THROUGH-THE-WALL RADAR IMAGING

Edited by

Moeness G. Amin

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THROUGH-THE-WALL

RADAR IMAGING

Preface

During the past decade, the technology associated with "seeing" through walls has witnessed a growing interest. The objectives of sensing through walls and inside enclosed structures range from determining building layouts, discerning the nature of activities inside buildings, and imaging building interiors to detect, identify, classify, and track the whereabouts of humans and moving objects. These attributes are highly desirable for a range of organizations, including police, fire and rescue personnel, first responders, and defense forces.

To achieve these objectives, electromagnetic waves are considered very effective due to their ability to penetrate man-made building materials and to image targets behind opaque structures. Through-the-wall radar imaging (TWRI) is a multifaceted technology. It requires a blending of several disciplines in the field of electrical engineering, especially those that involve signal, array, and image processing as well as radars, antennas, and electromagnetic (EM) waves. Solutions of TWRI problems must, however, take phenomenological issues into consideration and should be based on a solid understanding of the intricacies of EM wave interactions with exterior and interior building objects and structures. Furthermore, urban sensing operations put various demands and constraints on the imaging system, which may limit its application. Many factors must be considered, namely, size, weight, mobility, acquisition time, aperture distribution, power, bandwidth, standoff distance, and, most importantly, reliable performance and delivery of accurate information.

This book provides a broad overview of TWRI and discusses possible applications. It provides comprehensive coverage of all the important aspects from the algorithmic, modeling, experimentation, and system design perspectives. The book is motivated by the fact that there are important differences in the physics and objectives between TWRI and other typical radar imaging and remote sensing technologies. The phenomenology of wave propagations and interactions with and within exterior and interior walls, floors, and ceiling, and in between multiple targets, combined with the underlying nature and peculiar demands of indoor settings on system requirements make TWRI rather unique.

The recent developments in TWRI are captured in the 15 chapters of this book. The content and organization of the chapters allow a smooth transition from topic to topic.

Chapter 1 examines the electromagnetic properties of walls and building materials, which is of paramount importance to study and model the effects of walls on signal delay time, amplitude, and pulse shape. These effects must be properly incorporated when dealing with target images, detection, and localization. Various types of lossy and lossless walls are considered, including homogeneous material composition and heterogeneous air hole

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structure organization. The chapter also discusses wall attenuation and dispersion effects in view of angles of incidence and antenna polarization.

Chapter 2 covers important techniques in the design of antenna elements and array configurations. It discusses key antenna-related integration issues for consideration in TWRI systems and describes an implemented prototype mobile imaging system along with its onboard antennas. It also covers wideband, low-profile, and printed antennas, as well as planar/conformal ultrawideband antennas. Finally, it provides a detailed account of array developments for portable systems using slotted microstrip and printed Vivaldi arrays, together with system control mechanisms.

Chapter 3 discusses a number of beamforming concepts and issues that arise in TWRI. It presents the notion of point spread function (PSF), which is a standard measure of beamforming performance, with special emphasis on the PSF characteristics that result from the use of ultrawideband waveforms. The effect of various wall types on beamforming is also examined. Various array configurations and beamforming algorithms that may be employed for imaging are described and evaluated, and the issues associated with array implementation are addressed.

Chapter 4 describes technologies to image, localize, and track behind-the-wall targets using an antenna array with collocated and distributed apertures. It discusses coherent and noncoherent imaging techniques and provides practical examples. It also describes successful experiments for detecting moving targets behind walls using change-detection techniques. The chapter advocates the use and applicability of a dual-frequency radar in TWRI, which uses two CW signals with separate frequencies to provide range information of a single target or a small number of targets.

Chapter 5 discusses several suitable waveforms for use in TWRI applications. In addition to image resolution, it presents other key factors in waveform selection and design that are related to wall characteristics, building structure materials, electromagnetic interference, and covertness, and that are pertinent to system specifications, such as size and weight constraints. The design of emerging waveforms to optimize target detection by increasing target-to-noise and clutter ratio is discussed, with special emphasis on matched illumination-based signature exploitation techniques.

