, \(\varepsilon_r''\) is the imaginary part of the complex permittivity or loss factor, and \(\varepsilon_0\) is permittivity in free space (a lossless medium) = \(8.854 \times 10^{-12}\) Farad/meter.

The real part of the relative complex permittivity \(\varepsilon_r'\) is a measure of how much energy from an external electric field is stored in a material and is more commonly called as the dielectric constant. The dielectric constant \(\varepsilon_r'\) is \(> 1\) for most solid and liquids.

The imaginary part of the relative complex permittivity \(\varepsilon_r''\) is a measure of how dissipative or lossy a material is to an external electric field and is referenced to the relative loss factor or simply loss factor. The loss factor \(\varepsilon_r''\) is always \(> 0\) and is usually much smaller than \(\varepsilon_r'\) for dielectric materials.

The ratio of the energy lost to the energy stored in a material is given as loss tangent:

\[
tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon_r''}{\varepsilon_r'}
\] (3-6)

where \(tan \delta\) is loss tangent or tangent loss. In dielectric materials, energy losses occur as a consequence of current conduction or dielectric hysteresis effects [McIntire, 1986].

It is important to note that these EM properties are not constant. They change with frequency, temperature, moisture, and mixture of the material. In what follows, the physical significance of the dielectric constant and loss factor for NDE are examined.

### 3.3 Significance of the Electromagnetic Properties

The focus of the discussion is on the complex permittivity \(\varepsilon^*\) since the permeability of concrete is the same as the permeability of free space. The complex permittivity \(\varepsilon^*\) has real and imaginary parts. The dielectric constant is the real part of the relative complex permittivity in Eq. (3-5) and denoted as \(\varepsilon_r'\) or simply as \(\varepsilon_r\) hereafter. Sections 3.3.1 through 3.3.3 deal with physical significance of the dielectric constant in NDE. The loss
factor refers to the imaginary part of the relative complex permittivity $\varepsilon_r$" in Eq. (3-5). The significance of the loss factor is discussed in Sections 3.3.4 and 3.3.5.

### 3.3.1 Velocity of the Wave inside Concrete

In vacuum or air, electromagnetic waves travel at the velocity of light, $c$. The velocity is changed and determined by the medium through which the wave is propagating. Within media other than vacuum, the waves propagate with velocities lower than the velocity in free space as:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \quad (3-7)$$

where $v$ is the velocity of the wave inside concrete (a dielectric medium) and $c$ is the velocity of light in free space (a vacuum) = $3 \times 10^8$ meters/sec. Since the velocity is the main parameter affected by the EM properties of the medium, most NDE techniques rely on this delay of velocity to detect change of properties and configuration of the object under testing. The reflected echo delayed by the presence of a dielectric material is picked up by a receiving antenna, which is usually the same as the transmitting antenna.

### 3.3.2 Wavelengths inside Concrete

The wavelength $\lambda$ is a function of the oscillation frequency $f$ and the wave velocity $v$ which is determined by the dielectric constant of the medium as in Eq. (3-7).

$$\lambda = \frac{1}{f} \times v$$

$$= \frac{1}{f} \times \frac{c}{\sqrt{\varepsilon_r}} \quad (3-8)$$

where $\lambda$ is the wavelength inside concrete and $v$ is the velocity of the wave inside concrete.

For example, in free space, a 1 GHz wave has a wavelength of 0.3 m. Its wavelength is shortened to 0.15 m in concrete if the concrete has a dielectric constant of 4. As the wavelength decreases inside concrete, detectability increases since the wavelength of the transmitted wave into concrete must be smaller than the object size embedded inside
concrete in order to detect it. Thus, a larger value of the dielectric constant is better for good detection. However, in general, as the value of the dielectric constant increases, loss factor of the material also increases; this limits the penetration depth of the wave in concrete. The tradeoff between the detectability and the penetration depth has to be considered based on the EM properties of the material which vary as a function of frequency.

3.3.3 Reflection and Transmission of the Waves at an Interface

When a uniform plane wave impinges on the boundary at an oblique angle, the normal of the boundary and the incident ray form a plane called the plane of incidence (Figures 3-1 and 3-2). The mismatch between the dielectric constants at the boundary of the two different media causes some of the incident waves to reflect and the rest to be transmitted into the new medium. This interaction permits the nondestructive inspection of the material’s interior for property determination and the detection of anomalies. The mathematical expressions of the reflected wave can be written as

\[ R_{TE} = \frac{\sqrt{\varepsilon_{r1}} \cos \theta_i - \sqrt{\varepsilon_{r2}} \cos \theta_i}{\sqrt{\varepsilon_{r1}} \cos \theta_i + \sqrt{\varepsilon_{r2}} \cos \theta_i} \]  

(3.9)

where \( R_{TE} \) is reflection coefficient for perpendicular polarization or Transverse Electric (TE) in Figure 3-1, \( \varepsilon_{r1} \) is dielectric constant for medium 1 (for air, \( \varepsilon_{r1} = 1 \)), \( \varepsilon_{r2} \) is dielectric constant for medium 2 (for concrete, \( \varepsilon_{r2} = 4 \sim 15 \)), \( \theta_i \) is the angle of incidence in Figure 3-1, and \( \theta_i \) is the angle of transmission in Figure 3-1.

\[ R_{TM} = \frac{\sqrt{\varepsilon_{r2}} \cos \theta_i - \sqrt{\varepsilon_{r1}} \cos \theta_i}{\sqrt{\varepsilon_{r2}} \cos \theta_i + \sqrt{\varepsilon_{r1}} \cos \theta_i} \]  

(3.10)

where \( R_{TM} \) reflection coefficient for parallel polarization or Transverse Magnetic (TM) in Figure 3-2.

The term polarization refers to the direction of the electric field. If the electric field of the wave is perpendicular to the plane of incidence (Figure 3-1), it is called perpendicular polarization or Transverse Electric (TE) for the reason that the electric field is transverse to the plane of incidence. Similarly, if the electric field is parallel to the plane of incidence (Figure 3-2), it is called parallel polarization or Transverse Magnetic (TM) for the reason that the magnetic field is transverse to the plane of incidence. It is beneficial to have different polarizations because any anomalies inside concrete as steel reinforcing bars
(rebars) oriented parallel to the polarized direction of the electric field will show strong response and may be easily detected.

In Eq. (3-9) and Eq. (3-10), dielectric constants for media 1 and 2 are assumed to be known as well as the angle of incidence $\theta_1$. To get the angle of transmission $\theta_t$, a relationship from the Snell's law is needed, which states

$$\sqrt{\varepsilon_{r1}} \sin \theta_1 = \sqrt{\varepsilon_{r2}} \sin \theta_t$$  \hspace{1cm} (3-11)

Then, $\cos \theta_t$ can be obtained as

$$\cos \theta_t = \sqrt{1 - \sin^2 \theta_t}$$  \hspace{1cm} (3-12)

Square of reflection coefficient $|R|^2$ is called reflectivity and denoted as $r$. The transmissivity $t$ is obtained as

$$t = 1 - r$$  \hspace{1cm} (3-13)

Thus, the energy is conserved at the interface of the two media.

### 3.3.4 Attenuation of the Wave inside Concrete

The propagation of electromagnetic waves is governed by the Maxwell's equations. A plane wave propagating along $z$-direction (Figure 3-1) is of the form [Kong, 1990],

$$\vec{E} = \hat{y}E_0 e^{-jk_1^*z + jox}$$  \hspace{1cm} (3-14)

where $\vec{E}$ is electric field vector, $\hat{y}$ is a unit vector in $y$-direction, which is perpendicular to the direction of wave propagation (or it can be $\hat{x}$ for $x$-direction), $E_0$ is the initial amplitude of the wave's electric field, and $k_1^*$ is complex wavenumber in $z$-direction.

If only the spatial term in Eq. (3-14) is considered and the complex wavenumber is replaced with its real and imaginary parts, Eq. (3-14) becomes

$$\vec{E} \propto e^{-jk_1^*z}$$

$$\propto e^{-jk_1^*z} e^{-k_1^z}$$  \hspace{1cm} (3-15)
Figure 3-1. Reflection and transmission of a perpendicular-polarized (TE) plane wave at a dielectric boundary shown on the x-z plane (the plane of incidence). The electric field $\mathbf{E}$ is in $y$-direction.

Figure 3-2. Reflection and transmission of a parallel-polarized (TM) plane wave at a dielectric boundary shown on the x-z plane (the plane of incidence). The magnetic field $\mathbf{H}$ is in $y$-direction.
where \( k_z^*z = k_z'z - jk_z''z \). The second term in Eq. (3-15) represents the amplitude loss of the electric field with distance (in z-direction) due to material attenuation. More concisely, Eq. (3-15) can be written as

\[
\overline{E} \propto e^{-k_z'z} \tag{3-16}
\]

only considering the amplitude loss. The loss is exponential in nature as \( k_z'' \) increases. \( k'' \) is the imaginary part of the complex wavenumber. For dielectric materials with low conductivity, it is approximated as

\[
k'' = \frac{\sigma}{2} \sqrt{\frac{\mu_0}{\epsilon'}} \tag{3-17}
\]

\( k'' \) is often termed as the attenuation coefficient. It determines the amplitude loss of the wave in a dielectric material and changes as a function of conductivity and the real part of the complex permittivity, which in turn changes as frequency changes. The significance of the attenuation coefficient for nondestructive evaluation is that its inverse is a penetration depth of the wave in a dielectric medium.

### 3.3.5 Penetration Depth in Concrete

A penetration depth \( d_p \) is a distance through a lossy dielectric over which the field strength falls by \( 1/e \) due to energy absorption. Thus, the penetration depth is as follows:

\[
d_p = \frac{1}{k''} \tag{3-18}
\]

For conducting media,

\[
k = \omega \sqrt{\mu_0 \epsilon_0} \frac{1}{1 - \frac{j \sigma}{\omega \epsilon_0}} \frac{1}{j^2} = k' - jk'' \tag{3-19}
\]

A slightly conducting medium is one for which \( \frac{\sigma}{\omega \epsilon_0} << 1 \). The value of \( k \) in Eq. (3-19) can be approximated by
\[ k = \omega \sqrt{\mu \varepsilon_0 / \left( 1 - \frac{j \sigma}{\omega \varepsilon_0} \right)} \]

Thus, after entering a slightly conducting medium and traveling a penetration depth

\[ d_p = \frac{1}{k''} = \frac{2}{\sigma \sqrt{\mu_0}} \] (3-21)

the amplitude of the wave will decay to \( 1/e \) times its original value.

It should be noted that both attenuation and penetration depth depends on the conductivity of the material, and consequently on the frequency of the wave. Thus, penetration capability of the wave into concrete depends on both the frequency of the wave and the conductivity of the concrete.

### 3.4 Development of a Measurement Technique

In order to accurately measure the electromagnetic properties of concrete, an appropriate measurement method needs to be selected and a measurement procedure must be developed. Two factors were considered in the selection of a method: first, the measurement must be good for the wide frequency range from 0.1 to 18 GHz; second, the equipment must be suitable for measuring a concrete specimen. The reason for measuring the properties from 0.1 to 18 GHz is that the wideband radar system available for the research is capable of transmitting waves over that frequency range. Consequently, information about the EM properties of concrete over the same frequency range is required.

Available methods are the resistivity cell method, the parallel plate method, the open-ended coaxial probe method, the transmission line method, the resonant cavity method, and the free space method [Hewlett-Packard, 1992]. Among those, the open-ended coaxial probe method is used because it can be used in measuring the EM properties over the wide frequency range from 0.1 to 18 GHz and it is convenient to use for different size of concrete specimens.
The probe allows measurements of the complex permittivity of solid materials such as concrete. Connected with a network analyzer and a computer for control and data acquisition, the system can yield dielectric constant, loss factor, and loss tangent versus frequency. Accuracy of measurements is typically 5%.

A schematic diagram of the measurement network is shown in Figure 3-3.

![Diagram of measurement network](image)

Figure 3-3. A block diagram of dielectric constant measurements using a probe method.

The principle of the probe method is that a measurement of the reflection from and/or a material under test along with a knowledge of its physical dimensions provides the information to characterize the permittivity and permeability of the material. Vector network analyzers such as the HP 8510 makes stimulus-response measurements from 300 KHz to 110 GHz. A vector analyzer consists of a signal source, a receiver, and a display. The source launches a signal at a single frequency to the material under test. The receiver is tuned to that frequency to detect the reflected and/or transmitted signals from the material. The measured response produces the magnitude and phase data at that frequency. The source is then stepped to the next frequency and the measurement is repeated to display the reflection and/or transmission measurement response as a function of frequency.
Simple components and connecting wires that perform well at low frequencies behave differently at high frequencies. At microwave frequencies wavelengths become small compared to the physical dimensions of the devices such that two closely spaced points can have a significant phase difference. Low frequency lumped-circuit element techniques must be replaced by transmission line theory to analyze the behavior of devices at higher frequencies. Additional high frequency effects such as radiation loss, dielectric loss and capacitive coupling make microwave circuits more complex and expensive.

It is time consuming and costly to try to design a perfect microwave network analyzer. Instead, a measurement calibration is used to eliminate the systematic (stable and repeatable) measurement errors caused by the imperfections of the system. Random error due to noise, drift or the environment (temperature, humidity, pressure) cannot be removed with a measurement calibration. This makes a microwave measurement susceptible to errors from small changes in the measurement system. These errors can be minimized by adopting good measurement practices such as visually inspecting all connectors for dirt or damage, and by minimizing any physical movement of the test port cables after a calibration.

The open-ended coaxial probe is a cut off section of transmission line. The material is measured by touching the probe to a flat face of a solid or immersing it into a liquid. The fields at the probe end "fringe" into the material and change as they come into contact with the material under test. The reflected signal \( S_{11} \) can be measured and related to \( \varepsilon^* \).

### 3.5 Calibration and Measurement Accuracy

Calibration of the experimental system using the probe was made by measuring methanol, short, and air. It can also be calibrated using air/short/load, air/short/water, or any other known material. Methanol was used because its electromagnetic properties were relatively close to those of concrete compared to the other possible calibration material over the wide frequency range of interest.

Four material parameters are needed as calibration standards. The parameters are used in the following Cole-Cole dielectric model equation to compute \( E^* \) for any frequency \( f \).

\[
E^*(f) = E_{inf} + (e_0 - E_{inf}) / \left[ 1 + (j2\pi\tau\alpha)^{1-Alphat} \right]
\]  

(3-22)

Table 3-1 lists those parameters for two materials.
Measurements results can be greatly affected by the accuracy of the calibration. Different calibration techniques are discussed by other investigators [Otto et al., 1990; Nyshadham et al., 1992; Kraszewski et al., 1983].

The calibration was checked by measuring materials with known EM properties prior to the actual measurements of concrete specimens. The results are shown in Figures 3-4, 3-5, and 3-6. The measured values showed good agreement with published values [von Hippel, 1954] with error less than 10%.

Table 3-1. Material Parameters for Calibration.

<table>
<thead>
<tr>
<th>Material</th>
<th>(E_0)</th>
<th>(E_{inf})</th>
<th>(\tau)</th>
<th>Alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (@ 26°C)</td>
<td>78.2</td>
<td>4.21</td>
<td>(8 \times 10^{-12})</td>
<td>0.0124</td>
</tr>
<tr>
<td>Methanol (@ 25°C)</td>
<td>32.6</td>
<td>5.6</td>
<td>(48 \times 10^{-12})</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Figure 3-4. Dielectric constant of reference materials.
Figure 3-5. Loss factor of reference materials.

Figure 3-6. Loss tangent of reference materials.
3.6 Results of Electromagnetic Property Measurements

The open-ended coaxial probe method was used to measure the real and imaginary parts of the complex permittivity of concrete over the wide frequency range from 0.1 to 20 GHz. In addition to the frequency variation, different moisture content was introduced as the second parameter to examine the effect of moisture on the EM properties of concrete. The purpose of the measurements is to develop a data base for the electromagnetic properties of hardened concrete over the wide frequency range.

The research work reported on the electromagnetic properties of concrete is extremely limited, especially over a wide frequency range. Most of previous research have been directed toward the measurements at limited frequency regions [Wilson, Whittington, and Forde, 1984] or the purpose was to monitor hydration process of concrete or cement pastes at their early ages of curing [Tamas, 1982; Moukwa et al., 1991].

Table 3-2. List of electromagnetic property measurements made.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Measured values</th>
<th>Derived values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dielectric constant &amp; loss factor</td>
<td>Loss tangent, Wavelength, Penetration Depth</td>
</tr>
<tr>
<td></td>
<td>oven dried</td>
<td>air dried</td>
</tr>
<tr>
<td>Concrete</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Mortar</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Cement</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Distilled water</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Methanol</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Air</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

In what follows, experimentally obtained values of the electromagnetic properties of concrete as a function of frequency from 0.1 to 18 GHz, moisture content, and density are...
presented. In this Section of 3.6, the real and imaginary parts of a complex permittivity for tested specimens are provided in a graphic format. In Section 3.7, derived values from the measured properties are given, which include loss tangent, wavelength, and penetration depth. Table 3-2 summarizes the measurements made and the derived values from the measurements.

3.6.1 Measured Electromagnetic Properties of Concrete

Concrete specimens for the EM property measurements were cast with water/cement/sand/coarse aggregate mix ratio of 1:2.22:5.61:7.12 (by weight). Water/cement ratio was 0.45. This is the same mix ratio used in the U.S. Army Engineer Waterways Experiment Station. Portland cement of Type I was used. Coarse aggregates have maximum size of 1.5 inches. The age of the specimens at the time of the measurements was 4 weeks. The uniaxial compression strength of the specimen was 21 MPa at 28 days. Four different types of concrete specimens are used for the measurements: i) wet specimens with watery surface, ii) saturated specimens which contained moisture only inside, iii) air dried specimens exposed to ambient room temperature and humidity, and iv) oven dried specimens with zero moisture content by weight. Dimensions of the specimens are 3" diameter x 6" height.

The experimentally obtained values of the dielectric constants $\varepsilon_r'$ of four different groups of concrete specimens are shown in Figure 3-7. The dielectric constant is the real part of the relative complex permittivity in Eq. (3-5). It determines the velocity of the wave inside concrete, the wavelength inside concrete, the amount of reflection and transmission of the wave at a concrete interface with other materials, and the Brewster angle of concrete. The results represent the information about the EM properties of concrete over the wide frequency range. This information is required for the radar measurements, interpretation of the data from the radar measurements, and theoretical modeling of the wave scattering by concrete.

In Figure 3-7, at a given moisture level, the dielectric constant does not change much over the measured frequency range. However, the change of the dielectric constant is significant when the moisture level varies from air dried to saturated and wet. The dielectric constant of the saturated specimen is almost twice of that of the oven dried specimen. This is due to the high value of the dielectric constant of water as seen in Figure 3-4. Consequently, the increase of water content in concrete greatly affects the change of the dielectric constant of the concrete. Moisture content is one of the major constituents which influence the EM properties of concrete.
The detailed definition and significance of the dielectric constant in nondestructive evaluation are discussed in the Section 3.3.

The experimentally obtained values of the loss factor for four different groups of concrete specimens are shown in Figure 3-8. In Figure 3-8, the loss factor of concrete increases slightly as frequency increases. The effect of the presence of water on the lossyness of concrete is clearly shown as the loss factor of the more moisturized concrete specimen exhibits the higher value than that of the less moisturized specimen.

The measured values also can be expressed in the format of equations as follows:

Table 3-3. Measured electromagnetic properties of concrete.

<table>
<thead>
<tr>
<th>Condition of specimens</th>
<th>Dielectric constant</th>
<th>Loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>( y = 15.06 - 0.21 \times )</td>
<td>( y = 1.72 + 0.0047 \times )</td>
</tr>
<tr>
<td>Saturated</td>
<td>( y = 8.42 - 0.10 \times )</td>
<td>( y = 0.72 + 0.0076 \times )</td>
</tr>
<tr>
<td>Air dried</td>
<td>( y = 4.52 - 0.0063 \times )</td>
<td>( y = 0.0025 + 0.020 \times )</td>
</tr>
<tr>
<td>Oven dried</td>
<td>( y = 4.00 - 0.011 \times )</td>
<td>( y = 0.03 + 0.0040 \times )</td>
</tr>
</tbody>
</table>

Note: \( x \) is frequency in GHz.

3.6.2 Measured Electromagnetic Properties of Mortar

The EM property measurements were made on mortar specimens to examine the difference of the EM properties between concrete and mortar. No coarse aggregates were used for mortar specimens compared to concrete specimens. The mix ratio for mortar specimens was water/cement/sand of 1:2.22:5.61 (by weight). Water/cement ratio was 0.45 Portland cement of Type I was used. The age of the specimens at the time of the measurements was 4 weeks. Four different types of concrete specimens are used for the measurements: i) wet specimens with watery surface, ii) saturated specimens which contained moisture only inside, iii) air dried specimens exposed to ambient room temperature and humidity, and iv) oven dried specimens with zero moisture content by weight. Dimensions of the specimens are 3" diameter x 6" height.

The results of the measurements are shown in Figure 3-9 and Figure 3-10, for the dielectric constant and loss factor, respectively. The dielectric constants of mortar show similar trend as concrete. They are frequency independent for air and oven dried specimens and decreased over the frequency for saturated and wet specimens. The phenomena of decreased dielectric constant for those two specimens due to the increased content of water. Since the dielectric constant of water decreases as frequency increases (Figure 3-4),
specimens with more water show the nature of dielectric constant variation of water. The dielectric constant of mortar of watery specimens is lower than those of concrete specimens. Loss factor of mortar is similar to that of concrete.

