# Electromagnetic Models for Indoor Wave Propagation Analysis and their Application for Ultra-wideband Near-field Radar Imaging of Building Interiors and Human Movement Detection 

by<br>Michael Thiel

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
(Electrical Engineering)
in The University of Michigan
2010

Doctoral Committee:
Professor Kamal Sarabandi, Chair
Professor Eric Michielssen
Associate Professor Gustavo J. Parra-Montesinos
Assistant Professor Anthony Grbic
(c) Michael Thiel 2010

All Rights Reserved

Für meine Eltern.

## ACKNOWLEDGEMENTS

First I would like to thank my parents for their love and support throughout all my education and my time at the University of Michigan, without I would not have been able to accomplish what I did. A special thanks goes to my brother who encouraged me to pursue a Ph.D. abroad.

I am very grateful to my advisor Professor Kamal Sarabandi, for the opportunity to conduct research with him and his patient mentorship, encouragement and guidance throughout my studies, I have learned a lot from him. I would also like to thank Prof. Eric Michielssen, Prof. Anthony Grbic and Prof. Gustavo Parra-Montesinos for their support and advice while serving as my dissertation committee members. Furhter I would like to acknowledge the help of Dr. Adib Nashashibi and Dr. Mojtaba Dehmollaian for my measurements and the help of Dr. Leland Pierce for my computational problems.

I would like to extend my thanks to all of my friends in the Radiation Laboratory, the former and current graduate students who I enjoyed hanging out with and made my stay pleasant one and an unforgettable memory.

I am also grateful to Beth Leslie for the strenuous task of proofreading my thesis.

## TABLE OF CONTENTS

DEDICATION ..... ii
ACKNOWLEDGEMENTS ..... iii
LIST OF FIGURES ..... vii
LIST OF TABLES ..... xvi
LIST OF ABBREVIATIONS ..... xvii
CHAPTER
I. Introduction ..... 1
1.1 Background ..... 1
1.2 Motivation ..... 2
1.3 Thesis Framework ..... 7
II. Ray-tracing for Indoor Wave Propagation Analysis ..... 9
2.1 Theory of Ray-tracing ..... 9
2.1.1 Geometrical Component ..... 10
2.1.2 EM component ..... 12
2.2 Realistic Wall Types and its EM Approximation for Ray-Tracing ..... 13
2.2.1 Homogeneous Walls ..... 14
2.2.2 Inhomogeneous Walls ..... 15
2.3 Conclusions ..... 19
III. The Brick-Tracing Method for Indoor Wave Propagation Anal- ysis ..... 21
3.1 Theory of Brick-Tracer Method ..... 23
3.1.1 Current Calculation Using FDTD ..... 23
3.1.2 Multi-Path Calculation Using Iterative Field Com- putation ..... 23
3.1.3 Convergence and Validity ..... 27
3.2 Numerical Rresults ..... 31
3.2.1 Homogeneous Walls ..... 31
3.2.2 Inhomogeneous Periodic Walls ..... 31
3.2.3 Complex Indoor Environment ..... 36
3.3 Performance and Possible Improvements ..... 38
3.4 Summary ..... 41
IV. 3D-Wave Propagation Analysis of Indoor Wireless Channels Using the Brick-Tracer ..... 42
4.1 Theory of 3D Brick-Tracer ..... 43
4.1.1 Brick Analysis ..... 43
4.1.2 Multi-Path Calculation Using Iterative Field Com- putation ..... 43
4.2 Implementation and Performance ..... 45
4.3 Validation ..... 47
4.4 Wave Propagation Analysis with 3D Brick-Tracer ..... 50
4.5 Channel Characterization and Comparison to Homogeneous Wall Models ..... 51
4.5.1 Path Loss Exponent Model ..... 53
4.5.2 Fast Fading Statistics ..... 57
4.6 Summary ..... 61
V. Incorporation of Human Body Model into Brick-Tracer ..... 62
5.1 Human Body ..... 63
5.1.1 Model ..... 63
5.1.2 Incorporation into Brick-Tracer ..... 64
5.2 Validation and Sample Scenario ..... 67
5.3 Summary ..... 71
VI. Analysis of Human Scattering in Buildings for the Detection and Localization ..... 72
6.1 1D Imaging ..... 72
6.1.1 Background ..... 73
6.1.2 Human Scattering ..... 74
6.1.3 Human Behind a Single Wall ..... 76
6.1.4 Human in Building ..... 77
6.1.5 Human Detection Through Time-Differencing ..... 79
6.2 2D Imaging ..... 82
6.2.1 Background ..... 82
6.2.2 Human in Building ..... 83
6.2.3 Human Localization Through Time-Differencing ..... 85
6.3 Imaging Improvement Combining Co- and Cross-pol. Response ..... 97
6.4 Effects of Inhomogeneous Periodic Walls on Localization ..... 100
6.5 Measurement Validation ..... 102
6.6 Summary ..... 109
VII. Advanced Imaging of Building Layout and Interior Using Spectral Estimation and Wall Estimation Techniques ..... 111
7.1 Theory of Spectral Estimation ..... 113
7.2 Implementation ..... 117
7.3 Imaging Examples ..... 119
7.4 Wall Subtraction Enhanced Spectral Imaging ..... 123
7.5 Summary ..... 126
VIII. Conclusions and Future Work ..... 128
8.1 Contribution ..... 129
8.2 Future Work ..... 130
BIBLIOGRAPHY ..... 133

## LIST OF FIGURES

## Figure

2.1 Sample building layout with ray paths up to three wall interactions (reflection and transmission only). Tx at $(2.0,2.0) \mathrm{m}$ and Rx at (5.0, 7.0) m. ..... 11
2.2 Pathloss versus traveled time of each received ray for the indoor sce- nario of Fig. 2.1 in dB. ..... 13
2.3 The multiple bounces of a plane wave inside a homogeneous dielectric slab, incident at an angle of $\theta_{\mathrm{i}}$ towards the normal of the slab, and the composition of the reflected and transmitted plane wave. ..... 14
2.4 The scattering of a plane wave incident on a periodic wall (periodicity $d$ ) at an angle $\theta_{\text {in }}$ towards its normal. ..... 16
2.5 The unit cells of two periodic walls, reinforced concrete (rebar) and cinderblock, drawn to scale, units in cm . ..... 17
2.6 A cylindrical vertical polarized wave incident on a homogeneous di- electric slab $\left(\epsilon_{r}=6.0, \sigma=0.01 \mathrm{~S} / \mathrm{m}\right)$ of thickness 0.2 m at 1.0 GHz (normalized $E_{z}$-field in dB ). ..... 18
2.7 A cylindrical vertical polarized wave incident on a rebar wall (peri- odicity 0.3 m ) (a) and on a cinderblock wall (periodicity 0.4 m ) at 1.0 GHz (normalized $E_{z}$-field in dB ). ..... 19
3.1 FDTD setup for the simulation of an unit cell of periodic wall. ..... 24
3.2 Geometry of a complex room and its discretization for the multipath calculation ..... 24
3.3 Visualization of the iterative multi-path field calculation. ..... 26
3.4 Visualization of iterative field computation convergence for a homo- geneous dielectric box illuminated by a electric line source at 1.0 GHz , continued in Fig. 3.5 ..... 28
3.5 Visualization of iterative field computation convergence for a homo- geneous dielectric box illuminated by a electric line source at 1.0 GHz , continuation of Fig.3.4. ..... 29
3.6 Maximum change of E-field in dB after each current iteration step of the homogeneous dielectric box illuminated by electric line source of Fig. 3.4 and Fig. 3.5 ..... 30
3.7 Brick-tracer simulation result ( $E_{z}$ in dB ) of a homogeneous dielectric box (dimensions in meters) at 1.0 GHz with Transmitter at (0.5,-1.5). ..... 32
3.8 Full FDTD simulation result ( $E_{z}$ in dB ) of the same setup as Figure 3.7 including internal fields (dimensions in meters) at 1.0 GHz . ..... 32
3.9 Comparison of full FDTD and brick-tracer result ( $E_{z}$ in dB) of ho- mogeneous dielectric box along two traces, $y=0.5 \mathrm{~m}$ and $y=1.5 \mathrm{~m}$ (lowered by 20 dB ). ..... 33
3.10 Normalized magnitude of electric field on the surface of the periodic rebar structure unit cell for two plane wave incidence angles. ..... 34
3.11 Brick-tracer simulation result ( $E_{z}$ in dB) of an infinite rebar wall (dimensions in meters, Transmitter location $(0,-2.0)$ ) at 1.0 GHz . ..... 35
3.12 Full FDTD simulation result ( $E_{z}$ in dB ) of the same setup as Figure 3.11 including internal fields (dimensions in meters) at 1.0 GHz . ..... 35
3.13 Comparison of full FDTD and brick-tracer result ( $E_{z}$ in dB ) of infinite rebar wall along two traces, $y=0.4 \mathrm{~m}$ and $y=1.1 \mathrm{~m}$ (lowered by 10 dB ). ..... 36
3.14 Brick-tracer simulation result ( $E_{z}$ in dB ) of a divided box of rebar wall (dimensions in meter, Transmitter location ( $-0.1,-2.0$ )) at 1.0 GHz . 37 ..... 37
3.15 Full FDTD simulation result ( $E_{z}$ in dB ) of the same setup as Figure 3.14 including internal fields (dimensions in meter) at 1.0 GHz . ..... 37
3.16 Comparison of full FDTD and brick-tracer result ( $E_{z}$ in dB) of di- vided box of rebar wall along two traces, $y=0.3 \mathrm{~m}$ and $y=1.7 \mathrm{~m}$ (lowered by 30 dB ). ..... 38
3.17 Geometry of a complex room with rays from the transmitter to the visible bricks. ..... 39
3.18 Full brick-tracer simulation result ( $E_{z}$ in dB ) of the complex room of Figure 3.17 (dimensions in meter, transmitter location (0.5,-2.0)) at 1.0 GHz . ..... 39
4.1 The mesh of one quarter of the unit hemisphere generated through triangulation of an icosahedron for a $5^{\circ}$ angular separation. ..... 46
4.2 Brick-tracer (a) and image theory (b) field coverage (normalized re- ceived E-field in V/m) of a corner reflector at 1.0 GHz . ..... 48
4.3 The unit cells of the walltypes, cinderblock (left) with overall dimen- sions $0.4 \times 0.2 \times 0.2 \mathrm{~m}$ and cross-rebar (right) with cell size $0.3 \times 0.2 \times 0.2 \mathrm{~m}$. ..... 49
4.4 Hybrid method result (solid line) of a cinderblock wall (unit cell shown in Fig. 4.3) compared to measurement (dashed line) for both vertical (gray) and horizontal (black) polarization including the av- erage (over distance) of all four curves at 1.0 GHz . ..... 50
4.5 Layout of office building floor (floor and ceiling not plotted). ..... 52
4.6 Field coverage (received E-field in dB) of building floor (Fig. 4.5) with inhomogeneous periodic walls for v-polarization. ..... 53
4.7 Field coverage (received E-field in dB ) of building floor (Fig. 4.5) with inhomogeneous periodic walls for h-polarization. ..... 54
4.8 Field coverage (received E-field in dB) of building floor (Fig. 4.5) with effective homogeneous walls for v-polarization. ..... 55
4.9 Field coverage (received E-field in dB ) of building floor (Fig. 4.5) with effective homogeneous walls for h-polarization. ..... 56
4.10 Normalized path loss for 700 sample point of the field coverage of Figure 4.6, plotted against the logarithm of the normalized distance to the Tx . ..... 57
4.11 Normalized path loss for 700 sample point of the field coverage ofFigure 4.8, plotted against the logarithm of the normalized distanceto the Tx.57
4.12 Cumulative distribution function for receiver points in the lower right room of the building floor of Fig. 4.5 for both periodic and effective homogeneous walls and its matching Ricean distribution. The re- ceived signal level is normalized to its median. ..... 60
4.13 Cumulative distribution function for receiver points in the upper right room of the building floor of Fig. 4.5 for both periodic and effective homogeneous walls and its matching Ricean/Rayleigh distribution. The received signal level is normalized to its median. ..... 60
5.1 Human body model of Semcad virtual family (taken form Semcad X Manual) and bistatic RCS comparison (horizontal plane, inc. wave at $\alpha=90^{\circ}$ ) of exact model to homogeneous assumption for vertical polarized plane wave from the front at 1.0 GHz . ..... 65
5.2 Human body model of Semcad virtual family (taken form Semcad X Manual) and bistatic RCS comparison (horizontal plane, inc. wave at $\alpha=90^{\circ}$ ) of exact model to homogeneous assumption for vertical polarized plane wave from the front at 0.5 GHz (left) and 1.5 GHz (right). Compare to Fig. 5.1 ..... 65
5.3 Human body model of Semcad virtual family (taken form Semcad X Manual) and bistatic RCS comparison (horizontal plane, inc. wave at $\alpha=45^{\circ}$ ) of exact model to homogeneous assumption for horizontal polarized plane wave from the side at 1.0 GHz . Compare to Fig. 5.1. ..... 66
5.4 Surface model of walking person. ..... 66
5.5 SEMCAD mesh of walking person with sample Huygens box excitation. ..... 67
5.6 Validation setup (PEC sphere in front of PEC wall) for combined brick-tracer/SEMCAD simulations. ..... 68
5.7 Field coverage (normalized magnitude of E-field) for full SEMCAD simulation of Fig. 5.6 (left) compared to combined brick-tracer/SEMCAD simulation (right) at 1.0 GHz (cut through center of the sphere, per- pendicular to the wall). ..... 68
5.8 Field coverage of $z$-directed Hertian dipole in front of reinforced con- crete wall at 1.0 GHz (E-field in dB, normalized). ..... 69
5.9 Field coverage of human backscattering behind reinforced concrete wall at 1.0 GHz (E-field in dB, normalized to max. of inc. field). ..... 70
5.10 Top view of human and field plot at $z=1.3 \mathrm{~m}$ of SEMCAD simulation of human behind reinforced concrete wall at 1.0 GHz .
6.1 Surface models of different humans, a) man standing still, b) - d) woman standing still from different look angles, e) f) walking woman from front and side, g) woman sitting on chair, h) dog from behind. Models are drawn to scale.
6.2 Frequency and time domain backscattering response of human (a) and (f) of Fig. 6.1, 5 m away from the Tx for vertical polarized Tx and Rx antennas (normalized to max. co-pol. response of man).
6.3 Co- (left) and cross-pol. (right) time-domain backscattering of a human ( 8 m away from Tx ) behind a single homogeneous wall ( 3 m away from Tx ) for vertical polarized Tx and Rx antennas, compared to scattering of a human at same position without wall (dotted line). The gray dashed line is the human scattering portion of the human behind the wall return. Normalized to max. wall return.
6.4 Co- (left) and cross-pol. (right) time-domain backscattering of a human ( 8 m away from Tx ) behind a single homogeneous wall ( 7.3 m away from Tx ) for vertical polarized Tx and Rx antennas, compared to scattering of a human at same position without wall (dotted line). The gray dashed line is the human scattering portion of the human behind the wall return. Normalized to max. wall return of Fig. 6.3.

6.5 Building layout (right) and top view (left) with Transmitter, Receiver
and human position (floor and ceiling not shown).

6.6 Co- (left) and cross-pol. (right) backscattering of a human inside the
building of Fig. 6.5 for vertical polarized Tx antenna, normalized to
its maximum. The gray dashed line is the human scattering portion
of the scene.

6.7 Co- (left) and cross-pol. (right) backscattering of a human inside the
building of Fig. 6.5 for vertical polarized Tx antenna, normalized to
its maximum, human located in the second room. The gray dashed
line is the human scattering portion of the scene.
6.8 Surface model of walking person. ..... 81
6.9 The time-difference time domain backscattering of a walking human in the building of Fig. 6.5, normalized to the maximum wall return. Compare to the backscattering of one shot (Fig. 6.6).
6.10 2D multistatic radar reflectivity image for an array of ideal point targets $(x=0 \ldots 12 \mathrm{~m}$ and $y=-2 \ldots 6 \mathrm{~m}$ in 2 m steps $)$, imaged with a 6 m long Rx array centered at the $\mathrm{Tx}(-2.0,1.0) \mathrm{m}$ from 0.5 to 1.4 GHz .

6.11 2D near-field reflectivity image of co- (left) and cross-pol. (right)
backscattering of human inside the front room of building (Fig. 6.5),
normalized to max. co-pol. reflectivity.

6.12 2D near-field time-difference reflectivity image of co- (left) and cross
pol. (right) backscattering of human walking inside the front room
of building (Fig. 6.5). Compare to single shot image of Fig. 6.11.

6.13 Visualization of the multipath propagation and location of possible
ghost/shadow images of the human in the 2D reflectivity image of
Fig. 6.12.
6.15 2D multistatic radar reflectivity image for an array of ideal point targets $(x=0 \ldots 12 \mathrm{~m}$ and $y=-2 \ldots 6 \mathrm{~m}$ in 2 m steps) for a 6 m long Rx array (spacing 30 cm centered around the $T x(-2.0,2.0) \mathrm{m}$, from 0.5 GHz to 1.0 GHz .

6.16 Building geometry with human path (left) and 2D co-pol. reflectivity
image of building with human at start position (right), in dB and
normalized to its maximum.

6.17 2D near-field consecutive time-difference reflectivity images of co
pol. backscattering of human walking inside the building (Fig. 6.16),
normalized to max. co-pol. wall return.
6.18 2D near-field consecutive time-difference reflectivity images of crosspol. backscattering of human walking inside the building (Fig. 6.16), normalized to max. co-pol. wall return
6.19 Layout of complex building with four rooms, overall dimensions 11.0
by 6.5 m , ground and ceiling not plotted. . . . . . . . . . . . . . . 93
6.20 2D multistatic radar reflectivity image for an array of ideal point targets $(x=-3 \ldots 9 \mathrm{~m}$ and $y=-9 \ldots 9 \mathrm{~m}$ in 2 m steps) for a 4 m long $R x$ array (spacing 10 cm ) centered around the $T x$ at ( -4.2 , 1.0) m from 0.5 Ghz to 1.4 GHz .94
6.21 2D near-field reflectivity image of co- (left) and cross-pol. (right) backscattering of two walking humans inside the complex building of Fig. 6.19, normalized to max. co-pol. reflectivity. ..... 95
6.22 2D near-field time-difference reflectivity image of co- (left) and cross- pol. (right) backscattering of two walking humans inside the building of Fig. 6.19, normalized to max. co-pol. reflectivity of single image. ..... 95
6.23 2D near-field reflectivity image of co- (left) and cross-pol. (right) backscattering of one walking human inside the complex building of Fig. 6.19, normalized to max. co-pol. reflectivity. ..... 96
6.24 2D near-field time-difference reflectivity image of co- (left) and cross- pol. (right) backscattering of one walking human inside the building of Fig. 6.19, normalized to max. co-pol. reflectivity of single image. ..... 97
6.25 Combined multistatic co- and cross-polarized time-difference radar image of Figure 6.12 (walking human in the building of Fig. 6.5) ..... 98
6.26 Combined multistatic co- and cross-polarized time-difference radar image of Fig. 6.22. ..... 99
6.27 Combined multistatic co- and cross-polarized time-difference radar image of Fig. 6.24. ..... 99
6.28 2D near-field reflectivity image of co-pol. backscattering of human 5 m behind a wall (left: homogeneous concrete, right: reinforced con- crete), recorded with a 6 m long Rx array (dB-scale, normalized to max.). Tx position and Rx array center is $(0.0,0.0) \mathrm{m}$. ..... 101
6.29 2D near-field reflectivity image of co-pol. backscattering of human 0.5 m behind a wall (left: homogeneous concrete, right: reinforced concrete), recorded with a 6 m long Rx array (dB-scale, normalized to max.). Tx position and Rx array center is $(0.0,0.0) \mathrm{m}$. ..... 101
6.30 2D near-field reflectivity image of the co-pol. backscattering portion attributed to the human of Fig. 6.29. ..... 102
6.31 Measurement setup with antennas in front of cinderblock wall and mannequin behind cinderblock wall and absorber covered lab walls. ..... 103
6.32 Measured time-domain radar response of mannequin behind a solid concrete wall ( 1.7 m away from radar, thickness 9 cm ), standing 0.5 m(left) and 2.4 m behind the wall (right), with extracted human scat-tering.105
6.33 Measured time-domain radar response of mannequin behind a cinderblock wall ( 1.7 m away from radar, thickness 20 cm ), standing 0.5 m (left) and 2.4 m behind the wall (right), with extracted human scattering.
6.34 2D multistatic radar reflectivity image for an array of ideal point targets $(x=-1 \ldots 7 \mathrm{~m}$ in 2 m steps at $y=0 \mathrm{~m})$ corresponding to a 1 m long Rx array (spacing 0.5 m ) centerer around the Tx at $(0.0,0.0) \mathrm{m}$ from 1.0 GHz to 2.0 GHz .
6.35 Multistatic measurement radar image of solid wall with mannequin 0.5 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.
6.36 Multistatic measurement radar image of solid wall with mannequin 2.4 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.
6.37 Multistatic radar image of simulated solid wall with mannequin 2.4 m behind resembling the measurement of Fig. 6.36 for co-polarization in dB , normalized to max. of wall return.
6.38 Multistatic measurement radar image of cinderblock wall with mannequin 0.5 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.
6.39 Multistatic measurement radar image of cinderblock wall with mannequin 2.4 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.
7.1 (a) Unwindowed 2D near-field SAR image of target behind a wall (normalized in dB ) with synthetic aperture center at $(0.0,0.0) \mathrm{m}$ and (b) 2D IFFT of it (normalized linear)
7.2 MVM (left) and MUSIC estimated (right) 2D near-field SAR reflectivity image of co-pol. backscattering of one target behind a wall (dB scale, normalized). Synthetic aperture center is $(0.0,0.0) \mathrm{m}$.
7.3 Unwindowed regular (left) and MUSIC estimated (right) 2D nearfield SAR reflectivity image of co-pol. backscattering of five targets behind a wall (dB scale, normalized). Synthetic aperture center is $(0.0,0.0) \mathrm{m}$.120
7.4 2D regular SAR image of a trihedral reflector behind a cinderblock wall, generated from unwindowed (a) and windowed (b) data, dB scale normalized to max. wall reflection.121