Chapter 6 deals with inverse scattering approaches and revolves around the relevance of physical-based model approaches in TWRI. It studies EM wave propagation through walls and shows the dispersion and blurring effects on behind-the-wall target images. Refocusing, in which wall electric properties are estimated from the early wall returns and then taken into account to produce a focused image, is shown to achieve impressive deblurring results. A class of linear and effective inverse scattering approaches based on simplified models of EM scattering is also presented.

Chapter 7 presents theoretical and experimental research in 3D building tomography using microwave remote sensing. It addresses the highly nonlinear inverse problem with the potentially huge number of degrees of freedom associated with building elements. The inverse problem uses prior information and performs a hierarchy of local inversions, isolations, and subtractions to achieve higher levels of building details. This chapter describes the physics of ray interaction with various types of buildings, especially those that have a periodic transverse internal wall structure, causing Bragg conditions.

Chapter 8 presents high-frequency asymptotic modeling methods that have been successfully used to carry out building imagery within the framework of the uniform geometric theory of diffraction (UTD), with an emphasis on multiple wall transmission, reflection, and diffraction. The methods discussed are based on generalizations of the UTD coefficients, and include both edge and corner diffraction coefficient generalizations that are modified to account for penetrable dielectric walls. This chapter demonstrates that the UTD with ray tracing technologies can create accurate 3D building images.

Chapter 9 describes synthetic aperture radar (SAR) techniques for TWRI. It discusses SAR image formulation methods based on strip-map and spotlight SAR techniques, and applies these methods to both modeling and experimental data. It demonstrates the benefits of using EM modeling to obtain high-fidelity results, permitting the separation of the scattering phenomenology and the artifacts introduced by image formation processing. This chapter presents radar signatures of the human body and shows a variety of simple and complex SAR images.

Chapter 10 covers impulse radars, which emit carrierless and very short pulses and implement SAR techniques. It demonstrates that ImpSAR can produce high-fidelity images, which assist in weapon and human detection and classification. Both inanimate objects and static people inside buildings at reasonably large standoff distances are considered in the analyses and experimentations. This chapter introduces the properties of an ImpSAR system, including phenomenology, hardware, and signal processing, and touches upon the ImpSAR system design principles.

Chapter 11 tackles the issue of airborne radar imaging of multi-floor buildings. It describes a technique for estimating the scattering primitives, such as dihedral and trihedral, from the radar returns, and uses the results to infer information about the building interiors. A maximum likelihood estimation technique is applied and efficiently implemented to obtain the location of primitive features and wall propagation/reflection parameters. The imaging and parameter estimation technique presented is successfully validated using EM simulations of a two-story building.

Chapter 12 presents strategies for target detection in TWRI applications. Different approaches based on centralized and decentralized detection schemes are discussed. Behind-the-wall target detection is addressed for a single view and also for multiple views, when available. The latter is possible when dealing with buildings at street corner locations or when reimaging with different system positions along the same side of the building. The focus of this chapter is on stationary targets, and the detection schemes are applied to the images generated using wideband synthetic aperture beamforming.

Chapter 13 deals with the detection of concealed targets, such as weapons and explosives, in TWRI applications. It addresses the unique challenges of distinguishing the signal returns arising from the sought target inside walls in which the target is concealed. It describes an imaging technique based on the inverse scattering and tomography approaches. This technique does not depend on high- or low-frequency approximations and is specifically designed to detect and possibly identify a target or a repository of targets concealed behind a wall.

Chapter 14 considers fast imaging acquisition schemes based on reduced data volume. The schemes presented include compressive sensing (CS), which allows a radar image of almost the same resolution and quality to be generated as that produced when employing all data samples. This chapter shows how targets behind walls can be accurately located using a fraction of the data measurements by using model and experimental data. Finally, data reduction methods and CS strategies under both frequency-domain and time-domain pulsing are delineated.