<table>
<thead>
<tr>
<th>Condition of specimens</th>
<th>Dielectric constant</th>
<th>Loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>( y = 12.62 - 0.16 \times )</td>
<td>( y = 1.31 + 0.0018 \times )</td>
</tr>
<tr>
<td>Saturated</td>
<td>( y = 7.03 - 0.060 \times )</td>
<td>( y = 0.51 + 0.0071 \times )</td>
</tr>
<tr>
<td>Air dried</td>
<td>( y = 4.36 - 0.012 \times )</td>
<td>( y = 0.082 + 0.013 \times )</td>
</tr>
<tr>
<td>Oven dried</td>
<td>( y = 3.87 - 0.0082 \times )</td>
<td>( y = 0.0016 + 0.0094 \times )</td>
</tr>
</tbody>
</table>

Note: \( x \) is frequency in GHz.

3.6.3 Measured Electromagnetic Properties of Aggregate, Cement, and Sand

Concrete is made of water, cement, sand, and coarse aggregates with a certain mix ratio. Mortar is made without coarse aggregates. The EM properties of these constituents determine the EM properties of concrete and mortar.

The EM properties of coarse aggregate, cement, and sand are measured using the same probe method. Coarse aggregates have maximum size of 1.5" and were cut using a sharp saw to have very smooth flat surface for a good contact with the probe. Several measurements were made for each aggregate sample and average values are used for plot. Portland cement Type I was used for the measurement. The cement was put into a plastic bag and measured by inserting the probe into the cement bag. Sand was measured in the same way as cement was measured.

The measurement results are shown in Figure 3-11 and Figure 3-12, for the dielectric constant and loss factor of constituents, respectively. For the dielectric constant, coarse aggregates show the higher value than cement and sand. Since aggregates are more dense than the others, the result seems reasonable. Cement and sand have dielectric constants of 4 and 2, respectively. Those values are constant over the frequency range. Since there was no water at all in the specimens for the constituents, dielectric constant didn't vary at all.
Figure 3-7. The measured dielectric constant $\varepsilon_r'$ of concrete.

Figure 3-8. Loss factor of concrete.
Figure 3-9. Dielectric constant of mortar.

Figure 3-10. Loss factor of mortar.
Figure 3-11. Dielectric constant of constituents.

Figure 3-12. Loss tangent of constituents.
3.7 Results of the Derived Values from the Property Measurements

3.7.1 Loss Tangent of Concrete and Mortar

The ratio of the energy lost to the energy stored in a material is given as loss tangent:

\[ \tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon_r''}{\varepsilon_r'} \]  \hspace{1cm} (3-23)

where \( \tan \delta \) is loss tangent or tangent loss. In dielectric materials, energy losses occur as a consequence of current conduction or dielectric hysteresis effects [McIntire, 1986]. The loss tangents for concrete and mortar are shown in Figure 3-13 and Figure 3-14, respectively.

3.7.2 Wavelengths inside Concrete and Mortar

The wavelength \( \lambda \) is a function of the oscillation frequency \( f \) and the wave velocity \( v \) as shown in Eq. (3-8). The detectability is increased at high frequency. To detect any object, the wavelength must be shorter than the size of the object. With increased frequency \( f \), the wavelength \( \lambda \) is shortened, which results in the improved detectability. The wavelengths of concrete and mortar are shown in Figure 3-15 and Figure 3-16, respectively.

3.7.3 Penetration Depths inside Concrete and Mortar

A penetration depth \( d_p \) is a distance through a lossy dielectric over which the field strength falls by \( 1/e \) due to energy absorption as defined in Eq. (3-18) and discussed in Subsection 3.3.5. The penetration depths for concrete and mortar are shown in Figure 3-17 and Figure 3-18, respectively.
Figure 3-13. Loss tangent of concrete.

Figure 3-14. Loss tangent of mortar.
Figure 3-15. Wavelength inside concrete.

Figure 3-16. Wavelength inside mortar.
Figure 3-17. Penetration depth inside concrete.

Figure 3-18. Penetration depth inside mortar.
3.8 Results of Predicting Radar Cross Section from the Property Measurements

Based on the experimentally obtained values of the electromagnetic properties of concrete, a generalized radar cross section (RCS) as a function of frequency can be obtained. RCS is a measure of the power that is returned or scattered in a given direction, normalized with respect to the power density of the incident field as defined and described in Subsection 2.2.6. By obtaining the RCS, the penetration capability of the wave over a frequency range with a specific combination of electromagnetic properties of a concrete target can be estimated.

The RCS calculation is based on the physical optics approach [Knott et al., 1985] and the exact formula for the calculation of reflection coefficients for a two-layer medium [Kong, 1986]. The expression for RCS is

$$\frac{4\pi A^2}{\lambda^2} |R_1(f)|^2$$  \hspace{1cm} (3-24)

where $A$ is the cross-sectional area of a concrete target, $\lambda$ is the wavelength corresponding to a frequency of the wave, and $R_1(f)$ is the reflection coefficient for a two-layer medium.

The expression for the reflection coefficient from the exact formulation [Kong, 1990] is

$$R_1(f) = \frac{1}{R_{01}} + \frac{\left[1 - \left(\frac{1}{R_{01}}\right)^2\right]}{\left(\frac{1}{R_{01}} + R_{12}e^{i2kd}\right)}$$  \hspace{1cm} (3-25)

$$= \frac{R_{01} + R_{12}e^{i2kd}}{1 + R_{01}R_{12}e^{i2kd}}$$

where $R_{01}$ is the reflection coefficient from air (material 0) to concrete (material 1), $R_{12}$ is the reflection coefficient from concrete to air, $k$ is a complex wavenumber in a lossy medium, and $d$ is the thickness of a concrete target. The complex wavenumber $k$ is defined as

$$k = \omega \sqrt{\mu (\varepsilon' + j\varepsilon'')}$$  \hspace{1cm} (3-26)
Reflection coefficients \( R_{01} \) and \( R_{12} \) are described as

\[
R_{01} = \frac{\sqrt{\varepsilon_{r0} \cos \theta_i} - \sqrt{\varepsilon_{r1} \cos \theta_i}}{\sqrt{\varepsilon_{r0} \cos \theta_i} + \sqrt{\varepsilon_{r1} \cos \theta_i}} \tag{3-27}
\]

\[
R_{12} = \frac{\sqrt{\varepsilon_{r1} \cos \theta_i} - \sqrt{\varepsilon_{r2} \cos \theta_i}}{\sqrt{\varepsilon_{r1} \cos \theta_i} + \sqrt{\varepsilon_{r2} \cos \theta_i}} \tag{3-28}
\]

With plane incident waves, \( \theta_i \) and \( \theta_r \) becomes both zero, which reduce Eq. (3-27) and Eq. (3-28) to

\[
R_{01} = \frac{\sqrt{\varepsilon_{r0}} - \sqrt{\varepsilon_{r1}}}{\sqrt{\varepsilon_{r0}} + \sqrt{\varepsilon_{r1}}} \tag{3-29}
\]

and

\[
R_{12} = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \tag{3-30}
\]

Results of RCS prediction based on the electromagnetic properties measured in Section 3.6 are presented in Figure 3-19 and Figure 3-20 for air dried concrete and water saturated concrete, respectively. Dielectric constant and loss factor of concrete used in the prediction were obtained from the measured data in Table 3-3. The variation of dielectric constant and loss factor as a function of frequency has been exactly incorporated using the Eq. (3-25). The frequency range used is 2 – 3.4 GHz and the concrete has thickness of 4” as d in Eq. (3-25). After obtaining complex numbers for reflection coefficients in frequency domain as a function of frequency, the coefficients are plugged into Eq (3-24) to obtain the RCS. The cross-sectional area of the concrete is assumed to be 12" x 12". The RCS in frequency is then inverse Fourier transformed into time domain to generate imagery as shown in Figure 3-19 and Figure 3-20.

In Figure 3-19, the front and back surfaces of 4" thick concrete are shown at zero and 0.25 m in the range. In Figure 3-20, the front surface is seen at zero range, but the back surface is not seen due to the lossyness of the material as determined by its measured loss factor. In Figure 3-19, the distance between the peaks exactly detect the actual dimension of the concrete thickness as 4" by considering the delayed signal due to the value of the dielectric constant. Similar RCS predictions can be made if electromagnetic properties of a concrete target is known.
Figure 3-19. 1-D image obtained from an air dried concrete target with cross-sectional dimensions of 12" x 12" and with 4" thickness at 2 ~ 3.4 GHz.

Figure 3-20. 1-D image obtained from a water saturated concrete target with cross-sectional dimensions of 12" x 12" and with 4" thickness at 2 ~ 3.4 GHz.
3.9 Discussion

Electromagnetic properties determine how concrete interacts with electromagnetic waves. The significance of the research work performed and presented in this chapter is the development of a measurement technique suitable for concrete over a wide frequency range. The developed technique can be readily applied to any other concrete specimens with different mix, as needed.

The purpose of measuring the electromagnetic properties in this research work was to understand and capture the general trend of the variation of the properties as a function of frequency, moisture level, and density. The measured values are used in predicting radar cross-section, as an input data for numerical modeling of wave propagation and scattering, and as a basis in determining radar measurement setup as to an incident angle and determination of initial thickness of concrete specimens as a part of computer simulation work. As the properties also can vary with other factors such as chemical components of mixture, temperature, pressure, etc., more measurements can be made if it is needed for a specific application area of the radar method.

The results of electromagnetic property measurements indicate that at a given moisture content the dielectric constant of concrete appear to be frequency independent over the frequency range from 0.1 to 20 GHz, while the loss factor increases over the frequency range. The moisture content of concrete significantly affects the dielectric constant and loss factor of concrete. The significance of the dielectric constant of concrete for radar measurements is that it reduces both the velocity and wavelength of the transmitted wave inside concrete, therefore increases the detectability. The loss factor of concrete determines how deep the wave can penetrate into concrete. For radar measurements, the increased loss factor at higher frequency and/or with higher moisture content reduces the penetration depth of the wave in concrete, which compromises the benefit of increased detectability. This phenomenon indicates that there is a tradeoff between the detectability and the penetration depth for radar measurements.

In summary, the data base established in this study for concrete as a function of frequency, moisture level, and density represents an initial and original information in its applications to NDE of concrete using a radar.
Chapter 4

Computer Simulation of Radar Measurements

4.1 Objectives

The goal of any NDE techniques is to detect an object located at a certain distance below the surface in an optically opaque medium. In the radar method, the detectability of an object inside concrete and the penetration capability of a wave into concrete are affected by a variety of measurement parameters including the following: frequency, bandwidth, beam width, polarization, incident angle of the wave, measurement distance, and geometric and material properties of the target. This necessitates a study to examine the influence of each parameter on the radar measurement results and to establish optimum combination of the parameters. For the study, a numerical technique which can simulate the electromagnetic phenomena and provide information as to how the wave propagates through and scatters by a concrete target is needed. Study of wave scattering by a target which has known geometric and material properties is called a forward problem. A candidate approach for this purpose is the finite difference-time domain (FD-TD) solution of Maxwell’s curl equations, which are the governing equations for the electromagnetic waves. The FD-TD is a marching-in-time procedure which can simulate continuous wave propagation in concrete.

4.2 Finite Difference-Time Domain Modeling Method

The method employed in the analysis is the finite difference-time domain technique [Taflove and Umashankar, 1975]. It is based on the discretization of the electric and magnetic fields over rectangular grids together with the finite difference approximation of the spatial and temporal derivatives appearing in the differential form of Maxwell’s equations. The reasons for which the FD-TD methodology was selected include the relative ease of implementation for complicated geometries with dielectrics, the requirement of only simple arithmetic operations in the solution process, and the flexibility for time- and frequency-domain analyses [Li et al., 1992].
4.2.1 Discretization

In the FD-TD technique, a computational domain is first defined and divided into rectangular cells (Figure 4-1). Electric field ($\vec{E}$) and magnetic field ($\vec{H}$) are spatially discretized in a staggered manner [Yee, 1966]. Electric fields are assigned to integer ($n$) time steps and magnetic fields are assigned to half-integer ($n+1/2$) time steps for the temporal discretization of fields. Next, the spatial and temporal derivatives of the two Maxwell's curl equations are approximated using center differences. Maxwell's curl equations for a homogeneous, isotropic, time- and frequency-invariant medium are:

$$\nabla \times \vec{H} = \sigma_e \vec{E} + \varepsilon_0 \varepsilon_r \frac{\partial \vec{E}}{\partial t}$$  \hspace{1cm} (4-1)

$$\nabla \times \vec{E} = -\mu_0 \mu_r \frac{\partial \vec{H}}{\partial t}$$  \hspace{1cm} (4-2)

where $\varepsilon_0$ is the free-space permittivity, $8.854 \times 10^{-12}$ F/m and $\mu_0$ is the free-space permeability, $4\pi \times 10^{-7}$ H/m. In addition, $\varepsilon_r$ and $\mu_r$ are respectively the dielectric constant and relative permeability of the medium; while $\sigma_e$ is the electric conductivity. Maxwell’s divergence equations are ignored since the curl equations with appropriate boundary conditions uniquely determine the solution. In rectilinear coordinates, the curl equations can be rewritten as a set of six independent scalar equations. For a number of independent scalar-field variables in Maxwell’s equations, there are 12 unknowns, one for each component of $\vec{E}$, $\vec{D}$, $\vec{H}$, and $\vec{B}$ in x, y, and z, for example, $E_x$, $E_y$, and $E_z$ for $\vec{E}$. Therefore, the six independent equations from the set of Maxwell's equations is not sufficient to solve for the 12 unknowns. Six more equations are obtained from the constitutive relations.

$$\vec{D} = \varepsilon \vec{E}$$  \hspace{1cm} (4-3)

$$\vec{B} = \mu \vec{H}$$  \hspace{1cm} (4-4)

Eq. (4-3) and Eq. (4-4) are the constitutive relations for the simple medium. There are three independent equations obtained from Eq. (4-3) and the other three independent equations obtained from Eq. (4-4). Thus, 12 equations are now available to solve for 12 unknowns.
For two-dimensional problems, which are assumed to be uniform and infinite in one direction, these equations decouple into the H-field and E-field polarizations. The three equations governing the H-field polarization assuming y is the uniform direction are as follows,

\[ \mu_r\mu_0 \frac{\partial H_y}{\partial t} = \frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \]  
\[ (4-5) \]

\[ \varepsilon_r\varepsilon_0 \frac{\partial E_x}{\partial t} = -\frac{\partial H_y}{\partial z} - \sigma E_x \]  
\[ (4-6) \]

\[ \varepsilon_r\varepsilon_0 \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x} - \sigma E_z \]  
\[ (4-7) \]

and for E-field polarization,

\[ \varepsilon_r\varepsilon_0 \frac{\partial E_y}{\partial t} = \frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial z} - \sigma E_y \]  
\[ (4-8) \]
\[ \mu_r \mu_0 \frac{\partial H_x}{\partial t} = \frac{\partial E_y}{\partial z} \] 
(4-9) \]

\[ \mu_r \mu_0 \frac{\partial H_z}{\partial t} = -\frac{\partial E_y}{\partial x} \] 
(4-10)

The following notation for any function of time and space will be used in the finite difference equations,

\[ f(i \Delta x, k \Delta z, n \Delta t) = f^n(i, k) \] 
(4-11)

The partial derivatives in space and time, within Maxwell's equations, are approximated using center differences,

\[ \frac{\partial f(\xi)}{\partial (\xi)} = \frac{f(\xi + \Delta \xi / 2) - f(\xi - \Delta \xi / 2)}{\Delta \xi} \] 
(4-12)

The electric and magnetic field components are interlaced in time, and are calculated in a leap-frog manner (i.e., first the electric fields are calculated, then the magnetic fields are calculated, and the sequence is repeated). The electric and magnetic field components are interlaced spatially a half-grid cell apart.

### 4.2.2 Finite Difference Equations

Difference equations for H-field polarization are derived from Eqs (4-5), (4-6), and (4-7) by applying center differencing. The center difference ensures that the spatial and temporal discretizations are of second-order accuracy, where errors are proportional to the square of the cell size and time increment [Yee, 1966]. The electric field terms involving conductivity are approximated by using the average of the field values at a half time step before and after the desired time.

\[ H^{n+1/2}_{y(i+1/2,k+1/2)} = H^{n-1/2}_{y(i+1/2,k+1/2)} + \frac{\Delta t}{\mu_r \mu_0} \left[ \frac{E^n_{z(i+1,k+1/2)} - E^n_{z(i,k+1/2)}}{\Delta x} - \frac{E^n_{x(i+1/2,k+1)} - E^n_{x(i+1/2,k)}}{\Delta z} \right] \] 
(4-13)
\[ E_{x(i+1/2,k)}^{n+1} = \frac{2\varepsilon_r\varepsilon_0 - \sigma\Delta t}{2\varepsilon_r\varepsilon_0 + \sigma\Delta t} E_{x(i+1/2,k)}^n - \frac{2\Delta t}{2\varepsilon_r\varepsilon_0 + \sigma\Delta t} \left[ \frac{H_{y(i+1/2,k+1/2)}^{n+1/2} - H_{y(i+1/2,k-1/2)}^{n+1/2}}{\Delta z} \right] \]  \hspace{1cm} (4-14)

\[ E_{z(i,k+1/2)}^{n+1} = \frac{2\varepsilon_r\varepsilon_0 - \sigma\Delta t}{2\varepsilon_r\varepsilon_0 + \sigma\Delta t} E_{z(i,k+1/2)}^n - \frac{2\Delta t}{2\varepsilon_r\varepsilon_0 + \sigma\Delta t} \left[ \frac{H_{y(i+1/2,k+1/2)}^{n+1/2} - H_{y(i-1/2,k+1/2)}^{n+1/2}}{\Delta x} \right] \]  \hspace{1cm} (4-15)

### 4.2.3 Initial and Boundary Conditions

With appropriate initial and boundary conditions, the solutions to the difference equations are obtained through explicit leapfrog time marching. This corresponds to alternating the advance of electric and magnetic fields (i.e., first the electric fields are calculated, then the magnetic fields are calculated, and the sequence is repeated). Fields are set to be zero initially everywhere to satisfy the causality condition consistent with zero excitation for time less than zero.

The boundary conditions are continuity of tangential electric and magnetic fields on material interfaces, vanishing tangential electric fields on perfect conductors, and the absorbing boundary conditions on the boundary of the computational domain. Second-order absorbing boundary conditions [Mur, 1981] are used to limit the computational domain by simulating unbounded space. The second-order approximation derived by Engquist and Majda [1977] is

\[ \left( \frac{\partial^2}{\partial n \partial \tau} + \frac{\partial^2}{\partial \tau^2} - \frac{1}{2} \frac{\partial^2}{\partial T^2} \right) w = 0 \]  \hspace{1cm} (4-16)

where \( w \) is a field quantity which is tangential to the absorbing boundary, \( \hat{n} \) is the normal direction, \( \hat{T} \) is the tangential direction, and \( \tau \) is time normalized with respect to the speed of light. The second-order absorbing boundary condition (ABC) works very well for waves which are at or near normal incidence, and not as well for waves which are incident at grazing angles. This second-order ABC can be applied to all the edges of the
computational domain, except in the vicinity of any media other than free space which extends beyond the computational domain.

4.2.4 Stability and Accuracy

The choices of grid size are motivated by reasons of accuracy and stability [Taflove and Brodwin, 1975; Bayliss et al., 1985]. To achieve accurate results, the cell sizes are taken to be a fraction (~ 1/20) of the smallest wavelength in any media expected in the model. The time increment and the cell size are related by the stability criterion [Taflove and Brodwin, 1975]:

\[
\Delta t \leq \frac{1}{c_0 \sqrt{(1/\Delta x)^2 + (1/\Delta z)^2}} \tag{4-17}
\]

where \(c_0\) is the speed of light in free space.

4.2.5 Excitation Source

In the modeling, two different waves are used as excitation sources: a Gaussian pulse plane wave and a Gaussian pulse modulated sinusoidal wave. The first wave is centered at direct current (dc), while the second one can be centered at any center frequency with the use of a carrier frequency.

The Gaussian pulse plane wave has a form of

\[
V(t) = e^{-2(t-t_0)^2/T^2} \tag{4-18}
\]

where \(V(t)\) is the electric field of an incident wave (V/m), \(t\) is time, \(t_0\) is time delay, and \(T\) is the pulse width. The Gaussian pulse is used for the modeling because it contains multi-frequency information which can simulate wideband radar measurement, compared to a single frequency signal. The modeling scheme allows to select any frequency bandwidth of interests by changing the pulse width \(T\) as shown in Figure 4-2. The sample Gaussian pulse in time domain with the time delay \(t_0 = 0.2\) ns is shown in the figure with an amplitude of 1 V/m. The pulse width \((T)\) of the incident wave is 0.0762 ns in time. The incident Gaussian pulse in Figure 4-2 has a half power bandwidth of 5 GHz in frequency domain as shown in Figure 4-3.
Figure 4-2. The incident wave of a Gaussian pulse centered at the time delay of 0.2 ns with an amplitude of 1 V/m. The pulse width \((T)\) is 0.0762 ns.

Figure 4-3. The incident wave in frequency domain with a half power bandwidth of 5 GHz.
Figure 4-4. A modulated Gaussian pulse in time domain $V_{inc}(t)$.