7.5 2D SAR image of a trihedral reflector behind a cinderblock wall (com
pare to Fig. 7.4), generated with MVM (a) and MUSIC (b) (dB scale
normalized) ..... 121

7.6 Unwindowed regular (left) and MUSIC estimated (right, 92 esti
mated targets) 2D near-field multistatic reflectivity image of co-pol.
backscattering of human inside a $4 \times 4 \mathrm{~m}$ concrete box, dB scale nor
malized. Tx and Rx array center is $(0.0,0.0) \mathrm{m}$. ..... 122
7.7 MUSIC estimated (44 estimated targets) 2D near-field multistatic reflectivity image of co-pol. backscattering of human inside a $4 \times 4 \mathrm{~m}$ concrete box, dB scale normalized. Tx and Rx array center is (0.0, $0.0) \mathrm{m}$. ..... 123
7.8 Normalized waterfall image of five point targets behind a wall and extracted linear features in the image. ..... 124
$7.9 \quad 2 \mathrm{D}$ regular SAR image of a wall with five targets behind (left) and wall subtracted image of the same scene (right), in dB , normalized to max. wall return ..... 125
7.10 MUSIC imaging result of the SAR images of Fig. 7.9. ..... 125
7.11 Wall subtracted 2D SAR image of a trihedral reflector behind a cin- derblock wall, generated regularly (a) and with MUSIC (b). ..... 126

## LIST OF TABLES

## Table

4.1 Comparison of PLE model parameters between periodic and homo- geneous wall scenario. ..... 56
4.2 Comparison of $K$-factor between periodic and homogeneous wall sce- nario fast fading statistics ..... 59
6.1 Comparison of time-domain co- and cross-polarized backscattering for the different human body poses of Fig. 6.1. ..... 76

## LIST OF ABBREVIATIONS

$c_{0}$ Speed of Light in Vacuum
$k$ Wavenumber
3D Three-dimensional
CDF Cumulative Distribution Function
co-pol. Co-polarized
cross-pol. Cross-polarized
EM Electromagnetic
FDTD Finite-difference-time-domain
GO Geometrical Optics
GTD Geometrical Theory of Diffraction
h-pol. horizontal polarization
IFFT Inverse Fast Fourier Transform
LoS Line of Sight
MRI Magnetic Resonance Imaging
MUSIC Multiple Signal Classification
MVM Minimum Variance Method
PDF Probability Density Function
PEC Perfect Electric Conducting
PLE Path Loss Exponent
PO Physical Optics

Radar Radio Detection and Ranging
RCS Radar Cross Section
Rebar Reinforcing Bar
Rx Receiver
SBR Shoot-and-bouncing Ray
TWR Through-the-Wall Radar
TWRI Through-the-wall Radar Imaging
Tx Transmitter
UHF Ultra High Frequency Band; 0.5 to 3.0 GHz
UWB Ultra-wideband
v-pol. Vertical Polarization

## CHAPTER I

## Introduction

### 1.1 Background

Imaging, detection and classification of targets using electromagnetic (EM) waves is omnipresent in nature and is used by most creatures to preserve and sustain their life. One obvious example of such a system is the human eye: using the sun or other sources of light as illuminators, the human eye can detect and record the light reflected or scattered from surrounding objects over an octave bandwidth and over a wide dynamic range. The received information is processed in the brain to reconstruct a three-dimensional representation of the scene and also to identify targets of interest (food, threat, obstacles, etc.). The visible EM wave spectrum has also been used extensively for imaging in the form of photography and video for a wide range of applications, including remote sensing, security systems, surveillance and target tracking. One obvious reason for the prevalent use of optical devices and sensors is the intuitive nature of data interpretation by the user and operator.

While imaging within the visible light spectrum has several advantages, it has one major disadvantage: most materials we encounter in everyday life are opaque when illuminated with visible light, limiting our ability to infer all desired information from a scene under investigation. Since every material shows a different electromagnetic response at different frequencies, research was initiated in the 20th century to use
the lower frequency portion of the spectrum (known as radio- or microwaves) for the detection of distant or visually obscured objects. This lead to the development of Radio Detection and Ranging (radar) systems during the second world war. Among the first applications was a radar system utilizing microwave frequencies for detection of flying airplanes regardless of weather conditions. Since then, radar systems and radar data processing have been significantly improved to enable far more complicated tasks including air traffic control, weather radar, and detection of buried or foliagecamouflaged objects. [1, 2].

### 1.2 Motivation

One emerging radar application is the mapping of building interiors and the detection of humans or other objects within building structures. External detection through radar measurements from a distant location is highly desirable. This technology can be used by firefighters and rescuers to search for people and pathways in burning and collapsing buildings. Such a system offers a fast and efficient approach for the task at hand with minimal risk for the operator, while maximizing the chances of rescue for the trapped individuals. Wider applications of this technology can be extended to include detection of people, weapons and contraband by law enforcement and military agents.

Radar imaging and detection of targets in free space or simple environments has been investigated thoroughly, and the related research has lead to many commercially available radar based systems. However, identification of targets embedded in highly complex surroundings like a building still remains an unsolved problem. Adverse effects of such environments can be grouped into two categories. The first pertains to the direct scattering from the environment itself which can dominate the radar response from both scene and target. In this case, the response from the target cannot be easily distinguished. The second issue is related to the distortion of the incident
wave on the target. Basically, the incident wave undergoes multiple reflections, scattering, polarization changes and attenuation before it arrives at the target. In such cases the target is illuminated from multiple directions with different amplitudes and phases. The same is true for the scattered wave that reradiates off the target as it travels back to the receiver. This leads to a distortion of the target return, to the point where it is no longer distinguishable from the environment. Consequently, an in-depth understanding of the propagation phenomena inside the environment in addition to the scattering properties of the target itself are necessary to facilitate interpretation of the return and for separation of the environment's radar response from that of the target.

The necessary components of the forward and inverse problem for building interior mapping and human movement detection are investigated in this thesis. A hybrid method is developed to simulate realistic building environments, and then this method is expanded to include targets like a walking person. The method is computationally efficient and can obtain a realistic human response within a building to an ultra wideband (UWB) through-wall imaging radar. Such simulation capability is essential because carrying out experiments with radar is very costly, and it is impossible to determine all possible building parameters.

The first step towards obtaining the interior layout of a building from a distant location is to thoroughly understand the structural features of buildings including the materials and wall types. From an EM point of view, walls can be grouped into two major categories: 1) homogeneous walls like concrete or brick walls and 2) inhomogeneous walls like reinforced concrete, cinderblock or drywall. The reflectivity and transmissibility of the homogeneous walls can be determined analytically using the Fresnel reflection and transmission coefficients for homogeneous dielectric slabs if the dielectric constants and conductivities of the materials are known. Various methods to measure those values exist, or they can be looked up in tables once
the material type is identified [3]. The second group of wall types has also been studied extensively in recent years $[4,5,6,7]$. Periodic wall structures create Bragg modes at frequencies where the wall periodicity exceeds half a wavelength. This usually happens above 1 GHz for most wall structures. Analysis of such wall structures in hybrid models can be very cumbersome, and only closed-form formulations for reinforced concrete walls have been developed so far [8].

For the purpose of interior building imaging, only maximum transmissibility is of interest to ensure penetration through as many interior walls of the building as possible. It has been shown that the Bragg modes of periodic walls point in non-specular directions, grow in number, carry more power and hence lower transmissibility with increased frequency $[9,10,11]$. Furthermore, while the attenuation through walls composed of plastic, glass, wood and drywalls is relatively low up to millimeter wave frequencies, the attenuation through brick or concrete is relatively high due to the loss-tangent of the material and its moisture content [12]. Consequently, the lower the maximum frequency of the UWB waveform, the better the penetration through all possible wall types $[10,13]$. On the other hand the minimum frequency is limited by the size of the antennas which is proportional to the wavelength. The lowest frequency also puts a limitation on the cross-range resolution for a fixed aperture length. This leads to a practical frequency range starting at about 0.5 GHz and up to 3.0 GHz (ultra high frequency (UHF) band) for the common wall types .

As a next step, wave propagation inside buildings has to be analyzed accurately to provide insight into the nature of signal scattering and multipath propagation. At the proposed frequency band, the simulation domain of a simple scenario already exceeds the maximum size in term of wavelengths that a full-wave method can handle properly on standard computers [14, 15]. Contrary to full-wave approaches, ray-tracing is capable of handling a full 3D environment and is not drastically limited by the size of the simulation domain. For this reason, ray-tracing is the usual choice for indoor
propagation modeling [16, 17, 18]. However, ray-tracing is based on geometrical optics (GO) which assumes electrically large and homogeneous objects. If structures are small or highly inhomogeneous, ray-tracing fails to correctly predict the scattered field [19]. Furthermore, if the walls exhibit a periodic structure, they have to be approximated by dielectric slabs with effective material parameters [7] which neglects the propagation phenomena of periodic structures [4]. As a possible solution, hybrid methods have been proposed which combine ray-tracing with full-wave methods like FDTD in order to gain accuracy by sacrificing simulation time [20, 21]. So far these hybrid methods have only been proposed, implemented and validated in 2D because of their complexity. A 2D implementation allows for qualitative simulations and can be used as an intermediate step to validate the concept of the hybrid method. Additionally, 2D models can provide accurate results for large simulation domains allowing for better understanding of the wave propagation. However, it should be mentioned that the results for indoor wave propagation analysis lack some important features like vertical inhomogeneities in walls, the floor, the ceiling, windows and doors etc., that can drastically alter the results. A 3D hybrid method that introduces small inhomogeneous objects analyzed by FDTD into the ray-tracing domain as point scatterers [22] and a 3D hybrid method that combines ray-tracing with the periodic method of moments to analyze propagation in staircases has been proposed [23]. But no 3D hybrid method which includes large building interiors with inhomogeneous periodic walls has been developed so far. A hybrid method that fully includes the effects of periodic inhomogeneous walls for indoor wave propagation [24] is presented in this thesis. In this approach the inhomogeneous periodic walls are analyzed accurately using a full-wave method. The interactions between them are accounted for using a physical optics (PO)- like iterative field calculation based on precalculated surface currents.

The thesis also deals with detection of human movement inside buildings. For
this purpose, a full-wave analysis of a human body model is fully incorporated into the hybrid method for accurate human backscattering analysis inside buildings. This new method introduces simulation of the scattering response of humans within realistic building environments for a through-wall radar imaging problem using a UWB waveform at UHF frequencies.

Current systems on standoff detection and localization of humans within building structures are limited. Human detection and imaging at millimeter waves based on body movement caused by breathing has been researched by several $[25,26]$ but the systems have extremely poor wall penetration capabilities and are not feasible for larger building structures [13]. Additionally, simple systems operating at UHF band are proposed that can detect movement detection but without localization [27, 28] and limited to on-wall operation [29]. In contrast, imaging of building interiors using UHF through-wall radar is an active research area, but object detection is primarily based on long-time surveillance, good access to the building, and computationally costly reconstruction algorithms $[30,31,11,10,32]$. This neglects both the special features of human backscattering and the need for real-time results of the radar imaging in order to localize fast-moving humans.

Based on my newly developed simulation tool, human backscattering at the UHF band and how it is affected by the building environment is investigated in this thesis. The accuracy of the simulation tool is verified by measurement. Various radar techniques like monostatic, multistatic or polarimetric radar are evaluated for their capability to detect human motion inside buildings. Multistatic time-differencing radar imaging is proposed that can extend UHF through-wall radars from simple motion detection to the detection and localization of a moving human inside complex building environments. Furthermore, to support the localization of human motion inside buildings, spectral estimation imaging is introduced to through-the-wall radar imaging (TWRI) for the mapping of exterior and interior building walls, and it is
combined with a wall-extraction method to enhance imaging of stationary targets inside a building.

### 1.3 Thesis Framework

This thesis consists of seven chapters organized as follows: Chapter 2 introduces the asymptotic method "ray-tracing" which is the usual choice for indoor wave propagation analysis. EM scattering features of walls at UHF band and their ray-tracing model are discussed followed by the limitations of the wall model and the ray-tracing method. Chapter 3 introduces the concept of a hybrid method that does not suffer from the limitations of ray-tracing, as well as its implementation in two dimensions (2D). This method is validated via full-wave analysis, and simulation results for a sample scenario are presented. Based on the comparison to the full-wave analysis, the accuracy and limitations of the method are discussed. This hybrid method is extended to 3D in Chapter 4. The features of the 3D implementation are pointed out and the 3D implementation is validated via theory and measurement. A realistic indoor scenario is analyzed, and the parameters of the wireless channel are extracted and compared to ordinary ray-tracing. The improved accuracy of the hybrid method over ray-tracing is demonstrated.

In the following chapter, the 3D hybrid method is extended using a Huygens box to include arbitrary objects in the simulation domain which are analyzed with a commercial 3D full-wave solver. The interface between the hybrid method and the full-wave solver is described and verified for a simple scenario. The human body model is also introduced and validated in this chapter. Chapter 6 begins with human backscattering analysis for simple scenarios. Based on the findings, a method for instant detection, localization and tracking of human movement inside building structures is derived and applied to the simulations. The detection and localization method is then verified with measurements of human backscattering in a laboratory
environment and then applied to realistic indoor scenarios. In conclusion, the physical limitations of human detection inside buildings are discussed.

A method for advanced mapping of exterior and interior building walls is discussed next. The theory of the proposed method is described and tested for sample simulated and measured scenarios. This imaging method is further combined with a wallestimation technique to facilitate detection of stationary objects inside buildings.

Finally, the work presented in this thesis is summarized and future research directions are outlined in the last chapter.

## CHAPTER II

## Ray-tracing for Indoor Wave Propagation Analysis

This chapter briefly describes the asymptotic method known as "ray-tracing" for the computation of electromagnetic (EM) wave propagation and its application to indoor wave propagation. Ray-tracing has been used successfully for a variety of applications like characterization of indoor wave propagation channel $[17,18]$ or the urban propagation channel [33]. Being an asymptotic method, it has certain advantages over other methods for the analysis of EM wave propagation but also several disadvantages due to the underlying simplifying assumptions. The advantages and disadvantages will be discussed as the theory of ray-tracing is described and then conclusions for the accuracy of ray-tracing will be drawn.

### 2.1 Theory of Ray-tracing

The ray-tracing approach is derived from an asymptotic high-frequency method based on Geometrical optics (GO). Maxwell's equations are approximated in a quasioptical fashion, so that at sufficiently high frequencies, the transport of energy from one point to another follows the law of conservation of energy in ray tubes [34]. The rays interact locally with interfering objects, and each ray follows a path which minimizes its optical path length. A ray that is incident on an object will lead to a reflected and refracted ray where both rays follow Snell's law. In order for
this approximation to be valid, the size of the interfering objects has to be much larger than the wavelength, and also its curvature has to be much larger than the wavelength. Indoor scenarios usually only contain flat walls and therefore satisfy the second condition. However the walls, themselfs, may not be large enough so that the scattered field of the wall is sufficiently described by a reflected or refracted ray only, as required by the Geometrical Optics approximation. At microwave frequencies, the edge effects have to be taken into account, and for this reason ray-tracing is usually combined with the Geometrical theory of diffraction (GTD) for the analysis of indoor wave propagation $[16,33]$. The GTD adds the paths of diffracted rays at edges and corners of walls to the ray-tracing scenario. A ray that hits the edge of a wall will generate a cone of diffracted rays. The diffracted ray adds to the reflected and direct ray and smooths the GO shadow boundaries generated by wall corners.

In general, a ray-tracing simulation can be split into two independent components: the geometrical component, which is independent of frequency and where the rays are traced from the transmitter ( Tx ) position through the scene toward the receiver ( Rx ) and the electromagnetic component where the vector field of each ray is calculated and added to find the received field. A short overview of the two parts will be given here, the details are extensively covered in the literature [16, 33, 17, 18].

### 2.1.1 Geometrical Component

The most common and efficient ray-tracing algorithm is shoot-and-bouncing ray (SBR) launching. Rays are launched from the Tx and at each intersection with an object, a reflected and transmitted ray is generated, both of which are traced further (in case of intersection with an edge a cone of diffracted rays around the edge is generated). The consecutive generation of new rays and their traces leads to a tree representation where the Tx is the root, each intersection point a node and the reflected, transmitted or diffracted rays the children of a node. Tracing of rays is
terminated once a preset number of intersections has been reached.
It is important to pay attention to the initial ray generation at the Tx. Since each ray has to be viewed as a ray tube that expands, the further the ray propagates, the spherical wavefront the Tx launches has to be subdivided equidistantly according to a preset angular resolution to ensure that each ray tube has the same size. Consequently, a ray counts as received if the receiver point falls within the ray tube of one ray path. The angular resolution of initial rays has to be set according to the longest possible ray path (based on the number of intersections) and the smallest object in the scene so that this object can still be resolved.

Figure 2.1 illustrates the ray paths determined through SBR ray-tracing for one simple indoor scenario. Only reflected or transmitted rays with three or fewer wall interactions are plotted. Including floor/ceiling reflections, a total of 25 possible ray paths from the Tx to the Rx with three or less intersections are found.


Figure 2.1: Sample building layout with ray paths up to three wall interactions (reflection and transmission only). Tx at $(2.0,2.0) \mathrm{m}$ and Rx at $(5.0,7.0) \mathrm{m}$.

It can be concluded that the computational cost of ray-tracing is independent of frequency and the size of the simulation domain, and it only depends on the number
and size of the objects in the scene. Because of this and contrary to any other computational methods, ray-tracing allows the analysis of scenarios much larger than the wavelength ( $>1000 \lambda$ ).

### 2.1.2 EM component

Once the geometrical tracing of the rays is finished and all the ray paths that hit the receiver are identified, the EM component can be calculated. This is usually done in the frequency domain. Determination of the electric field of rays that only include reflection and transmission is straight-forward: after the initial field vector is found through the polarization and gain of the Tx antenna, it is subsequently decomposed into the local parallel and perpendicular polarization of the intersection point and adjusted with the reflection and transmission coefficient of each wall. If the ray path includes one diffraction (multiple diffraction paths are usually not considered and traced because of the their low energy), the electric field is determined analogous but diffraction coefficients of the edge have to be calculated beforehand based on the traveled distance to and from the diffraction point. It should be noted that an analytic solution for the diffraction coefficients of GTD only exits for perfect electric conducting (PEC) wall corners [34]. For dielectric wall corners, the solutions are adjusted heuristically by the reflection and transmission coefficients of the adjacent walls [35] so that the diffracted rays still smooth out the GO boundaries. It should be noted that although the EM field of the rays can be calculated for every desired frequency, the validity of the solution decreases as the objects become smaller in terms of wavelength. Overall the objects have to be much larger than the wavelength ( $>5 \lambda$ as a rule of thumb).

Figure 2.2 illustrates the EM computation of each ray path and shows the computed pathloss of each ray in the scenario of Fig. 2.1. $\epsilon_{r}=4.8$, conductivity $\sigma=$ $0.015 \mathrm{~S} / \mathrm{m}$ and thickness 0.2 m have been assigned to all walls (including floor/ceiling)
and the path loss of each ray was calculated and plotted versus the traveled time of each ray. Obviously, the direct ray which travels the shortest distance contains most of the power and the further a ray has traveled (and intersected) the less power it contains. The last step from Fig. 2.2 is to add the found path loss of all rays coherently to find the overall path loss from the Tx to the Rx.


Figure 2.2: Pathloss versus traveled time of each received ray for the indoor scenario of Fig. 2.1 in dB.

### 2.2 Realistic Wall Types and its EM Approximation for RayTracing

The previous section shows that, for ray-tracing analysis, a wall can only have specular reflection and transmission according to Snell's law and is characterized by a reflection and transmission coefficient. Consequently, a ray-tracing algorithm treats walls as homogeneous and all other wall types have to be modeled as homogeneous. But depending on utilization, architecture, and the specific region, one encounters different wall types with different materials, constructions, and wall thicknesses. Nevertheless, from the electromagnetic point of view, walls can be grouped into two major categories: 1) homogeneous walls (like concrete or brick) and 2) inhomogeneous walls
(like reinforced concrete, cinderblock or drywall).

### 2.2.1 Homogeneous Walls

Walls are considered homogeneous in terms of electromagnetic properties if its structure is uniform and the materials used for construction exhibit approximately the same dielectric constant and conductivity throughout. Examples include a solid concrete wall, a solid wooden wall or solid brick wall. The wall can then be modeled as a uniform dielectric slab and the reflection and transmission behavior of an electromagnetic plane wave incident on the wall can be found analytically directly from Maxwell's equations. The transmission through the slab is only dependent on the complex dielectric constant of the material, which is usually frequency dependent, and the thickness of the wall. One heuristic, but exact approach for calculation of the reflection and transmission coefficient is via utilization of the plane wave Fresnel reflection and transmission coefficients of a half-space dielectric interface by summation over the multiple bounces of the wave inside the dielectric slab according to Figure 2.3.


Figure 2.3: The multiple bounces of a plane wave inside a homogeneous dielectric slab, incident at an angle of $\theta_{\mathrm{i}}$ towards the normal of the slab, and the composition of the reflected and transmitted plane wave.

The advantage of this approach is that it clearly demonstrates the fact that an electromagnetic pulse that goes through a wall emerges with significant dispersion. The final result is

$$
\begin{equation*}
T_{v, h}=\frac{4 e^{-j\left(k_{1 z}-k_{0 z}\right) d}}{\left(1+p_{01}\right)\left(1+p_{10}\right)\left(1+R_{01} R_{10} e^{-2 j k_{1 z} d}\right)} \tag{2.1}
\end{equation*}
$$

with the Fresnel reflection coefficients of a dielectric half space given by

$$
\begin{equation*}
R_{10}=-R_{01}=\frac{1-p_{10}}{1+p_{10}} \quad \text { with } \quad p_{10}=\frac{1}{p_{01}} . \tag{2.2}
\end{equation*}
$$

Here $p_{10}=k_{0 z} / k_{1 z}$ for horizontal and $p_{10}=\epsilon_{r} \cdot k_{0 z} / k_{1 z}$ for vertical polarization of the incident field [36]. $\epsilon_{r}$ is the relative dielectric constant, $d$ is the thickness of the wall and $k_{0 z}=k_{0} \cos \theta_{\mathrm{i}}$ and $k_{1 z}=\sqrt{{k_{1}}^{2}-{k_{0 x}}^{2}}$ are the normal components of the propagation constants in the air and in the dielectric, respectively. An incident plane wave is called horizontal polarized when the E-field vector is perpendicular to the plane of incidence (as defined by the wavevector and normal vector) and vertical polarized if the E-field vector is parallel to it. The reflection coefficient of the slab can be obtained from:

$$
\begin{equation*}
\Gamma_{v, h}=\frac{R_{01}+R_{10} e^{-2 j k_{1 z} d}}{1+R_{01} R_{10} e^{-2 j k_{1 z} d}} . \tag{2.3}
\end{equation*}
$$

If a wall consists of multiple dielectric layers, an exact reflection and transmission coefficient can also be found, but then an iterative procedure has to be applied [36].