Chapter 15 focuses on the detection of indoor moving targets and discusses how the Doppler principle can be used to measure motion at a very fine level of detail. The material in this chapter describes the biometric radar in which micro-Doppler signatures, associated with human gait, breathing, and heartbeat, are used for the remote monitoring of human motion pertinent to TWRI applications. Moving target indicator techniques implemented in the raw signal domain and the final image domain are discussed and used for target detection and identification.

I would like to express my sincere gratitude to all book contributors. They have applied their expertise in modeling, experimentation, algorithm development, and system design to deliver high-quality documentations of the state of the art in the area of TWRI and urban sensing. The results is a comprehensive coverage of the subject, supported by relevant references. The breadth and diversity of the topics covered will allow students, engineers, academicians, technical group leaders, and program managers to gain a deep understanding of the challenges facing this technology, and to appreciate the various contributions that have been made in this area.

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Editor

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Dr. Moeness Amin received his PhD in 1984 from the University of Colorado, Boulder. He has been on the faculty of Villanova University since 1985, where is currently serving as a professor in the Department of Electrical and Computer Engineering and as the director of the Center for Advanced Communications. He received the 2009 Individual Technical Achievement Award from the European Association of Signal Processing. He is a fellow of the IEEE, a fellow of the International Society of Optical Engineering, a recipient of the IEEE Third Millennium Medal, a distinguished lecturer of the IEEE Signal Processing Society for 2003 and 2004, a recipient of the 1997 Villanova University Outstanding Faculty Research Award, and a recipient of the 1997 IEEE Philadelphia Section Service Award.

Dr. Amin has over 450 publications in the areas of wireless communications, time–frequency analysis, smart antennas, interference cancellation in broadband communication platforms, GPS and satellite navigations, over-the-horizon radar, and radar imaging. Since 2002, he has been a principal investigator and project director on several research contracts and grants from the Department of Defense and National Science Foundation, which are in excess of $13 million. He was a guest editor of the May 2009 *IEEE Transactions on Geoscience and Remote Sensing Special Issue on Remote Sensing of Building Interior* and a guest editor of the September 2008 *Journal of Franklin Institute* special issue on advances in indoor radar imaging.

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Contents

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Wall Attenuation and Dispersion

Ali Hussein Muqaibel, M.A. Alsunaidi, Nuruddeen Mohammed Iya, and Ahmad Safaai-Jazi

CONTENTS

1.1 Introduction

Electromagnetic waves passing through a medium are subject to amplitude and phase distortions. These distortions are categorically attributed to dispersive and attenuative properties of the medium of propagation. There is an increasing need to understand and model these impairing effects in order to find better ways of mitigating them. In the context of through-the-wall imaging, the ultimate objective is to use the dispersion and attenuation models in developing algorithms for detection, classification, and localization of objects behind walls. This, in turn, necessitates accurate modeling of electromagnetic effects associated with wave propagation and scattering, in pursuit of devising credible solutions. Ignoring the propagation effects limits the scope of our understanding of the sensed data, decreases resolution, and reduces the effective depth for which accurate results can be obtained. An imaging architecture must address the physical propagation effects as well as modeling of the environment so that the system can sense deeper within the buildings.