Figure 4-5. A modulated Gaussian pulse in frequency domain $F\{V_{inc}(t)\}$.
The Gaussian pulse modulated sinusoidal wave has a form of

\[ V(t) = e^{-2(t-t_0)^2/\tau^2} \cos(\omega t) \]  \hspace{1cm} (4-19)

where \( \omega \) is the carrier frequency which shifts the center of the wave to a center frequency in frequency domain. A sample Gaussian pulse modulated sinusoidal wave with a carrier frequency of 4.6 GHz is shown in Figure 4-4 in time domain and Figure 4-5 in frequency domain.

### 4.2.6 Limitations

While the FD-TD technique can provide very accurate predictions and solutions to various electromagnetic phenomena, there are a number of approximations inherent to the technique. The center difference approximations applied to Maxwell's equations are accurate to the second order [i.e., the error term is proportional to the square of the grid size \( (\Delta^2) \)]. This error can be kept to a minimum by choosing the grid size to be less than a twentieth of the shortest wavelength of interest. Some dispersion is introduced by the discretization of Maxwell's equations (i.e., different frequency components travel at slightly different velocities). Geometries are discretized on a rectangular grid. Hence, the dimensions of any scatterer are restricted to integer multiples of the grid size, and curved surfaces must be approximated with staircases. At the outer boundary some reflections will occur because the absorbing boundary condition is an approximate condition. These reflections can be kept tolerable by locating the outer boundary at least half a wavelength away from the scatterer [Lee, 1990].

### 4.3 Results of Modeling for the Study of Target Geometry

In this section, a novel application of the finite difference-time domain (FD-TD) modeling technique to concrete is presented to study the interaction of concrete with electromagnetic waves. The purpose is to visualize the propagation of the electromagnetic fields in a dielectric medium of concrete in an effort to obtain one-dimensional images of a concrete target for nondestructive testing purposes. An emphasis is given to examine edge effect of concrete specimens through modeling. A Gaussian pulse plane wave is directed to laboratory size concrete specimens as an excitation source. Snap shots of computer
simulation are shown to display wave propagation and scattering through and by the concrete specimens. Geometry of the targets is varied with different dimensions, and with or without an inclusion.

**4.3.1 Concrete Specimens Modeled**

Three different types of laboratory size concrete specimens are modeled as targets for the modeling of wave scattering (Figure 4-6). To examine the effects of different shape and size of the specimens, 152.4 mm diameter concrete cylinders (Figure 4-6a), 152.4 mm x 152.4 mm concrete squares (Figure 4-6b), and 609.6 mm x 152.4 mm concrete rectangles (Figure 4-6c) are used. For each group of the specimens, three cases are considered involving no inclusion, an inclusion of a 25.4 mm diameter #8 steel reinforcing bar (rebar) located at the center, and a void of 25.4 mm diameter at the specimen center.

(a) Cylindrical specimens with a 152.4 mm diameter

(b) Square specimens with dimensions of 152.4 mm x 152.4 mm

(c) Rectangular specimens with dimensions of 609.6 mm x 152.4 mm

Figure 4-6. Laboratory size concrete specimens used for the modeling. Each group of specimens have either no inclusion, a 25.4 mm diameter rebar at the center, or a 25.4 mm diameter void at the center.
The dimensions and configurations of these specimens are chosen so that they represent an initial and relatively simple set of laboratory size concrete targets and provide a basis for further study on more complex concrete targets. With the two-dimensional modeling, the third dimension of the specimen normal to the cross-section is assumed to be infinite.

4.3.2 Incorporating Electromagnetic Properties into Modeling

The concrete specimens are characterized by their electromagnetic properties in the modeling. The electromagnetic properties of concrete used for the modeling are 4.8 for the dielectric constant and 0.15 mhos/m for the conductivity. These values represent measured electromagnetic properties at 5 GHz for normal strength concrete exposed to normal ambient temperature and humidity with uniaxial compressive strength of 21 MPa at 28 days and moisture content of 6.7% by weight. Concrete specimens were cast with water/cement/sand/coarse aggregate mix ratio of 1:2.22:5.61:7.12 (by weight). Water/cement ratio was 0.45. A Portland cement of Type I was used. An open-ended coaxial probe method was used to measure the real and imaginary parts of the complex permittivity of the hardened concrete. The conductivity was deduced from the imaginary part of the measured values. The penetration depth of concrete is 77.4 mm at 5 GHz.

When the dielectric losses occur as a result of conduction currents through the dielectric, the equivalent conductivity \( \sigma \) serves in the imaginary part of the complex permittivity in \( \varepsilon'' \).

\[
\sigma = \varepsilon'' \omega \\
= (\varepsilon' \tan \delta) \omega \\
= (\varepsilon_r \varepsilon_0 \tan \delta) \omega \\
= (\varepsilon_r \varepsilon_0 \tan \delta) (2\pi f) \tag{4-20}
\]

where \( \sigma \) is conductivity (mhos/meter), \( \omega \) is angular frequency (rad/sec), and \( f \) is the number of cycles per second (Hz). The conductivity is calculated from the loss factor measured in Chapter 3. The calculated values of conductivity are presented in Figure 4-7 for concrete, in Figure 4-8 for mortar, and Figure 4-9 for reference materials.

The electromagnetic properties determine how concrete interacts with electric and magnetic fields of an incoming wave. One of the important aspects of the electromagnetic properties of concrete is that they vary with frequency and other physical conditions of concrete such as moisture content and density.
Figure 4-7. Conductivity of concrete.

Figure 4-8. Conductivity of mortar.
In this modeling, a single set of constitutive parameters, dielectric constant and conductivity, is used because the dielectric constant does not vary with frequency over the frequency range up to 5 GHz and the variation of the conductivity is small enough that the single value of conductivity at 5 GHz can represent the property of concrete up to 5 GHz. Fixed values of the electromagnetic properties of concrete can be used for the modeling if these values are constant over the interested frequency range or the variation is negligible especially over a narrow bandwidth as the case presented here. The changing electromagnetic properties of concrete can be also incorporated in the FD-TD modeling [Lee et al., 1991; Joseph et al., 1991].

4.3.3 Computational Domain and Incident Wave

A computational domain is discretized by square grids as a single grid size is denoted as $\Delta$. The domain consists of 800 x 1400 grids as shown in Figure 4-10. To ensure no reflections from the boundaries, a concrete target must be located within 400 grids, away 200 grids from the boundaries for each side. Then, a physical size of the grid $\Delta$ is decided based on the size of a concrete specimen. Throughout the modeling work
performed in this research, a grid size of 0.001524 m is used. This grid size satisfies the above requirement for all of concrete specimens used for the modeling.

In the modeling, a plane wave generated by an excitation source located at the top of the computational domain travels downward as a function of time. As the wave hits the concrete target, a part of the wave is reflected back upward and the remainder of the wave travels through concrete. The reflected signal can be captured at any desired point within the domain, for example, point A or B in Figure 4-10. The reflected signal is also collected as a function of time in this finite difference-time domain method.

Figure 4-10. A computational domain used for the modeling.
The incident wave used for the modeling is a Gaussian pulse plane wave, \( V(t) = e^{-2(t-t_0)^2/T^2} \) (Figure 4-2). To achieve accurate results, the grid sizes are taken to be less than a fraction of (~ 1/10) of the smallest wavelength in any medium within the domain. Thus, 1.524 mm is used as a single grid size, which corresponds to a fraction of the wavelength at 5 GHz inside concrete specimens. Based on the grid size, the physical size of the computational domain is to be 1.2192 m x 2.1336 m. The detector which collects the reflected signal from the target is located at point A in Figure 4-10. The physical distance between the detector and the outer boundary of the concrete cylinder is 0.9754 m. This puts the detector in the far field, based on the far field criterion, which gives 0.7742 m from the outer edge of the target. The incident field is a transverse electric, where the electric field is in z-direction in Figure 4-10.

### 4.3.4 Results of Modeling

Results of the two-dimensional FD-TD simulation for the model of a 154.2 mm diameter concrete cylinder with a 25.4 mm diameter rebar at the center are shown in Figure 4-11. The total electric field is shown at four instances of time. The magnitude of the electric field is represented by the intensity of the dark strip. The rebar is modeled as a perfect electric conductor.

In Figure 4-11, the Gaussian pulse plane wave is directed from top to bottom in the picture. As the wave hits the front surface of the concrete cylinder, a part of the wave is reflected toward the direction where the wave came from and the remaining part of the wave is transmitted into the concrete continuing to propagate through the concrete cylinder. The slow-down of the wave inside concrete is clearly seen in Figure 4-11b. The speed of the wave inside concrete is decreased by the dielectric constant, \( \varepsilon_r \) of 4.8 in this modeling, as \( 1/\sqrt{\varepsilon_r} \). As the wave passes through the rebar in Figure 4-11c, another reflection occurs. In Figure 4-11d, the last reflection occurs from the back surface of the cylinder as the wave completely moves away from the cylinder.

It should be noted that major reflections are coming from the boundaries where the material property discontinuity occurs (air/concrete, concrete/metal, or concrete/air). The significance of performing modeling of wave scattering as in this paper is to study detectability of such reflections from the boundaries for various types of concrete specimens. High order reflections inside the target and multiple reflections are taken into consideration by the modeling. In the following, one-dimensional images obtained as results of the simulation are provided. In Figures 4-12 through 4-17, color snap shots of modeling results for the other concrete specimens modeled are presented.
Figure 4.11. Two-dimensional FD-TD simulation of wave scattering by a 152.4 mm diameter plain concrete cylinder. The electric field is polarized perpendicular to the picture. The dielectric constant of concrete is 4.8 and conductivity is 0.15 mhos/m. The time width of the incident Gaussian pulse is 0.0762 ns.
Figure 4.12. A close-up snap shot of 2-D modeling of wave scattering by a 6" diameter concrete cylinder. Red and blue colored strips are for incident and reflected waves.

Figure 4.13. A close-up snap shot of 2-D modeling of wave scattering by a 6" x 6" concrete block. Red and blue colored strips are for incident and reflected waves.
Figure 4-14. A close-up snap shot of 2-D modeling of wave scattering by a concrete slab with a steel bar. Red and blue colored strips are for incident and reflected waves.

Figure 4-15. A close-up snap shot of 2-D modeling of wave scattering by a concrete slab with a steel bar. Red and blue colored strips are for incident and reflected waves.
Figure 4-16. A close-up snap shot of 2-D modeling of wave scattering by a plain concrete slab. Red and blue colored strips are for incident and reflected waves, respectively.

Figure 4-17. A close-up snap shot of 2-D modeling of wave scattering by a plain concrete slab. Red and blue colored strips are for incident and reflected waves, respectively.
One-dimensional images of three groups of the specimens are shown in Figures 4-18, 4-19, and 4-20. The images were obtained by capturing the reflected electric field at point A in Figure 4-10. The received electric field is plotted as a function of time. The results of the cylindrical specimens are discussed first and compared to the square and rectangular specimens.

In Figure 4-18a, for the case of a plain concrete cylinder with no inclusion, the region around the peaks B and C correspond to the front and back surfaces of the cylinder, respectively. These peaks are clearly identified by tracing the reflections from the computer run as shown in Figure 4-11. The negative sign of B comes from the reflection coefficient at the air/concrete boundary, which is the front surface of the concrete cylinder. The positive sign of C comes from the reflection coefficient at the concrete/air boundary, which is the back surface of the cylinder. These examinations of the sign of reflection coefficients confirm the identification of the peaks. The diameter of the cylinder can be calculated by taking the difference between the peaks and multiplied by the speed of wave inside concrete, which is reduced by the permittivity of concrete. Then, the total distance is divided by 2 for one way distance as:

\[
\text{distance} = \text{velocity} \times \text{time} = \frac{c}{\sqrt{\varepsilon_r}} \times \text{time difference} / 2 \tag{4-21}
\]

where \(c\) is speed of wave in air = \(3 \times 10^8 \, \text{m/s}\) and \(\varepsilon_r\) is the permittivity of concrete. The calculated distances are summarized in Table 4-1.

In Figure 4-18b, for the case of a concrete cylinder with a 25.4 mm diameter rebar at the center, the front and back surfaces of the cylinder are captured as peaks B and C. The third peak D represents the rebar. This image is obtained from the simulation shown in Figure 4-11. The locations of the peaks B and C do not change due to the rebar when they are compared to the ones in Figure 4-18a. Instead, the magnitude of the peak C decreased compared to Figure 4-18a because of high scattering due to the rebar. The sign of D in the negative direction confirms that it is a reflection from an electric conductor.

In Figure 4-18c, for the case of a concrete cylinder with a 25.4 mm diameter void at the center, the peak E represents the presence of the void. Again, the locations of the peaks B and C do not change due to the void when they are compared to the ones in Figure 4-18a. Unlike the case with a rebar, the magnitude of peak C does not decrease due to the void.
Figure 4-18. One-dimensional images of 152.4 mm diameter concrete cylinders.
(a) Square specimen with no inclusion

(b) Square specimen with a 25.4 mm diameter rebar at the center

(c) Square specimen with a 25.4 mm diameter void at the center

Figure 4-19. One-dimensional images of 152.4 mm x 152.4 mm square concrete blocks.
(a) Rectangular specimen with no inclusion

(b) Rectangular specimen with a 25.4 mm diameter rebar at the center

(c) Rectangular specimen with a 25.4 mm diameter void at the center

Figure 4-20. 1-D images of 609.6 mm x 152.4 mm rectangular concrete specimens.
The peak E is positive indicating the wave is reflected at the concrete/air boundary, which is the front surface of the void. As the wave gets back into the concrete after passing the void, the sign of the electric field changes to negative as shown in peak F.

The one-dimensional images obtained from the cylindrical specimens clearly capture the existence of the target and its inclusion of the rebar or void at a distance of 0.9754 m. Results of the modeling for square and rectangular specimens are shown in Figures 4-19 and 4-20. The larger magnitude of reflections from the front surfaces are noticed with the square and the rectangular specimens compared to those of the cylindrical specimens. This is due to the larger contact area of the surface exposed to the incoming electromagnetic waves. Edge effects are shown with the square and rectangular specimens, which are not observed with the cylindrical specimens. The calculated distances between the front and the back surfaces and the locations of the inclusions for the three different types of the specimens are summarized in Table 4-1.

Table 4-1. Calculated distances between material boundaries obtained from the numerical modeling.

<table>
<thead>
<tr>
<th>Concrete Specimens</th>
<th>Cylinders (152.4 mm diameter)</th>
<th>Squares (152.4 mm x 152.4 mm)</th>
<th>Rectangles (609.6 mm x 152.4 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Front to back surface distance actual: 152.4 mm</td>
<td>124.32 mm</td>
<td>137.29 mm</td>
<td>155.66 mm</td>
</tr>
<tr>
<td>b) Front surface to rebar distance actual: 63.5 mm</td>
<td>64.86 mm</td>
<td>65.94 mm</td>
<td>65.94 mm</td>
</tr>
<tr>
<td>c) Front surface to void distance actual: 63.5 mm</td>
<td>64.86 mm</td>
<td>65.94 mm</td>
<td>65.94 mm</td>
</tr>
</tbody>
</table>

The results of the FD-TD modeling scheme demonstrate the capability of the method in detecting the front and back surfaces of the specimens as well as the inclusions embedded inside. Identification of these reflections are possible by visually following the reflections shown on the computer screen as a function of time, by examining the sign of the reflection coefficients, and by comparing the calculated distances between the peaks to the actual dimensions of the target.

The cylindrical targets produce smoother reflected signals compared to the square and rectangular shaped targets. For all three types of specimens, the location of the first reflection from the front surface is the same indicating that there is no shape or dimension
effect on the front surface reflection. However, for the back surface reflection, cylindrical specimens produce earlier return than the squares and the rectangles due to creeping wave mechanism, which is a phenomenon generally associated with smooth bodies. Both the square and the rectangular specimens show edge effects. The edge effect is more severe with the square specimens when there is an inclusion. The wave interacting with edges interrupts the signal from the inclusions as seen in Figure 4-19b and 4-19c. The rectangular specimens give good results in picking up the dimensions of the whole target and the location of the inclusions. The locations of inclusions for rectangular specimens are clearly seen in the larger scale plots for clarity.

The source of error for the FD-TD modeling comes from the fact that the target is discretized and modeled by square grids. Curved edge of cylinders are approximated by squares. The computational domain has open boundary condition simulating open air measurement. Absorbing boundary condition applied in the modeling can have a certain error, even though it should absorb any reflection passing through the outer boundary of the domain.

Another aspect of this modeling is that it incorporates the measured electromagnetic properties of concrete as input data. The physical condition of concrete and the frequency of incoming wave determine the electromagnetic properties of concrete. If the frequency dependency of the property is small or the incident wave has narrow frequency bandwidth, constant values of the properties may be used as in this modeling. Incorporation of changing electromagnetic properties is possible but may not be absolutely necessary, if the variation is negligible.

4.4 Implementation of a Signal Processing Scheme for Wideband Radar Measurements

In the previous section, the modeling has been performed with a Gaussian pulse plane wave. The wave has a wide bandwidth but centered at dc. The actual radar measurement is always performed with a center frequency other than dc. Thus, radar measurements need to be simulated with a Gaussian pulse modulated sinusoidal wave, which has a center frequency at anywhere in the microwave frequency spectrum.

In this section, a signal processing technique implemented to simulate actual radar measurement with the Gaussian pulse modulated sinusoidal wave is presented. A computer simulation of radar measurement of 12" x 4" x 12" plain concrete block at 3.4 to 5.8 GHz is presented here as a sample case. The simulation was done using the FD-TD program to
incorporate the same measurement parameters as the actual radar measurements have. The following is the comparison of measurement parameters used for both radar measurements and computer simulation.

<table>
<thead>
<tr>
<th></th>
<th>ISAR Measurement</th>
<th>Computer Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>3.4 to 5.8 GHz</td>
<td>3.4 to 5.8 GHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>4.6 GHz</td>
<td>4.6 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2.4 GHz</td>
<td>2.4 GHz (half powered)</td>
</tr>
<tr>
<td>Polarization</td>
<td>VV/HH</td>
<td>TE/TM</td>
</tr>
<tr>
<td>Grid Size for Computation</td>
<td>-</td>
<td>0.001524 m</td>
</tr>
<tr>
<td>Incident Angle</td>
<td>normal</td>
<td>normal</td>
</tr>
<tr>
<td>Electromagnetic Properties</td>
<td>6.6 for dielectric constant</td>
<td>6.6 for dielectric constant</td>
</tr>
<tr>
<td></td>
<td>0.2 mhos/m for conductivity</td>
<td>0.2 mhos/m for conductivity</td>
</tr>
</tbody>
</table>

### 4.4.1 Signal Processing Scheme Implemented

One-dimensional imaging is performed from the FD-TD modeling. A signal processing program is developed to simulate 1-D radar measurement situation. The signal processing scheme is summarized as follows with corresponding figures indicated in the parentheses.

A modulated Gaussian pulse plane wave \( V_{\text{incidem}}(t) \) is directed to a concrete target either with the electric field of the wave perpendicular or parallel to the cross-sectional area of a specimen (Figure 4-4), which has a center frequency and bandwidth in frequency (Figure 4-5). Using the FD-TD numerical modeling technique, the reflected wave from the concrete specimen is captured in the far field as \( V_{\text{reflected}}(t) \) (Figure 4-21). The reflected waves contain information about the concrete target in its interaction with the incident wave, as well as the characteristics of the incident wave. Thus, to extract information about the specimens only out of the reflected waves, a numerical scheme is applied. The reflected wave in time domain, \( V_{\text{reflected}}(t) \), is Fourier transformed to the frequency domain (Figure 4-22). The incident modulated Gaussian pulse \( V_{\text{incidem}}(t) \) is also Fourier transformed as in Figure 4-5. Then, the reflected wave is normalized to the incident wave in frequency (Figure 4-23). The normalized response is multiplied by a hamming window (Figure 4-24) to examine the result with an emphasis of the initially given center frequency and
bandwidth (Figure 4-25). Finally, the windowed normalized response in frequency domain is inverse Fourier transformed to time domain to obtain the true reflection from the concrete target (Figure 4-26). The procedure is summarized as,

$$F^{-1}\left[\text{hamming window} \ast \frac{F\{V_{\text{reflected}}(t)\}}{F\{V_{\text{incident}}(t)\}}\right]$$ (4-22)

The inverse Fourier transformed signal in V/m is plotted in linear scale in absolute value in Figure 4-27 and in dB scale for view in Figure 4-28,

$$\text{magnitude in dB} = 20 \times \log(\text{absolute(processed signal in V/m)})$$ (4-23)

The results of 1-D modeling for a 12" x 4" x 12" concrete block for both TE and TM cases are shown in Figure 4-29. Figure 4-29 is the final output of the signal processing.
Figure 4-21. The reflected wave $V_{\text{reflected}}(t)$.

Figure 4-22. Fourier transform of the reflected wave $F\{V_{\text{reflected}}(t)\}$.
Figure 4-23. Normalization of the reflected wave with respect to the incident wave

\[ \frac{F\{V_{\text{reflected}(t)}\}}{F\{V_{\text{incident}(t)}\}}. \]

Figure 4-24. The hamming window.
Figure 4-25. The normalized response multiplied by the hamming window

\[ \text{hamming window} \ast \left\{ \frac{F\{V_{\text{reflected}}(t)\}}{F\{V_{\text{incident}}(t)\}} \right\}. \]

Figure 4-26. The inverse Fourier transform, \( F^{-1}\left[ \text{hamming window} \ast \left\{ \frac{F\{V_{\text{reflected}}(t)\}}{F\{V_{\text{incident}}(t)\}} \right\} \right] \)
Figure 4-27. The process signal in linear scale in absolute value.