### 2.2.2 Inhomogeneous Walls

Walls are considered inhomogeneous if the dielectric properties of the composing materials differ as a function of position. The most prominent examples are cinderblock wall (concrete with air gaps), reinforced concrete wall (concrete with metallic structures embedded) and drywall (wood with air gaps covered with plas-
ter). Most inhomogeneous walls are constructed in such a way to have one dimensional or two-dimensional periodicity. Examples of one-dimensional periodic walls include drywall and reinforced concrete wall with vertical rebars (reinforcing bars). Walls constructed from cinderblock or crossbar reinforced concrete constitute examples of two-dimensional periodic walls.


Figure 2.4: The scattering of a plane wave incident on a periodic wall (periodicity $d$ ) at an angle $\theta_{\text {in }}$ towards its normal.

If an EM plane wave is incident on a periodic wall as shown in Figure 2.4, it is possible that the periodic wall scatters the plane wave in other directions than specular reflection and transmission. By looking at Fig. 2.4, one can see that the scattered field of two neighboring scattering centers in direction $\theta_{\text {out }}$ has a path length difference of $\Delta_{1}+\Delta_{2}$. In order for the rays to add coherently and to see a plane wave in this direction (called Bragg mode), the path length difference has to be a multiple of the wavelength, i.e.

$$
\begin{equation*}
\Delta_{1}+\Delta_{2}=d \sin \theta_{\text {in }}+d \sin \theta_{\text {out }}=m \lambda, \tag{2.4}
\end{equation*}
$$

where $\lambda$ is the wavelength of the plane wave and $m \in \mathbb{N}_{0}$. It should be noted that $-90^{\circ} \leq \theta_{\text {out }} \leq 90^{\circ}$ and that Bragg modes launched in the direction of reflection also follow equation 2.4. $m=0$ leads to regular specular reflection and transmission. For $d<\lambda / 2$, equation 2.4 has no solution for $m \geq 1$ and the periodic wall will scatter an
incident plane wave from all angles like a homogeneous wall. If $d \geq \lambda / 2$ or in terms of frequency $f \geq c_{0} / d$ Bragg modes can be excited, growing in number with increasing frequency. While it is possible to find the number of Bragg modes and their direction through equation 2.4, the actual power contained in each Bragg mode has to be found numerically $[37,7,6]$.

In order to illustrate the Bragg modes of periodic walls compared to homogeneous walls, full-wave finite-difference-time-domain (FDTD) simulations of a cylindrical wave incident on a homogeneous wall and two 1D periodic walls are compared. For all three walls, the field distribution in front and behind of the wall has been recorded. An electrical line source has been placed 2 m in front of each wall. The first wall is a homogeneous concrete wall of thickness 0.2 m ( $\epsilon_{r}=6.0$ with conductivity $\sigma=0.01 \mathrm{~S} / \mathrm{m}$, the second reinforced concrete (periodicity 0.3 m ) and finally cinderblock (periodicity 0.4 m ). Figure 2.5 shows the unit cells of the two periodic walls.


Figure 2.5: The unit cells of two periodic walls, reinforced concrete (rebar) and cinderblock, drawn to scale, units in cm .

The electric line source is excited with a time-harmonic signal at 1.0 GHz , allowing Bragg modes for both wall types. Figure 2.6 shows the resulting field coverage of the homogeneous wall (normalized magnitude of the z -directed electric field in dB ). In front of the wall, a standing wave pattern can be seen resulting from the direct wave emitted from the Tx and the reflected wave of the wall. Behind the wall only a single
cylindrical wave propagates, leading to a smooth field distribution. In contrast, the magnitude of the electric field varies significantly behind both periodic walls (Figure 2.7). This variation is caused by the additional Bragg paths through the periodic wall, leading to constructive and destructive interference depending on the position. Furthermore, the standing wave in front of the wall is also modulated by the additional Bragg modes of the reflection.


Figure 2.6: A cylindrical vertical polarized wave incident on a homogeneous dielectric $\operatorname{slab}\left(\epsilon_{r}=6.0, \sigma=0.01 \mathrm{~S} / \mathrm{m}\right.$ ) of thickness 0.2 m at 1.0 GHz (normalized $E_{z}$-field in dB).

These examples demonstrate that inhomogeneous periodic walls show a completely different reflection and transmission behavior than homogeneous walls. Nevertheless, they have to be approximated with homogeneous walls for incorporation into a raytracing code. Therefore, the inhomogeneous periodic wall is replaced with a (layered) homogeneous dielectric wall with an effective dielectric constant. In the case of rebar wall, the PEC rods are simply ignored and for cinderblock, the effective dielectric constant can be found through an electrostatic approximation of the wall [9].


Figure 2.7: A cylindrical vertical polarized wave incident on a rebar wall (periodicity 0.3 m ) (a) and on a cinderblock wall (periodicity 0.4 m ) at 1.0 GHz (normalized $E_{z}$-field in dB ).

### 2.3 Conclusions

This chapter introduced the asymptotic method ray-tracing for the analysis of indoor wave propagation. The method was briefly described and afterwards the representation of walls in ray-tracing was discussed. It was shown that homogeneous walls can be modeled exactly with ray-tracing, but inhomogeneous periodic walls have to be approximated as homogeneous slabs, neglecting the different propagation phenomena of inhomogeneous periodic walls. Since these inhomogeneous periodic walls are an essential part of buildings, one cannot expect accurate results if the wave propagation inside buildings is analyzed with ray-tracing. Nethertheless, ray-tracing can succesfully provide a general overview of the multipath propagation inside a building, and the homogeneous wall approximation of periodic walls can provide estimates on the average path loss inside the building $[16,17]$. However, ray-tracing fails to predict the fast-fading phenomenon caused by the inhomogeneities as already seen for the simple transmission through a single periodic wall examples [19]. Consequently, to analyze wave propagation inside buildings thoroughly, ray-tracing is not a good
choice.

## CHAPTER III

# The Brick-Tracing Method for Indoor Wave Propagation Analysis 

As demonstrated in the previous chapter, ray-tracing fails to predict the fastfading propagation phenomena of periodic walls. On the other hand, a single inhomogeneous and periodic wall can be accurately and easily analyzed by a full-wave method like FDTD to capture the fast-fading phenomenon. However, due to the large size of a standard building (in terms of wavelength), it is impossible to analyze the whole building structure with full-wave methods since both memory and CPU requirements vastly exceed what standard computers can provide at this time.

This dilemma can be resolved by introducing hybrid methods. A combination of ray-tracing and FDTD has already been proposed to include complex wall structures: for example in [19], the complex wall structure in the scenario is isolated and analyzed via FDTD while the rest of the domain, including the transmitter, is analyzed with ray-tracing. However, in this approach the ray-tracing domain only interacts once with the FDTD domain, and the receiver locations must be a part of the FDTD domain. The interaction between the FDTD domain and the ray-tracing domain has been expanded in a follow-up paper [20] to include receiver points outside the FDTD domain. Still, the method is limited to only one interaction between FDTD and ray-tracing and after that the inhomogeneous periodic walls are treated
as homogeneous. This approximation may lead to satisfactory results if only a small portion of the building consists of inhomogeneous walls [20], but if all or most of the walls are inhomogeneous, the multiple interactions are obviously important and applying the paper's concepts in this case becomes a time consuming convoluted series of alternating FDTD and ray-tracing simulations.

This chapter will describe a novel hybrid approach that utilizes the periodicity of the inhomogeneous walls in a way such that FDTD and ray-tracing are separated and multiple interactions between the inhomogeneous walls are included in a simple manner. Furthermore, the ray-tracing component is generalized to an iterative field calculation algorithm based on the field equivalence principle (physical optics (PO) approach) to overcome ray-tracing inherit problems like missed or double-count rays. First, periodic FDTD is used to analyze and completely characterize the reflection and transmission behavior of the walls. Because of the periodicity, a FDTD simulation of only a single building block from each wall is necessary and FDTD simulation can be used to find the equivalent surface currents for arbitrary angle and polarization of incidence. Then Huygens's principle can be applied to calculate the radiated field in arbitrary directions. An iterative field calculation algorithm is then used to compute the interaction among all building blocks based on the geometry of the indoor environment. In this way, the physical phenomena associated with periodic walls are fully accounted for.

The theory and implementation details of a 2D version of the proposed hybrid method which will be called brick-racing are described in detail in the following section. Afterwards, the 2D hybrid method is validated against 2D full-wave simulations and the numerical results for a complex indoor environment are shown. In the end, its performance and possible improvements are discussed.

### 3.1 Theory of Brick-Tracer Method

The hybrid method utilizes the field equivalence principle which states that the scattered field from a wall can be fully described by the knowledge of surface fields (currents) on the wall. These equivalent surface currents on both sides of a building block (brick) in a periodic arrangement are computed and stored over a wide range of incidence angles. An iterative field computation algorithm is also needed to account for the effect of multi-path among all "bricks." The two components of the hybrid method are completely separated, which means that the FDTD part is totally independent of the indoor environment geometry.

### 3.1.1 Current Calculation Using FDTD

The FDTD simulations of surface currents must be run a priori and are independent of the building layout. Given all wall types, i.e., the structure and its periodicity, in addition the desired frequency range, a unit cell of each wall type is discretized and meshed for the FDTD simulations. The unit cell (called brick) is terminated by periodic boundary conditions and illuminated by a plane wave at all possible incident angles (in the 2D case $\theta_{\text {in }}=0^{\circ} \ldots 90^{\circ}$ ). Figure 3.1 illustrates the 2D-FDTD simulation setup. The time domain results are converted to the frequency domain via Fourier transform and at the desired frequency for every plane wave incident angle. Only the electric fields at the surfaces of the brick are written to a file. The electric fields are post-processed as follows: 1) on the reflection side the incident field is subtracted, and 2) all field values are normalized to the incident field. After this step, all walls are fully characterized in their reflection and transmission behaviors.

### 3.1.2 Multi-Path Calculation Using Iterative Field Computation

The iterative field computation component (2D) is realized in the frequency domain and has to account for the outdoor/indoor environments and the building ge-


Figure 3.1: FDTD setup for the simulation of an unit cell of periodic wall.
ometry. Every wall of the building is discretized into its unit cells (bricks) and the Tx and Rx are added. Figure 3.2 shows the discretization of an example indoor environment containing rebar and cinderblock walls. Now the interaction between the Tx and the bricks and among the bricks themselves can be computed. To simplify the explanation, vertical polarization with the three field components $E_{z}, H_{y}$ and $H_{x}$ is assumed. The derivation for horizontal polarization is analogous.


Figure 3.2: Geometry of a complex room and its discretization for the multipath calculation.

At first the incident field of the Tx on each lit brick with a line of sight (LoS) to the $T \mathrm{x}$ is

$$
\begin{equation*}
\vec{E}=\frac{\omega \mu I_{0}}{4} \cdot H_{0}^{(2)}\left(k\left|\vec{r}-\vec{r}^{\prime}\right|\right) \cdot \hat{z}, \tag{3.1}
\end{equation*}
$$

where $H_{0}^{(2)}$ is the Hankel function of second kind, $\vec{r}$ the vector to the $\mathrm{Tx}, \vec{r}^{\prime}$ the vector to the brick point and $k$ the wavenumber. Knowing the incident field on the brick and its direction, the appropriate FDTD simulation results are loaded, adjusted by the
incident field and saved for each brick. According to the surface equivalence principle, the scattered field of the brick can be computed from the magnetic surface currents

$$
\begin{equation*}
\vec{M}_{s}=2 \vec{E}_{s} \times \vec{n}, \tag{3.2}
\end{equation*}
$$

where $\vec{E}_{s}=E_{s} \hat{z}$ are the saved electric surface fields in $z$-direction and $\vec{n}$ is the surface normal vector of the brick. It should be noted that omitting the magnetic field for the surface currents is only valid for infinite planar currents sheets. Omitting the magnetic field introduces a small error at corner and terminal locations, however it significantly improves computational speed [39].

All computed surface currents on the bricks are now the new sources for the computation of the next order surface currents on the bricks. If a brick has an LoS to another brick, the incident field of the brick on the other brick can be calculated by radiating the magnetic currents of equation 3.2 which leads to the following integral over the surface fields of the transmitting brick:

$$
\begin{equation*}
\vec{E}=\frac{k}{4 j} \cdot \int 2 E_{s} \cdot H_{0}^{(2)^{\prime}}\left(k\left|\vec{r}-\vec{r}^{\prime}\right|\right) \cdot \frac{\vec{n} \cdot\left(\vec{r}-\vec{r}^{\prime}\right)}{\left|\vec{r}-\vec{r}^{\prime}\right|} d l \cdot \hat{z} . \tag{3.3}
\end{equation*}
$$

Once again the appropriate FDTD simulation results for the known incident angle are loaded, adjusted with the incident field, and stored.

This step is repeated to generate higher order currents; whereas every iteration in the current generation is equivalent to a reflection/transmission of a ray in an ordinary ray-tracing algorithm.

The final step is to compute the field at a given receiver location. If a brick has an $\operatorname{LoS}$ to the receiver point, all stored surface fields of this brick are needed using equation 3.3 to compute the received field and finally the Tx contribution has to be added if an LoS to the receiver exists (using equation 3.1).

Figure 3.3 visualizes the concept of the hybrid method: all bricks of the left wall
are visible to the Tx so the incident field on its left side can be computed and zeroorder surface currents are generated on the wall's surface (solid arrows from Tx in Figure 3.3 (a)). The right wall is now visible to the zero-order currents of the left wall. The radiated fields coming from the zero-order currents on the right side of the left wall need to be calculated on every brick of the right wall in order to load the appropriate first order currents on the right wall (dashed arrows in Figure 3.3 (a), only contribution from one brick plotted to keep figure clear). Now the left wall is visible to the first-order currents of the right wall and once again the incident fields coming from every brick with a first order current on every brick of the left wall needs to be calculated for second-order current generation (dashed arrows in Figure 3.3 (b), only contribution from one brick plotted to keep figure clear). This is repeated until the desired number of current iterations has been reached and finally the sum of all currents of every brick that is visible to the Rx (in this example the right wall) is used for the received field calculation (solid arrows in Figure 3.3 (b)).


Figure 3.3: Visualization of the iterative multi-path field calculation.

### 3.1.3 Convergence and Validity

It is necessary to repeat the iterative field calculation until the surface currents have converged (and consequently the field coverage inside the building structure). It can easily be shown that this happens fast and reliably: The Tx launches a cylindrical wave in which the field decays with $1 / \sqrt{r}$ where $r$ is the overall traveled distance which includes the multiple bounces between the walls. Furthermore, the incident wave on a wall is always split into two scattered waves, the transmitted and reflected wave. Since the walls are passive and lossy, they absorb some energy of the incident wave and divide the remaining energy between reflection and transmission. Consequently, this iterative and tree-like fragmentation of the cylindrical wave launched by the Tx combined with its spread leads to an almost exponentially decaying incident field on the walls after each current iteration.

Figure 3.4 and Figure 3.5 illustrate the convergence for one example, a homogeneous dielectric box (outer dimensions 4.0 m by 2.0 m , thickness 0.12 m ) with material constants $\epsilon_{r}=6.0$ and $\sigma=0.015 \mathrm{~S} / \mathrm{m}$ illuminated by an electric line source from outside at 1.0 GHz . The field coverage ( $E_{z}$-field in dB ) after each current iteration is plotted together with its difference to the previous field coverage. The difference of the field coverage (right column) drops from close to 20 dB (after the second iteration, Fig. 3.4b) to below 40 dB after the sixth iteration (Fig. 3.5c), indicating that the simulation converged to less than $1 \%$ remaining change of the transmitted field. Consequently the coverage plot of Fig. 3.5c does not differ from the one of Fig. 3.5b because the color range is limited to -40 dB . Figure 3.6 confirms the exponential convergence behavior of this example, the maximum field coverage difference of each current iteration to the previous iteration is plotted in dB against the progressing current iterations (the maximum field of current iteration 0 ( $T x$ in free space) serves as a reference).

Homogeneous walls have been utilized for this example but inhomogeneous peri-
odic walls do not change this result. The cylindrical wave incident on the periodic walls is only additionally modulated by the Bragg modes but the tree-like fragmentation and wave spreading remain which lead to the convergence.

a) Field coverage after one iteration

b) Field coverage after two iterations

c) Field coverage after three iterations


Difference to previous result


Difference to previous result

Figure 3.4: Visualization of iterative field computation convergence for a homogeneous dielectric box illuminated by a electric line source at 1.0 GHz , continued in Fig. 3.5.

a) Field coverage after four iterations

b) Field coverage after five iterations

c) Field coverage after six iterations


Difference to previous result


Difference to previous result


Difference to previous result

Figure 3.5: Visualization of iterative field computation convergence for a homogeneous dielectric box illuminated by a electric line source at 1.0 GHz , continuation of Fig.3.4.

Another aspect is the validity of the found solution. As it was shown, the surface fields always converge to one unique solution predetermined by the geometry of the


Figure 3.6: Maximum change of E-field in dB after each current iteration step of the homogeneous dielectric box illuminated by electric line source of Fig. 3.4 and Fig. 3.5.
building structure. The accuracy of the found solution then depends on how well the underlying assumptions of the PO method are met. Based on surface currents which are found with LoS calculations from the source, this method is more accurate than the previously described ray-tracing which is completely based on GO, meaning that the underlying assumptions are less strict. Since ray-tracing is successfully used for analyzing indoor scenarios at UHF $[16,17,18,33]$, once can assume that the underlying assumptions are also met for PO. Nevertheless, they should be discussed as they lead to possible sources of inaccuracy:

- As for ray-tracing, objects must be larger than the wavelength.
- Currents of a plane wave incident on an infinite wall are also loaded for all corner and edge bricks, leading to incorrect corner and edge diffraction.
- The Tx cannot be placed too close to the walls otherwise the assumption of a local plane wave incident at each surface current point of the wall is not met.
- Wave propagation inside the walls is also assumed to be plane wave leading to errors for transmission through thick walls and thick wall corners.


### 3.2 Numerical Rresults

### 3.2.1 Homogeneous Walls

In order to verify the concept of the brick-tracing algorithm, the results are tested against a homogeneous dielectric slab. The reflection coefficient of an infinite homogeneous dielectric slab illuminated by a plane wave can be computed analytically [35] so the brick-tracer can handle homogeneous dielectric slabs without a single FDTD simulation. Figure 3.7 shows one result of a hybrid simulation with homogeneous dielectric walls compared to a full FDTD simulation (Figure 3.8) at 1.0 GHz . The geometry is a single hollow box (outer dimensions 4.0 m by 2.0 m , thickness 0.12 m ) with material constants $\epsilon_{r}=6.0$ and $\sigma=0.015 \mathrm{~S} / \mathrm{m}$. Currents up to the ninth order are calculated for this simulation. The received E-field (in dB ) of both simulations along two sample traces inside the box is plotted in Figure 3.9 which shows that the discrepancy between brick-tracer and full FDTD simulation is relatively small. The differences are caused by the corner bricks for which the analytic reflection and transmissions coefficient are not accurate because of the truncation of the slab. Note that an ordinary ray-tracer would encounter the same problems under these conditions since it can only accommodate dielectric corners with heuristic diffraction coefficients (especially inner corner diffraction) [38].

### 3.2.2 Inhomogeneous Periodic Walls

Having demonstrated the validity of the hybrid method for homogeneous dielectric walls, this same method was augmented with the FDTD component in order to accommodate inhomogeneous dielectric walls.


Figure 3.7: Brick-tracer simulation result ( $E_{z}$ in dB ) of a homogeneous dielectric box (dimensions in meters) at 1.0 GHz with Transmitter at (0.5,-1.5).


Figure 3.8: Full FDTD simulation result ( $E_{z}$ in dB ) of the same setup as Figure 3.7 including internal fields (dimensions in meters) at 1.0 GHz .

Two common periodic wall structures are chosen to demonstrate the capability of the brick-tracer to handle complex building structures: 1) concrete rebar wall with a periodicity of 30 cm and 2) cinderblock wall with a periodicity of 40 cm (see Figure 2.5 of previous chapter for details). Simulations are carried out at 1.0 GHz . Both wall


Figure 3.9: Comparison of full FDTD and brick-tracer result ( $E_{z}$ in dB ) of homogeneous dielectric box along two traces, $y=0.5 \mathrm{~m}$ and $y=1.5 \mathrm{~m}$ (lowered by 20 dB ).
structures have been simulated with FDTD in $5^{\circ}$ incident angle increments. It should be noted that it is necessary that the wall materials are slightly lossy so that surface waves along the wall, which are excited at certain incidence angles, decay quickly. But this condition is satisfied by all realistic wall types.

The FDTD output of electric surface field distributions of the rebar structure are shown in Figure 3.10 at two incident angles. The normalized electric field magnitude (adjusted by the incident field on the front side) for an incident plane wave (incidence angle $0^{\circ}$ and $45^{\circ}$ ) is plotted over a unit cell of the wall. Contrary to a homogeneous slab, the field varies significantly.