A propagation path obstruction is defined as a man-made or natural physical object that lies close enough to a radio wave path to cause a measurable effect on the path loss exclusive of reflection effects [TIA]. Thus, electrical properties of the materials that make up these obstructions are important data for indoor radio communication planning and modeling in addition to imaging [Hua96]. It is, therefore, of paramount importance to study the electromagnetic properties of these materials for examining through-the-wall detection and imaging issues and devising the desired solutions. In addition to materials that make the wall, the shape of the wall and its composition also influence the propagation effects. Another effect is caused by multiple reflections within the wall. This impact becomes more pronounced if the wall is heterogeneous. The dielectric constants of obstructions and their thicknesses introduce variable delays in the propagation path. The travel time through the thickness of an object on the signal path is critical to the delay measurement when high accuracy is desired. To assess the effects on delay time, amplitude, and pulse shape, different materials are inserted in the path between transmit and receive antennas. First, a free-space measurement is conducted, and then a slab of material is inserted and the through signal is acquired, as depicted in Figure 1.1. Three examples are presented here to illustrate the effect of the wall on the signal delay and, hence, the imaging capability. For additional examples, the reader is referred to [Muq05]. In the first example, a typical plywood as a relatively homogeneous material is used. The thickness of the plywood is 1.52 cm. The second example is for typical construction concrete blocks with air holes. The thickness of the wall made of concrete blocks is 19.45 cm. The third example is for a wall made of bricks with a thickness of 8.72 cm. Figure 1.2 illustrates the free-space and through measurements for these three cases. Due to the behavior of the transmit antenna, the shape of the received signal is related to the derivative of the transmitted pulse. The damped ringing effects and multipath components are also noted in the figure. The second peak shown in Figure 1.2 is the reflection from the floor.

A major challenge arises when dealing with thick walls or very lossy materials like reinforced concrete, because of their high transmission loss due to reflection and/or absorption. Weak signal levels cannot be measured accurately due to the presence of noise and the limited dynamic range of the

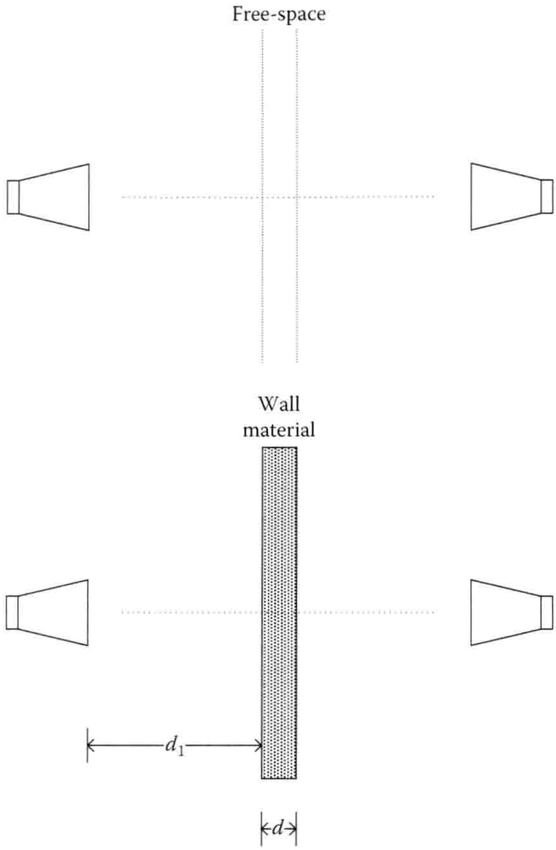

FIGURE 1.1
Transmission measurements—"free space" (without material) and "through" (with material).

measurement equipment. The effect is illustrated in Figure 1.3 with the weak through signal scaled by a factor of 10. The problem becomes more severe in typical imaging applications where transmit and receive antennas are collocated on the same side of the wall. This requires the transmitted signal to propagate through the wall twice as illustrated in Figure 1.4.

Another important challenge is associated with angles of incidence of the wave on the wall or from (to) the transmit (receive) antenna. Furthermore, in practical situations, coupling effects, radiation pattern, input impedance, and polarization of transmit and receive antennas are important factors that need to be taken into consideration. The difficulty when using omnidirectional antennas, which can cause stronger multipath signals, is more pronounced than the case of directional antennas.

We address the dielectric properties of wall materials and relate them to dispersion and attenuation effects in the following sections. An overview of the dielectric properties of materials at the basic level is presented

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