Figure 4-28. magnitude in \( dB = 20 \times \log(\text{absolute}(\text{processed signal in V/m})) \),
4.4.2 Significance of the Processing Scheme Implemented

In Section 4.3, the electromagnetic wave propagation and scattering through and by concrete specimens are modeled using a Gaussian pulse as an incident wave. As results, reflected signals from the specimens contain information about the incident wave, which is centered at dc. This limits simulation capability without considering different center frequency. Actual radar measurements are made at a certain center frequency which is not centered at dc. Thus, the signal processing scheme developed in Section 4.4 enable to simulate various radar measurement situation with different combination of center frequency and bandwidth.

In Figure 4-29, a typical computer simulation result of a radar measurement is presented. In the following sections, computer simulations made using a Gaussian pulse modulated sinusoidal wave as an incident wave are presented. The imagery obtain from numerical modeling and signal processing scheme presented in Subsection 4.4.1 is shown in Figure 4-28. The figure was a result of inverse Fourier transforming the frequency domain result in Figure 4-23. In this subsection of 4.4.2, the imagery obtained by taking the same number of data points as radar measurements in frequency domain and then the data was inverse FFT, which produced the plot in Figure 4-29.

![Figure 4-29](image_url)

Figure 4-29. Results of computer simulation of radar measurements in one-dimensional image. Peak A and B represents front and back surface of a concrete specimen,
respectively. Peak C corresponds the reflection from a steel reinforcing bar located at the center.

## 4.5 Results of Simulation for Target Geometry Effect

### 4.5.1 Concrete Specimens Modeled

To simulate actual radar measurements, the signal processing scheme developed in Section 4.4 is used. Radar measurements of concrete specimens at 3.4 to 5.8 GHz are simulated. Concrete specimens used for modeling are given in Figures 4-30, 4-31, and 4-32.

![Figure 4-30](image1)

Figure 4-30. Cross-sectional view of 6 in. diameter cylindrical concrete specimens; (a) plain concrete with no inclusion, (b) with a 0.5 in. diameter steel reinforcing bar, and (c) with a 0.5 in. diameter void at the center of the cylinder. All the specimens have 12 in. height.

![Figure 4-31](image2)

Figure 4-31. Cross-sectional view of 6 in. x 6 in. concrete specimens; (a) plain concrete with no inclusion, (b) with a 1 in. diameter steel reinforcing bar, and (c) with a 1 in. diameter void at the center. All the specimens have 12 in. height.
Figure 4-32. Cross-sectional view of 12 in. x 4 in. concrete specimens: (a) plain concrete, (b) with 1 in. diameter steel reinforcing bars, (c) with 1 in. diameter voids, and (d) with a 10 in. x 1 in. delamination at the center. All the specimens have 12 in. height.

4.5.2 Results of Simulation

Results of computer simulation are shown in Figures 4-33 through 4-42. These results are compared to the modeling results in Figures 4-18, 4-19, and 4-20. The sizes of specimens and inclusions are not the same in Section 4.5 and Section 4.3. In the modeling results in Section 4.3, the reflected signals are much clearer than the ones in Section 4.5. However, it does not simulate actual radar measurement condition by having the center frequency at dc. The results in Section 4.5 have more complex returns than the ones in Section 4.3, but simulate radar measurement situation more closely. Computer simulation provided a basis in determining concrete specimen sizes prior to radar measurements. Even though there are limitations in simulating radar measurements, the size effect of target geometry was examined through modeling.

4.5.3 Corresponding Radar Measurements Made

Actual radar measurements are made on the specimens modeled in the simulation. Radar measurements results of the specimens shown in Figure 4-30 and Figure 4-31 are given in Appendix A and the specimens shown in Figure 4-32 are given in Appendix B, respectively.
Figure 4-33. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 6" diameter concrete cylinder.

Figure 4-34. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 6" diameter concrete cylinder with a 0.5" diameter bat at the center,
Figure 4-35. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 6" diameter concrete cylinder with a 0.5" diameter void at the center.

Figure 4-36. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 6" x 6" concrete block.
Figure 4-37. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 6" x 6" concrete block with a 1" diameter steel bar at the center.

Figure 4-38. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 6" x 6" concrete block with a 1" diameter void at the center.
Figure 4-39. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 12" x 4" concrete block.

Figure 4-40. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 12" x 4" concrete block with three 1" diameter steel bars at 1" depth.
Figure 4-41. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 12" x 4" concrete block with three 1" diameter voids at 1" depth.

Figure 4-42. 1-D image obtained from computer simulation from 3.4 to 5.8 GHz on 12" x 4" concrete block with 10" x 1" delamination at 1" depth.
4.6 Results of Simulation for the Study of Center Frequency and Bandwidth

The frequency bandwidth determines range resolution, which improves detection capability. The advantage of the ISAR used for the study is its capability to generate wideband signal. In this section, effect of wide bandwidth in combination with different center frequency of the waves is illustrated using the developed one-dimensional signal processing technique. A Gaussian pulse modulated sinusoidal wave is used to simulate different center frequency and bandwidth. Six cases studied are listed in Table 4-3.

Table 4-3. Combination of center frequency and bandwidth.

<table>
<thead>
<tr>
<th>Center frequency</th>
<th>Bandwidth</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 GHz</td>
<td>2.2 GHz</td>
<td>4.3 GHz</td>
</tr>
<tr>
<td>10 GHz</td>
<td>2.2 GHz</td>
<td>4.3 GHz</td>
</tr>
<tr>
<td>15 GHz</td>
<td>2.2 GHz</td>
<td>4.3 GHz</td>
</tr>
</tbody>
</table>

Figures 4-43, 4-44, 4-45, 4-46, 4-47, and 4-48 illustrate wideband measurement simulation for a 6" x 6" concrete specimen with different combination of center frequency and bandwidth. The specimen is first shined by a wave centered at 4.5 GHz with 2.2 GHz bandwidth as shown in Figure 4-43. The reflections from the first and back surfaces are shown near 6 and 8.5 ns with wide peaks. The peaks get sharper with the wider bandwidth of 4.3 GHz in Figure 4-44. Between Figures 4-43 and 4-44, the only difference is the bandwidth, $B$. The bandwidth determines range resolution as in Eq. (5-1). By doubling the bandwidth, the image becomes sharper in Figure 4-44 than the one in Figure 4-43.

Now, the center frequency is shifted from 4.5 GHz to 10 GHz with the same bandwidths for the same concrete specimen in Figures 4-45 and 4-46. At higher frequency, the reflections are slightly higher than the ones in Figures 4-43 and 4-44. And the peaks are more dense at higher frequency. The same phenomenon is observed in Figures 4-47 and 4-48 with even sharper contrast compared to the returns in Figures 4-43 and 4-44.
Figure 4-43. 1-D image with an incident wave centered at 4.5 GHz with 2.2 GHz bandwidth.

Figure 4-44. 1-D image with an incident wave centered at 4.5 GHz with 4.3 GHz bandwidth.
Figure 4-45. 1-D image with an incident wave centered at 10 GHz with 2.2 GHz bandwidth.

Figure 4-46. 1-D image with an incident wave centered at 10 GHz with 4.3 GHz bandwidth.
Figure 4-47. 1-D image with an incident wave centered at 15 GHz with 2.2 GHz bandwidth.

Figure 4-48. 1-D image with an incident wave centered at 15 GHz with 4.3 GHz bandwidth.
This simulation case presents the significance of sending waves over wide bandwidth. As illustrated, wide bandwidth signal is better for clear imagery. The higher center frequency gives higher return of reflections and the image is more dense. Simulations presented here can be applied to other measurement cases, for example, with inclusions or with different dimensions of specimens for the prediction of radar measurement results and for the identification of appropriate combination of radar measurement parameters to achieve a certain goal in the measurements.

Especially, the radar available for the research work has wideband capability. The development of wideband radar measurement simulation technique as used in this wideband simulation is an essential tool in parallel with radar measurements for comparison and interpretation of radar measurement results.

4.7 Results of Simulation for Detectability of Thin Delaminations inside Concrete

As an extended work of the condition monitoring, detectability of thin cracks is examined. Condition monitoring basically depends on the detectability of small abnormalities including cracks. Again, the detectability of a crack is determined by center frequency, bandwidth, and the electromagnetic properties and size of the crack.

Computer simulation is a useful tool in conducting this type of predictive work. As a sample case, a concrete block which has cross-sectional dimensions of 12" x 4" is modeled. Three parameters are studied: bandwidth of an incident wave, crack location measured from the surface of the concrete block, and the thickness of the crack as summarized in Table 4-4.

Table 4-4. Parameters used for thin delamination detectability study.

<table>
<thead>
<tr>
<th>Size of a crack</th>
<th>Distance from the surface to the center of a crack</th>
<th>Frequency of an incident wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8&quot; x 6&quot; (3 mm x 152.4 mm)</td>
<td>1&quot;, 2&quot;, and 3&quot;</td>
<td>3.4-5.8, 2.2-7 GHz</td>
</tr>
<tr>
<td>1/4&quot; x 6&quot; (6 mm x 152.4 mm)</td>
<td>1&quot;, 2&quot;, and 3&quot;</td>
<td>3.4-5.8, 2.2-7 GHz</td>
</tr>
<tr>
<td>1/2&quot; x 6&quot; (12 mm x 152.4 mm)</td>
<td>1&quot;, 2&quot;, and 3&quot;</td>
<td>3.4-5.8, 2.2-7 GHz</td>
</tr>
<tr>
<td>1&quot; x 6&quot; (24 mm x 152.4 mm)</td>
<td>1&quot;, 2&quot;, and 3&quot;</td>
<td>3.4-5.8, 2.2-7 GHz</td>
</tr>
</tbody>
</table>
The modeling predicted radar measurement results using a combination of the above parameters. Selected results are shown in Figures 4-49, 4-50, 4-51, and 4-52. With narrower frequency bandwidth of 2.4 GHz with 3.4 to 5.8 GHz waveforms, the existence of a 1/8" crack and a 1/4" crack is shown in Figures 4-49 and 4-50, respectively. The exact location of a crack is not clearly seen for the narrower frequency measurement case. This is due to less resolution with a narrow bandwidth. With a doubled bandwidth of 4.8 GHz from 2.2 to 7.0 GHz, the cracks are clearly distinguishable as shown in Figures 4-51 and 4-52.
Figure 4-49. 1-D image obtained from modeling at 3.4 to 5.8 GHz for a 12" x 4" concrete block with a 1/8 in. (3 mm) x 6 in. (15 cm) crack located at 2 in. (5 cm) from surface.

Figure 4-50. 1-D image obtained from modeling at 3.4 to 5.8 GHz for a 12" x 4" concrete block with a 1/4 in. (6 mm) x 6 in. (15 cm) crack located at 2 in. (5 cm) from surface.
Figure 4-51. 1-D image obtained from modeling at 2.2 to 7 GHz for a 12" x 4" concrete block with a 1/8 in. (3 mm) x 6 in. (15 cm) crack located at 2 in. (5 cm) from surface.

Figure 4-52. 1-D image obtained from modeling at 2.2 to 7 GHz for a 12" x 4" concrete block with a 1/4 in. (6 mm) x 6 in. (15 cm) crack located at 2 in. (5 cm) from surface.
4.8 Discussion

As defined in Chapter 2, numerical modeling refers to the modeling of electromagnetic wave propagation and scattering through and by concrete specimens modeled. Computer simulation refers to a process of data manipulation to simulate actual radar measurement situation, which involve the use of center frequency and bandwidth. Based on these definitions used throughout this thesis, computer simulation includes numerical modeling as a part of its process.

The finite difference-time domain (FD-TD) method was selected as modeling tool because of its ease in modeling a variety of incident waves and target geometry with inclusions. The other modeling methods include infinite cylinder method and method of moment. However, the other methods either cannot have inclusions or takes much more computational time than the FD-TD method.

Numerical modeling provides a theoretical tool to predict or verify radar measurement results. The study of geometry effect was presented in Section 4.3 and computer simulation of actual radar measurements on preliminary concrete specimens was presented in Section 4.5. At the initial stage of the research work, determination of proper geometry and dimensions of concrete specimens for radar measurements was an important issue. In that specimen size selection process, computer simulation on various types of specimens provided essential information as to how the results changed depending on the different geometry of specimens with the same thickness. Cylindrical specimens with 6" diameter x 12" height gave less edge effect but it underestimated the thickness. Square specimens with 6" width x 6" thickness x 12" height had severe edge effects, while rectangular specimens with 24" width x 6" thickness x 12" height had the least edge effects. All of these phenomena could be studied through computer simulation without actually performing radar measurements. Thus, it can be emphasized that computer simulation provides a useful means of radar measurement prediction whenever approximate results of radar measurements are needed.

Computer simulation scheme implemented in the research work is a viable tool for NDE of concrete systems. As demonstrated in Section 4.6 and Section 4.7, the simulation scheme is now expanded for wideband, shifted center frequency radar measurements. Similar to the target geometry effect study, detectability of thin 6" long delaminations with thickness varied from 1/8" to 1" located at either 1", 2" or 3" from the surface of concrete has been examined. The delaminations are detected with an incident wave which has center frequency of 4.6 GHz and a bandwidth of 4.8 GHz. With the narrower bandwidth of 2.4 GHz, the presence of delaminations are detected but not clearly seen as in the wider
bandwidth case. Actual radar measurements of concrete specimens with delaminations are performed in Chapter 5 and the results are presented in Appendix B.

The significance of the implemented signal processing schemes for computer simulation is that any other types of inclusions at any given combination of measurement parameters can be simulated. This is a useful tool whenever an estimation is needed prior to radar measurements.

It should be pointed out that there are differences between computer simulation and radar measurements. First, the measurements are all three-dimensional: the measurement setup and the concrete specimens, while the modeling is two-dimensional. Thus, inclusions such as steel bars and voids are modeled as infinitely long objects in the modeling. This causes different returned signal in the modeling compared to the radar measurements. Second, the modeling assumes that the material under testing is homogeneous. This means that a concrete target modeled has homogeneous material properties throughout the cross-sectional area modeled, while actual concrete specimens have variation of their properties over the whole specimen. Third, the incident wave generated by the modeling scheme has the same bandwidth as the incident wave in the radar in terms of a half-power bandwidth. This is slightly different from the bandwidth that a radar is generating as an output of gated continuous wave with sweeping frequency. Fourth, the numerical modeling has made approximations in its numerical solution process. Radar measurements also have background noise during measurements and sometimes slight inconsistency of placing concrete specimens at the right location on the top of the Styrofoam tower. All of these attribute errors and differences in comparing the results from modeling and the results from measurements.

In overall, the results from both modeling and measurements are comparable despite some intrinsic differences as discussed above. By generating enough data both from modeling and measurements, more exact match between those two results can be made.
Chapter 5
Radar Measurements of Concrete Specimens

5.1 Objectives

The objectives of conducting radar measurements are to determine characteristics of concrete specimens upon radar measurements and to develop an appropriate measurement technique for nondestructive evaluation (NDE) of concrete. Radar measurements are affected by measurement parameters such as center frequency, frequency bandwidth, and polarization of incident waves, geometric and material properties of concrete, and inclusions embedded inside concrete. Throughout the measurements, emphases are given to three areas of interests for NDE applications: i) determination of penetration and detection capabilities of a radar system in connection with plain concrete specimens with different thickness and dimensions without inclusions, ii) monitoring of deterioration inside concrete which involves small holes and delaminations in different sizes at different locations, and iii) detection of inclusions embedded inside concrete such as steel reinforcing bars and bars in combination with delaminations.

In this chapter, a description of an inverse synthetic aperture radar used for measurements is given with a measurement setup. Signal processing schemes developed to process raw data from measurements to generate one- and two-dimensional imagery are provided. Examples of imaging concrete specimens are given. Results of the three major cases stated above are discussed with analysis.

Computer simulation performed in parallel with the radar measurements are described in Chapter 4.

5.2 Inverse Synthetic Aperture Radar (ISAR)

5.2.1 Principles

Sets of wideband radar measurements are made using an inverse synthetic aperture radar (ISAR). The ISAR is used because of its capability in generating 2-D imagery, and ease and versatility in conducting measurements on laboratory size concrete specimens. The
ISAR is similar to synthetic aperture radar (SAR) in principles in achieving range and cross-range resolutions with wide bandwidth of frequency at a distance [Menon et al, 1993; Mensa, 1981].

In the principles of radar imaging, the resolution of closely spaced object features can be accomplished by narrowing the transmitted pulse width \( T \) and increasing the system bandwidth \( B \) such that \( BT = 1 \), thus yielding range resolution \( \rho_r \equiv \frac{c}{2B} \). A time-bandwidth product approximating unity is inherent to the class of pulse radars in which a carrier is amplitude modulated by a pulsed waveform. Resolution is the ability to distinguish closely spaced objects. An arbitrarily high degree of range accuracy can be obtained by using signals with large bandwidth or high energy [Skolnik, 1970].

The purpose of using either SAR or ISAR is to generate cross-range imagery. SAR can provide significant improvement in cross-range resolution over that given by a real aperture radar system. The SAR concept employs a coherent radar system and is based on a single moving antenna to simulate the function of all the antennas in a real linear antenna array. This single antenna sequentially occupies the spatial positions of a synthesized array. All received signals, both amplitude and phase, are stored for each antenna position in the synthetic array. These stored data are then processed to re-create the image of the illuminated area seen by the radar. The SAR system produces high cross-range resolution imagery by processing stored backscatter amplitude and phase information obtained by sequentially transmitting and receiving electromagnetic energy along a linear aperture path, re-creating in time a long linear antenna array. The mathematical relationship on which the SAR concept is based is the equivalence between the cross-range target position and the instantaneous Doppler shift of the radar energy backscattered by the target.

If a target itself is rotating and the radar is stationary, return signals can be processed in a manner similar to that previously described to recreate a high cross-range resolution target image. This technique is often referred to as inverse synthetic aperture radar. ISAR techniques have been used to produce target images for objects on rotating platforms, for satellites rotating in orbit, and even for ships at sea which roll rhythmically on the sea surface [Eaves and Reedy, 1987].

There are three major measurement parameters to be considered prior to ISAR measurements: center frequency \( (f_r) \), frequency bandwidth \( (B) \) of incident waves, and rotational angle \( (\Delta \theta_{rad}) \) of a target. These three parameters determine range and cross-range resolutions.

The range and cross-range resolutions which can be achieved by ISAR are determined by the following relationships:
\[
\rho_r = \frac{c}{2B}
\]  
\[
\rho_{xr} = \frac{\lambda_c}{2(\Delta \theta_{rad})}
\]

where \( \rho_r \) is range resolution, \( \rho_{xr} \) is cross range resolution, \( \lambda_c \) is the wavelength of center frequency, and \( \Delta \theta_{rad} \) is the angular rotation of a target in radian during measurement. The resolutions expressed in Eq. (5-1) and Eq. (5-2) are for air. Resolution for concrete is affected by the dielectric constant of concrete as:

\[
\rho_r = \frac{\left( \frac{c}{\sqrt{\varepsilon_r}} \right)}{2B} \text{ in concrete}
\]  
\[
\rho_{xr} = \frac{\left( \frac{c}{f_c \sqrt{\varepsilon_r}} \right)}{2(\Delta \theta_{rad})} \text{ in concrete}
\]

For a reference, range resolution achievable by SAR is the same as Eq. (5-1) and (5-3), where the cross-range resolution by SAR is

\[
\rho_{xr} = \frac{R\lambda_c}{2L} \text{ in air}
\]  

and

\[
\rho_{xr} = \frac{R\left( \frac{c}{f_c \sqrt{\varepsilon_r}} \right)}{2L} \text{ in concrete}
\]

where \( \rho_{xr} \) is cross-range resolution, \( R \) is distance between the radar and the target, \( \lambda_c \) is a wavelength at center frequency, and \( L \) is synthetic aperture length.

A combination of center frequency and bandwidth can be selected from the microwave frequency spectrum as shown in Figure 5-1 to achieve desired range and cross-
range resolution. In reality, the frequency bandwidth is antenna limited. For example, the frequency range and bandwidth available for ISAR measurements used in this research work are determined by antenna as shown in Figure 5-2. In general, a bandwidth increases as a center frequency increases. One of the important objectives of this research work is to find out a proper combination of center frequency and frequency bandwidth suitable for a specific application of the radar method for NDE of concrete.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>0.1</th>
<th>0.3</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Description</td>
<td>VHF</td>
<td>L</td>
<td>S</td>
<td>C</td>
<td>X</td>
<td>Ku</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>(0.2)</td>
<td>(1)</td>
<td>(2)</td>
<td>(4)</td>
<td>(4)</td>
<td>(6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-1. Microwave frequency spectrum with frequency band description and bandwidth.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>1</th>
<th>2</th>
<th>3.4</th>
<th>5.8</th>
<th>8</th>
<th>12</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISAR antenna</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>(1)</td>
<td>(1.4)</td>
<td>(2.4)</td>
<td>(2.2)</td>
<td>(4)</td>
<td>(6)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-2. Frequency range and bandwidth available for ISAR measurements. The bandwidth is limited to antenna.

The third measurement parameter for ISAR measurements is rotational angle of a specimen. As indicated in Eq. (5-2), the rotational angle which is expressed in radian determines the cross-range resolution together with a center frequency. Thus, the larger the rotational angle is, the better the cross-range resolution is. Large rotational angle is not always necessary in case of axisymmetric objects such as concrete cylinders or symmetric objects such as square and rectangular shape concrete blocks. Also, the more the rotational
angle is, it takes more time to complete a measurement. Therefore, an optimum rotational angle is desired for good cross-range resolution and fast measurement.