First an infinite rebar wall illuminated by a line source is considered. Only zero order currents exist here (currents generated by the Tx). Since a single point source is not compatible with periodic boundaries in FDTD, the simulation domain for a finite-size rebar wall was truncated with perfect matched layers. This truncation is equivalent to the problem of an infinite dielectric slab with a finite size periodic


Figure 3.10: Normalized magnitude of electric field on the surface of the periodic rebar structure unit cell for two plane wave incidence angles.
embedded rebar. As a consequence, both results cannot match exactly, especially near the termination. The brick-tracer simulation (Figure 3.11) correctly predicts the variation of the received field behind and in front of the wall caused by scattering of the inhomogeneities in non-specular directions (FDTD simulation shown in Fig. 3.12). Both results are in excellent agreement as demonstrated as demonstrated in the 1D field plot along two sample traces (Figure 3.13). The small errors are artifacts of using the periodic FDTD simulations with plane wave incidence angle steps of $5^{\circ}$ which do not capture all details of the reflection and transmission behaviors of the wall.

As a next step, a simple building structure with two rooms is examined. This structure supports higher order currents. The box is built of rebar walls having an overall outer dimension of 4.2 m by 2.2 m . The structure consists of 46 bricks, and surface currents up to ninth order are calculated. Figure 3.14 shows the results of the brick-tracer simulation. Full-wave results obtained from FDTD simulations of the same structure are shown in Figure 3.15. Figure 3.16 shows two field coverage traces


Figure 3.11: Brick-tracer simulation result ( $E_{z}$ in dB ) of an infinite rebar wall (dimensions in meters, Transmitter location $(0,-2.0))$ at 1.0 GHz .


Figure 3.12: Full FDTD simulation result ( $E_{z}$ in dB ) of the same setup as Figure 3.11 including internal fields (dimensions in meters) at 1.0 GHz .
inside the box for a direct comparison of the different methods. This structure is intended to demonstrate the limitations of the brick-tracing algorithm: It is expected


Figure 3.13: Comparison of full FDTD and brick-tracer result ( $E_{z}$ in dB ) of infinite rebar wall along two traces, $y=0.4 \mathrm{~m}$ and $y=1.1 \mathrm{~m}$ (lowered by 10 dB ).
that the accuracy of the brick-tracer degrades compared to the previous examples because the scenario consists of short (in terms of wavelength) walls and many corners, all of which have assumed period currents. The main error occurs around the shadow boundary of the inner wall in the bigger room. The brick-tracer slightly overestimates the field coverage in the shadow region (see $y=1.7 \mathrm{~m}$ trace between $x=0.5 \mathrm{~m}$ and $x=1.4 \mathrm{~m}$ in Fig. 3.16). In general, the assigned periodic currents for the lower T-corner generate an incorrect corner diffraction which also affects the smaller room to the left. Nevertheless, the results still show good agreement. It should be noted that a realistic scenario with bigger rooms will automatically lead to a more accurate brick-tracer simulation result.

### 3.2.3 Complex Indoor Environment

Having demonstrated the accuracy of the brick-tracer algorithm for simple buildings with homogeneous and periodic walls, its application for analyzing complex structures is examined. The field computation component of the algorithm is not limited


Figure 3.14: Brick-tracer simulation result ( $E_{z}$ in dB ) of a divided box of rebar wall (dimensions in meter, Transmitter location ( $-0.1,-2.0$ )) at 1.0 GHz .


Figure 3.15: Full FDTD simulation result ( $E_{z}$ in dB ) of the same setup as Figure 3.14 including internal fields (dimensions in meter) at 1.0 GHz .
to a particular wall type or wall setup, it can handle every combination of periodic walls. The example shown in Figure 3.17 is selected as a complex propagation envi-


Figure 3.16: Comparison of full FDTD and brick-tracer result ( $E_{z}$ in dB ) of divided box of rebar wall along two traces, $y=0.3 \mathrm{~m}$ and $y=1.7 \mathrm{~m}$ (lowered by 30 dB ).
ronment composed of a room constructed of rebar walls with outer dimensions 6.0 m by 5.9 m , with an inner cinderblock room divider. The example consists of 83 bricks (13 cinderblock and 70 rebar). The rays in Figure 3.17 indicate the initial excitation emanated from the transmitter location. Figure 3.18 shows the field plot of the hybrid method.

### 3.3 Performance and Possible Improvements

The FDTD component of the hybrid method is straight-forward. A single 2D periodic FDTD simulation of the previously described structures requires less than 5,000 FDTD cells, so one simulation per angle of incidence requires less than one minute on a standard PC. Furthermore, it was shown that only 17 simulation runs (equals $5^{\circ}$ increments in incidence angle) for a wall type are sufficient, and linear interpolation can be used for angles in between. If the surface currents of a wall type (especially with less loss and higher inhomogeneity) vary more rapidly with the


Figure 3.17: Geometry of a complex room with rays from the transmitter to the visible bricks.


Figure 3.18: Full brick-tracer simulation result ( $E_{z}$ in dB ) of the complex room of Figure 3.17 (dimensions in meter, transmitter location (0.5,-2.0)) at 1.0 GHz .
incident angle, a higher angular resolution may be needed. But the required amount of time is still negligible since the FDTD simulations have to be done only once and can be used afterwards for any possible geometry in the multi-path computation component.

The main advantage of the hybrid method is its memory efficiency; it only needs to allocate memory for the surface currents on each brick. That means that the required memory only grows with the square root of the covered building area (2D case) and is independent of the transmitter location. Compare to FDTD where the required memory is proportional to the area of the simulation domain which has to include the transmitter. The existing, non-optimized version of the code only allocates 4 Mb of RAM for the second validation scenario of Section 3.2.2 on a standard PC compared to 150 Mb for the full FDTD simulation. The simulation time is mainly dependent on the number of current points/bricks: The runtime for generating the currents grows with the square of the number of bricks because at every surface current point the incident field radiated by every other surface current point has to be calculated. Nevertheless, the current-generation time for the same example is only 30 s with an additional 4 min for a coverage plot consisting of 40,000 receivers on a standard PC, compared to 20 min for the full FDTD simulation.

One further advantage of the hybrid method is that its accuracy can be increased without adding much complexity: the main cause for the differences between full FDTD simulations and the hybrid method are the corner (or terminal) bricks for which periodic currents on its surface cannot be assumed. But the wall corners or terminal bricks can also be simulated with FDTD beforehand for all possible plane wave incident angles and the surface fields can be stored. If those stored currents are assigned properly for all corner bricks, exact corner diffraction can be added to the hybrid method.

### 3.4 Summary

This chapter introduced a new approach to study the problem of wave propagation and scattering in an indoor environment in the presence of inhomogeneous periodic walls. The proposed method makes it possible to accurately study the effect of inhomogeneous periodic walls without adding much computational complexity compared to an ordinary ray-tracing algorithm. Numerical examples of this method have been compared to full-wave analysis and show good agreement.

## CHAPTER IV

# 3D-Wave Propagation Analysis of Indoor Wireless Channels Using the Brick-Tracer 

So far the hybrid method has only be proposed, implemented and validated in 2D. While a 2D implementation provides proof of concept for the hybrid method and provides accurate results in less time than full-wave simulation, its results for indoor wave propagation analysis are erroneous because it omits important features like vertical inhomogeneities in walls, the floor, the ceiling, windows and doors etc., that affect the wireless indoor channel.

This chapter presents the 3D implementation of the brick-tracer for realistic 3D indoor wave scenarios. The theory of the 3D hybrid method is described in the next section, which is then followed by its implementation procedure. Afterwards, two validation cases are presented where simulation results are compared against theory and measurement.

Finally, the application of the brick-tracer is demonstrated on realistic indoor scenarios, its result are applied to wireless indoor propagation models, and signal statistics are extracted. In order to examine the improvement that is achieved using this analysis, the indoor channel parameters are compared to those obtained from an ordinary ray-tracing analysis with effective homogeneous walls.

### 4.1 Theory of 3D Brick-Tracer

The basic principle is the same as in the 2D method (section 3.1) so this section is kept short with an emphasis on the differences between the 3D and 2D methods.

### 4.1.1 Brick Analysis

As in the case for 2 D , the surface current calculation is run a priori and independent of the building layout. Given all wall types, i.e., the structure and their periodicity, a unit cell of each wall type is analyzed with a full-wave analysis tool at a particular frequency. The unit cell (brick) is terminated by periodic boundary conditions to the side and illuminated by a plane wave at all possible 3D incidence angles and principal polarizations. The electric and magnetic fields are written to files, the scattered field on the reflection side and the total field on the transmission side after both are normalized to the incident field.

### 4.1.2 Multi-Path Calculation Using Iterative Field Computation

The iterative field computation component has to accommodate the outdoor/indoor environment and building geometry. Every wall of the building is discretized into its unit cells (bricks). The interaction between the transmitter antenna (Tx) and the bricks is computed, followed by the computation of the interaction between the bricks, themselves. The algorithm imposes no restrictions on the Tx. That is, any desired radiation pattern and polarization can be chosen. First, the incident field of the Tx on bricks with a line of sight (LoS) is computed and decomposed into its principal polarization on the brick. The appropriate pre-calculated surface fields are loaded for each brick, adjusted by the incident field and stored. For higher order current calculations, the reradiated field generated by the surface fields of the bricks has to be determined. According to the surface equivalence principle, the scattered field of one brick can be computed from the magnetic and electric surface currents
$\vec{M}_{s}=\vec{E}_{s} \times \vec{n}$ and $\vec{J}_{s}=\vec{n} \times \vec{H}_{s}$ of the surface fields $\vec{E}_{s}$ and $\vec{H}_{s}$. The field radiated by the currents is given by

$$
\begin{align*}
\vec{E} & =-\nabla \times \vec{F}-j \omega \mu \vec{A}+\frac{1}{j \omega \epsilon} \nabla(\nabla \cdot \vec{A}) \\
\vec{H} & =\nabla \times \vec{A}-j \omega \epsilon \vec{F}+\frac{1}{j \omega \mu} \nabla(\nabla \cdot \vec{F}) \tag{4.1}
\end{align*}
$$

where $\vec{F}$ and $\vec{A}$ are the electric and magnetic vector potentials. The vector potentials can be found via integration of the radiating brick surface $A$ :

$$
\begin{align*}
\vec{F} & =\frac{1}{4 \pi} \int_{A} \frac{\vec{M}_{s} e^{-j k\left|\vec{r}-\vec{r}^{\prime}\right|}}{\left|\vec{r}-\overrightarrow{r^{\prime}}\right|} \mathrm{d} r^{\prime} \\
\vec{A} & =\frac{1}{4 \pi} \int_{A} \frac{\vec{J}_{s} e^{-j k\left|\vec{r}-\vec{r}^{\prime}\right|}}{\left|\vec{r}-\overrightarrow{r^{\prime}}\right|} \mathrm{d} r^{\prime} \tag{4.2}
\end{align*}
$$

with the position $\vec{r}^{\prime}$ of the surface currents and $\vec{r}$ of another brick or a receiver ( Rx ) point. If the other brick or receiver is in the far-field of the transmitting brick, i.e. $|\vec{r}| \gg|\vec{r}|$, the above equations can be simplified to

$$
\begin{align*}
& E_{\theta}=-j \omega \mu A_{\theta}-j k F_{\phi} \\
& E_{\phi}=-j \omega \mu A_{\phi}-j k F_{\theta} \tag{4.3}
\end{align*}
$$

with $E_{\theta}=\eta H_{\phi}$ and $E_{\phi}=\eta H_{\theta}$, where both potentials are split into their spherical coordinate components [39]. Now that the incident field of the surface currents and its direction on a brick are known, the appropriate surface fields are again loaded and stored as higher order surface fields. This iterative surface field calculation is terminated once the surface fields on all bricks converge, i.e. the change in the surface fields falls below a certain threshold. Afterwards, all surface currents on a brick surface are summed up, and the field at a given receiver position can be found via equation 4.1. The received field is finally given by the incident field decomposed
into the Rx polarization.
The 2D convergence and validity discussion of the method (section 3.1.3) remains valid for 3D, the only difference is that the cylindrical wave is replaced with a spherical wave which decays with $1 / r$.

### 4.2 Implementation and Performance

The brick analysis can be done with any full-wave solver that includes periodic boundary conditions but since the hybrid method is a frequency domain method, a commercial frequency domain solver was chosen [40]. All required incident wave vectors describe the surface of a hemisphere. This surface needs to be meshed to find the wave vectors for full-wave simulation, and an interpolation scheme has to be used for surface fields of wave vectors in between. In this paper, triangulation of an icosahedron was used, which leads to a constant separation of the mesh points (hence incident angles) and points in between are linearly interpolated. Furthermore, only one quarter of the hemisphere is needed if the unit cell's symmetry is utilized. The brick analysis is run by a script, and in this way a $5^{\circ}$ angular separation of the incident plane waves leads to 345 simulation runs for each polarization. Figure 4.1 shows the resulting incident wave vectors points on the unit sphere. The surface fields of every run are stored in files. It should be noted that more highly sophisticated meshing and interpolation may lead to fewer simulation runs.

The calculated surface currents are assigned to all bricks including corner and terminal bricks. While this simplification is required to maintain the complexity of the method within manageable levels, it only introduces a minimal degree of error to the diffraction around corners and edges [21].

Although this brick analysis requires high computational cost initially, it only needs to be done once for each wall type because the calculated surface fields are universal, that is, they are independent of geometry and the overall building size.


Figure 4.1: The mesh of one quarter of the unit hemisphere generated through triangulation of an icosahedron for a $5^{\circ}$ angular separation.

Consequently, the maximum feasible simulation domain size is only limited by the iterative field calculation. While the iterative field calculation is memory efficient (only needs to allocate memory for the surface fields on the walls), it requires substantial CPU time for the interaction calculations. Because of this, several modifications have to be made to reduce the runtime of the iterative field calculations:

- The surface currents convergence is checked for each room separately, and converged rooms are excluded from further higher order current calculations.
- The algorithm is implemented in parallel. Field calculations from one brick to another are independent of each other, so parallelism can be achieved by dividing the transmitting bricks between processors.

The CPU run time grows linearly with the number of current iterations, but the surface currents from one room converge exponentially once the source field has propagated into the room (due to consecutive splitting into transmitted and reflected waves). This implementation leads to reasonable algorithm run times for realistic
scenarios. An actual example of RAM and CPU used time is given in Section 4.4. It should be noted that choosing a different simulation frequency requires a change of the wall surface current sampling which affects both memory and run time. Doubling the frequency for a given scenario results in increasing the surface current points (and required memory) by a factor of four and the overall runtime by almost a factor of 16. In comparison, this is the same runtime increase as FDTD when a homogeneous mesh is assumed.

### 4.3 Validation

In order to validate the 3D iterative field calculation, a PEC corner reflector was chosen for which an approximate analytical solution already exists based on image theory. The corner reflector consists of three planes, each of which coincides with a Cartesian coordinate surface. Each reflector covers an area of 2 m by 2 m in the positive coordinate axis direction. The reflector was illuminated by a $z$-directed Hertzian dipole at the position $(1.0 ; 1.0 ; 1.5) \mathrm{m}$. The received field was recorded at $z=0.5 \mathrm{~m}$ and is plotted in Figure 4.2a. The analytical solution includes the original source and seven image sources, all located at $( \pm 1.0 ; \pm 1.0 ; \pm 1.5) \mathrm{m}$. The results of image theory (Figure 4.2b) agree well with the brick-tracing simulation. The slight differences are caused by the finite reflector size of the brick-tracer simulation which lead to edge diffraction. The discrepancy in field values between the brick-tracer and image theory results for points very close to the walls ( $<3 \mathrm{~cm}$ distance) is due to the surface current mesh of 2.5 cm , which is too coarse for field evaluation at such close distance.

Contrary to 2D, the domain size of even simple 3D problems is too big for validation of the hybrid method against a full wave analysis. The concept of the hybrid method was already verified in the 2D case [21], so the 3D method is valid as long as the transition from 2D to 3D is implemented correctly, as proven by the corner


Figure 4.2: Brick-tracer (a) and image theory (b) field coverage (normalized received E-field in $\mathrm{V} / \mathrm{m}$ ) of a corner reflector at 1.0 GHz .
reflector example.
Nevertheless, the integration of 2D-periodic brick analysis of walls was tested against measurements. A cinderblock wall (overall unit cell dimensions 0.2 x 0.2 x 0.4 m , shown in Figure 4.3) was constructed in the lab and a transmitting horn was placed 0.8 m away from it. On the other side, an identical horn was placed 0.8 m away from the wall and moved horizontally along the wall by 1.0 m . The field variation was recorded. A reference measurement was taken with the same setup but without the wall. Measurements were performed between 0.9 GHz and 6.0 GHz and post-processed in order to gate out multipath not caused by the wall structure, itself. The received field of the brickwall normalized to the free space transmission at 1.0 GHz is plotted in Figure 4.4.

The shape of the cinderblock was reproduced in the 3D solver. The dielectric properties of the concrete were measured using an L-Band microstrip ring resonator and was found to be $\epsilon_{r}=4.8 \sigma=0.02 \mathrm{~S} / \mathrm{m}$ [41]. The unit cell with the measured material parameters was analyzed using full-wave at 1.0 GHz , and the equivalent surface currents were stored for a large set of discrete incidence angles. The brick-tracer simulation was performed, and the results are compared with the measurements in Fig. 4.4. A reasonable agreement between the measured and simulated results is


Figure 4.3: The unit cells of the walltypes, cinderblock (left) with overall dimensions 0.4 x 0.2 x 0.2 m and cross-rebar (right) with cell size $0.3 \times 0.2 \times 0.2 \mathrm{~m}$.
shown. The average (over distance) field discrepancy is less than $13 \%$. The simulations exhibits patterns similar to the ones measured for both polarizations.

The discrepancies can be attributed primarily to two factors: 1) local plane wave illumination assumption and, 2) structural dissimilarity between the constructed wall and the simulated wall. In this experiment we placed the transmitter and receiver very close to the wall to minimize the effect of multipath in the room. As a result, the blocks were illuminated with a spherical phase front instead of being illuminated locally by a plane wave. This is why the measured transmissibility is smoother. The deviation from exact periodicity in the wall structure, the overall small wall size ( 2.4 m by 2.0 m ) and the remaining multipath omitted in the simulation are also responsible for some of the observed differences.

It is worth mentioning that the transmissiblitly through the wall is higher than free-space at $z=0.0 \mathrm{~m}$ in both the measurement and the simulation because the Bragg modes add up coherently at this point. Furthermore, there is always a discrepancy between the simulated perfect periodically wall and any real periodic wall. This is caused by small variations of the material, shape and alignment of the actual parts the wall is composed of. While this affects the field coverage and any result computed from the field coverage, it only introduces a small error because it does not change the presence of additional multipath caused by the Bragg modes. It only modulates
it.


Figure 4.4: Hybrid method result (solid line) of a cinderblock wall (unit cell shown in Fig. 4.3) compared to measurement (dashed line) for both vertical (gray) and horizontal (black) polarization including the average (over distance) of all four curves at 1.0 GHz .

### 4.4 Wave Propagation Analysis with 3D Brick-Tracer

After verification of the 3D brick-tracer algorithm and having shown that real walls follow the complex transmission behavior predicted by the brick-tracer, a realistic indoor scenario consisting of periodic walls was simulated to study indoor wave propagation in the presence of periodic walls. The vertical walls are shown in Figure 4.5. The actual simulations include the floor and the ceiling as well. The walls along $y$-direction are reinforced concrete with a cross-rebar wall having a periodicity of 30 cm , and the walls containing the doors and windows are cinderblock with a periodicity of 40 cm . The unit cells of both wall types are shown in Figure 4.3. The concrete for both walls is assumed to have $\epsilon_{r}=4.8$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$. The floor and ceiling are dense homogeneous concrete with $\epsilon_{r}=6.0$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$.

The scene consists of more than 6,000 bricks total. It resembles an office building floor with eight small rooms each of which has a window and a door. The overall dimensions are 12.2 x 11.2 x 2.4 m or in terms of wavelength (at 1.0 GHz ) $40 \mathrm{x} 37 \mathrm{x} 8 \lambda_{0}$. An infinitesimally small electric or magnetic dipole in $z$-direction transmitting at 1.0 GHz is placed in one room at a height of 1.5 m , and the received field is computed at the same height with a matching vertical or horizontal polarized isotropic antenna. The field variation in $z$-direction is also recorded. Depending on the polarization, currents up to the $15^{\text {th }}$ order have been calculated after which the maximum current change of all bricks fell below $10.0 \%$. The threshold was set to $10 \%$ because tests with different scenarios have shown that once the maximum current change of all bricks in one room is $10 \%$ of the average surface current change is already minimal and further iterations do not alter the field coverage anymore. The current generation ran for 13.6 h on one core of a 2.5 GHz AMD Phenom X4 processor using 605 Mb of RAM. The simulation was run for both electric Tx-dipole with vertically polarized $R x$-antenna (v-pol.) and magnetic Tx-dipole with horizontally polarized Rx-antenna (h-pol.), Figure 4.6 shows the field coverage for v-polarization and Figure 4.7 for h-polarization. It can be seen that the field variation in $z$-direction is much less for v-pol. than for h -pol. because of the higher reflectivity of the floor and ceiling for perpendicular incidence, to which a h-polarized antenna translates. Consequently, signal coverage is higher for h-pol. in rooms far away from the Tx.

### 4.5 Channel Characterization and Comparison to Homogeneous Wall Models

In this section the results of the indoor propagation simulations are postprocessed and channel parameters are extracted. In order to determine how the additional multipath caused by the periodic walls affects the indoor wireless channel, the floor


Figure 4.5: Layout of office building floor (floor and ceiling not plotted).
layout of the previous section was simulated with effective homogeneous dielectric slabs. If the brick-tracer algorithm is only run with dielectric slabs, it resembles an ordinary ray-tracer plus physical optics diffraction coefficients, the usual choice for wireless indoor analysis.

The effective homogeneous wall for rebar is just concrete without the metal rods, and for cinderblock it is a homogeneous dielectric with a lower $\epsilon_{r}$ of 1.9. Figure 4.8 and Figure 4.9 show the field coverage plot of the scenario with homogeneous walls for v- and h-polarization. Computation time for the homogeneous scenarios is only 3.5 h on one core of a 2.5 GHz AMD Phenom X4 processor because surface currents are calculated analytically and do not need to be searched and interpolated on a lookup table. In general, one can immediately see that the coverage plots for periodic walls exhibit a higher field variation while the overall average path loss tends to be the same. The $x z$-plots differ less because the model with inhomogeneous vertical


Figure 4.6: Field coverage (received E-field in dB) of building floor (Fig. 4.5) with inhomogeneous periodic walls for v-polarization.
walls has a homogeneous floor and ceiling, too. What follows is a propagation model parameter extraction and statistical analysis of the field coverage that verifies these observations.