Resolution is an ability of a radar to resolve two closely placed objects. Based on Eq. (5-1) and Eq. (5-2), large bandwidth at the higher center frequency with a large rotational angle will give the better resolution. But, higher center frequency will result in less penetration into concrete which becomes more lossy at the higher frequency. This tradeoff between detection and penetration capabilities is quantitatively determined through radar measurements in this these work. The results are presented in Section 5.6.

The range and cross-range resolution achievable by the ISAR is estimated in Table 5-1. Refer to Eq. (5-1) and Eq. (5-2) for calculation.

Table 5-1. Selected range and cross-range resolutions by ISAR.

<table>
<thead>
<tr>
<th>ISAR band (GHz)</th>
<th>ISAR bandwidth (GHz)</th>
<th>ISAR center frequency (GHz)</th>
<th>Range resolution</th>
<th>Cross-range resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ~ 2</td>
<td>1</td>
<td>1.5</td>
<td>15 cm (5.9&quot;)</td>
<td>28.7 cm (11.3&quot;)</td>
</tr>
<tr>
<td>2 ~ 3.4</td>
<td>1.4</td>
<td>2.7</td>
<td>10.7 cm (4.2&quot;)</td>
<td>15.9 cm (6.3&quot;)</td>
</tr>
<tr>
<td>3.4 ~ 5.8</td>
<td>2.4</td>
<td>4.6</td>
<td>6.3 cm (2.5&quot;)</td>
<td>9.3 cm (3.7&quot;)</td>
</tr>
<tr>
<td>5.8 ~ 8</td>
<td>2.2</td>
<td>6.9</td>
<td>6.8 cm (2.7&quot;)</td>
<td>6.2 cm (2.5&quot;)</td>
</tr>
<tr>
<td>8 ~ 12</td>
<td>4</td>
<td>10</td>
<td>3.8 cm (1.5&quot;)</td>
<td>4.3 cm (1.7&quot;)</td>
</tr>
<tr>
<td>12 ~ 18</td>
<td>6</td>
<td>15</td>
<td>2.5 cm (1&quot;)</td>
<td>2.9 cm (1.1&quot;)</td>
</tr>
</tbody>
</table>

Note: Resolutions are for air. Resolutions improve inside concrete based on the value of dielectric constant. Cross-range resolution is calculated assuming that the angular rotation is 20 degrees.

The ISAR used for the measurements is capable of transmitting waves at wide frequency range from 0.1 to 18 GHz and fully polarimetric. For the research work, three different frequency bands are used: 2 ~ 3.4 GHz (S/C Band), 3.4 ~ 5.8 GHz (C Band), and 8 ~ 12 GHz (X Band). These three frequency bands are selected in a way that the measurements represent low, medium, and high frequency levels in the microwave frequency spectrum in Figure 5-1. Output power of the ISAR is 20 dBm and dynamic range is 50 dB.
5.2.2 Radar Measurement Setup

A concrete specimen is placed vertically as a target at the top of a turntable made of Styrofoam. The turntable is capable of rotating the target for 360 degrees or less as needed. A monostatic wideband radar is located at a distance which sends and receives the wave. The measurements were made by sweeping frequency from starting frequency $f_1$ to ending frequency $f_2$ with 0.1 GHz increments at a fixed angle. The target is rotated 1 degree at a time for each frequency sweeping. This generates two-dimensional data made of angle and frequency. For typical measurements in the thesis work, the target is rotated for 20 degrees. The frequency sweeping provides the range resolution while the rotation of the target provides the cross-range resolution. A schematic view of the measurement setup is shown in Figure 5-3.

![Diagram](image)

**Figure 5-3.** A schematic view of the ISAR measurements setup.
Figure 5-4. A concrete specimen placed on the top of a rotating Styrofoam tower. The wave is incident from the antenna through the small reflector in Figure 5-5 to the specimen.

Figure 5-5. An X-Band (8 - 12 GHz) antenna shown with a small disc reflector
The measurement distance \( R \) of 14.4 meters was chosen to satisfy far field criterion

\[
\text{Far - field criterion} \geq \frac{2d^2}{\lambda_{\text{shortest}}} = \frac{2d^2}{c} \left( \frac{\lambda_{\text{shortest}}}{f_{\text{highest}}} \right) \tag{5-7}
\]

where \( d \) is the maximum dimension of the target and \( \lambda \) is wavelength [Knott et al., 1985]. The criterion requires that the phase of the incident wave at the center of the target is different from the phase at the extremes of the target less than \( \pi/8 \) radians (22.5°). This limiting process essentially requires that the target be illuminated by a nearly plane wave.

The far-field criterion for a typical size of concrete specimen used for measurements at ISAR frequency ranges are listed in Table 5-2.

<table>
<thead>
<tr>
<th>ISAR band (GHz)</th>
<th>ISAR highest frequency (GHz)</th>
<th>Minimum measurement distance to satisfy far-field criterion (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ~ 2</td>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td>2 ~ 3.4</td>
<td>3.4</td>
<td>2.1</td>
</tr>
<tr>
<td>3.4 ~ 5.8</td>
<td>5.8</td>
<td>3.6</td>
</tr>
<tr>
<td>5.8 ~ 8</td>
<td>8</td>
<td>5.0</td>
</tr>
<tr>
<td>8 ~ 12</td>
<td>12</td>
<td>7.4</td>
</tr>
<tr>
<td>12 ~ 18</td>
<td>18</td>
<td>11.1</td>
</tr>
</tbody>
</table>

5.3 Laboratory Size Concrete Specimens for Radar Measurements

5.3.1 Manufacturing of Concrete Specimens

Laboratory size concrete specimens with different dimensions are used as targets for the measurements. Concrete specimens were cast with water/cement/sand/coarse aggregate mix ratio of 1:2.22:5.61:7.12 (by weight). This is the mix ratio provided by the Concrete
Concrete specimens were made using Plexiglas moulds for 12" x 4" x 12" and 6" x 6" x 12" specimens. Fresh concrete made from the mix ratio above was mixed using a mixer and poured into the mould. During casting, the fresh mix was rodded with a steel bar. The mix was vibrated on a vibration table for about 15 to 20 minutes until no more air bubbles were seen. After hardening 24 hours inside the mould, the hardened concrete specimen was then removed from the mould and placed into water for seven days for curing. Depending on the measurements to be made, dry specimens were air dried in ambient temperature and humidity, while wet specimens were placed in water until right before the measurements. For 6" diameter cylindrical specimens, 6" inside diameter tin shells were used to shape fresh concrete mix into a cylinder. The age of the specimens at the time of the measurements was 4 weeks. The uniaxial compression strength of the specimen was 21 MPa at 28 days.

Sample pictures of concrete specimens made are shown in Figure 5-6 and Figure 5-7. The entire concrete specimens used for the measurements are shown in Figures 5-8 through 5-14. Concrete specimens have mainly three types of dimensions: i) 12" x 4" x 12" blocks, ii) 6" x 6" x 12" blocks, and iii) 6" diameter x 12" cylinders. The dimensions are selected based on numerical modeling results, prediction of penetration and detection possibilities, and weight limit imposed by the Styrofoam tower as a part of the ISAR measurement setup.

The numerical modeling performed prior to radar measurements suggested in its results that there is an edge effect for specimens with finite face dimensions. As discussed in detail in Section 4.3, specimens with the same thickness but with different dimensions which face a radar give different returned signals. Ideally, the larger the face dimension is, the less the edge effect is and the better the results are. However, weight of concrete specimens must be less than about 50 pounds in order not to damage the Styrofoam tower. Thus, after runs of numerical modeling for different size of specimens, a typical specimen dimension is decided as 12" x 4" x 12". To verify the edge effect predicted from the numerical modeling, 6" x 6" x 12" and 6" diameter x 12" specimens are made as well. Table 5-3 gives weight of specimens.
Table 5-3. Weight of concrete specimens

<table>
<thead>
<tr>
<th>Dimensions of concrete specimens</th>
<th>Weight of specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>50 pounds</td>
</tr>
<tr>
<td>6&quot; x 6&quot; x 12&quot;</td>
<td>37.5 pounds</td>
</tr>
<tr>
<td>6&quot; diameter x 12&quot;</td>
<td>29.5 pounds</td>
</tr>
</tbody>
</table>

* The specimen weight is calculated based on a unit weight of concrete as 150 pounds/cubic feet.

5.3.2 Concrete Specimens for Radar Measurements

Concrete specimens are largely grouped into dry and wet specimens. Dry specimens are exposed to air at least 4 weeks after 7 day curing, while wet specimens left in water at least 4 weeks after 7 day curing. As illustrated in the following figures, specimens have either no inclusion, single or multiple steel bars, or single or multiple voids. The size of bars or voids is either 1" or 0.5" in diameter. Delamination has 10" x 1" size with 12" length. These specimens represent basic concrete elements of concrete systems simulating simple steel reinforcement or deterioration.

Table 5-4. List of concrete specimens for the measurements.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Geometry</th>
<th>Inclusions</th>
<th>Number of Measurements (Band)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6&quot; dia. x 12&quot;</td>
<td>Cylinder</td>
<td>0.5&quot; dia. bar/ hole</td>
<td>3 (S,C)</td>
</tr>
<tr>
<td>6&quot; x 6&quot; x 12&quot;</td>
<td>Square Block</td>
<td>1&quot; dia. bar/ hole</td>
<td>3 (S,C,X)</td>
</tr>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>Rectangular Block</td>
<td>None</td>
<td>2 (S,C,X)</td>
</tr>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>Rectangular Block</td>
<td>0.5&quot; / 1&quot; dia. holes</td>
<td>4 (S,C,X)</td>
</tr>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>Rectangular Block</td>
<td>0.5&quot; / 1&quot; delamination</td>
<td>4 (S,C,X)</td>
</tr>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>Rectangular Block</td>
<td>0.5&quot; / 1&quot; bars</td>
<td>12 (S,C,X)</td>
</tr>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>Rectangular Block</td>
<td>1&quot; water filled delamination</td>
<td>8 (S,C)</td>
</tr>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>Rectangular Block</td>
<td>0.5&quot; dia. bars with 1&quot; delam.</td>
<td>4 (S,C)</td>
</tr>
<tr>
<td>12&quot; x 4&quot; x 12&quot;</td>
<td>Rectangular Block</td>
<td>0.5&quot; dia. cross reinforced bars</td>
<td>1 (S,C)</td>
</tr>
</tbody>
</table>
Figure 5.6. A 12" x 4" x 12" concrete specimen with a 10" x 1" x 12" delamination.

Figure 5.7. A 12" x 4" x 12" concrete specimen with three 1" diameter steel bars inserted.
Figure 5-8. Cross-sectional view of 6 in. diameter cylindrical concrete specimens: (a) plain concrete with no inclusion, (b) with a 0.5 in. diameter steel reinforcing bar, and (c) with a 0.5 in. diameter void at the center of the cylinder. All the specimens have 12 in. height.

Figure 5-9. Cross-sectional view of 6 in. x 6 in. concrete specimens: (a) plain concrete with no inclusion, (b) with a 1 in. diameter steel reinforcing bar, and (c) with a 1 in. diameter void at the center. All the specimens have 12 in. height.

Figure 5-10. Cross-sectional view of 12 in. x 4 in. concrete specimens: (a) plain concrete, (b) with 1 in. diameter steel reinforcing bars, (c) with 1 in. diameter voids, and (d) with a 10 in. x 1 in. delamination at the center. All the specimens have 12 in. height.
Figure 5-11. Cross-sectional view of 12 in. x 4 in. concrete specimens: (a) with 0.5 in. diameter steel bars, (b) with 0.5 in. diameter voids, (c) with a 0.5 in. diameter steel bar, (d) with a 0.5 in. diameter void, and (e) with a 10 in. x 1 in. delamination at the center. All the specimens have 12 in. height.

Figure 5-12. Cross-sectional view of 12 in. x 4 in. concrete specimens with multiple inclusions: (a) three 0.5 in. steel bars placed vertically and three 0.5 in. steel bars placed horizontally, and (b) three 0.5 in. steel bars placed vertically with 10 in. x 1 in. delamination positioned in parallel to steel bars. All the specimens have 12 in. height.
Figure 5-13. Cross-sectional view of 12 in. x 4 in. wet concrete specimens: (a) plain concrete, (b) with 1 in. diameter steel reinforcing bars, (c) with 1 in. diameter voids, and (d) with a 10 in. x 1 in. delamination at the center. All the specimens have 12 in. height.

Figure 5-14. Cross-sectional view of 12 in. x 4 in. concrete specimens with 10 in. x 1 in. delaminations filled with water: (a) water pouch inside dry concrete and (b) water pouch inside wet concrete specimens. All the specimens have 12 in. height.

The more complicated specimens are shown in Figure 5-12 and Figure 5-14. Cross reinforcement and combination of multiple bars and delamination cases are presented in Figure 5-12. Delamination filled with water inside dry or wet concrete specimens are shown in Figure 5-14. These specimens represent various deterioration scenarios inside any concrete system.

As it can be noted in the figures, inclusions of steel bars, voids, and delaminations are located off the center of the specimens. Thus, by rotating the specimens, the specimens
become new targets for measurements with different cover thickness. This doubles the possible combination of measurements. In addition to this, specimens with steel bars are designed so that bars can be inserted at any desired spot. For example, a specimen with three holes can hold bars in 8 different ways. This also greatly increases possible number of different measurement situations.

As results, a total number of 180 measurements were made throughout the research work. It is also noted that the nature of nondestructive testing gives a benefit of not destroying the specimens during the experimental work. Once a specimen is made, there is no need or possibility of destroying it. This demonstrates the advantage of nondestructive evaluation technique for condition assessment in practice.

5.4 One-Dimensional Radar Imaging of Concrete Specimens

5.4.1 Radar Measurements and Raw Data Obtained

Upon radar measurements of concrete specimens, sets of raw data are collected which contain information about the returned signals from the targets. By processing the raw data, one- and two-dimensional imagery can be obtained.

The incident wave generated by the antenna of the ISAR system is stepped frequency continuous wave as shown in Figure 5-15. It has a pulse width of 20 ns and power of 30 dBm. The antenna transmits the waves from a starting frequency of $f_1$ to an ending frequency of $f_2$ by a frequency increment of 0.1 GHz. Thus, the frequency is swept from $f_1$ to $f_2$ at different time steps. The Fourier transform of the incident wave is shown in Figure 5-12. The incident wave can be also viewed as frequency vs. time step and power vs. frequency as in Figure 5-16 and 5-17. Reflected wave is collected in frequency by the same antenna, which is shown in Figure 5-15.

![Figure 5-15. Incident wave of the ISAR in time domain.](image)

$f_1$ $\Delta f$ $f_2$
Figure 5-16. Incident wave in frequency domain.

Figure 5-17. The incident wave.

Figure 5-18. The incident wave.
The measured data has the following information: aspect angle, frequency, amplitude and phase of VV polarization, and amplitude and phase of HH polarization.

Table 5-5. A sample 1-d data from ISAR measurement of 6" diameter concrete cylinder with a 0.5" diameter steel bar at 3.4 to 5.8 GHz.

<table>
<thead>
<tr>
<th>Aspect Angle (degree)</th>
<th>Frequency (MHz)</th>
<th>VV Amplitude (dBsm)</th>
<th>Polarization Phase (degree)</th>
<th>HH Amplitude (dBsm)</th>
<th>Polarization Phase (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>3400</td>
<td>-9.84</td>
<td>-88.91</td>
<td>-9.67</td>
<td>-82.23</td>
</tr>
<tr>
<td>0.00</td>
<td>3500</td>
<td>-9.69</td>
<td>-71.39</td>
<td>-9.11</td>
<td>-68.10</td>
</tr>
<tr>
<td>0.00</td>
<td>3600</td>
<td>-9.34</td>
<td>-54.21</td>
<td>-9.06</td>
<td>-54.16</td>
</tr>
<tr>
<td>0.00</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.00</td>
<td>5800</td>
<td>-8.46</td>
<td>26.47</td>
<td>-8.37</td>
<td>29.19</td>
</tr>
</tbody>
</table>

5.4.2 Implementation of a 1-D Imaging Algorithm

The raw data in Table 5-4 contains information about a target received by an antenna as a function of frequency at a fixed incident angle for one-dimensional imaging. Each entry in the data has amplitude and phase change of the received signal at each frequency. This information is collected in frequency. In order to have an image, the data in Table 5-4 needs to be converted into time domain with an appropriate processing scheme.
First, the raw data is converted into a format of real and imaginary parts to form a complex number.

\[
\text{real} = 10^{\text{amplitude/20}} \times \cos(\text{phase}) \\
\text{imaginary} = 10^{\text{amplitude/20}} \times \sin(\text{phase}) \\
\text{complex number} = \text{real} + j \times \text{imaginary}
\] (5-8)

This conversion is performed for each polarization, separately. For example of VV polarization, the data in Table 5-5 is changed as shown in Table 5-6.

<table>
<thead>
<tr>
<th>Aspect Angle (degree)</th>
<th>Frequency (MHz)</th>
<th>Real part</th>
<th>Imaginary part</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>3400</td>
<td>-0.0444</td>
<td>-0.3355</td>
</tr>
<tr>
<td>0.00</td>
<td>3500</td>
<td>0.0811</td>
<td>-0.3246</td>
</tr>
<tr>
<td>0.00</td>
<td>3600</td>
<td>0.2063</td>
<td>-0.3044</td>
</tr>
<tr>
<td>0.00</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>0.00</td>
<td>5800</td>
<td>0.3883</td>
<td>0.1101</td>
</tr>
</tbody>
</table>

Table 5-6. Converted raw data for one-dimensional imaging.

The converted reflected signal in Table 5-6 is windowed in frequency domain using Hamming Window as in Figure 5-20. Hamming window has the following property:

\[
w[n] = 0.54 - 0.46 \cos(2\pi n / M) \quad 0 \leq n \leq M \\
= 0 \quad \text{otherwise}
\] (5-9)

When a run of \( N \) sampled points of periodogram spectral estimation is selected, an infinite run of sampled data \( c_j \) is in effect multiplied by a window function in time, one which is zero except during the total sampling time \( N \Delta \), and is unity during that time. In other words, the data are windowed by a square window function.

As the square window function turns on and off so rapidly, there is a leakage at high frequencies. To remedy this situation, the input data \( c_j, \quad j = 0, \ldots, N - 1 \) is multiplied
by a window function \( w_j \) that changes more gradually from zero to a maximum and the back to zero as \( j \) ranges from 0 to \( N-1 \).

Figure 5-20. Hamming window used to process the reflected signal.
5.4.3 Imaging Result

As results, one-dimensional imagery is obtained for both VV and HH polarizations and plotted together in Figure 5-21, which is for a cylindrical concrete specimen with a steel reinforcing bar embedded at the center.

![Graph showing VV and HH polarizations](image)

Figure 5-21. A sample 1-D image of a concrete cylinder from ISAR measurement. The cylinder has dimensions of 6" diameter x 12" height with a 1" diameter steel bar at the center. The peaks A, B, and C represent the front and back surfaces, and the rebar, respectively.
5.5 Two-Dimensional Radar Imaging of Concrete Specimens

5.5.1 Radar Measurements and Raw Data Obtained

To generate a two-dimensional image, measurements should be made over a certain angle of rotation of a target. The ISAR measurement is performed over a predetermined angular rotation of 20 degrees. This rotation of a concrete target provides cross-range imagery for two-dimensional imaging.

![Diagram of ISAR measurements for 2-D imaging](image)

Figure 5-22. Schematic view of the ISAR measurements for 2-D imaging. A concrete specimen rotates during measurements to provide cross-range imagery.

Raw data from the measurements contains information about amplitude and phase of each polarization over the sweeping frequency range as a function of angular rotation. A sample raw data from 2-D measurements is given in Table 5-7.

5.5.2 Implementation of an 2-D Imaging Algorithm

Two-dimensional imaging is based on two-dimensional Fourier transform from a measured data which contains information as a function of aspect angle and frequency in comparison to the one-dimensional imaging which had one-dimensional data only as a function of frequency. Two-dimensional imaging scheme is explained with a sample plot after brief discussion of fundamentals.
Table 5-7. A sample 2-D data from ISAR measurement of 6" diameter x 12" cylinder with no inclusion at 3.4 to 5.8 GHz for 20 degree angular rotation from -10 to +10 degrees.

<table>
<thead>
<tr>
<th>Aspect Angle (degree)</th>
<th>Frequency (MHz)</th>
<th>VV Amplitude (dBsm)</th>
<th>VV Polarization Phase (degree)</th>
<th>HH Amplitude (dBsm)</th>
<th>HH Polarization Phase (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>3400</td>
<td>-10.28</td>
<td>36.62</td>
<td>-10.53</td>
<td>23.31</td>
</tr>
<tr>
<td>-10</td>
<td>3500</td>
<td>-10.72</td>
<td>27.01</td>
<td>-13.02</td>
<td>19.70</td>
</tr>
<tr>
<td>-10</td>
<td>3600</td>
<td>-11.10</td>
<td>31.88</td>
<td>-13.96</td>
<td>47.25</td>
</tr>
<tr>
<td>-10</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>-10</td>
<td>5800</td>
<td>-9.95</td>
<td>76.31</td>
<td>-10.82</td>
<td>87.31</td>
</tr>
<tr>
<td>-9</td>
<td>3400</td>
<td>-10.42</td>
<td>33.96</td>
<td>-10.09</td>
<td>17.76</td>
</tr>
<tr>
<td>-9</td>
<td>3500</td>
<td>-10.66</td>
<td>23.72</td>
<td>-13.08</td>
<td>17.93</td>
</tr>
<tr>
<td>-9</td>
<td>3600</td>
<td>-11.47</td>
<td>28.29</td>
<td>-14.02</td>
<td>41.70</td>
</tr>
<tr>
<td>-9</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>-9</td>
<td>5800</td>
<td>-9.89</td>
<td>71.22</td>
<td>-10.78</td>
<td>83.18</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>+10</td>
<td>3400</td>
<td>-10.50</td>
<td>27.36</td>
<td>-10.58</td>
<td>5.50</td>
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<tr>
<td>+10</td>
<td>3500</td>
<td>-9.91</td>
<td>16.42</td>
<td>-13.18</td>
<td>3.60</td>
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<tr>
<td>+10</td>
<td>3600</td>
<td>-11.17</td>
<td>14.70</td>
<td>-14.04</td>
<td>35.25</td>
</tr>
<tr>
<td>+10</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>+10</td>
<td>5800</td>
<td>-9.62</td>
<td>56.59</td>
<td>-10.29</td>
<td>67.70</td>
</tr>
</tbody>
</table>

Given a complex function $h(k_1,k_2)$ defined over the two-dimensional grid $0 \leq k_1 \leq N_1 - 1$, $0 \leq k_2 \leq N_2 - 1$, its two-dimensional discrete Fourier transform can be defined as a complex function $H(n_1,n_2)$, defined over the same grid,

$$H(n_1,n_2) \equiv \sum_{k_2=0}^{N_2-1} \sum_{k_1=0}^{N_1-1} e^{2\pi j k_2 n_2 / N_2} e^{2\pi j k_1 n_1 / N_1} h(k_1,k_2) \quad (5-10)$$

By pulling the "subscript 2" exponential outside of the sum over , or by reversing the order of summation and pulling the "subscripts 1" outside of the sum over , it is seen instantly that the two-dimensional FFT can be computed by taking one-dimensional FFTs sequentially on each index of the original function. Symbolically,
\[ H(n_1,n_2) = \text{FFT-on-index-1} \left( \text{FFT-on-index-2} \left[ h(k_1,k_2) \right] \right) \]
\[ = \text{FFT-on-index-2} \left( \text{FFT-on-index-1} \left[ h(k_1,k_2) \right] \right) \quad (5-11) \]

5.5.3 Imaging Result

Two-dimensional Fourier transform is performed on the raw data in frequency domain. Hamming window is applied in frequency domain for both frequency and angular rotation. A sample plot of a 2-D image of the same cylindrical specimen provided in the one-dimensional case is shown in Figure 5-23.

![Figure 5-23. A sample 2-D image of a plain concrete cylinder from radar measurement.](image)
5.6 Results of Radar Imaging

Results of radar imaging for various laboratory size concrete specimens shown in Section 5.3 are provided in Appendix B. The specimens are measured using the measurement scheme and setup discussed in Section 5.2. For all of the specimens one- and two-dimensional imaging have been performed using the imaging algorithms implemented and discussed in Section 5.4 for one-dimensional imaging, and in Section 5.5 for two-dimensional imaging, respectively. In this section, measurement parameters used and results of the measurements are presented in reference to Appendix B for detailed plots of the specimens and imaging results. As results of extensive measurements and parametric study, three major applications areas have been identified: concrete thickness measurement, monitoring of deterioration inside concrete, and detection of inclusions such as steel reinforcing bars embedded inside concrete.

In the following radar measurement results with a variation of measurement parameters are provided: center frequency and bandwidth, incident angle, polarization of incident wave, physical condition of concrete targets, comparison of radar measurement result to modeling, radar imaging with electromagnetic properties of concrete incorporated, and the three major application areas identified are presented. The radar measurement results with concrete specimens are given in Appendix B and those figures are referenced from the text.

5.6.1 Effect of Radar Measurement Parameters

The most important measurement parameters are center frequency and bandwidth. In the measurements, the following combinations of center frequency and bandwidth are used.

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>Center frequency</th>
<th>Frequency bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 ~ 3.4 GHz (S band)</td>
<td>2.7 GHz</td>
<td>1.4 GHz</td>
</tr>
<tr>
<td>3.4 ~ 5.8 GHz (S/C band)</td>
<td>4.6 GHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>8 ~ 12 GHz (X band)</td>
<td>10 GHz</td>
<td>4 GHz</td>
</tr>
</tbody>
</table>

Table 5-8. Combination of center frequency and bandwidth used for the radar measurements.
The frequency bandwidth determines resolution that can be achieved by a radar system. Resolution is the ability to resolve two adjacently located objects. The wider bandwidth is, the better range resolution is. The study of different bandwidth with respect to range resolutions that can be obtained is presented in Section 4.6. The center frequency determines the capability of penetration. As shown in the radar measurement results in Appendix B, Figures B-5, B-8, and B-26, the higher frequency range resulted in limited penetration capability. Detailed discussion of the detection and penetration capabilities of a radar system based on the combination of center frequency and bandwidth is given in Subsection 5.6.3.

The effect of incident angle on the radar measurement results has been also studied by transmitting waves either at normal angle or at oblique angle to specimens. The results are shown in Figures 5-24 to 5-27. In Figure 5-24, a 12" x 4" x 12" concrete specimen was imaged at 8-12 GHz at a normal incident angle. In Figure 5-25, the same specimens was imaged at an incident angle of 10 degrees. In Figure 5-25, edge of the specimen at an angle is seen. The advantage that might be gained by transmitting waves at an angle is to increase the detectability of inclusions by separating the reflection of an inclusion from the reflection of concrete. Especially, in the case of steel reinforcing bar, an oblique angle measurement can still receive reflection from the steel bar which is a perfectly conducting material, while the reflection from concrete itself goes away from the incident source due to the angle. However, the results obtained from the radar measurements showed that with a finite size of target, edge effect appears more clearly than the advantage of sending waves at an angle. In Figure 5-26, a concrete specimen with the same outside dimensions as the one imaged at normal angle has three 1" diameter steel reinforcing bars at 1" depth as shown in Appendix B, Figure B-27. The existence of bars are shown in the figure. With an oblique angle measurement with bars in Figure 5-27, the same edge appears as shown in Figure 5-25. The existence of bar is no longer distinguishable. The same results are found in the other measurements with different specimens. Thus, it is concluded that the oblique angle measurement didn’t work with small size specimens. If the size of a specimen is very large so that no edge effect can play a role, then sending waves at an oblique angle might improve the detectability of inclusions embedded inside concrete.

Polarization of a incident wave from a radar also plays an important role as a radar measurement parameter. If the orientation of the radar signal is parallel with the orientation of an inclusion, the reflection is maximum. On the other hand, in the worst case, if the orientations of the incident wave and the inclusion is perpendicular, the reflection is minimized. With the use of polarization, detectability of steel reinforcing bars embedded inside concrete is examined in Subsection 5.6.5. Also the radar measurement results with
various types of inclusions with vertical (VV) and horizontal (HH) polarizations are provided in Appendix B.

The physical condition of concrete targets is the other important measurement parameter which affects the measurement results. As discussed in Chapter 3, the electromagnetic properties of concrete are directly related to the physical condition of concrete. The effect of moisture level on the measurement results are shown in the measurement results of wet concrete specimens with various inclusions. The imaging results of wet concrete specimens are presented in Appendix B, Figures B-14 through B-18. A detailed list of specimens and their dimensions and physical conditions are provided at the beginning of Appendix B. The returned radar signal change due to the different physical condition of concrete targets makes possible to monitor condition change inside concrete targets. Dry concrete allows the wave penetrate deep into the target, while wet concrete severely limits penetration capability of the radar signal. Inclusions such as voids, holes, and delaminations certainly affect the returned radar signal. The radar measurement results of this case is presented in detail with a possible scenario of concrete deterioration in Subsection 5.6.4.

The radar measurement results are compared to computer simulation results to verify the validity of the simulation results. Figure 5-28 and Figure 5-29 are the radar measurement result at 2 to 3.4 GHz and the computer simulation result for the same frequency range, respectively. The front and back surface reflections correspond to each other in the figures. Minor peaks seen in Figure 5-29 are due to ambiguity results from signal processing process.
Figure 5-24. 1-D plot of a dry 12" x 4" x 12" plain concrete block imaged at a normal incident angle with VV and HH polarizations at 8 to 12 GHz.

Figure 5-25. 1-D plot of a dry 12" x 4" x 12" plain concrete block imaged at an oblique (10 degrees from normal) incident angle with VV and HH polarizations at 8 to 12 GHz.
Figure 5-26. 1-D plot of a dry 12" x 4" x 12" concrete block with three steel bars at 1" depth imaged at a normal incident angle at 8 to 12 GHz.

Figure 5-27. 1-D plot of a dry 12" x 4" x 12" concrete block with three steel bars at 1" depth imaged at an oblique (10 degrees from normal) incident angle at 8 to 12 GHz.
Figure 5-28. 1-D image of a dry 12" x 4" x 12" plain concrete block with VV and HH polarizations at 2 to 3.4 GHz from radar measurement.

Figure 5-29. 1-D image of a dry 12" x 4" x 12" plain concrete block with VV and HH polarizations at 2 to 3.4 GHz from computer simulation.
5.6.2 Results of Radar Imaging with Electromagnetic Properties

Throughout the thesis, radar measurement results presented are obtained by processing the raw measured data without incorporating the electromagnetic properties. The reason is that the delay of the returned signal due to the value of dielectric constant and lossyness due to the value of loss factor of concrete can be readily compared with other materials with free space imaging algorithm. The capability of incorporating electromagnetic properties of concrete is presented in this subsection. For practical applications of the radar method, once a specific application area is identified, the electromagnetic properties of concrete can be readily incorporated as shown in the following.

In this subsection radar imaging with electromagnetic properties incorporated are presented in Figures 5-30 to 5-32. The basic of imaging algorithm is that electromagnetic waves generated by a radar system through an antenna at microwave frequencies travel through air until they reach the front surface of a concrete specimen. The first and largest reflection occurs at the front surface of the concrete specimen and travels back toward the same antenna that the waves came from. The remainder of the waves which is not reflected back penetrates into concrete and travels until it reaches the back surface of the specimen. During this propagation through concrete, the velocity of the waves is decreased by a square root of the dielectric constant of the material as

\[ v = \frac{c}{\sqrt{\varepsilon_r}} \]  \hspace{1cm} (5-12)

Due to this delay, the 1-D image obtained from measurements processed using a free space imaging algorithm is stretched compared to the physical size of a target as shown in Figure 5-30. Thus, the range axis readings do not correspond to the actual dimensions of the specimen.

To correct this image, a dielectric constant of concrete is incorporated into the free space imaging algorithm so that the returned signal is compressed as a function of the dielectric constant. The corrected image is shown in Figure 5-31 in the same scale as in Figure 5-30 for comparison. This image in Figure 5-31 represents the actual size of the specimen.

In Figure 5-32, the image obtained in consideration of the dielectric constant of concrete is replotted over a proper scale as a final output.
Figure 5-30. A concrete specimen imaged based on free space imaging algorithm.

Figure 5-31. The same concrete specimen imaged with a dielectric constant of 6.6.
Figure 5-32. 1-D image of a concrete specimen replotted using an imaging algorithm which incorporated the dielectric constant of concrete.
5.6.3 Identification of Application Area I: Concrete Thickness Measurement

In this research work, the use of radar for nondestructive evaluation (NDE) of concrete is examined in a systematic way by investigating electromagnetic properties of concrete, experimental radar measurements of laboratory size concrete specimens, computer simulation of radar measurements through numerical modeling, and development of signal processing techniques for one- and two-dimensional imaging. Now, the results are analyzed and combined to suggest possible application areas of the method to NDE of concrete in civil engineering applications.

In general, the radar method has advantages of remote sensing, fast measurement, high resolution, sensitivity to metallic objects, and safety during measurements. In addition to these advantages, the radar system used for the thesis work can generate cross-range resolution, which is essential for two-dimensional imaging. This will enhance the usefulness of the radar by providing imagery similar to optic images. Secondly, the radar system used has versatility in adjusting its center frequency and bandwidth. This will be effectively used to optimize detection and penetration capabilities. Thirdly, the computer simulation techniques developed are utilized in predicting and interpreting prior to and after radar measurements. Based on these tools, three major application areas of the radar method have been identified: i) concrete thickness measurement, ii) condition monitoring of concrete systems, and iii) identification of inclusions embedded inside concrete.

In the following, those three application areas are presented as three cases with supporting results and discussion.

The measurement of concrete thickness is a basic but important application in the use of radar for NDE of concrete systems. The result provides evidence of deterioration by indicating remaining thickness of pavements and bridge decks, location and size of foundations, abutments, and retaining walls. The thickness measurement results can be also used as a basis for deterioration monitoring by periodic measurements. Thus, in this reported research period, the main emphasis is given on the determination of concrete thickness with different measurement parameters.

There are two major factors to be considered for concrete thickness determination through radar measurements; detection and penetration capabilities of a radar system. The detection capability is related to frequency bandwidth of an incident wave, while the penetration capability is related to center frequency of the wideband incident wave. In general, as a center frequency increases, a frequency bandwidth also increases for a typical radar hardware system. This results in better detectability but reduced penetration
capability. As the center frequency decreases, penetration capability increases but with poor detectability. There is a tradeoff between achieving good detectability and penetration. This qualitative relationship between two goals are studied quantitatively in this section.

Radar measurement results of a 12" x 4" x 12" concrete specimen at three different frequency ranges are provided. The measurements were made at 2~3.4, 3.4~5.8, and 8~12 GHz ranges with both VV and HH polarizations. Angular rotation of the target was 20 degrees. Frequency was swept from the starting to the ending frequency by 0.1 GHz increment over the 20 degree angle. Measurement distance was 14.4 m for all three frequency ranges. The pulse width of the wave was 20 ns and the power of the wave was 30 dBm.

After measurements, a angle versus frequency two-dimensional data is inverse Fourier transformed with a hamming window as discussed in Chapter 4. From the signal processing, three-dimensional plots of two-dimensional image are obtained as well as one-dimensional image of targets at normal incident angle. In Figures 5-33, 5-34, 5-35, 5-36, 5-37, and 5-38, two-dimensional imaging results at three different frequency ranges are presented for VV and HH polarizations. In Figures 5-39, 5-40, and 5-41, one-dimensional images are given for the three frequency ranges.

It is possible to view specimens in the cross-range direction also due to the inverse synthetic aperture radar (ISAR) measurements, which conventional radars cannot generate. Three-dimensional plots are good for visualization of the results, even though one-dimensional plots are more suitable for analysis with clear view. Thus, discussion is directed to one-dimensional plots with a reference to three-dimensional plots.
Figure 5-33. Three-dimensional plot of 2-D measurements of a 12" x 4" x 12" concrete block with VV polarization at 2 to 3.4 GHz.

Figure 5-34. Three-dimensional plot of 2-D measurements of a 12" x 4" x 12" concrete block with HH polarization at 2 to 3.4 GHz.
Figure 5-35. Three-dimensional plot of 2-D measurements of a 12" x 4" x 12" concrete block with VV polarization at 3.4 to 5.8 GHz.

Figure 5-36. Three-dimensional plot of 2-D measurements of a 12" x 4" x 12" concrete block with HH polarization at 3.4 to 5.8 GHz.
Figure 5-37. Three-dimensional plot of 2-D measurements of a 12" x 4" x 12" concrete block with VV polarization at 8 to 12 GHz.

Figure 5-38. Three-dimensional plot of 2-D measurements of a 12" x 4" x 12" concrete block with HH polarization at 8-12 GHz.
Figure 5-39. One-dimensional image of a 12" x 4" x 12" concrete block at 2 to 3.4 GHz.

Figure 5-40. One-dimensional image of a 12" x 4" x 12" concrete block at 3.4 to 5.8 GHz.
Figure 5-41. One-dimensional image of a 12" x 4" x 12" concrete block at 8 to 12 GHz.

In Figure 5-39, peaks are wider than the ones in Figure 5-40 and Figure 5-41 due to narrower bandwidth of 1.4 GHz compared to 2.4 and 4 GHz, respectively. The narrower bandwidth gives less resolution as in Eq. (5-1). It is also noticed that the amplitude of the largest peak which comes from the front surface is smaller than the ones in Figure 5-40 and 5-41 due to less scattering in the lower frequency range. However, the reflection from the back surface is clearly captured in the 2 to 3.4 GHz measurement. This comes from the less attenuation through concrete thickness during the travel of the waves and less sensitivity to the edges of the specimens in the lower frequency range. Thus, the results shown in Figures 5-39, 5-40, and 5-41 clearly indicate that detection capability is a function of center frequency and frequency bandwidth through actual radar measurements. Quantitative prediction of penetration and detection capabilities are provided at the end of this section.

In the following, more measurement results on three different types of concrete specimens other than the ones shown above are presented. These following measurements are made to examine the effect edges and geometry of specimens as a part of penetration and detection capability investigation.
In the discussion, prediction of the penetration and detection capabilities of a radar is provided based on the investigation performed through radar measurements. This study of thickness measurement provides a basic but essential application for the use of radar as a tool for NDE of concrete.

A typical 1-D image from radar measurement has certain components as shown in Figure 5-42. To examine detection and penetration capability of a radar system, it is necessary to notice each component in the figure. Points A, B, C represent reflections from the front surface and back surface of the specimen, and noise floor level, respectively. $\Delta H$ is related to the thickness of the specimen, while $\Delta AB$ is related to the lossyness of the specimen. $\Delta AC$ indicates the difference of signal to noise. In the following each of components is analyzed in its relation to NDE applications. Conclusions are drawn at the end of this subsection.

![Figure 5-42. Schematic view of 1-D image from radar measurement.](image)

i) Reflection from the front surface, $\text{RCS}_A$ (Point A in Figure 5-42)

The magnitude of the point A in Figure 5-42 represents the reflection from the front surface of the specimen, denoted as radar cross section (RCS), $\text{RCS}_A$. This RCS is determined by reflectivity of the wave at the air/concrete boundary, frequency of the wave, and the cross-sectional area of the specimen.
where \( A \) is the cross-sectional area of a specimen facing the antenna, \( \lambda \) is the wavelength at the center frequency of an incident wave, and \( R \) is the reflection coefficient. \( R \) is a function of a dielectric constant and can be \( R(f) \) if it varies over a frequency range. In this thesis work, the dielectric constant of concrete is taken as a constant due to its negligible variation over the microwave frequency range.

This formula is based on the physical optics approximation for a target with a projected area of \( A \), which will have the above expression for a forward scatter cross section which is the same as the backscatter cross section for a perfectly conducting plate of area \( A \) at normal incidence.

To obtain an expression for the reflection coefficient term \( R \) in Eq. (5-1), the following is reviewed. Figure 5-43 shows the reflection and transmission occurring of the wave impinging upon a concrete target. In the figure, \( r \) denotes reflectivity and \( t \) denotes transmissivity, respectively. The numbers 1, 2, and 3 indicates time sequence. As the wave hits the front surface of concrete, a part of the wave is reflected back toward the antenna as \( 1r \). This reflection is the largest reflection from the target. The remainder of the wave is transmitted into concrete as \( 1t \). As the wave \( 1t \) hits the back surface of concrete, it is divided into \( 2t \) and \( 2r \), which are 2 transmitted to air and 2 reflected back to concrete. Similarly, the wave \( 2r \) is divided into \( 3t \) and \( 3r \) at the original concrete/air boundary. The \( 3t \) becomes the second largest reflection in the 1-d image, which represents the reflection from the back surface traveled back through the concrete thickness.

\[
4\pi \frac{A^2}{\lambda_c^2} |R|^2
\]

(5-13)

Figure 5-43. Reflection and transmission mechanism of a multiple layered system.
When a uniform plane wave impinges on the boundary at an oblique angle, the normal of the boundary and the incident ray form a plane called the plane of incidence. The mismatch between the dielectric constants at the boundary of the two different media causes some of the incident waves to reflect and the rest to be transmitted into the new medium. This interaction permits the nondestructive inspection of the material's interior for property determination and the detection of anomalies. The mathematical expressions of the reflected wave can be written as

$$R_{TE} = \frac{\sqrt{\varepsilon_r \cos \theta_i} - \sqrt{\varepsilon_r \cos \theta_i}}{\sqrt{\varepsilon_r \cos \theta_i} + \sqrt{\varepsilon_r \cos \theta_i}}$$  \hspace{1cm} (5-14)$$

where $R_{TE}$ is reflection coefficient for perpendicular polarization or Transverse Electric (TE), $\varepsilon_r$ is dielectric constant for medium 1 (for air, $\varepsilon_r = 1$), $\varepsilon_r$ is dielectric constant for medium 2 (for concrete, $\varepsilon_r = 4 - 15$), $\theta_i$ is the angle of incidence, and $\theta_t$ is the angle of transmission.

$$R_{TM} = \frac{\sqrt{\varepsilon_r \cos \theta_i} - \sqrt{\varepsilon_r \cos \theta_i}}{\sqrt{\varepsilon_r \cos \theta_i} + \sqrt{\varepsilon_r \cos \theta_i}}$$  \hspace{1cm} (5-15)$$

where $R_{TM}$ is reflection coefficient for parallel polarization or Transverse Magnetic (TM).

The term polarization refers to the direction of the electric field. If the electric field of the wave is perpendicular to the plane of incidence, it is called perpendicular polarization or Transverse Electric (TE) for the reason that the electric field is transverse to the plane of incidence. Similarly, if the electric field is parallel to the plane of incidence, it is called parallel polarization or Transverse Magnetic (TM) for the reason that the magnetic field is transverse to the plane of incidence. It is beneficial to have different polarizations because any anomalies inside concrete as steel reinforcing bars (rebars) oriented parallel to the polarized direction of the electric field will show strong response and may be easily detected.