### 4.5.1 Path Loss Exponent Model

A widely used simple indoor path loss model is based on the following formula [42]:

$$
\begin{equation*}
P(\mathrm{db})=P_{0}+10 n \log \frac{d}{d_{0}}+X_{\sigma} \tag{4.4}
\end{equation*}
$$

with the signal power $P$ at a distance $d$ from the transmitter and the signal power


Figure 4.7: Field coverage (received E-field in dB) of building floor (Fig. 4.5) with inhomogeneous periodic walls for h-polarization.
$P_{0}$ (in dB ) at a given small distance $d_{0}$ from the transmitter. $X_{\sigma}$ represents a normally distributed random variable in dB and $n$ is the path loss exponent (PLE). With this model, the wireless indoor channel is solely characterized by $X_{\sigma}$ and $n$, and both variables depend highly on the floor layout and wall material [42]. This model was applied to the brick-tracer simulation result. The normalization distance was chosen as $d_{0}=1.2 \mathrm{~m}$ with an average received power of $P_{0}=-16.4 \mathrm{~dB}$. Figure 4.10 shows the normalized power in $d B$ plotted against the normalized distance in $d B$ for the v-polarized field coverage of the periodic wall scenario in the $x y$-plane. Only every 100th field coverage point is plotted to keep the figure clear. It can be seen that the simulation follows the path loss model well and the extracted model parameters are: $n=3.75$ (found via regression) with a standard deviation of $\sigma=7.3 \mathrm{~dB}$. The plot


Figure 4.8: Field coverage (received E-field in dB ) of building floor (Fig. 4.5) with effective homogeneous walls for v-polarization.
for h-pol. is almost identical and therefore not shown. The values for the PLE and standard deviation are: $n=3.37$ and $\sigma=6.2 \mathrm{~dB}$. Measured data for both values can be found in the literature [42] where $n$ varies between 1.8 and 3.3 and $\sigma$ varies between 3 and 14 dB . The simulated value for $\sigma$ agrees well with these data. Only the PLE is slightly higher which is due to the small room size, i.e. many walls that block signal propagation.

The analogous signal analysis for the homogeneous wall scenario is plotted in Figure 4.11 (v-pol.). With the same normalization factors $d_{0}=1.2 \mathrm{~m}$ and $P_{0}=$ -16.4 dB , the predicted PLE is $n=3.65$ and the standard deviation is $\sigma=6.1 \mathrm{~dB}$. For h-pol. the values are $n=3.14$ and $\sigma=5.7 \mathrm{~dB}$. These values are compared to the parameters for the periodic scenario in Table 4.1. It should be noted that the values


Figure 4.9: Field coverage (received E-field in dB) of building floor (Fig. 4.5) with effective homogeneous walls for h-polarization.

Table 4.1: Comparison of PLE model parameters between periodic and homogeneous wall scenario.

|  |  |  | v-pol. |  |
| ---: | :---: | :---: | :---: | :---: |
| h-pol. |  |  |  |  |
|  | $n$ | $\sigma$ in dB | $n$ | $\sigma$ in dB |
| periodic | 3.75 | 7.3 | 3.37 | 6.2 |
| homogeneous | 3.65 | 6.1 | 3.14 | 5.7 |

for h-pol. are less meaningful because they are only based on one $x y$-field coverage plot which neglects the higher variation in $z$-direction. It can be concluded that the average path loss is well predicted with a simplified wall model that only consists of effective homogeneous walls. This is already reported in the literature [17]. The higher variance of the field variation for periodic walls indicates that the fast-fading behavior may differ between periodic walls and effective homogeneous walls.


Figure 4.10: Normalized path loss for 700 sample point of the field coverage of Figure 4.6, plotted against the logarithm of the normalized distance to the Tx.


Figure 4.11: Normalized path loss for 700 sample point of the field coverage of Figure 4.8, plotted against the logarithm of the normalized distance to the Tx.

### 4.5.2 Fast Fading Statistics

In order to verify that the fast fading of the received field is different for periodic wall scenarios compared to its effective homogeneous walls realization, local statistics
for both cases are compared in this subsection. The cumulative distribution function (CDF) of the received signal in both the upper and lower right rooms is computed and compared against Rayleigh and Ricean distribution which are commonly used to describe fast fading [42]. The two rooms have been chosen because the mean field inside the room can be assumed to be constant because of its remote distance to the Tx.

If a path on which signal statistics are employed has an LoS component or one dominant propagation path, it is described by the Ricean distribution. The Ricean distribution has one degree of freedom: the parameter $K$ (Ricean factor), which is the ratio between the LoS power and the variance of the multipath power. The Ricean distribution degenerates to the Rayleigh distribution for $K$ going to zero, which describes a non-LoS signal or a signal with no dominant propagation path.

The Ricean probability density function (PDF) is given by

$$
\begin{equation*}
p(r)=\frac{r}{\sigma^{2}} \cdot \exp \left(-\frac{r^{2}+A^{2}}{2 \sigma^{2}}\right) \cdot I_{0}\left(\frac{A r}{\sigma^{2}}\right), \tag{4.5}
\end{equation*}
$$

where $r$ is the magnitude of the received voltage, $A$ the peak amplitude of the dominant signal, $\sigma$ the variance of the multipath and $I_{0}$ the modified Bessel function of the first kind and zero-order. The Ricean factor $K$ is defined as $K=A^{2} / 2 \sigma^{2}$. For $K=0$ equation 4.5 simplifies to the Rayleigh PDF

$$
\begin{equation*}
p(r)=\frac{r}{\sigma^{2}} \cdot \exp \left(-\frac{r^{2}}{2 \sigma^{2}}\right) . \tag{4.6}
\end{equation*}
$$

The CDF of both distributions is found via integration over the PDF from zero to the given signal level $r$.

The analysis will be performed on the v-polarization data, while only the results will be given for h-polarization. Figure 4.12 shows the actual fast-fading statistics of the lower right room of the floor for both periodic and homogeneous walls and its fit

Table 4.2: Comparison of $K$-factor between periodic and homogeneous wall scenario fast fading statistics.

| $K$-factor | v-pol. |  | h-pol. |  |
| ---: | :---: | :---: | :---: | :---: |
|  | lower r. | upper r. | lower r. | upper r. |
| periodic | 1.9 | 0.0 | 0.9 | 0.4 |
| homogeneous | 3.9 | 1.4 | 7.4 | 1.4 |

to Ricean distributions, all normalized to the median received field. The parameters for the corresponding Ricean distributions were found by matching the Ricean PDF via method of least squares to the signal statistics generated from the field coverage plot. A Ricean distribution matches the signal statistics in both cases because there is a dominant direct path through the three walls. However, the multipath power is more than twice as much in the case of periodic walls ( $K=1.9$ compared to $K=3.9$ ).

The comparison of the fast fading statistics of the upper right room generates the same result (Figure 4.13): since the room is further away from the $T x$, the statistics only catch a low power dominant signal path for the homogeneous scenario $(K=1.4)$. Because of the Bragg-modes caused by the periodic walls, in this case there is no dominant path left, and the CDF follows the Rayleigh distribution. The results have been summarized in Table 4.2 including the $K$-factors for h-polarization.

Overall, the fast-fading statistics differ significantly for periodic walls compared to its effective homogeneous implementation. In general, if a realistic indoor scenario which often consists of inhomogeneous periodic walls like cinderblock, dry-wall or rebar structure of any kind is approximated with an effective homogeneous dielectric wall, the multipath of the received signal will be underestimated throughout the whole simulation domain. This results in an overestimation of the Ricean factor. The Bragg modes caused by the periodic walls are a major contributing factor to the received signal and can only be included in simulation if a hybrid method is employed.


Figure 4.12: Cumulative distribution function for receiver points in the lower right room of the building floor of Fig. 4.5 for both periodic and effective homogeneous walls and its matching Ricean distribution. The received signal level is normalized to its median.


Figure 4.13: Cumulative distribution function for receiver points in the upper right room of the building floor of Fig. 4.5 for both periodic and effective homogeneous walls and its matching Ricean/Rayleigh distribution. The received signal level is normalized to its median.

### 4.6 Summary

The hybrid brick-tracer method was extended to full 3D in this chapter in order to study wave propagation and scattering within a realistic 3D indoor environment in the presence of inhomogeneous periodic walls. First, the 3D method was validated against theory and measurement for two simple scenarios. Then the indoor wave propagation was analyzed and model parameters and fast-fading statistics were extracted for a sample floor plan with inhomogeneous periodic walls. The same analysis was repeated with the assumption of effective homogeneous dielectric walls, a simplification often made for indoor propagation analysis. It was shown that while simulations of an indoor environment with effective homogeneous dielectric walls can predict the average received field, the fast-fading of the signal cannot be predicted with effective homogeneous walls. The inhomogeneous periodic walls are a significant source of multipath throughout the floor layout that return different fast-fading signal statistics compared to effective homogeneous wall models. Therefore the approximation of inhomogeneous dielectric walls with effective homogeneous walls introduces a systematic error into the fast-fading statistics which can only be overcome by hybrid methods like the described 3D brick-tracer.

## CHAPTER V

# Incorporation of Human Body Model into Brick-Tracer 

This chapter lays the foundation for the analysis of human scattering inside buildings for through-the-wall radar (TWR) systems as it adds a human body model to the brick-tracer method. The human body is complexly shaped and built object, and its size is in the order of a couple of wavelengths at the UHF band. One needs to model the human body accurately to correctly predict human scattering in buildings for phenomenological studies which can be the basis for investigations into reliable human body detection and localization algorithms avoiding costly measurements. While approximating humans with cylinders or evaluating human scattering behind a single wall can prove the concept of human detection/localization [43, 44] one needs more complex models to accurately estimate the human fully polarimetric scattering and examine all building effects on it. It would be possible to conduct a complete full-wave analysis of the building including the human. But at this frequency band, as already stated in the previous chapter, such analysis would require high computational resources and it is not feasible for human backscattering analysis in larger buildings with standard computers [45].

This chapter will combine the brick-tracing algorithm with a full-wave analysis of a human body model to derive a realistic and computationally efficient method
to obtain the human response within a building to UWB through-wall radars over a wide bandwidth covering UHF. Using a full-wave analysis of the human body only, combined with the PO-like building analysis, this method is computationally feasible compared to a complete full-wave analysis but still accurate as it accounts for the presence of inhomogeneous periodic walls and windows as demonstrated in the last chapter.

This chapter is structured in the following manner: first a simple but anatomically accurate human model is utilized in conjunction with a full-wave electromagnetic model to generate the scattered field of a human in a building environment. The human model was derived from an actual human MRI scan, and it can be animated to assume any desired position. Next, the combination of this model with the indoor propagation component based on the surface equivalence principle is described.

### 5.1 Human Body

### 5.1.1 Model

The human body consists of many parts, most of them having a high dielectric constant of 40 to 50 with high conductivity of $\sigma \approx 1.0 \mathrm{~S} / \mathrm{m}$ (for a frequency of 1 GHz ) because of its high water content. The only exceptions are bones with $\epsilon_{r}=12$ and $\sigma=0.2 \mathrm{~S} / \mathrm{m}$ and fat with $\epsilon_{r}=5$ and $\sigma=0.05 \mathrm{~S} / \mathrm{m}[46]$. The human body is covered with clothes which are usually thin and air filled (like cotton), and they show low $\epsilon_{r}$ and loss tangent. Consequently, the clothes can be assumed to be transparent at the desired frequency range. While detailed human body models and models for electric properties of the body parts exist, it is not practical to use them for backscattering analysis in conjunction with large indoor propagation tools because of their complexity, especially if movable joints are needed to emulate realistic body movement like walking. Furthermore, the skin depth at this frequency is in the range from 1 cm to

3 cm , so the incident wave does not fully penetrate the human body. The human body structure and its dielectric properties are suitable for a simplified approximation of a homogeneous dielectric material with an average dielectric constant of all body parts. Therefore, for a full male human MRI scan with 84 distinct body parts [47], full-wave FDTD RCS simulations are compared with the RCS simulations of the same model having an average dielectric constant [48]. Simulations were carried out for $0.5 \mathrm{GHz}, 1.0 \mathrm{GHz}$ and 1.5 GHz to cover the full frequency band and for various plane wave incidence angles and polarizations. The average dielectric properties are $\epsilon_{r}=41.5$ and $\sigma=0.97 \mathrm{~S} / \mathrm{m}$. Figure 5.1 shows the complete human model and compares azimuthal 2D cuts of the human RCS pattern for a vertical polarized plane wave incident from the front for the homogeneous and complete human models at 1.0 GHz . Three other examples are given in Figure 5.2 and 5.3; Fig. 5.2 repeats the RCS comparison at 0.5 GHz and 1.5 GHz and Fig. 5.3 shows the RCS comparison for a horizontal polarized plane wave incident from the side at 1.0 GHz . It can be seen that the homogeneous model predicts the human backscattering very well. If one compares the full bistatic 3D RCS, it is found that the average relative error of the RCS in directions the human significantly scatters always remains between 1 and 2 dB for both co- and cross-polarizations over all bistatic angles and frequencies.

### 5.1.2 Incorporation into Brick-Tracer

A freely available program is used to generate a surface mesh of an arbitrarily shaped human in arbitrary body position (like the person walking in Figure 5.4) [49]. This model is meshed as a solid in a commercial full-wave 3D FDTD solver with the average dielectric properties [48]. The body can now be excited with an arbitrarily loaded field distribution on a surface enclosing it (frequency domain signal Huygens Source, see [48]). Figure 5.5 left shows the FDTD mesh of a sample human body at 1.0 GHz . The inner box is the enclosing Huygens box and the outer box represents


Figure 5.1: Human body model of Semcad virtual family (taken form Semcad X Manual) and bistatic RCS comparison (horizontal plane, inc. wave at $\alpha=90^{\circ}$ ) of exact model to homogeneous assumption for vertical polarized plane wave from the front at 1.0 GHz .



Figure 5.2: Human body model of Semcad virtual family (taken form Semcad X Manual) and bistatic RCS comparison (horizontal plane, inc. wave at $\alpha=90^{\circ}$ ) of exact model to homogeneous assumption for vertical polarized plane wave from the front at 0.5 GHz (left) and 1.5 GHz (right). Compare to Fig. 5.1.
the boundaries of the simulation domain. To the right to it are two cuts through the empty Huygens box with a user-defined field excitation. Figure 5.5 right shows the same field exciting the human body (electric field at 1.0 GHz , linear scale).


Figure 5.3: Human body model of Semcad virtual family (taken form Semcad X Manual) and bistatic RCS comparison (horizontal plane, inc. wave at $\alpha=45^{\circ}$ ) of exact model to homogeneous assumption for horizontal polarized plane wave from the side at 1.0 GHz . Compare to Fig. 5.1.


Figure 5.4: Surface model of walking person.
This is combined with the brick-tracer [21, 24]. The full-wave analysis is incorporated into the brick-tracer in the following manner: first the scene is fully simulated with the brick-tracer and the fields on the surface of the Huygens box are recorded. These recorded fields are used as the incident field for the full-wave simulation of the human body model. Next the full-wave simulation of the human body is performed. After the full-wave simulation converges, the scattered field of the human body (readout outside the Huygens box) is written to a file and transferred to the


Figure 5.5: SEMCAD mesh of walking person with sample Huygens box excitation.
brick-tracer. As a last step the Huygens box is allowed to act as a distributed transmitter in the brick-tracer, and the scattered field is radiated through the scene to the receiver points. This first-order approximation is sufficient for accurate human scattering analysis in buildings as the second and higher order interactions (illumination of the Huygens box by the reflected primary scattered field from the walls) are small compared to the first-order scattered field.

### 5.2 Validation and Sample Scenario

The simulation concept was validated with one sample setup; a PEC sphere in front of a finite PEC wall, illuminated by a plane wave from the front (Figure 5.6). The complete setup was simulated full-wave and compared to a combined bricktracer and SEMCAD simulation where the wall was simulated with the brick-tracer. Only the sphere was simulated full-wave with SEMCAD, and then interfaced via the Huygens box. Figure 5.7 shows the resulting field plot (normalized magnitude of E-field) through the center of the sphere, perpendicular to the wall, at 1.0 GHz of
the full SEMCAD simulation (left) compared to the combined brick-tracer/SEMCAD simulation, including the second-order scattered field of the sphere (right, the black square is the Huygens box around the sphere). As one can see, the field coverage plots match exactly, demonstrating that the interface between the brick-tracer and the full-wave simulation SEMCAD is working.


Figure 5.6: Validation setup (PEC sphere in front of PEC wall) for combined bricktracer/SEMCAD simulations.


Figure 5.7: Field coverage (normalized magnitude of E-field) for full SEMCAD simulation of Fig. 5.6 (left) compared to combined brick-tracer/SEMCAD simulation (right) at 1.0 GHz (cut through center of the sphere, perpendicular to the wall).

As a next step a simple scenario is considered that shows how the Huygens box is interfaced with the brick-tracer and the human body model: a reinforced concrete wall ( $\epsilon_{r}=4.8$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$ with metal rods every 30 cm ) on a homogeneous concrete ground plane is illuminated by a $z$-directed Hertzian dipole from a distance of 3 m . Tx height is 1.3 m , wall height is 2.6 m and length is 8 m . Fig. 5.8 shows the resulting field distribution around the wall at the Tx height. The field around the human centered at $x=2.8 \mathrm{~m}$ and $y=2.8 \mathrm{~m}$ is recorded. Fig. 5.10 shows the top view of the human model used in full-wave simulation and the E-field distribution in constant $z$-plane at $z=1.3 \mathrm{~m}$. Using the surface fields over the Huygens box, the scattered field of the human interacting with the wall is calculated and shown in Fig. 5.9.


Figure 5.8: Field coverage of $z$-directed Hertian dipole in front of reinforced concrete wall at 1.0 GHz (E-field in dB, normalized).

The required CPU time for the full-wave simulation of a typical walking human ranges from a couple of minutes at 0.5 GHz to approximately 50 min at 1.5 GHz on an Intel Xeon 3.16 GHz workstation. Approximately 40,000 field points are needed to correctly transfer the incident field of the brick-tracer to the FDTD solver for frequencies up to 1.5 GHz . A brick-tracer simulation to find the incident on or scattered field of the human can range from a couple of seconds for a simple wall to a maximum of 13 h for a complex scenario (like Fig. 4.5) on an AMD Phenom 2.5 GHz workstation.


Figure 5.9: Field coverage of human backscattering behind reinforced concrete wall at 1.0 GHz (E-field in dB , normalized to max. of inc. field).


Figure 5.10: Top view of human and field plot at $z=1.3 \mathrm{~m}$ of SEMCAD simulation of human behind reinforced concrete wall at 1.0 GHz .

In order to retrieve the UWB time-domain response from the frequency domain simulations, the simulations have to be carried out for every frequency at the desired band, with appropriate frequency steps according to the maximum range of the scene. The SEMCAD human body simulations are therefore automated via a Phyton script which loops the frequency and automatically loads the appropriate input file, runs the simulation and writes out the scattered field for each frequency step. Once the received voltage at the receiving antennas of the scene has been determined using the hybrid indoor propagation method for each frequency point, the received voltage can be inverse Fourier-transformed to get the time-domain radar response.

### 5.3 Summary

A simple but accurate human body model with movable joints was derived from an exact CAD model of a human. The incorporation of this model into the hybrid method brick-tracer via a Huygens box interface was introduced and validated.

## CHAPTER VI

## Analysis of Human Scattering in Buildings for the Detection and Localization

This chapter will utilize the human body model combined with the brick-tracer as introduced in the previous chapter for accurate analysis of human scattering in buildings to UWB radar systems at UHF. A fully polarimetric analysis is performed, starting from simple scenarios to examine the human scattering, itself, up to complex scenarios to examine the effect of the building on the human scattering. Furthermore, multistatic radar scattering will be analyzed which allows instantaneous 2D image formation for the scene under investigation. A viable way to detect and localize the human in the building is introduced by taking into account the movement of the human body. Finally, the effects of the building on the dectection on localization performance are elucidated.

### 6.1 1D Imaging

First, human scattering and human scattering in buildings are analyzed for monostatic radar systems (Tx and Rx antenna at same location). The human return can then be related to the wall/building return and conclusions for the detection of humans can be drawn.

### 6.1.1 Background

The basic principle of a monostatic radar is relatively simple: a short pulse is transmitted through the Tx antenna which is reflected/scattered by the targets in front of the Tx. The scattered pulse of the targets is then received with a time delay by the Rx antenna and the amplitude of the received pulse contains information about the RCS of the target, while the distance of the target from the radar (range) can be computed from the time delay of the pulse $\left(s=\Delta t \cdot c_{0} / 2\right)$. The radar cannot distinguish direction; all targets located on a concentric circle in the area illuminated by the Tx antenna are imaged at one location. The radar can also be implemented as a stepped frequency system, measuring the frequency domain response of the scene from $f_{\min }$ to $f_{\max }$, and range and RCS information can be gathered after an IFFT of the collected data.

No matter how the radar is implemented, the minimum distance required for distinction of the radar return between two targets (range resolution $s_{r}$ ) is related to the bandwidth of the radar:

$$
\begin{equation*}
s_{r}=\frac{c_{0}}{2 B W}, \tag{6.1}
\end{equation*}
$$

where $B W=f_{\text {max }}-f_{\text {min }}$ is the bandwidth of the system and $c_{0}$ the speed of light in air. Unfortunately, in order to achieve this theoretical resolution one has to tolerate high sidelobe levels of each target return (i.e. a $\operatorname{sinc}(x)=\sin x / x$ function in the time domain with the first sidelobes at -13.3 dB for a flat frequency response from $f_{\text {min }}$ to $f_{\max }$ ). These high sidelobe levels clutter the return and can conceal weak targets if the imaged scene consists of many targets. Therefore the radar return is usually windowed in the frequency domain, reducing the sidelode level to clean up the image. However, this also reduces the range resolution. An example is the Hamming window, which leads to a point spread function $42 \%$ wider than the sinc function but with a reduced first sidelobe level of -42.5 dB .