In Eq. (5-14) and Eq. (5-15), dielectric constants for media 1 and 2 are assumed to be known as well as the angle of incidence $\theta_i$. To get the angle of transmission $\theta_t$, a relationship from the Snell's law is needed, which states

$$\sqrt{\varepsilon_r \sin \theta_i} = \sqrt{\varepsilon_r \sin \theta_i}$$  \hspace{1cm} (5-16)$$

Then, $\cos \theta_t$ can be obtained as
\[ \cos \theta_i = \sqrt{1 - \sin^2 \theta_i} \quad (5-17) \]

Square of reflection coefficient \( |R|^2 \) is called reflectivity and denoted as \( r \). The transmissivity \( t \) is obtained as

\[ t = 1 - r \quad (5-18) \]

Thus, the energy is conserved at the interface of the two media.

With a reflection coefficient for the TE case as in Eq. (5-14), Eq. (5-13) for the RCS becomes,

\[ 4\pi A^2 \frac{\sqrt{\varepsilon_{r1}} \cos \theta_i - \sqrt{\varepsilon_{r2}} \cos \theta_i}{\lambda_c \sqrt{\varepsilon_{r1}} \cos \theta_i + \sqrt{\varepsilon_{r2}} \cos \theta_i}^2 \quad (5-19) \]

For a concrete specimen as shown in Figure 5-37, if the dielectric constant of concrete \( \varepsilon_{r2} \) is 6.6 and \( \varepsilon_{r1} \) is equal to 0 for air, Eq. (5-19) is reduced to

\[ 4\pi A^2 \frac{1 - \sqrt{6.6}}{\lambda_c \sqrt{1 + \sqrt{6.6}}}^2 \quad (5-20) \]

for a normal incidence, where \( \theta_i, \theta_i = 0 \). For a concrete specimen which has the radar facing dimensions of 12" x 12" and the incident wave of the frequency range from 2 to 3.4 GHz, \( A \) is 0.0929 m², \( \lambda_c \) at 2.7 GHz is 0.1111 m, and the value of RCS from Eq. (5-20) becomes 2.3 dBsm. This value coincides with the magnitude of the first peak in Figure 6-7, which verifies the theoretical prediction by the experimental result. As noticeable in Eq. (5-20), the RCS increases as the center frequency of the incident wave increases. For a case of measurement of the same specimen at higher frequency of 3.4 to 5.8 GHz as shown in Figure 5-20, the value of RCS is 7 dBsm for \( \lambda_c = 4.6 \) GHz. The RCS also increases as the cross-sectional area of concrete increases. This phenomenon will be discussed later.

ii) Reflection from the back surface, RCS\(_B\) (Point B in Figure 5-42)

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The magnitude of reflected signal from the back surface of the concrete specimen is denoted as $\text{RCS}_B$. The expression of $\text{RCS}_B$ is similar to Eq. (5-13) with a different value for the reflection coefficient. As illustrated in Figure 5-43, the $\text{RCS}_B$ is the reflected signal from the back surface, which has to go through the steps of $l_t$, $2r$, and $3t$. During this process, the wave is lost in the lossy medium of concrete. Thus, Eq. (5-13) becomes

$$4\pi \frac{A^2}{\lambda_c^2} \{l_t * r * t\} e^{-\text{i}k_f d}$$  \hspace{1cm} (5-21)

where $t$ is transmissivity, $r$ is reflectivity, $k_f$ is the imaginary part of a wave number, and $d$ is the thickness of the specimen.

$$k = \omega \sqrt{\mu \varepsilon}$$  \hspace{1cm} (5-22)

Thus, $\text{RCS}_B$ can be calculated from Eq. (5-22) and Eq. (5-21).

iii) Noise floor level (Point C in Figure 5-42)

For any radar measurement system, a noise level exists. The noise can be coming from the inside of the system or from the measurement background. The significance of the noise level is that if the strength of the reflected signal is weaker than the noise level, it cannot be detected. In Figure 5-39, for example, the noise level is around -40 dBsm and the back surface reflection is seen above the level. However, in Figure 5-41, the back surface reflection is not identifiable, which should be seen around 0.3 m in the range direction. Detectability of the back surface reflection is discussed next in association with RCS and the noise level.

iv) Detectability of back surface reflection

There are two factors in determining the detectability of the back surface reflection. The point B in Figure 5-42 has to be in between points A and C in order to be detected (In case of a lossy medium of concrete, the back surface reflection cannot be higher than the front surface reflection). In other words, $\Delta AB$ should be less than $\Delta AC$. $\Delta AB$ is related to the lossyness of concrete.

By looking at Eq. (5-13), the points A and B can be increased by enlarging the size of the target or by increasing the frequency of the incident wave. The increase of frequency
might not be the right idea because more attenuation is expected at higher frequency. Thus, increase of the size of a specimen can improve the detectability of the back surface reflection. It is concluded that increase of cross-sectional area of a target will increase the detectability of each surfaces. There is a limit in terms of increasing the size of a target to improve detectability. The area illuminated by an antenna is limited by the measurement distance and beam width of an antenna. Thus, increase of the target size infinitely is not practical. Tradeoff between the detectability and the size of specimen have to be made.

v) Penetration capability ($\Delta AB$)

Once, the conductivity is known, the penetration capability determined from the lossyness of concrete based on the conductivity can be estimated by relating the conductivity to $\Delta AC$. This is based on the assumption that if the returned signal from the back surface is weaker than the noise level, it cannot be detected. As long as the cross-sectional area and the frequency used remain as the same, this assumption holds.

By letting the difference in RCS between the points A and C equal to the ratio of RCS from the front and back surfaces, penetration capability is calculated as the thickness of a concrete specimen, d.

$$\frac{RCS_w}{RCS_A} = \frac{4\pi \frac{A^2}{\lambda_c^2} \{t * r * t\} e^{-4k_ld}}{4\pi \frac{A^2}{\lambda_c^2} \{r\}}$$

$$= t^2 e^{-4k_ld}$$

$$10^{-\Delta AC/10}$$

(5-23) (5-24)

By equating Eq. (5-23) and Eq. (5-24), the penetration limit of d can be calculated.

By correlating the above relationship and the radar measurement results, Figure 5-39 is obtained which shows penetration limit of the particular radar system, the ISAR, over the frequency range. This prediction of the penetration limit is only valid with 12" x 4" x12" concrete specimens.

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Figure 5-44. Penetration limit over a frequency range.

\[ \rho_r = \frac{v}{2B} = \frac{c/\sqrt{\varepsilon_r}}{2B} \leq d \]

\[ B \geq \frac{c/\sqrt{\varepsilon_r}}{2d} \]  \hspace{1cm} (5-25)

Figure 5-45. Required bandwidth for a thickness measurement.
Far-field criterion \( \geq \frac{2d_{\text{max}}^2}{\lambda_{\text{shortest}}} = \frac{2d_{\text{max}}^2}{c f_{\text{highest}}} \) (5-26)

Figure 5-46. Minimum distance from a target to be in the far-field.

The significance of the findings in this section of concrete thickness measurement part is that a procedure of determining detection and penetration capabilities of a radar system has been developed. The penetration depth is not only a function of material properties as generally conceived but also a function of sensitivity of a radar system such as frequency, dynamic range, and signal-to-noise level and importantly cross-sectional area of concrete targets. Thus, prediction of detectability and penetration capability can be quantitatively obtained based on the procedure discussed in this section.

It should be pointed out that a specific combination of radar measurement and hardware parameters has to be identified for a specific application area. In other words, it is difficult to have a system workable for every possible cases.
5.6.4 Identification of Application Area II: Condition Monitoring of Deteriorating Concrete

Condition monitoring of deteriorating concrete using a radar is provided as one of the application areas developed from the thesis work. This application intends to detect any change inside concrete by measuring the response difference between a defective and sound material.

A deterioration scenario is given as follows:

i) a 12" wide x 12" high x 4" thick sound dry plain concrete exists (Figure 5-47a).
ii) a 0.5" diameter x 12" high hole is initiated inside concrete at 2" depth, from the surface (Figure 5-47b).
iii) the hole is further deteriorated and enlarged to 10" x 1" x 12" delamination at the same location (Figure 5-47c).
iv) the concrete block is then moisturized due to intrusion of water (Figure 5-47d).
v) the delamination is filled with water over a period of time inside the wet concrete (Figure 5-47e).

Physical states of concrete specimens corresponding to each step of the deterioration scenario are illustrated in Figure 5-47. Five concrete specimens are made for radar measurements which represent each step of the deterioration. Specimens 5-47d and 5-47e are submerged into water for two months prior to measurements to make sure that the entire specimen is moisturized, and the delamination inside specimen 5-47e is filled with water before the measurement.

Results of radar measurements are presented in Figures 5-48 through 5-57 for both two- and one-dimensional images. In Figure 5-48, the sound plain concrete is imaged, which shows the front and back surface reflections also shown in one-dimensional plot in Figure 5-49. The initiation of 0.5" diameter hole is not clearly seen in Figure 5-50 due to its small size, however, the reflected signal is definitely changed as shown in Figure 5-51. Due to the existence of the hole, back surface reflection is distorted and disappeared. In Figure 5-52, delamination due to the enlargement of the hole is positively identified as the second peak as well as in Figure 5-53. After the moisturization of the concrete block, reflection from the delamination is decreased due to the increased lossyness of the wet block. This phenomenon is shown in Figures 5-54 and 5-55. This illustrates the difficulty of detecting objects inside wet concrete. As the last step of the deterioration scenario, the delamination is now filled with water after a period of time. The delamination is visible again due to the strong reflection from the water filled inside the delamination.
It is concluded that condition monitoring of a concrete target over a period of time is possible as illustrated because the change in the reflected signal represents the quality change. This technique can be applied to condition monitoring of concrete dams, detection of hazardous materials underground, and detection of subsurface condition change.

Antenna at a distance

Figure 5-47. Five concrete specimens which represent five deterioration states.
Figure 5-48. Three-dimensional plot of 2-D measurements of a dry sound plain 12" x 4" x 12" concrete block with VV polarization at 3.4 to 5.8 GHz.

Figure 5-49. One-dimensional imaging of the above concrete block with VV and HH polarizations at 3.4 to 5.8 GHz.
Figure 5-50. Three-dimensional plot of 2-D imaging of a dry 12" x 4" x 12" concrete block with a 0.5" hole at 2" depth from the front surface with VV polarization at 3.4 to 5.8 GHz.

Figure 5-51. One-dimensional imaging of the above concrete block with VV and HH polarizations at 3.4 to 5.8 GHz.
Figure 5-52. Three-dimensional plot of the dry concrete block with a 1" thick delamination located at 2" depth from the front surface with VV polarization at 3.4 to 5.8 GHz.

Figure 5-53. One-dimensional imaging of the above concrete block with VV and HH polarizations at 3.4 to 5.8 GHz.
Figure 5-54. Three-dimensional plot of a wet 12” x 4” x 12” concrete block with VV polarization at 3.4 to 5.8 GHz.

Figure 5-55. One-dimensional imaging of the above concrete block with VV and HH polarizations at 3.4 to 5.8 GHz.
Figure 5-56. Three-dimensional plot of a water filled delamination inside the wet 12" x 4" x 12" concrete block with VV polarization at 3.4 to 5.8 GHz.

Figure 5-57. One-dimensional imaging of the above concrete block with VV and HH polarizations at 3.4 to 5.8 GHz.
5.6.5 Identification of Application Area III: Detection of Inclusions Embedded inside Concrete

The third application area developed from the thesis work is to detection of inclusions such steel reinforcing bars (rebars) or the rebars with delamination. One of the advantages of the radar method is its sensitivity to metallic objects such rebars. The strongest reflection is expected from the metallic objects than any other materials since the metal is a perfect conducting material not allowing any wave penetrated into the material.

In this section, radar measurement results of concrete specimens with three 0.5\" diameter x 12\" long rebars in combination with a 10\" x 1\" x 12\" delamination are presented. The specimens have inside configurations as shown in Figure 5-58.

![Figure 5-58. 12\" x 4\" x 12\" concrete specimens with three 0.5\" diameter x 12\" long rebars and a 10\" x 1\" x12\" delamination. Specimen (a) has the rebars facing an antenna and specimen (b) has the delamination facing the antenna.](image)

Results of the radar measurements of two specimens are shown in Figures 5-59 through 5-64. With the rebars facing the antenna, the reflections are stronger than the case with the delamination facing the antenna as clearly seen in Figures 5-63 and 5-64. In Figure 5-63, VV polarization remains higher than HH polarization right after 0.2 m location in the range direction due to the same orientation of the bars and the electric field, which cause strong reflection. On the other hand, in Figure 5-64, VV and HH polarization remain almost same because the size and orientation of the delamination is identical in both vertical and horizontal direction.
Figure 5-59. Three-dimensional plot of a dry 12" x 4" x 12" concrete block with 1" delamination and three 0.5" bars with VV polarization at 3.4 to 5.8 GHz.

Figure 5-60. Three-dimensional plot of a dry 12" x 4" x 12" concrete block with 1" delamination and three 0.5" bars with HH polarization at 3.4 to 5.8 GHz.
Figure 5-61. Three-dimensional plot of a dry 12" x 4" x 12" concrete block with three 0.5" bars and 1" delamination with VV polarization at 3.4 to 5.8 GHz.

Figure 5-62. Three-dimensional plot of a dry 12" x 4" x 12" concrete block with three 0.5" bars and 1" delamination with HH polarization at 3.4 to 5.8 GHz.
Figure 5-63. One-dimensional image of a concrete block with 1" delamination and three 0.5" bars with VV and HH polarizations at 3.4 to 5.8 GHz.

Figure 5-64. One-dimensional image of a concrete block with three 0.5" bars and 1" delamination with VV and HH polarizations at 3.4 to 5.8 GHz.
As a continuation of the detection of inclusions inside concrete, a cross-reinforced concrete specimen is imaged to examine the relationship between the polarization and the orientation of steel bars. As shown in Figure 5-65, a 12” x 4” x 12” concrete specimen with three 0.5” diameter x 12” long and the other three 0.5” diameter x 12” long rebars placed both vertically and horizontally is imaged with the electric field oriented vertically and horizontally, which represent VV and HH polarizations, respectively.

Figure 5-65. A 12” x 4” x 12” concrete specimen cross-reinforced with six 0.5” diameter x 12” long rebars; three vertically and three horizontally.

Results of radar measurements are shown in Figures 5-66 through 5-68. The effect of polarization with respect to its orientation to the steel bars are clearly seen in Figure 5-68. After the higher peak from the front surface of the concrete specimen, the second peak in VV polarization comes from the three vertically placed rebars. Following in HH polarization in Figure 5-68 is the reflection from the three horizontally placed rebars strongly responding to the HH polarization wave.

Thus, it is indicated that the use of polarization of the wave is essential to detect and identify the existence of steel bars embedded inside concrete. The application of this scheme is possible when there is a need to identify steel bars inside any concrete systems.
Figure 5-66. Three-dimensional plot of a cross-reinforced 12" x 4" x 12" concrete block with VV polarization at 3.4 to 5.8 GHz.

Figure 5-67. Three-dimensional plot of a cross-reinforced 12" x 4" x 12" concrete block with HH polarization at 3.4 to 5.8 GHz.
Figure 5-68. One-dimensional image of a cross-reinforced (three vertical and three horizontal) 12" x 4" x 12" concrete block with VV and HH polarizations at 3.4 to 5.8 GHz.
5.7 Discussion

The work presented in Chapter 5 has two major significances in NDE of concrete using a radar. First, an original and initial data base for actual radar measurement results on various types of laboratory size concrete specimens is established. This data base will serve as a basis for further advancement of hardware and software systems as well as understanding of the radar method for NDE of concrete. Second, signal processing schemes for imaging of concrete specimens using a radar have been implemented and now available for obtaining imagery from any raw data generated by radar measurements.

Radar measurement results presented in this chapter are categorized into two groups: geometry effect of a target and probing of a target for NDE. The geometry effect has been also studied in the modeling in Chapter 4. Relatively small specimens cause edge effect which disturbs the returned signal from obtaining clear imagery of the target. Large size target has less problem with geometry effect. Due to the weight limit of the styrofoam tower, the dimensions of concrete specimens tested are limited to 12" x 4" x 12". This typical size of concrete provided good results in determining its size and inclusions.

For the center frequency and bandwidth, it has been shown that low range of 2 ~ 3.4 GHz was good for thickness detection, middle frequency range of 3.4 ~ 5.8 GHz was good for deterioration detection, and 8 ~ 12 GHz was good for rebar or inclusion detection. Therefore, a specific combination of measurement parameters is required to solve a specific problem. The significance of the research work presented here is the fact that a procedure has been developed to examine measurement parameters and identify a proper set of parameters. Comparison of the radar measurement results to computer simulation is given in Section 5.6.

Regarding the use of an oblique incident angle to increase the detectability of an inclusion, the measured data showed that edge effect came into play which disturbed the reflected signal. This make it unable to detect an inclusion compared to normal incident angle measurement. The effect of incident angle of concrete, at which the reflection of concrete is minimized, needs to be further studied when a radar measurement system can handle large size concrete specimens. Therefore, for the size of concrete specimens up to 12" x 4" x 12" used in this work, sending waves at an oblique angle did not improve the detectability of inclusions.

Polarization of an incident wave is an important measurement parameter. Especially, if the purpose of a specific NDE application area is to detect steel reinforcing bars, the parallel orientation of the electric fields of the waves with respect to the orientation
of the bars increases the amount of returned signals. This phenomena have been shown in the radar measurement results in Section 5.6.5. The advantage of using polarization needs to be studied together with sending waves at an oblique angle. Because increasing the detectability of steel bars with polarizations of incident waves while minimizing the reflection from concrete will result in improved detectability. Again, large size specimens are needed to study this effect as a future work.

Physical condition also affects the radar measurement results. Wet concrete specimens did not allow the waves to penetrate deeper into the specimens. The penetration capability is a function of cross-sectional area of a target, center frequency of the incident wave, and dielectric constant and loss factor of a concrete target. Quantitative prediction of penetration and detection capabilities for a specific set of measurement parameters are given in Section 5.6.3. Based on the observation, the radar method is very sensitive to the presence of water. The concrete thickness determination should be oriented to apply the method to dry and not much moisturized concrete targets. For wet specimens, condition monitoring of deterioration process is still possible. Because changed returned signals can be obtained from the radar measurement results as shown in Section 5.6.4, objects such as concrete dams can be subject to radar probing for detection of deterioration process.

Comparison of radar measurement results to computer simulation based on numerical modeling suggests that simulation provides a reference imagery for both prediction and interpretation of radar measurement results. Expanding a data base for computer simulation and radar measurements can be used to identify signals for unknown targets, for example, using a neural network. As discussed within the chapter, It is inevitable to avoid some of the intrinsic differences between the simulation and the measurement results.

Radar measurement results as a whole suggest about hardware system design. As clearly shown in the results, a specific combination of the radar measurement parameters can provide or achieve a specific goal of NDE. For example, if the purpose of the measurements was for thickness detection and a typical dimension of the thickness is known, a proper set of measurement parameters can be used instead of having all the other unnecessary features in a hardware system. A handy, portable radar measurement equipment should be considered as a practical use of the method, rather than having a gigantic machinery with all the features included.
Chapter 6

Summary, Conclusions, And Future Work

6.1 Summary

The objective of this research work was to develop a methodology to investigate a radar method as a tool for NDE of concrete systems in a systematic way so that suggestions could be made to solve real problems using the radar.

Accomplishments have been made to meet the objectives of developing and providing both theoretical and experimental basis of the microwave technique as an NDE of concrete systems. The research tasks accomplished are as follows:

I. Development of a data base for electromagnetic properties of concrete.
II. Radar measurements of laboratory size concrete specimens with inclusions embedded inside and establishment of a data base regarding characteristics of concrete in its interaction with electromagnetic waves.
III. Development of computer simulation schemes through numerical modeling of wave propagation and scattering through and by various concrete targets.
IV. Development of signal processing techniques for generating one- and two-dimensional imaging of the specimens.

A data base for the electromagnetic properties of concrete was established as a function of frequency, moisture level, and density. The developed data is incorporated and utilized in the numerical modeling, radar measurements, and image reconstruction. An open-ended coaxial probe method was used and a measurement technique was developed suitable for concrete specimens and for a wide frequency range from 100 MHz to 20 GHz. The established data base provides a unique information about the behavior of concrete in its interaction with electromagnetic waves.

Computer simulation through numerical modeling of wave propagation and scattering through and by various concrete targets were performed to identify optimum radar measurement parameters for any given measurement condition. The measurement parameters studied include center frequency, frequency bandwidth, polarization, incident angle of the wave, measurement distance, geometric and material properties of the target. A parametric study was conducted to examine the effect of each parameter on the
measurement results, thus solving a forward problem. A finite difference-time domain method was used for the modeling and a signal processing technique was developed to simulate various wideband radar measurements.

A wideband inverse synthetic aperture radar (ISAR) was used for the radar measurements at different frequency ranges. The concrete targets contained different types of inclusions such as steel reinforcing bars and voids embedded inside. The radar measurements provided the detection and penetration capabilities of the systems at a given condition. An imaging algorithm was developed which incorporated the electromagnetic properties of concrete to improve a free space imaging algorithm. As results of research work performed, three major areas have been identified as possible applications of the radar method for NDE of concrete systems. First, the thickness measurement technique developed can be used for pavements and bridge decks, concrete covers of floor, retaining wall, etc., and pier and foundations. Based on the findings, penetration and detection capabilities of a radar system can be determined through selected radar measurements of concrete samples as shown in this work. Second, condition monitoring is possible over a period of time. This monitoring can detect any incipient deterioration occurring inside concrete systems. For example, a concrete dam subject to deterioration can be monitored periodically by a radar and any change in the returned signal indicates the presence of abnormalities. It is similar to quality control of existing structures. Third, detection of inclusions embedded inside concrete is possible by using different polarizations. The natural sensitivity of the electromagnetic waves to the metallic objects as steel reinforcing bars makes it possible to detect embedded objects.