### 6.1.2 Human Scattering

Initially the polarimetric backscatter response of different stationary human subjects in free-space above a ground plane at different look angles is studied. Various different human poses have been generated (Fig. 6.1, the view of the humans is the actual view of the radar). The radar was placed 1.3 m above the ground plane (dense concrete with $\epsilon_{r}=6.0$ and $\left.\sigma=0.02 \mathrm{~S} / \mathrm{m}\right)$ and the near-field backscattering of the human was recorded from 0.5 GHz to 1.2 GHz in 10 MHz steps for vertical polarized Tx and Rx antennas.


Figure 6.1: Surface models of different humans, a) man standing still, b) - d) woman standing still from different look angles, e) f) walking woman from front and side, g) woman sitting on chair, h) dog from behind. Models are drawn to scale.

Figure 6.2 shows the simulation result for the human backscattering of pose (a) and (f) with the radar placed 5 m away from the human. The frequency response of Fig. 6.2(a) was windowed with a Hamming window before calculating the time domain response of Fig. 6.2(b). It can be seen that the walking woman creates a relatively high cross-polarized (cross-pol.) response while the cross-pol. response of the man is almost 30 dB below it. Furthermore, because of the multiple scattering centers of the human body, its time-domain response is slightly broadened.

In order to estimate the general level of co-polarized (co-pol.) scattering of the human body, backscattering simulations have been carried out for all human poses


Figure 6.2: Frequency and time domain backscattering response of human (a) and (f) of Fig. 6.1, 5m away from the Tx for vertical polarized Tx and Rx antennas (normalized to max. co-pol. response of man).
from Fig. 6.1. The radar was placed 8 m away from the human and the radar parameters were maintained from the previous example. The time-domain co- and cross-pol. backscattering responses were recorded and the first line of Table 6.1 shows the maximum co-pol. response for each pose, all normalized to the maximum of copol. backscattering from pose (e) which was the highest overall. The second line shows the maximum cross-pol. response, normalized to the co-pol. response of each pose. As can be seen, the human body produces a stable co-pol. backscattering response for the given examples. It only varies within 10 dB . The cross-pol. response is about 10 dB to 15 dB lower than the co-pol. response, except for the standing man and woman facing the radar with straight arms and legs. This shows that the crosspol. response of the human at this frequency range is highly dependent on the arm and leg position and its look angle towards the radar. The standing woman generates a strong cross-pol. return at a different look angle as well as facing the radar but walking toward it. Interestingly, the dog produces the same level of co- and cross-pol. backscattering as the humans and consequently it would be difficult for a radar at this frequency to distinguish humans from tall animals.

Table 6.1: Comparison of time-domain co- and cross-polarized backscattering for the different human body poses of Fig. 6.1.

| Pose | a | b | c | d | e | f | g | h |
| ---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| co-pol. normalized | -6.2 | -7.5 | -3.7 | -6.0 | 0.0 | -4.7 | -8.0 | -6.6 |
| cross-pol. below co-pol. | -32.7 | -33.8 | -4.5 | -11.3 | -18.2 | -11.5 | -10.5 | -12.9 |

Overall the human produces a significant amount of cross-pol. with the exception of a few special poses. Although some wall or floor/ceiling reflections can possibly depolarize the transmitted signal slightly, this relatively high cross-pol. scattering of the human can still allow gathering additional information about humans inside buildings by recording the cross-pol. induced backscattering.

### 6.1.3 Human Behind a Single Wall

As a next step the human backscattering behind a single wall is evaluated: the magnitude of the human scattering can then be related to the walls and the distortion of the human return through walls can be analyzed. A scene was created where the human was standing 8 m away from the radar on a ground plane (dense concrete with $\epsilon_{r}=6.0$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$, radar height 1.3 m ). The human model is the walking female from Figure 6.1 (f). A finite wall was placed between the radar and the human (concrete with $\epsilon_{r}=4.8$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$, thickness 0.2 m , height 2.6 m and length 6 m or 8 m ), 3 m and 7.3 m away from the radar. The co- and cross-pol. backscattering of the scene was simulated from 0.5 GHz to 1.4 GHz in 10 MHz steps. For comparison, the same scene was analyzed without the wall. Figure 6.3 shows the time-domain result (Chebyshev window applied to reduce sidelobe level to -70 dB ) for the wall 3 m away from the radar, normalized to the max. co-pol. wall return. As can be seen, the specular reflection of the wall dominates the radar return, and the human return is 40 dB below the wall return. Because of the additional pathlength and attenuation through the wall the human return is approximately 10 dB lower than in free space and shifted 24 cm backwards. The same applies to the cross-pol.
human scattering behind the wall, but the wall itself only generates a small amount of cross-pol. caused by depolarization effects of the combined edge diffraction and ground reflection.

If the human is close to the wall (result of Figure 6.4 where the human is standing 0.5 m behind the wall, same normalization as Fig. 6.3), the human co-pol. return is completely hidden within the wall return. It can be seen that the human return is, in addition to the attenuation and position shift, also blurred because of the multiple bounces of the transmitted signal in the wall. However, the cross-pol. return is dominated by the cross-pol. of the human because the afore-mentioned depolarization effects of the wall are weaker if it is further away.


Figure 6.3: Co- (left) and cross-pol. (right) time-domain backscattering of a human ( 8 m away from Tx ) behind a single homogeneous wall ( 3 m away from Tx ) for vertical polarized Tx and Rx antennas, compared to scattering of a human at same position without wall (dotted line). The gray dashed line is the human scattering portion of the human behind the wall return. Normalized to max. wall return.

### 6.1.4 Human in Building

In the previous section, the effect of one wall on the human radar return was investigated with direct signal propagation from the Tx to the human target and back to the Rx. Since a building always consists of many walls, the emitted signal of the radar has more than one path to and from the target. This section will investigate how this multipath propagation of buildings affects the radar imaging of humans inside.


Figure 6.4: Co- (left) and cross-pol. (right) time-domain backscattering of a human ( 8 m away from Tx ) behind a single homogeneous wall ( 7.3 m away from Tx) for vertical polarized Tx and Rx antennas, compared to scattering of a human at same position without wall (dotted line). The gray dashed line is the human scattering portion of the human behind the wall return. Normalized to max. wall return of Fig. 6.3.

A sample building consisting of two rooms with overall dimensions of $8.0 \times 4.2 \mathrm{~m}$ was constructed with homogeneous concrete walls $\left(\epsilon_{r}=4.8\right.$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$, thickness 0.2 m ) including doors and windows. The ground (extends to the $\mathrm{Tx} / \mathrm{Rx}$ ) and ceiling are dense concrete ( $\epsilon_{r}=6.0$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$ ). The Tx was placed 2 m away from the front wall and a walking woman was placed in the front and back room. Figure 6.5 shows the building layout with the position of the $\mathrm{Tx} / \mathrm{Rx}$ and a perspective view of the building (without floor/ceiling).


Figure 6.5: Building layout (right) and top view (left) with Transmitter, Receiver and human position (floor and ceiling not shown).

First both co- and cross-pol. 1D backscattering of the building and human were recorded for a vertical polarized Tx antenna. The Tx was placed at a height of 1.3 m ,
and the building backscattering was calculated from 0.5 GHz to 1.4 GHz in 5 MHz steps. Figure 6.6 shows the resulting time-domain co- and cross-pol. backscattering at the Tx location. One can recognize the strong specular reflection of the three walls facing the Tx in the co-pol. return, interspersed with clutter caused by the multipath propagation. Although the human stands in the middle of the room, it cannot be distinguished from the clutter. The depolarizing effect of the wall-ground reflection is also stronger than the cross-pol. backscattering of the human. The same is true if the human is located in the second room (Figure 6.7). Its return is hidden even more within the multipath propagation of the building.


Figure 6.6: Co- (left) and cross-pol. (right) backscattering of a human inside the building of Fig. 6.5 for vertical polarized Tx antenna, normalized to its maximum. The gray dashed line is the human scattering portion of the scene.

### 6.1.5 Human Detection Through Time-Differencing

The previous sections demonstrated that human return is so weak compared to the wall return that a single wall alone can conceal the human return in the co-pol. backscatter. For a simple building, the human return is hidden within the building return for both co- and cross-pol., making it impossible to detect the human. Therefore additional processing is necessary to extract the human return. One possibility to isolate the human backscatter response from the building is to take advantage of


Figure 6.7: Co- (left) and cross-pol. (right) backscattering of a human inside the building of Fig. 6.5 for vertical polarized Tx antenna, normalized to its maximum, human located in the second room. The gray dashed line is the human scattering portion of the scene.
its movement. Basically by subtracting two temporally close backscatter measurements of the building with the human inside from the same transceiver location, one can remove much of the stationary response from the building itself and all stationary objects inside like furniture [51]. Already the movement of one arm changes the human backscattering significantly, resulting in a strong human return if two consecutive backscattering measurements are subtracted. If the backscattering measurements are taken every 0.5 s , the repetition frequency is long enough to differentiate a slowmoving human and short enough that a fast-moving human does not show up as two separated targets.

To demonstrate this concept, the two postures shown in Fig. 6.8, separated in position by 20 cm , are considered in the previous building example (Fig. 6.5). The human walks in $y$-direction from $(2.0,1.8) \mathrm{m}$ to $(2.0,2.0) \mathrm{m}$ and the arms and legs are properly adjusted. Figure 6.9 right shows the difference in co- and cross-polarized time-domain responses of the building with the moving human inside for the two positions and postures.

The human can now be easily localized 4.2 m away from the transmitter for both

## 1 <br> 

Figure 6.8: Surface model of walking person.


Figure 6.9: The time-difference time domain backscattering of a walking human in the building of Fig. 6.5, normalized to the maximum wall return. Compare to the backscattering of one shot (Fig. 6.6).
polarizations. A strong shadow effect on the wall behind the human can be seen (at $6.5 \mathrm{~m})$ for co-pol but not for cross-pol. Nevertheless both co- and cross-pol. return are affected by the multipath propagation inside the building which cause the multiple sidelobes and clutter. Because the return of additional humans could be concealed within this clutter, it is not possible to distinguish the multipath propagation sidelobes of the first human from the possible return of additional human farther away.

### 6.2 2D Imaging

The previous section showed that detection of humans with a monostatic radar is limited. For a single-shot image the human return is hidden within the building return, and for a time-difference image only the distance to the closest moving human can be identified. More information has to be gathered if one wants to localize the human or identify additional humans.

### 6.2.1 Background

Additional measurements at different positions have to be made in order to locate the targets. This is usually done by moving the monostatic radar along a predefined line in front of the scene to form a synthetic aperture. The measurement history together with the position data is then processed to form an 2D image. This setup has several advantages. First, only one small radar is required to form a 2D image that covers a large area. Furthermore, the point spread function of targets and the wall responses are well defined. However, the major disadvantage of this setup is that it requires a significant amount of time to form the synthetic aperture by moving the radar. In the case of a human target inside a building, the human can move a significant distance and cross rooms while the synthetic aperture is being formed, making it almost impossible to image the moving human. Additionally, the scene has to be imaged quickly in order to take action. Because of these problems, it is advantageous to form an instant 2D image of the scene by replacing the receiver with a receiver array centered around the Tx , forming a real aperture (multistatic radar). This can be implemented by mounting a Rx array (together with Tx ) on a van or truck which then can be positioned in front of the building under investigation.

The 2D image generation of the scene follows the standard method of SAR or multistatic radar image generation [50, 11]: given a frequency stepped continuous wave radar system which outputs the received voltage $v_{n m}$ at the $n$-th antenna and
$m$-th frequency point, the reflectivity $S$ at a given point $\vec{r}$ is found through focusing the array by

$$
\begin{equation*}
S(\vec{r})=\sum_{n} \sum_{m} v_{n m} e^{j \theta_{n m}(\vec{r})} \tag{6.2}
\end{equation*}
$$

where the phase shift $\theta_{n m}(\vec{r})$ is given by

$$
\begin{equation*}
\theta_{n m}(\vec{r})=k_{m}\left(\left|r_{T x}-\vec{r}\right|+\left|\vec{r}-\overrightarrow{r_{n}}\right|\right) \tag{6.3}
\end{equation*}
$$

with wavenumber $k_{m}$ and the Tx position $r_{T x}$ and position of the $n$-th Rx antenna $\overrightarrow{r_{n}}$. The reflectivity is estimated on a grid at receiver height to find the 2D image. Again, in order to reduce sidelobes of the image the input data is windowed along the frequency and also along the array. Contrary to image formation using a synthetic aperture, the resolution of the multistatic radar is dependent on the range and crossrange position of the target. One has to keep this in mind when forming a 2D multistatic radar image.

The image formation described is the most basic image generation if one has no previous knowledge of the imaged scene. It assumes point targets and free-space wave propagation to and from the targets without interaction between the targets. Hence, it can perfectly reconstruct the location and scattering magnitude of point targets in free space; however, if the targets are extended or there are obstacles in the way, the images will be distorted and shifted.

### 6.2.2 Human in Building

The scene introduced in section 6.1.4 (small building with two rooms) was simulated with an 6 m long receiver array (spacing 0.1 m ) centered around the Tx to generate a 2D image of the human inside the building. The images were generated according to section 6.2.1, while the data were windowed with a Hamming window along frequency and a Gaussian window along the array. The Tx is located at (-2.0,
1.0) m and the Rx array spans from $y=-1 \mathrm{~m}$ to $y=5 \mathrm{~m}$.

In order to evaluate this multistatic radar setup theoretically, an array of ideal point targets was imaged with it (Figure 6.10). It can be seen that the point spread functions only differ slightly because the extent of the image in cross-range does not significantly exceed the length of the array.


Figure 6.10: 2D multistatic radar reflectivity image for an array of ideal point targets $(x=0 \ldots 12 \mathrm{~m}$ and $y=-2 \ldots 6 \mathrm{~m}$ in 2 m steps $)$, imaged with a 6 m long Rx array centered at the $\mathrm{Tx}(-2.0,1.0) \mathrm{m}$ from 0.5 to 1.4 GHz .

The human in the first room is at $(2.0,2.0) \mathrm{m}$ and Figure 6.11 shows the 2D reflectivity of the scene. The reflectivity is overlaid with the building layout (dotted black line) for orientation. The human can be distinguished from the front wall reflection but if it was standing closer to the wall or if other objects like furniture, plants etc. were in the room its return would be lost in the clutter. The same is true for the cross-pol. reflectivity image.

It could be argued that if one has no prior knowledge of the building and the building interior, then the human is also undetectable in a single-shot 2D radar image of such a simple building layout as shown. Therefore, time-differencing is used again to extract the human return.


Figure 6.11: 2D near-field reflectivity image of co- (left) and cross-pol. (right) backscattering of human inside the front room of building (Fig. 6.5), normalized to max. co-pol. reflectivity.

### 6.2.3 Human Localization Through Time-Differencing

The same time-differencing concept as introduced in section 6.1.5 can be applied to the multistatic 2D reflectivity images. Since the reflectivity of the scene is recorded with a real aperture, the images can be generated instantly. If image generation takes less time then the separation of two radar measurements, 2D time-differencing images can be formed. This has been applied to the two-room building with the walking human in the front room (2D building image introduced in previous section as Fig. 6.11, 1D image of walking human already formed in section 6.1.5). As in 1 D , generating a 2D image of the human walking eliminates the wall return and the human can be easily identified at $(2.0,2.0) \mathrm{m}$ for both polarizations. But the image shows strong ghosts (caused by the walls to the side, e.g. at $(2.0,-2.0) \mathrm{m})$ and shadows on the walls behind the human, e.g. at $(4.0,2.0) \mathrm{m})$ which could be falsely identified as additional humans. An overview of possible ghosts and shadows along with the propagation path that causes them is shown in Figure 6.13. The ghost and shadow images are blurred and shifted in position. These effects are mainly caused by different propagation paths from the $T x$ to the target and from the target back to the Rx. This effect is explained and quantified in the following section 6.2.3.1.

Furthermore, if any path from the target to the receivers changes over the Rx array (like crossing an additional wall or passing through a door/window), the images of the target won't align and will be blurred as well.

The time-difference cross-pol. image also shows ghost and shadow human targets (Fig. 6.12 right). However the image is less cluttered and shows fewer wall shadows because the human, itself, generates most of the cross-pol.


Figure 6.12: 2D near-field time-difference reflectivity image of co- (left) and crosspol. (right) backscattering of human walking inside the front room of building (Fig. 6.5). Compare to single shot image of Fig. 6.11.


00
0

Figure 6.13: Visualization of the multipath propagation and location of possible ghost/shadow images of the human in the 2D reflectivity image of Fig. 6.12.

### 6.2.3.1 Multipath Effect on Multistatic Radar Images

The previously described shift and distortion of the human ghost and shadow images is quantified in this section. For this discussion one ideal point target is placed at the original human position $(2.0,2.0) \mathrm{m}$ in the scene. First, one ideal infinite PEC wall at $x=4 \mathrm{~m}$ behind the point target was added. With this single wall, there are four possible paths to and from the target:

1. Direct path to and from the target
2. Wall reflection to the target, direct path from the target
3. Direct path to the target, wall reflection from the target
4. Both path to and from the target wall reflected

Figure 6.14 left shows the resulting 2D image. As expected, the direct path (1) is imaged at the exact target position $(2.0,2.0) \mathrm{m}$ with the maximum achievable resolution. Path 2 and 3 are imaged at the same position of (4.0, 2.0) m, as expected from the overall traveled pathlength. But the pathlength difference to and from the target significantly blur the return of these paths in cross-range, causing a wider point spread function than a point target at this position. The double reflected path is imaged at $(6.0,2.0) \mathrm{m}$, as expected like a point target at this position.

As a second example, a wall perpendicular to the Rx array was placed in the scene at $y=0 \mathrm{~m}$ to evaluate the effects of a wall to the side. Again a total of four signal paths from the Tx towards the Rx array are possible. Figure 6.14 right shows the resulting 2D image. The direct path (1) and the double reflected path (4) are imaged at the expected locations, $(2.0,2.0) \mathrm{m}$ and $(-2.0,2.0) \mathrm{m}$ with the ideal point spread function, but the two other paths shows an unexpected behavior: path 2 is imaged behind the real target position at $(2.0,2.5) \mathrm{m}$ and path 3 is imaged close to the location of path 4 but shifted toward the $\operatorname{Tx}$ at $(1.7,1.7) \mathrm{m}$. Both path images
show a wider point spread function than a point target at this location. This result corresponds to the first ghost images of the human to the side of Figure 6.11.


Figure 6.14: 2D mulitstatic radar images of an ideal point target reflected on an infinite PEC wall at $x=4 \mathrm{~m}$ (left) and $y=0 \mathrm{~m}$.

This shows that in multistatic imaging, the image of multipath propagation to and from the target is mainly dependent on the multipath propagation of the target scattering. This scattering determines the location of the image target. If the signal to the point target undergoes fewer wall reflections, the non-matching pathlengths cause a shift of the target from its real image position towards the Tx (like path 3 in the previous example). If the signal to the point target undergoes more wall reflections than from the point target, the non-matching pathlengths cause a shift of the target away from its real image position (like path 2 in the previous example).

Now if one looks at the layout of the building (Fig. 6.5), one can identify many possible propagation paths to and from the human target (also paths including diffraction at corners, windows and doors must be counted) and it becomes obvious why the time-difference human image of Fig. 6.12 is accompanied by so many undefined ghosts.

### 6.2.3.2 Human Tracking

The previous section showed that it is possible to identify and localize a human inside a building based on its movement. However, strong ghost and shadow images appear which could be identified as additional humans. In this section, the human radar return inside a building has been simulated over seven consecutive frames, each resembling a radar measurment 0.5 s apart, to enable following the path of the human and the ghosts/shadows. The human was placed in the previously introduced two room building (Fig. 6.5) and walks along the path plotted in Figure 6.16. First it walks in $+y$-direction, then slowly on a curved path toward the door (at $y=3 \mathrm{~m}$ ) and then quickly through the door. The body orientation and the leg and arm positions were properly adjusted. The backscattering of the scene was recorded for a vertical polarized Tx antenna, 1.3 m above the ground, centered 2 m in front of the building ( 0.5 GHz to 1.0 GHz in 5 MHz steps). The Rx array is centered around the Tx , and it spans 6 m with a 30 cm spacing. Figure 6.15 shows the array of point spread function for this example. High sidelobes of the point targets close to the array can be seen which are due to the array spacing of 30 cm which is slightly to coarse for this frequency range.


Figure 6.15: 2D multistatic radar reflectivity image for an array of ideal point targets ( $x=0 \ldots 12 \mathrm{~m}$ and $y=-2 \ldots 6 \mathrm{~m}$ in 2 m steps) for a 6 m long Rx array (spacing 30 cm centered around the $\mathrm{Tx}(-2.0,2.0) \mathrm{m}$, from 0.5 GHz to 1.0 GHz .

Figure 6.16 on the right shows the backscattering of the building at the start position of the human which resolves the building walls parallel to the Rx array.


Figure 6.16: Building geometry with human path (left) and 2D co-pol. reflectivity image of building with human at start position (right), in dB and normalized to its maximum.

Figure 6.17 shows the resulting consecutive time-difference images for co-polarized Rx antennas, normalized to the maximum of the front wall return. First of all, it can be seen that the magnitude of the human return fluctuates which is caused by the variation of the human backscattering based on look angle and arm/leg position (as described in section 6.17). Consequently, the magnitude of the ghost and shadow images varies significantly, but the ghost path of the human caused by the wall at $y=4 \mathrm{~m}$ can be clearly identified. Also, the human movement is resolved in two closely spaced returns when the human walks quickly (frame $t=0.0 \mathrm{~s}$ and $t=2.5 \mathrm{~s}$ ).

Figure 6.18 shows the consecutive time-differencing images for cross-pol. Rx antennas, normalized to the maximum of the co-pol. building return. The cross-pol. return of the human inside the building fluctuates more than the co-pol. return but is on average 10 dB lower than the co-pol. return if compared to Fig. 6.17 (as already found in section 6.1.2). Again, the ghost path caused by the wall at $y=4 \mathrm{~m}$ can be clearly identified and the shadow on the wall at $x=4 \mathrm{~m}$ until the human walks through the door (frame $t=1.5 \mathrm{~s}$ ).

Overall it can be seen that if one starts to track the human over serveral frames, the human path and ghost paths can be traced. The shadow of the human on walls


Figure 6.17: 2D near-field consecutive time-difference reflectivity images of co-pol. backscattering of human walking inside the building (Fig. 6.16), normalized to max. co-pol. wall return.
to the rear remains localized in range while the human position shifts and the ghost paths mirror the human path. This can be a starting-point to eliminate human ghosts in the time-difference image and to identify the actual human.

### 6.2.3.3 Limitations of Localization in Realistic Scenario

In order to test the limits of human detection for realistic scenarios, a complex building setup with a smaller Rx array was considered. The buildings spans 11.0 by


Figure 6.18: 2D near-field consecutive time-difference reflectivity images of cross-pol. backscattering of human walking inside the building (Fig. 6.16), normalized to max. co-pol. wall return.
6.5 m and consists of four rooms, each with a door to the hallway and a window on the opposite walls (see Figure 6.19). All walls are homogeneous concrete $\left(\epsilon_{r}=4.8\right.$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$ ). The receiver array is 4.0 m long with an Rx spacing of 0.1 m and Tx in the middle, sits 1.3 m above the ground and 3 m away from the wall and simulations were performed from 0.5 to 1.4 GHz in 0.005 GHz steps. The frequency domain data was windowed with a Hamming function along frequency and with a Gaussian function along the array.


Figure 6.19: Layout of complex building with four rooms, overall dimensions 11.0 by 6.5 m , ground and ceiling not plotted.

Figure 6.20 plots the theoretical point spread functions of an array of point targets for this setup. Since a rather small Rx array images a large building it can be seen that point spread function differ significantly and the radar locates targets poorly if they are close to but to the side of the array (e.g. $y<-5 \mathrm{~m}$ and $x<0 \mathrm{~m}$ ). However, the results improve as the target moves further in range.

Figure 6.21 shows the calculated single radar image of the building overlaid with its layout (dotted black line) and Rx array marked (solid black line at $x=-4.2 \mathrm{~m}$, Tx at the center). For the co-pol. image, the Rx array only records specular wall reflections from the wall at the center in front of it, otherwise the only major contribution of the building at the receivers arises from the building corners. In the case of the cross-pol. image, the receiver array mostly records the ground reflected edge diffraction, therefore, the identified corners are all shifted to the back by the additional pathlength. The circular arcs that stick out of the specular reflection are again artifacts of multistatic point spread function as predicted in Fig. 6.20.

Two walking humans are in the building, one in the upper right and one in the lower left room (both marked with a solid black line). Both cannot be identified in


Figure 6.20: 2D multistatic radar reflectivity image for an array of ideal point targets ( $x=-3 \ldots 9 \mathrm{~m}$ and $y=-9 \ldots 9 \mathrm{~m}$ in 2 m steps) for a 4 m long Rx array (spacing 10 cm ) centered around the Tx at $(-4.2,-1.0) \mathrm{m}$ from 0.5 Ghz to 1.4 GHz .
the co-pol. image, but the cross-pol. return of the human in the front room is quite strong.

Again a difference image was taken with both humans walking in $y$-direction (the short black lines next to each other in the 2D images indicate the shoulder line of the humans while walking). As expected, the time-difference images eliminate the wall response and the humans appear 25 dB and 35 dB for co-pol., 30 dB and 46 dB for cross-pol. below the maximum building return. Because of the complex building layout, the signal delay through the walls is not equal for every Rx point, which distorts the return of both humans. Both humans are accompanied by various ghost images and the ghost images of the human in the front room are stronger than the return of the human in the rear room which is heavily attenuated by the multiple wall transmissions. If the path of the humans and its ghosts cannot be tracked, these ghost images lead to false detections of additional humans.


Figure 6.21: 2D near-field reflectivity image of co- (left) and cross-pol. (right) backscattering of two walking humans inside the complex building of Fig. 6.19, normalized to max. co-pol. reflectivity.



Figure 6.22: 2D near-field time-difference reflectivity image of co- (left) and cross-pol. (right) backscattering of two walking humans inside the building of Fig. 6.19 , normalized to max. co-pol. reflectivity of single image.

The simulations of the building have been repeated with the same $\mathrm{Tx} / \mathrm{Rx}$ array but placed on the short side of the building with only the walking human in the upper right room. Figure 6.23 shows the calculated co-pol. single radar image of
the building overlaid with its layout (dotted black line) and Rx array marked (solid black line at $y=-9.0 \mathrm{~m}$ ). As can be seen, the human is further away from the radar and the direct signal paths from the human to each Rx antenna of the array differ significantly, which negatively affects multistatic image generation and allows one to test the limitations of the human movement localization.


Figure 6.23: 2D near-field reflectivity image of co- (left) and cross-pol. (right) backscattering of one walking human inside the complex building of Fig. 6.19 , normalized to max. co-pol. reflectivity.

The time-difference images of the moving human are plotted in Figure 6.24. Contrary to the time-difference image from the other side, the localization of the human fails for both polarizations. First, the walls parallel to the Rx array have either a window or door and consequently distort the signal to and from the target significantly more than a solid wall. Secondly, the three closely spaced solid walls perpendicular to the Rx array reflect the incident field multiple times, leading to many ghost images of the human along the $x$-direction. Because of this and the non-aligning signal paths from the human to the Rx array, the maximum of the human difference return is in this case 60 dB and 75 dB below the maximum building return for co- and cross-pol., with ghost returns higher than the return at the actual human position. It is not possible to localize the moving human in cross range. It can only be detected on a circle approximately 13 m away from the multistatic radar.



Figure 6.24: 2D near-field time-difference reflectivity image of co- (left) and cross-pol. (right) backscattering of one walking human inside the building of Fig. 6.19 , normalized to max. co-pol. reflectivity of single image.

This example showed that the range of multistatic human movement localization is limited. When the human is further inside the building, every additional wall or inhomogeneity (like windows or doors) increases the number of ghosts, up to the point where it is impossible to separate the ghosts, shadows and real targets. While human movement detection is still possible, it can't be localized in cross-range and multiple humans cannot be distinguished.

### 6.3 Imaging Improvement Combining Co- and Cross-pol. Response

The evaluation of the human scattering itself in section 6.1.2 showed that the human reliably generates a significant amount of cross-pol. while moving. Furthermore, the cross-pol. induced backscattering of the scene can also be used for the tracking of the human (section 6.2.3.2, Fig. 6.18). But if one is able to reliably collect both co- and cross-polarized backscattering from the scene, they can be combined properly to form one enhanced time-difference image. One way to do so is a pixel-by-pixel multiplication [52] of the two co- and cross-pol. images. While there is always a strong return at the actual human position for both polarizations, the returns of the
ghost and shadows varies significantly in position and magnitude. Consequently, the multiplication can reduce the ghost and shadow targets. The combined single co- and cross-pol. 2D image of the example with human in the two room building (Fig. 6.12 of section 6.2.3) is plotted in Figure 6.25. The dB colorbar range of -110 to 50 of the image results from the addition of the dB colorbar ranges -50 to -20 and -60 to -30 of the original images. The clutter and wall shadows are clearly reduced compared to the original images, allowing a better location of the human and its ghosts.


Figure 6.25: Combined multistatic co- and cross-polarized time-difference radar image of Figure 6.12 (walking human in the building of Fig. 6.5).

However this possibility to improve the image is limited if one looks at the examples of the realistic detection scenario in section 6.2.3.3. For the $R x$ array along the long side of the building (shown in Fig. 6.19), the combined co- and cross-pol. images can eliminate some ghost images (Fig. 6.26, combination of Fig. 6.22). Nevertheless, strong ghost and shadows of the humans remain. The human in the front room is accompanied by four ghost/shadows and the human in the back room by one shadow.

The combined co- and cross-pol. image for the radar along the short side of the building can elliminate some of the clutter (Figure 6.27 as a combination of Fig. 6.24). Nevertheless, it is impossible to identify the real human target among these.


Figure 6.26: Combined multistatic co- and cross-polarized time-difference radar image of Fig. 6.22.


Figure 6.27: Combined multistatic co- and cross-polarized time-difference radar image of Fig. 6.24.

Consequently, the overall conclusion of section 6.2.3.3 remains: the further the human is inside the building the more it is subject to ghost and shadow images up to the point where it is impossible to distinguish between the ghosts and the real human, at which point the localization fails.

### 6.4 Effects of Inhomogeneous Periodic Walls on Localization

All conclusions on localization of moving humans have been based on simulations with homogeneous walls. This section will discuss the effect of periodic walls on the localization of humans. The human behind a single wall scenarios of section 6.1.3 have been repeated with periodic rebar walls replacing the homogeneous walls. The scenes have been imaged with an 6 m long receiver array (spacing 0.3 m ) centered around the Tx (same multistatic setup as in the human tracking section 6.2.3.2). The raw data was windowed with a Hamming window along frequency and a Gaussian window along the array. The Tx is located at $(0.0,0.0) \mathrm{m}$ and the human at $(0.7,8.0) \mathrm{m}$. The periodic rebar wall consists of homogeneous concrete with a thin vertical PEC rod embedded every 30 cm .

Figures 6.29 compares the computed reflectivity from the human behind the homogeneous wall with the human behind the periodic wall for the scene in which the wall is close to the Tx ( 3 m between wall and $\mathrm{Tx}, 4.8 \mathrm{~m}$ between wall and human). The strong return between $y=-1 \mathrm{~m}$ and $y=1 \mathrm{~m}$ is caused by the specular reflection of the wall. The Bragg modes of the periodic wall extend the wall return both along $y$ - (cross-range) and $x$-direction (range). Nevertheless, the Bragg modes of the periodic wall do not affect the localization of the human. It can be clearly identified at $(0.7,8.0) \mathrm{m}$ for both wall types.

Figure 6.29 compares the computed reflectivity of the human behind the homogeneous wall with the human behind the periodic wall for the scene in which the wall is far from the $T x$ but just in front of the human ( 7.3 m between wall and $\mathrm{Tx}, 0.5 \mathrm{~m}$ between wall and human). It can be seen that the image of the periodic wall shows less clutter because fewer Bragg modes are excited since the Tx sees the wall under a smaller opening angle. Now the corners of the wall show up clearly at $x=-2.5 \mathrm{~m}$ and $x=-3.5 \mathrm{~m}$ because of the corner diffraction (the circular arcs in front of the wall are artifacts of the point spread function in cross-range). Since the wall is only


Figure 6.28: 2D near-field reflectivity image of co-pol. backscattering of human 5 m behind a wall (left: homogeneous concrete, right: reinforced concrete), recorded with a 6 m long Rx array (dB-scale, normalized to max.). Tx position and $R x$ array center is $(0.0,0.0) \mathrm{m}$.
0.5 m away from the human, its image completely covers the image of the human as in the 1 D image of the same scenario (Figure 6.4).


Figure 6.29: 2D near-field reflectivity image of co-pol. backscattering of human 0.5 m behind a wall (left: homogeneous concrete, right: reinforced concrete), recorded with a 6 m long Rx array (dB-scale, normalized to max.). Tx position and $R x$ array center is $(0.0,0.0) \mathrm{m}$.

In order to see how the Bragg modes affect the image of the human that is close behind a wall, only the human scattering part of the human behind the wall was imaged (plotted in Fig. 6.30). The human return is only 30 dB below the wall return but, as seen in Fig. 6.29, it is still too weak to stand out next to the wall return. Again, the Bragg modes only distort the human return slightly. The localization is
not affected compared to the homogeneous walls.


Figure 6.30: 2D near-field reflectivity image of the co-pol. backscattering portion attributed to the human of Fig. 6.29.

In conclusion, periodic walls produce a significantly increased amount of static clutter around the wall which is eliminated by time-differencing imaging. However, the localization of the human target behind the wall is not affected. The main reason for this is that Bragg modes are frequency dependent and therefore the Bragg modes of double transmission through the wall will add up mostly incoherently. Consequently, only the specular transmission through the wall will remain in the image. Only if the Tx or the target is very close the wall, the Bragg modes of a finite wall distort the image of the target significantly, because the further away the Tx or target from the wall, the smaller the opening angle under which the $\mathrm{Tx} /$ target sees the wall, leaving out some Bragg modes. In general, periodic walls do not affect through-wall detection and localization of humans if the frequency is kept low enough to minimize the Bragg modes.

### 6.5 Measurement Validation

The presented simulation results and the detection and localization scheme were tested qualitatively against actual radar measurements. A stepped frequency radar system was set up in the lab environment using two double-ridge horn antennas, a
vector network analyzer and offline data processing [53]. The antennas were placed above each other for 1D backscattering measurements and an $x y$-table was utilized to emulate a receiver array for 2D measurements (Tx height of 1.5 m and Rx height of 1.2 m ). Two walls types were available, solid concrete with thickness of 9 cm and cinderblock with block length 0.4 m and thickness 20 cm (the cinder blocks resemble the drawing of Fig. 4.3 closely). Both walls were built up in front of the radar system ( 1.7 m away from the antennas), and the scene was terminated by absorbers on the side and at the rear wall. A full body plastic mannequin was used as a human target. In order to emulate the high dielectric constant of the body, the mannequin was painted with graphite-based conductive paint (transmissibility of less than -30 dB of one layer of paint with $10 \%$ absorption [54]). Figure 6.31 shows the described measurement setup in which the Tx and Rx antenna in front of the cinderblock wall can be seen in the left picture, and the mannequin standing 0.5 m behind the wall can be seen in the right picture. The measurements were taken between 1.0 GHz and 2.0 GHz with 201 stepped frequency points $(1.0 \mathrm{GHz}$ is the minimum frequency of the horn antennas).


Figure 6.31: Measurement setup with antennas in front of cinderblock wall and mannequin behind cinderblock wall and absorber covered lab walls.

As a first step, the 1D backscattering of the wall and the human behind the wall was measured. For each wall type, three measurements were taken with the wall 1.7 m away from the $\mathrm{Tx} / \mathrm{Rx}$ : the backscattering of the wall alone, of the human standing 0.5 m behind the wall (as shown in Fig. 6.31 on the right) and of the human 2.4 m behind the wall. The orientation of the human was not changed between measurements to make them comparable. Before each wall was set up, the backscattering of the empty scene (background) was also recorded. Figure 6.32 and 6.33 show the timedomain results after an IFFT of the Hamming windowed frequency domain data. For each of the four scenarios (human close/far behind solid/cinderblock wall) the backscattering of the wall with the human behind is plotted after the backscattering of the background was subtracted to remove antenna coupling and reflection off of other objects in the scene. Each plot also contains the backscattering of the wall with the human behind it minus the backscattering of the wall alone which extracts the human scattering portion of the scene. Everything is normalized to the maximum wall return. The radar measurement can resolve the reflection of the front and the back of the solid concrete wall (spaced about 25 cm apart, Fig. 6.32) and the wall return is followed by multipath clutter behind it. This is due to floor and ceiling reflections, imprecise network analyzer calibration and the imperfections of the absorber material at these low frequencies, allowing a noticeable reflection of the incident wave. Furthermore, objects behind the antennas contribute to this clutter because the measurement area was not terminated with absorbers to the back and the horn antennas used exhibit significant radiation in opposite directions in this frequency band. The human scattering is about 20 dB ( 0.5 m behind) and 30 dB below the wall return but in both cases the human scattering is completely hidden within the multipath propagation of the scene as predicted by the simulations.

Looking at the measurement results of the cinderblock wall (Fig. 6.33), the radar is also able to resolve the front from the back reflection of the wall (about 50 cm apart).


Figure 6.32: Measured time-domain radar response of mannequin behind a solid concrete wall ( 1.7 m away from radar, thickness 9 cm ), standing 0.5 m (left) and 2.4 m behind the wall (right), with extracted human scattering.

A high amount of clutter (between 2.5 m and 3.5 m ) follows the wall return which can be attributed to the Bragg modes of this periodic wall. The clutter beyond 3.5 m is comparable to the clutter of the solid wall and must be caused by the multipath propagation in the scene. The scattering of the human is now about 25 dB and 35 dB below the return of the wall, lower than the return of human scattering behind the solid wall because of the thicker wall (higher attenuation due to the conductivity of concrete) and Bragg modes. The human scattering is again hidden within the multipath of the scene.


Figure 6.33: Measured time-domain radar response of mannequin behind a cinderblock wall ( 1.7 m away from radar, thickness 20 cm ), standing 0.5 m (left) and 2.4 m behind the wall (right), with extracted human scattering.

Furthermore, 2D images of the four scenarios above have been created. The $x y$ table dimensions limited the overall array size to 1 m so 20 array points were measured centered around the Tx between 1.0 GHz and 2.0 GHz with 201 frequency points. The raw data were again windowed with a Hamming function along frequency and with
a Gaussian window along the array.
A theoretical evaluation of the point spread function in this case is given in Figure 6.34. The small $R x$ array size leads to a small point spread function close to the Tx which widens significantly further away from the Tx.


Figure 6.34: 2D multistatic radar reflectivity image for an array of ideal point targets $(x=-1 \ldots 7 \mathrm{~m}$ in 2 m steps at $y=0 \mathrm{~m})$ corresponding to a 1 m long Rx array (spacing 0.5 m ) centerer around the Tx at $(0.0,0.0) \mathrm{m}$ from 1.0 GHz to 2.0 GHz .

Figure 6.35 shows the 2D image for the solid wall corresponding to the 1D image of Fig. 6.32 left side. Figure 6.36 shows the corresponding image to Fig. 6.32 right side. The left image shows the background subtracted reflectivity of the wall with the human behind it and the right image shows the reflectivity of the wall with human behind it minus the reflectivity of the wall with the human behind it, moved 20 cm in $y$-direction. This emulates a time-differencing scenario. The 2D images are all normalized to the maximum reflectivity of the wall. The specular reflection around $(0.0,1.7) \mathrm{m}$ stands out in both single view images, and the reflection at the back wall of the lab appears at 6 m . The human cannot be identified and localized within the clutter of the 2D images. However, the difference image reduces the stationary scene return by more than 50 dB and the difference signal of the human appears at (2.4, $0.0) \mathrm{m}$ and $(4.2,0.0) \mathrm{m}$. Some clutter caused by the multipath propagation follows the human.

This measurement scene was recreated with the brick-tracer in order to quantify the effects of the laboratory environment on the measurement. The simulation



Figure 6.35: Multistatic measurement radar image of solid wall with mannequin 0.5 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.


Figure 6.36: Multistatic measurement radar image of solid wall with mannequin 2.4 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.
consists of a 9 cm thick solid concrete wall (length 3 m , height 2 m with $\epsilon_{r}=4.8$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m}$ assumed), two low dielectric walls $\epsilon_{r}=1.2$ to the side to the emulate the absorbers, a concrete floor and ceiling and one male human body model resembling the mannequin (simulated as a lossy metal surface with $\epsilon_{r}=12$ and $\sigma=10^{4} \mathrm{~S} / \mathrm{m}$ ). Simulations were carried out between 1.0 GHz and 2.0 GHz and Figure 6.37 shows the 2D multistatic radar image of the simulation. The wall return is well predicted with some additional multipath caused by the floor/ceiling reflection. Consequently, the additional clutter of the measurement seen in Fig. 6.36 is caused by reflections off of objects behind the antennas and calibration errors. Because the simulation does not show this clutter, the mannequin can be identified in the image at 4 m 20 dB below the wall return which is 10 dB higher than in the measurement. This is mainly due to the unknown electric properties of the conductive paint. Additionally, it is not possible to exactly recreate the shape and position of the mannequin in simulation
and section 6.1.2 already showed that slight changes in the positions of the body and the extremities can significantly alter the return.


Figure 6.37: Multistatic radar image of simulated solid wall with mannequin 2.4 m behind resembling the measurement of Fig. 6.36 for co-polarization in dB , normalized to max. of wall return.

Figures 6.38 and 6.39 show the cinderblock wall 2D images that compare to the solid wall 2D images of Fig. 6.35 and 6.36. Again, the specular reflection around $(0.0,1.7) \mathrm{m}$ stands out in the single view image, but it is also accompanied by strong clutter to the side which is caused by the Bragg modes of the periodic wall. This follows the simulation result of a single rebar wall in section 6.4, Figure 6.28. The cinderblock wall also creates additional clutter in range up to $x=3 \mathrm{~m}$ in the image. The reflection at the back wall of the lab can be seen again at $x=6 \mathrm{~m}$. If one looks at the difference image of the human close to the wall (Fig. 6.38 left), one can see that the localization is affected by the Bragg modes; the mannequin return is blurred in cross-range and in range. Nevertheless, it can be identified at $(2.6,0.0) \mathrm{m}$. The difference image of the mannequin far from the wall is less affected and can be clearly localized at $(4.5,0.0) \mathrm{m}$.

In general, the measurements support the simulations: the human return is so weak compared to the specular reflection of the walls that it is completely hidden within the multipath propagation of the surrounding building. The human return can be recovered by time-differencing of two consecutive frames, eliminating the stationary response such that only the response of the moving human remains. Furthermore, measurements show that the inhomogeneous walls do not degrade the localization



Figure 6.38: Multistatic measurement radar image of cinderblock wall with mannequin 0.5 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.


Figure 6.39: Multistatic measurement radar image of cinderblock wall with mannequin 2.4 m behind (left) and difference radar image of wall and mannequin moved by 20 cm to the side (right) for co-polarization in dB , normalized to max. of wall return.
of the human. Degradation only occurs if the Tx or the target is very close to the wall, then the Bragg modes of a finite wall distort the image of the target a significant amount (as in Fig. 6.38). This degradation could be reduced by changing the frequency from $1.0 \mathrm{GHz}-2.0 \mathrm{GHz}$ to $0.5 \mathrm{GHz}-1.5 \mathrm{GHz}$ or moving the multistatic radar futher away from the wall.