6.2 Conclusions

This work consists of measurements of electromagnetic properties of concrete, extensive radar measurements of various concrete specimens, and computer program development for modeling and imaging. The following conclusions are drawn from the results of the research work:

1. The radar method is proven to be an effective tool for NDE of concrete systems through both experimentally and theoretically based studies. In this study, phenomena which have been generally stated qualitatively in relation to the use of radar method for NDE of concrete are quantified.
2. The center frequency and frequency bandwidth of the waves play the most important role. For the concrete specimens studied in this investigation, the results showed that $2 \sim 3.4 \text{ GHz (S/C band)}$ waves are good for concrete thickness detection with penetration capability up to 6" for a dry concrete specimen with cross-sectional area of 12" x 12". This penetration capability is based on the detectability of the back surface of a target and it is a function of cross-sectional area of the target, frequency, and the electromagnetic properties of a concrete target. At $3.4 \sim 5.8 \text{ GHz (C band)}$, concrete thickness measurement can be still made with introduction of disturbed signals due to the increase frequency. This C band frequency is shown to be the best frequency to monitor the condition change inside concrete with sensitivity to holes and delaminations for the measurement condition used in this investigation. At the highest frequency range tested in the research, $8 \sim 12 \text{ GHz (X band)}$ waveforms did poor in determining the concrete thickness measurements, however, the waves were sensitive enough to detect increase in the returned signal due to the presence of steel reinforcing bars embedded at 1" or 2" depth of a 12" x 4" x 12" concrete specimens. Frequency bandwidth is related to the center frequency meaning that at higher center frequency the wider bandwidth is obtained as observed in three frequency ranges used in the research work. The bandwidth selection was limited by the employed antenna specifications.

3. The use of an oblique incident angle of the waves to increase the detectability of inclusions inside concrete did not show any advantage in the study. The incident angle was increased from zero (normal incident) to 10 degrees. As incident angle increases more edge effects were observed overshadowing any possible increase of inclusion detectability. Incident angle over 10 degrees returned even poorer results. These results at oblique incident angles are due to the relatively small size of concrete specimens used for the radar measurements. The size of the specimens was limited due to the weight limit on a rotating Styrofoam tower. Future measurements of large size concrete specimens without edge effects might prove the chance of improving detectability of inclusions by sending waves at an angle other than normal.

4. The vertical and horizontal polarizations of an incident wave showed promising results. When the electric field of the waves was parallel with the orientation of inclusions, the returned signal was maximized as expected. This provides a ground
to further use polarization for NDE of concrete, especially because most concrete structures have steel reinforcement inside.

5. The radar method showed sensitivity to the presence of moisture level. While it was possible to detect the back surface of 4" thick dry concrete specimen at 3.4 ~ 5.8 GHz, a wet specimen did not allow the waves to penetrate deep enough to the back surface. However, existence of steel bars and air or water filled delamination located at 3" from the front surface were detected in the wet specimen under the measurement condition investigated. This suggest that wet concrete targets are difficult to be probed for thickness determination, but can be probed for the detection of delaminations. The change in the returned signal from a wet target provided a basis in determining the deterioration inside concrete.

6. The FD-TD method is proven to be effective and useful as a predictive tool to simulate radar measurements. It is recommended that for a practical application of the method developed in this work, a data base of computer simulation combined with a data base of radar measurement results can be served as a reference in identifying the measured signal from an unknown objects. This interpretation technique can be implemented as a specific problem area is defined.

7. The hardware system used in the work, the inverse synthetic aperture radar (ISAR), operates inside a chamber, and it is capable of transmitting waves over a wide frequency range. For a hardware system development for practical application of the method, it is essential to identify a specific problem area which determines a required set of radar measurement parameters. This specification of measurement parameters and reduced set of radar hardware system features will make it possible to have a handy, portable radar measurement system.

8. The imaging algorithms implemented in the research work provides excellent presentation of the measured raw data in one- or two-dimensional imagery. This image presentation skills are important to better interpret the data. Implementation of software system with imaging tools make the measurement system complete.
6.3 Recommendations for Future Work

Future research activities on the topic include the following:

1. Electromagnetic property measurements of different types of concrete mix as needed.

2. In situ radar measurements of large size concrete targets.

3. Hardware equipment development which can utilize a proper set of measurement parameters for a specifically identified problem area.

4. Simulation and modeling techniques with improvement in computational speed, and more flexibility in simulating various objects with different sizes and shapes.

5. Development and application of advanced signal processing schemes for imaging such as super resolution techniques.
References


Appendices

Appendix A. Radar Measurement Results for Geometry Effect

In Appendix A, radar measurement results of laboratory size concrete specimens used for the study of target geometry effect are provided. The results obtained from the measurements at S/C band from 3.4 to 5.8 GHz are presented in the format of two- and one-dimensional imagery with a schematic view of a specimen. The measurements were made with the following measurement parameters as shown in Table A-1.

Table A-1. Radar measurement specifications.

<table>
<thead>
<tr>
<th>Radar system</th>
<th>inverse synthetic aperture radar (ISAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement frequency</td>
<td>3.4 ~ 5.8 GHz (S/C band)</td>
</tr>
<tr>
<td>Center frequency</td>
<td>4.6 GHz</td>
</tr>
<tr>
<td>Frequency bandwidth</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Waveform</td>
<td>stepped frequency gated continuous wave</td>
</tr>
<tr>
<td>Pulse width</td>
<td>20 ns</td>
</tr>
<tr>
<td>Polarization</td>
<td>co-polarizations (VV and HH)</td>
</tr>
<tr>
<td>Output power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>Measurement distance</td>
<td>14.4 m (48 ft.)</td>
</tr>
</tbody>
</table>

Detailed drawings of the specimens with dimensions are given in Figure A-1 and Figure A-2. The measurement results are shown in Figures A-3 to A-8. Table A-2 lists the radar measurement results presented.
Table A-2. List of radar measurements for geometry effect.

<table>
<thead>
<tr>
<th>Specimen name</th>
<th>Geometry</th>
<th>Inclusion</th>
<th>Frequency</th>
<th>Figure number</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1a</td>
<td>6&quot; diameter x 12&quot;</td>
<td>none</td>
<td>3.4 ~ 5.8 GHz</td>
<td>A-3</td>
</tr>
<tr>
<td>A-1b</td>
<td>6&quot; diameter x 12&quot;</td>
<td>0.5&quot; diameter bar</td>
<td>3.4 ~ 5.8 GHz</td>
<td>A-4</td>
</tr>
<tr>
<td>A-1c</td>
<td>6&quot; diameter x 12&quot;</td>
<td>0.5&quot; diameter void</td>
<td>3.4 ~ 5.8 GHz</td>
<td>A-5</td>
</tr>
<tr>
<td>A-2a</td>
<td>6&quot; x 6&quot; x 12&quot;</td>
<td>none</td>
<td>3.4 ~ 5.8 GHz</td>
<td>A-6</td>
</tr>
<tr>
<td>A-2b</td>
<td>6&quot; x 6&quot; x 12&quot;</td>
<td>0.5&quot; diameter bar</td>
<td>3.4 ~ 5.8 GHz</td>
<td>A-7</td>
</tr>
<tr>
<td>A-2c</td>
<td>6&quot; x 6&quot; x 12&quot;</td>
<td>0.5&quot; diameter void</td>
<td>3.4 ~ 5.8 GHz</td>
<td>A-8</td>
</tr>
</tbody>
</table>

Figure A-1. Cross-sectional view of 6 in. diameter cylindrical concrete specimens: (a) plain concrete with no inclusion, (b) with a 0.5 in. diameter steel reinforcing bar, and (c) with a 0.5 in. diameter void at the center of the cylinder. All the specimens have 12 in. height.

Figure A-2. Cross-sectional view of 6 in. x 6 in. concrete specimens: (a) plain concrete with no inclusion, (b) with a 1 in. diameter steel reinforcing bar, and (c) with a 1 in. diameter void at the center. All the specimens have 12 in. height.
Figure A-3. 6" diameter dry plain concrete specimen (Figure A-1a) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure A-4. 12" x 4" x 12" dry concrete specimen with a 0.5" diameter steel bar (Figure A-1b) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure A-5, 12" x 4" x 12" dry concrete specimen with a 0.5" diameter hole (Figure A-1c) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure A-6. 6" x 6" x 12" dry plain concrete specimen (Figure A-2a) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure A-7. 6" x 6" x 12" dry concrete specimen with a 1" diameter steel bar (Figure A-2b) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure A-8. 6" x 6" x 12" dry concrete specimen with a 1" diameter hole (Figure A-2c) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Appendix B. Radar Measurement Results for NDE

In Appendix B, radar measurement results of laboratory size concrete specimens used for NDE of concrete are provided. The results obtained from the measurements at 2 ~ 3.4 GHz (S band), 3.4 ~ 5.8 GHz (S/C band), and 8 ~ 12 GHz (X band) are presented in the format of two- and one-dimensional imagery with a schematic view of a specimen. The measurements were made with the following measurement parameters as shown in Table B-1.

Table B-1. Radar measurement specifications.

<table>
<thead>
<tr>
<th>Radar system</th>
<th>inverse synthetic aperture radar (ISAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement frequency</td>
<td>2 ~ 3.4 GHz (S band)</td>
</tr>
<tr>
<td></td>
<td>3.4 ~ 5.8 GHz (S/C band)</td>
</tr>
<tr>
<td></td>
<td>8 ~ 12 GHz (X band)</td>
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<tr>
<td>Center frequency</td>
<td>2.7 GHz (S band)</td>
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<td></td>
<td>4.6 GHz (S/C band)</td>
</tr>
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<td></td>
<td>10 GHz (X band)</td>
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<tr>
<td>Frequency bandwidth</td>
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<td></td>
<td>2.4 GHz (S/C band)</td>
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<tr>
<td></td>
<td>4 GHz (X band)</td>
</tr>
<tr>
<td>Waveform</td>
<td>stepped frequency gated continuous wave</td>
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<tr>
<td>Pulse width</td>
<td>20 ns</td>
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<tr>
<td>Polarization</td>
<td>co-polarizations (VV and HH)</td>
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<tr>
<td>Output power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>Measurement distance</td>
<td>14.4 m (48 ft.)</td>
</tr>
</tbody>
</table>

Detailed drawings of the specimens with dimensions are given in Figure B-1 and Figure B-4. The measurement results are shown in Figures B-5 to B-28. Table B-2 lists radar measurement results presented in Appendix B.
Table B-2, List of radar measurements for NDE.

<table>
<thead>
<tr>
<th>Specimen name</th>
<th>Physical condition and dimensions of specimen (width x thickness x height)</th>
<th>Size and number of inclusions and location from surface</th>
<th>Frequency used for the measurements</th>
<th>Figure number</th>
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<tr>
<td>B-1a</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>none</td>
<td>2 ~ 3.4 GHz</td>
<td>B-5</td>
</tr>
<tr>
<td>B-1b</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 1&quot;</td>
<td>2 ~ 3.4 GHz</td>
<td>B-6</td>
</tr>
<tr>
<td>B-1c</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 2&quot;</td>
<td>2 ~ 3.4 GHz</td>
<td>B-7</td>
</tr>
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<td>B-1a</td>
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<td>none</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-8</td>
</tr>
<tr>
<td>B-1b</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 1&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-9</td>
</tr>
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<td>B-1c</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 2&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-10</td>
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<tr>
<td>B-1d</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. holes at 1&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-11</td>
</tr>
<tr>
<td>B-1e</td>
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<td>10&quot; x 1&quot; delam at 1&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-12</td>
</tr>
<tr>
<td>B-1f</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>10&quot; x 1&quot; delam at 2&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-13</td>
</tr>
<tr>
<td>B-2a</td>
<td>wet 12&quot; x 4&quot; x 12&quot;</td>
<td>none</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-14</td>
</tr>
<tr>
<td>B-2b</td>
<td>wet 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 1&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-15</td>
</tr>
<tr>
<td>B-2c</td>
<td>wet 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 2&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-16</td>
</tr>
<tr>
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<td>10&quot; x 1&quot; delam at 1&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
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<td>3.4 ~ 5.8 GHz</td>
<td>B-18</td>
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<tr>
<td>B-3a</td>
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<td>10&quot; x 1&quot; delam at 1&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
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<tr>
<td>B-3b</td>
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<td>10&quot; x 1&quot; delam at 2&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-20</td>
</tr>
<tr>
<td>B-3c</td>
<td>wet 12&quot; x 4&quot; x 12&quot;</td>
<td>10&quot; x 1&quot; delam at 1&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-21</td>
</tr>
<tr>
<td>B-3d</td>
<td>wet 12&quot; x 4&quot; x 12&quot;</td>
<td>10&quot; x 1&quot; delam at 2&quot;</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-22</td>
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<tr>
<td>B-4a</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-0.5&quot; dia. vert. and 3-0.5&quot; dia. horiz. bars</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-23</td>
</tr>
<tr>
<td>B-4b</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-0.5&quot; dia. vert. bars and 10&quot; x 1&quot; delam.</td>
<td>3.4 ~ 5.8 GHz</td>
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<tr>
<td>B-4c</td>
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<td>10&quot; x 1&quot; delamination and 3-0.5&quot; dia. vert. bars</td>
<td>3.4 ~ 5.8 GHz</td>
<td>B-25</td>
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<td>B-1a</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>none</td>
<td>8 ~ 12 GHz</td>
<td>B-26</td>
</tr>
<tr>
<td>B-1b</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 1&quot;</td>
<td>8 ~ 12 GHz</td>
<td>B-27</td>
</tr>
<tr>
<td>B-1c</td>
<td>dry 12&quot; x 4&quot; x 12&quot;</td>
<td>3-1&quot; dia. bars at 2&quot;</td>
<td>8 ~ 12 GHz</td>
<td>B-28</td>
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</tbody>
</table>
Figure B-1. Cross-sectional view of 12 in. x 4 in. concrete specimens: (a) plain concrete, (b) with three 1 in. diameter steel reinforcing bars at 1 in. depth, (c) with three 1 in. diameter steel reinforcing bars at 2 in. depth, (d) with three 1 in. diameter voids at 1 in. depth, (e) with a 10 in. x 1 in. delamination at 1 in. depth, and (f) with a 10 in. x 1 in. delamination at 2 in. depth. All the specimens have 12 in. height.
Figure B-2. Cross-sectional view of 12 in. x 4 in. wet concrete specimens; (a) plain concrete, (b) with three 1 in. diameter steel reinforcing bars at 1 in. depth, (c) with three 1 in. diameter steel reinforcing bars at 2 in. depth, (d) with a 10 in. x 1 in. delamination at 1 in. depth, and (e) with a 10 in. x 1 in. delamination at 2 in. depth. All the specimens have 12 in. height.
Figure B-3. Cross-sectional view of 12 in. x 4 in. concrete specimens with a 10 in. x 1 in. delaminations filled with water: (a) inside dry concrete at 1 in. depth, (b) inside dry concrete at 2 in. depth, (c) inside wet concrete at 1 in. depth, and (d) inside wet concrete at 2 in. depth. All the specimens have 12 in. height.

Figure B-4. Cross-sectional view of 12 in. x 4 in. concrete specimens with multiple inclusions: (a) three 0.5 in. steel bars placed vertically and three 0.5 in. steel bars placed horizontally, (b) three 0.5 in. steel bars placed vertically with a 10 in. x 1 in. delamination, and (c) a 10 in. x 1 in. delamination with three 0.5 in. steel bars placed vertically. All the specimens have 12 in. height.
Figure B-5. 12" x 4" x 12" dry plain concrete specimen (Figure B-1a) viewed from the top. Measured at 2 to 3.4 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-6. 12" x 4" x 12" dry concrete specimen with three 1" diameter bars at 1" depth (Figure B-1b) viewed from the top. Measured at 2 to 3.4 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-7. 12" x 4" x 12" dry concrete specimen with three 1" diameter steel bars at 2" depth (Figure B-1c) viewed from the top. Measured at 2 to 3.4 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-8. 12" x 4" x 12" dry plain concrete specimen (Figure B-1a) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-9, 12" x 4" x 12" dry concrete specimen with three 1" diameter bars at 1" depth (Figure B-1b) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-10. 12" x 4" x 12" dry concrete specimen with three 1" diameter steel bars at 2" depth (Figure B-1c) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization,

1-D image of the specimen with VV and HH polarizations.
Figure B-11. 12" x 4" x 12" dry concrete specimen with three 1" diameter holes at 1" depth (Figure B-1d) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-12. 12" x 4" x 12" dry concrete specimen with a 10" x 1" delamination at 1" depth (Figure B-1e) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization,

1-D image of the specimen with VV and HH polarizations.
Figure B-13. 12" x 4" x 12" dry concrete specimen with a 10" x 1" delamination at 2" depth (Figure B-1f) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B.14. 12" x 4" x 12" wet plain concrete specimen (Figure B-2a) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-15. 12" x 4" x 12" wet concrete specimen with three 1" diameter steel bars at 1" depth (Figure B-2b) viewed from the top. Measure at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-16. 12" x 4" x 12" wet concrete specimen with three 1" diameter steel bars at 2" depth (Figure B-2c) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-17. 12" x 4" x 12" dry concrete specimen with a 10" x 1" delamination at 1" depth (Figure B-2d) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-18. 12" x 4" x 12" wet concrete specimen with a 10" x 1" delamination at 2" depth (Figure B-2e) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-19. 12" x 4" x 12" dry concrete specimen with a 10" x 1" delamination filled with water at 1" depth (Figure B-3a) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-20. 12" x 4" x 12" dry concrete specimen with a 10" x 1" delamination filled with water at 2" depth (Figure B-3b) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-21. 12 in. x 4 in. x 12 in. wet concrete specimen with a 10 in. x 1 in. delamination filled with water at 1" depth (Figure B-3c) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-22. 12" x 4" x 12" wet concrete specimen with a 10" x 1" delamination filled with water at 2" depth (Figure B-3d) viewed from the top. Measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-23. A dry plain concrete specimen with three 0.5" diameter steel bars placed vertically and three bars placed horizontally (Figure B-4a) measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-24. 12" x 4" x 12" dry plain concrete specimen with three 1" diameter steel bars and a 10" x 1" delamination (Figure B-4b) measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-25, 12" x 4" x 12" dry plain concrete specimen with a 10" x 1" delamination and three 1" diameter steel bars (Figure B-4c) viewed from the top measured at 3.4 to 5.8 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-26, 12" x 4" x 12" dry plain concrete specimen (Figure B-1a) viewed from the top. Measured at 8 to 12 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B-27. 12" x 4" x 12" dry concrete specimen with three 1" diameter bars at 1" depth (Figure B-1b) viewed from the top. Measured at 8 to 12 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Figure B.28. 12" x 4" x 12" dry concrete specimen with three 1" diameter steel bars at 2" depth (Figure B.1c) viewed from the top. Measured at 8 to 12 GHz.

2-D image of the specimen with VV polarization.

1-D image of the specimen with VV and HH polarizations.
Appendix C. Computer Programs Implemented

Computer programs implemented for the research work are described briefly in the appendix. A total of four programs are implemented as follows:

1. Finite Difference-Time Domain (FD-TD) modeling program, "fdtd.f",
2. Signal processing program for plotting FD-TD modeling results, "fdtdplot.m",
3. One-dimensional imaging program, "1d.m",
4. Two-dimensional imaging program, "2d.m",

Each program is described for its purpose, input, scheme, and output.

C.1 Finite Difference-Time Domain (FD-TD) modeling program

Computer language: FORTRAN
Source code name: fdtd.f
Executable file name: fdtd.exe
Hardware requirement: Personal Computer (PC) 386 or higher, or Digital Equipment Corporation (DEC) Workstation with alpha processor

Input: geometry information of a target and an incident wave
Procedure: Discretizes a computational domain with a concrete specimen located within the domain. Calculates electric and magnetic fields at each grid as a function of time for wave propagation and scattering. Collects reflected signal as a function of time
Output: reflected electric and magnetic field strengths from the target as a function of time

C.2 Signal processing program for plotting FD-TD modeling results

Computer language: Matlab
Source code name: fdtdplot.m
Executable file name: fdtdplot
Hardware requirement: Workstation

Input: output file from the FD-TD modeling program "fdtd.exe"
Procedure: Fourier transform the reflected signal in time domain to frequency domain. Normalize the reflected signal with respect to the incident wave in frequency. Apply a window for filtering and inverse Fourier transform to time. Output: signal processed one-dimensional image of a target from modeling

C.3 One-dimensional imaging program

Computer language: Matlab
Source code name: 1d.m
Executable file name: 1d
Hardware requirement: PC or Workstation

Input: measurement or modeling data for either polarization
Procedure: Takes an input data in the form of real and imaginary parts of a complex number in frequency and inverse Fourier transform to time after applying a window.
Output: One-dimensional image of a target for each polarization

C.4 Two-dimensional imaging program

Computer language: Matlab
Source code name: 2d.m
Executable file name: 2d
Hardware requirement: Workstation

Input: measurement or modeling data for either polarization
Procedure: Takes an input data in the form of real and imaginary parts of a complex number in frequency and perform two-dimensional inverse Fourier transform to time after applying a window.
Output: two-dimensional image of a target for each polarization