### 6.6 Summary

The characteristics of human scattering in buildings to mono- and multistatic radars have been pointed out in this chapter. It was demonstrated that the human backscattering fluctuates with human position and look angle about 10 dB , and a moving human produces a reliable high amount of cross-polarization (about 10 dB lower than co-pol.). The human return itself is weak compared to the backscatter-
ing return of any wall and can therefore be easily hidden within the wall return or multipath propagation effects of multiple walls within a building. Because of this, time-difference imaging relying on the human movement was introduced in order to successfully isolate the human return.

Furthermore, it was shown that multistatic time-difference imaging allows localization of human movement within a building subject to ghost and shadow images caused by the multipath propagation. These ghost and shadow images can lead to a false detection of additional humans because the return of each individual human inside a building can vary significantly. A human tracking example was given that allows tracing the paths of the ghosts and shadows, facilitating the identification of ghost/shadow targets. A complex building layout was analyzed that showed the limitations of the human localization. If the human is too far into the building, then the multipath target return dominates at the Rx array. This issue leads to too many human ghost images, and consequently localization of the human movement can fail.

Additionally, the differences between human movement detection through homogeneous and inhomogeneous walls were discussed. While the stationary response of homogeneous and inhomogeneous walls differs significantly because of the additional propagation paths of inhomogeneous walls, the time-differencing imaging and localization of the human are less affected, allowing a clear localization of the walking person in the presence of inhomogeneous periodic walls.

## CHAPTER VII

# Advanced Imaging of Building Layout and Interior Using Spectral Estimation and Wall Estimation Techniques 

The previous chapter showed that a multistatic radar setup is suited for the detection of human movement inside a building. An instant 2D image of the scene can be formed and the human can be localized based on time-differencing of consecutive measurements. However, multistatic radar imaging is less suitable for the mapping of the building walls and interior. If an 2D multistatic image is generated, only specular wall reflection extending over the center half of the Rx array can be recorded, at different cross-range positions only point scatterers can be located. Consequently, a multistatic radar image does not reveal much of the building layout as one can see in the multistatic image of the realistic building scenario of the last chapter (section 6.2.3.3 Fig. 6.21). Only the corners of the building can be identified. Furthermore, the resolution of a multistatic image and the multistatic point spread function is dependent on cross-range and range position, broadening the farther the scatterer from the Tx. This additionally complicates mapping the building layout with multistatic radars.

Because an instant image formation is not needed for mapping of the building
interior, the usual approach is measuring the building backscatter with a synthetic aperture, in which the $\mathrm{Tx} / \mathrm{Rx}$ is moved along the building walls to form a virtual array. This way the radar always captures the specular wall reflection perpendicularly incident on the wall leading to a smooth and constant return of the walls in the scenario. Furthermore, there are less resolution and point spread function issues. The 2D reflectivity in SAR mode is usually mapped according to the image formation of section 6.2.1 (now with Tx and Rx at same position $r_{\overrightarrow{T x} x}=\overrightarrow{r_{n}}$ ). If the antennas are a certain distance away from the scene under investigation, this image formation can be seen as an 2D Fourier transform of non-uniformly spaced data in the 2D $k$-space spanned by the frequency and the synthetic aperture [55, 56, 50]. However, applying an 2D Fourier transform is not the only way to generate an 2D reflectivity image from the raw data, 2 D reflectivity images have been successfully formed via spectral estimation methods like the Minimum Variance Method (MVM) [55] or Multiple Signal Classification (MUSIC) [56, 50].

For a single point scatterer in noise, the Fourier imaging maximizes the Signal-to-Interference ratio [55]. However, in more complex scenarios, sidelobes (or even the mainlobe) of the point spread function of one target can spill into the point spread function of another target. This indicates that Fourier transform may not be the most suitable imaging method for a highly cluttered environment like a building, and MUSIC imaging has already been suggested for TWRI SAR applications in the literature [50]. This chapter will use the concept of [50] to apply spectral estimation imaging to mapping of the building layout. Furthermore, if one is interested in identifying targets inside buildings besides the interior walls, wall subtraction might be useful to improve imaging of the interior $[57,10,58]$. This chapter also investigates one approach to subtract the wall response and combines it with spectral imaging.

First the theory of MUSIC and MVM imaging will be introduced, followed by its implementation. Then the spectral imaging methods will be applied to sample
simulated and measured scenarios. In the following, the wall subtraction method is introduced and applied to the previous examples. At the end, conclusions are drawn for both spectral estimation imaging and spectral estimation imaging combined with wall subtractions.

### 7.1 Theory of Spectral Estimation

If the scene under investigation consists of $P$ point targets, the received stepped frequency signal is

$$
\begin{equation*}
z(g, h)=\sum_{p=0}^{P} \sigma_{p} \cdot \exp \left(\frac{-j 4 \pi f_{g} r_{p, h}}{c_{0}}\right), \tag{7.1}
\end{equation*}
$$

where $g$ is the frequency index, $h$ the antenna index and $r_{p, h}$ the distance between the $p$-th target and the $h$-th antenna. If the scene is far from the antennas, $r_{p, h}$ can be approximated to

$$
\begin{equation*}
r_{p, h}=r_{h}+x_{p} \cos \theta_{h}-y_{p} \sin \theta_{h}, \tag{7.2}
\end{equation*}
$$

where $r_{h}$ is the range from the $h$-th antenna to the center of the scene and $\left(x_{p}, y_{p}\right)$ is the position of the $p$-th target relative to the center of the scene. $\theta_{h}$ is the looking angle of the $h$-th antenna to the center of the scene. This leads to a received signal (after compensation of the phase due to $r_{h}$ ) of

$$
\begin{equation*}
z(g, h)=\sum_{p=0}^{P} \sigma_{p} \cdot \exp \left(\frac{-j 4 \pi f_{g}\left(x_{p} \cos \theta_{h}-y_{p} \sin \theta_{h}\right)}{c_{0}}\right) . \tag{7.3}
\end{equation*}
$$

If $z(g, h)$ can be interpolated and uniformly sampled at $k_{m}^{x}=f_{g} \cos \theta_{h}$ and $k_{n}^{y}=$ $f_{g} \sin \theta_{h}$ one arrives at the 2 D spatial spectrum

$$
\begin{equation*}
z(m, n)=\sum_{p=0}^{P} \sigma_{p} \cdot \exp \left(-j \frac{4 \pi}{c_{0}}\left(k_{m}^{x} x_{p}-k_{n}^{y} y_{p}\right)\right) . \tag{7.4}
\end{equation*}
$$

This has the form of an 2D inverse Fourier transform and an FFT can now be
applied to this interpolated and sampled data to form the conventional radar image. Equation 7.4 can be put into vector notation, it then changes to

$$
\begin{equation*}
\mathbf{z}=\mathbf{A} \bar{\sigma} \tag{7.5}
\end{equation*}
$$

with the column-ordered vectors

$$
\begin{align*}
& \mathbf{z}=\left[\begin{array}{lllllll}
z_{00} & z_{10} & \cdots & z_{M-10} & z_{01} & \cdots & z_{M-1 N-1}
\end{array}\right]^{T}  \tag{7.6}\\
& \bar{\sigma}=\left[\begin{array}{llll}
\sigma_{0} & \sigma_{1} & \cdots & \sigma_{p}
\end{array}\right]^{T}  \tag{7.7}\\
& \mathbf{A}=\left[\mathbf{a}\left(x_{0}, y_{0}\right) \mathbf{a}\left(x_{1}, y_{1}\right) \cdots \mathbf{a}\left(x_{p}, y_{p}\right)\right] \tag{7.8}
\end{align*}
$$

with

$$
\begin{align*}
\mathbf{a}\left(x_{k}, y_{k}\right)= & {\left[\exp \left(j \frac{4 \pi}{c_{0}}\left(k_{0}^{x} x_{k}-k_{0}^{y} y_{k}\right)\right) \exp \left(j \frac{4 \pi}{c_{0}}\left(k_{1}^{x} x_{k}-k_{0}^{y} y_{k}\right)\right) \cdots\right.} \\
& \exp \left(j \frac{4 \pi}{c_{0}}\left(k_{M-1}^{x} x_{k}-k_{0}^{y} y_{k}\right)\right) \exp \left(j \frac{4 \pi}{c_{0}}\left(k_{0}^{x} x_{k}-k_{1}^{y} y_{k}\right)\right) \cdots \\
& \left.\exp \left(j \frac{4 \pi}{c_{0}}\left(k_{M-1}^{x} x_{k}-k_{N-1}^{y} y_{k}\right)\right)\right]^{T} \tag{7.9}
\end{align*}
$$

If one is able to space the measurement SAR data uniformly in the spatial domain according to equation 7.4 and sorts it according to equation 7.6 , spectral estimation can be applied to image the data. For this purpose a signal history correlation matrix $\mathbf{R}$ of the measured radar data $\mathbf{x}$ has to be obtained. It is defined as

$$
\begin{equation*}
\mathbf{R}=E\left[\mathbf{z z}^{H}\right], \tag{7.10}
\end{equation*}
$$

where $E[\cdot]$ is the ensemble average and $H$ denotes the complex conjugate transpose. Once the correlation matrix is found or estimated, the MVM reflectivity estimate
function $S$ is

$$
\begin{equation*}
S_{\mathrm{MVM}}(x, y)=\frac{\mathbf{a}(x, y)^{H} \mathbf{a}(x, y)}{\mathbf{a}(x, y)^{H} \mathbf{R}^{-1} \mathbf{a}(x, y)} \tag{7.11}
\end{equation*}
$$

where $\mathbf{R}^{-1}$ is the inverse the correlation matrix and $\mathbf{a}\left(x_{k}, y_{k}\right)$ the search vector of 7.9. The peaks of 7.11 are the scattering centers of the measured data.

In order to find the MUSIC estimate, the eigenvectors of the correlation matrix have to be calculated and are then divided into two subspaces, the signal subspace and the noise subspace. The MUSIC estimate reflectivity estimate is then

$$
\begin{equation*}
S_{\mathrm{MUSIC}}(x, y)=\frac{\mathbf{a}(x, y)^{H} \mathbf{a}(x, y)}{\mathbf{a}(x, y)^{H} \mathbf{W} \mathbf{W}^{H} \mathbf{a}(x, y)}, \tag{7.12}
\end{equation*}
$$

where the matrix $\mathbf{W}$ is the noise subspace

$$
\mathbf{W}=\left[\begin{array}{llll}
\mathbf{u}_{D+1} & \mathbf{u}_{D+2} & \cdots & \mathbf{u}_{M N} \tag{7.13}
\end{array}\right]
$$

of the ordered eigenvectors $\mathbf{u}_{1}, \mathbf{u}_{2}, \ldots, \mathbf{u}_{M N}$, arranged from the largest corresponding eigenvalues to the smallest. Again the peaks of 7.12 are the scattering centers of the measured data.

Consequently, one necessary step of spectral estimation imaging is to estimate the correlation matrix. Because only one dataset or a few data sets are available in radar imaging applications, the correlation matrix has to be estimated from virtual snapshots generated from the only available data set instead of averaging over time [50]. Hence $z(m, n)$ of equation 7.4 is put into matrix form $\mathbf{Z}$ of size $M \times N$ and $\mathbf{F}_{u, v}$
is chosen as a $K \times L$ sub-matrix of $\mathbf{Z}$ such that

$$
\mathbf{F}_{u, v}=\left[\begin{array}{cccc}
z(u, v) & z(u, v+1) & \cdots & z(u, v+L-1)  \tag{7.14}\\
z(u+1, v) & z(u+1, v+1) & \cdots & z(u+1, v+L-1) \\
\vdots & \vdots & \ddots & \vdots \\
z(u+K-1, v) & z(u+K-1, v+1) & \cdots & z(u+K-1, v+L-1)
\end{array}\right]
$$

Now, a virtual snapshot is defined as

$$
\begin{equation*}
\mathbf{z}_{u, v}=\operatorname{vec}\left\{\mathbf{F}_{u, v}\right\} \tag{7.15}
\end{equation*}
$$

with the definition of $\operatorname{vec}\}$

$$
\operatorname{vec}\left\{\left[\begin{array}{lll}
\mathbf{v}_{1} & \cdots & \mathbf{v}_{N}
\end{array}\right]\right\}=\left[\begin{array}{lll}
\mathbf{v}_{1}^{H} & \cdots & \mathbf{v}_{N}^{H} \tag{7.16}
\end{array}\right]^{H} .
$$

The estimated correlation matrix follows as

$$
\begin{equation*}
\hat{\mathbf{R}}=\frac{1}{2(M-K+1)(N-L+1)} \sum_{u=0}^{M-K} \sum_{v=0}^{N-L}\left(\mathbf{z}_{u, v} \mathbf{z}_{u, v}^{H}+\mathbf{J}_{u, \mathbf{z}}^{*} \mathbf{z}_{u, v}^{T} \mathbf{J}\right), \tag{7.17}
\end{equation*}
$$

with the exchange matix

$$
\mathbf{J}=\left[\begin{array}{cccc}
0 & \cdots & 0 & 1  \tag{7.18}\\
0 & \cdots & 1 & 0 \\
\vdots & \cdots & \vdots & \vdots \\
1 & 0 & \cdots & 0
\end{array}\right]
$$

The main challenge in order to apply the spectral estimation imaging methods is to uniformly sample the measured radar data. It was pointed out in [50] that an interpolation of the data is not robust to a low Signal-to-Noise Ratio and omits extended targets. Instead, a regular SAR image generation according to section 6.2.1 was suggested which is then inverse Fourier transformed to generate the uniform
sampled data in the spectral domain ( $k$-space) which serves as the basis of spectral estimation imaging.

### 7.2 Implementation

The process of the actual image generation is illustrated with one simulated nearfield SAR example of a single point target behind a homogeneous wall ( 4 m long, 20 cm thick). The $\mathrm{Tx} / \mathrm{Rx}$ was placed 2.5 m in front of the wall and moved 6 m along the wall with a backscattering measurement every 10 cm . A target ( 40 cm long metal plate) was placed 4 m behind the wall and 0.5 m offset from the wall center. Simulation frequency is 0.5 to 1.2 GHz in 10 MHz steps.

As a first step, the SAR image is generated with the raw unwindowed data on a grid with a grid spacing equal or less than half of the maximum achievable resolution. This image is inverse 2D Fourier transformed. Fig. 7.1 shows the unwindowed example scene and its 2D IFFT. Image size is $81 \times 101$. Because the image generation was oversampled the resulting $k$-space matrix shows zeros to the side and needs to be reduced to the area which contains the actual image information. The black frame in Fig. 7.1(b) shows the actual size to which the spatial frequency matrix is reduced $(44 \times 42)$. The correlation matrix estimation is started based on the reduced matrix. The size of the submatrix ( $K \times L$ of eq. 7.17) has to be chosen carefully, if $K$ and $L$ are too large, one has too few sample snapshots for a reliable correlation matrix estimation, if $K$ and $L$ are too small, the image cannot be split up properly into a signal and noise subspace and the resolution of the spectral estimation is reduced [50, 56]. A good compromise is $K=M / 2$ and $L=N / 2$ [55] which is used throughout this chapter and for this example.

For MVM, the image can now be generated according to equation 7.11. Figure 7.2 shows the MVM image. For MUSIC, the correlation matrix estimate has to be divided into the noise and signal subspace by a proper selection of the number of
targets $D$ in the scene. If there are only $P$ point targets, $D$ will be the same as $P$. If the estimation of $D$ is too small, weak scatterers will be omitted in the MUSIC image generation. The MUSIC estimated image is plotted Figure 7.2, for 47 estimated target points. It should be noted that the colorscale of the spectral estimated images is not a measure of reflectivity, it just allows location of the scattering centers.


Figure 7.1: (a) Unwindowed 2D near-field SAR image of target behind a wall (normalized in dB ) with synthetic aperture center at $(0.0,0.0) \mathrm{m}$ and (b) 2D IFFT of it (normalized linear)


Figure 7.2: MVM (left) and MUSIC estimated (right) 2D near-field SAR reflectivity image of co-pol. backscattering of one target behind a wall ( dB scale, normalized). Synthetic aperture center is $(0.0,0.0) \mathrm{m}$.

Both MVM and MUSIC imaging improve the resolution of the 2D reflectivity image and exhibit no sidelobes. The multiple bounces of the transmitted signal in
the wall are resolved as well as the target width of 40 cm . As predicted the information about the intensity of the scatterer are lost, the magnitude of the multiple wall bounces are not decaying as they should inside a dielectric slab.

The trade-off for improved imaging of the scene is an increase in computational cost. Since the spectral images are based on a regularly generated image, the computational cost of spectral estimation adds to it. The most time-consuming part is the estimation of the correlation matrix $R$, followed by the computation of the spectral estimation on a uniform grid along $x$ and $y$ to form the 2D spectral estimated image. Techniques like parallelization exist to speed up computation but should not be a part of this thesis, it rather evaluates if spectral imaging is suitable for imaging of building interiors and human movement.

### 7.3 Imaging Examples

The example of the previous section was extended, five targets (all the same 40 cm long metal plates) were placed behind the wall with the other simulation parameters unchanged. Consequently, the spectral imaging paramters have been kept and Figure 7.3 shows the MUSIC imaging result compared to the regular image of the unwindowed data. Although the area behind the wall is more cluttered the MUSIC algorithm can resolve the five target plates well.

As a next step, the MUSIC algorithm was tested against SAR measurements in a lab environment. The measurement setup is the same as described in section 6.5 of the previous chapter. Both Tx and Rx antenna were mounted on the $x y$-table to form a SAR measurement scenario. A trihedral reflector was placed 1.5 m behind the cinderblock wall at the height of the $\mathrm{Tx} / \mathrm{Rx}$ antennas and the antennas were placed 1.6 m away from the wall. Measurements have been carried out from 1.0 to 1.75 GHz . Figure 7.4 shows the regularly generated 2D SAR image. The image of the unwindowed data (Fig. 7.4a) can resolve the wall but the target (located at 3.5 m )



Figure 7.3: Unwindowed regular (left) and MUSIC estimated (right) 2D near-field SAR reflectivity image of co-pol. backscattering of five targets behind a wall (dB scale, normalized). Synthetic aperture center is $(0.0,0.0) \mathrm{m}$.
is almost hidden within the strong sidelobes of the wall. The target can be detected if the image generated from the windowed raw data but the range resolution is very low.

Spectral estimation imaging can clean up the image. In both spectral estimated images (Figure 7.5), the trihedral target can be clearly identified at $x=3.5 \mathrm{~m}$. The front and back-wall reflection can be localized, allowing calculation of the path length through the wall. Furthermore, the MUSIC image shows a higher resolution than the MVM image.

As a last example, a multistatic simulation is imaged with the MUSIC method. If the target is far from the receiver array and the receiver array is large compared to the extend of the target, imaging with the multistatic Rx array becomes similar to SAR imaging. It should be noted that if these conditions are not met (e.g. the scenario of section 6.2.3.3), correlation matrix estimation and spectral imaging will fail and therefore spectral estimation imaging cannot be applied to multistatic images. A human on a groundplane 7 m away from the Tx and Rx array center was considered, which was enclosed in a $4 \times 4 \mathrm{~m}$ building structure (homogeneous concrete $\epsilon_{r}=4.8$ and $\sigma=0.02 \mathrm{~S} / \mathrm{m})$. Simulation have been carried out between 0.5 to 1.2 GHz in 5 MHz


Figure 7.4: 2D regular SAR image of a trihedral reflector behind a cinderblock wall, generated from unwindowed (a) and windowed (b) data, dB scale normalized to max. wall reflection.


Figure 7.5: 2D SAR image of a trihedral reflector behind a cinderblock wall (compare to Fig. 7.4), generated with MVM (a) and MUSIC (b) (dB scale normalized).
steps. The $R x$ array spanned 6 m and the Rx antennas were spaced 10 cm apart.
Figure 7.6 shows the resulting regular image (generated without windowing) and the corresponding MUSIC image with estimated 92 targets in the scene. The MUSIC estimated image predicts the walls very well and can also locate the human target inside the concrete box. But since the human scattering is weak compared to the wall reflection, multipath clutter is also imaged.


Figure 7.6: Unwindowed regular (left) and MUSIC estimated (right, 92 estimated targets) 2D near-field multistatic reflectivity image of co-pol. backscattering of human inside a $4 \times 4 \mathrm{~m}$ concrete box, dB scale normalized. Tx and Rx array center is $(0.0,0.0) \mathrm{m}$.

If one is only interested in the building layout, weak targets inside can be discarded and the MUSIC image can be generated with less estimated targets. Figure 7.7 shows the image of the same scene with 44 estimated point targets. While the human return is now perished in the noise eigenvectors of the MUSIC estimation, the walls appear clearly, allowing an exact localization.

In conclusion, it can be said that the spectral estimation imaging can enhance the mapping of the exterior and interior walls from a building under investigation. Not only for the front wall but also for further walls facing the synthetic aperture, the front reflection together with the reflection of the back of each wall can be located accurately. This facilitates exact positioning of the walls and exact calculation of the signal path length through the wall which is needed for the correction of the

Figure 7.7: MUSIC estimated (44 estimated targets) 2D near-field multistatic reflectivity image of co-pol. backscattering of human inside a $4 \times 4 \mathrm{~m}$ concrete box, dB scale normalized. Tx and Rx array center is $(0.0,0.0) \mathrm{m}$.
position shift caused by the wall. Especially when the available bandwidth is limited, spectral estimation techniques can form a clear image. Because spectral imaging shows no sidelobes, the building interior is imaged with less clutter, improving the identification of stationary objects inside the building.

### 7.4 Wall Subtraction Enhanced Spectral Imaging

If one is less interested in the building layout but in imaging the stationary objects inside the rooms of the building, it is useful to eliminate the strong specular wall response in the building return to uncover the mostly weak return of the objects from the wall return. Estimation and subtraction of the walls in TWR images has been investigated recently $[57,58]$. This section introduces a flexible approach to eliminate the wall return and combines it with spectral imaging.

When a radar is placed in front of a wall, the delay of the transmitted pulse is determined by the distance to the specular reflection point at the wall. If the radar is moved along the wall to form a synthetic array, the specular reflection point moves with the radar and consequently the pulse delay remains constant. Contrary, if the radar is moved along the synthetic array to form an image of a point target, the pulse
delay changes according to the distance to the point target. The same is true for a point target behind a wall. Figure 7.8 (a) illustrates this fact where a 2D image is created from the time-domain radar returns collected at each array point (known as waterfall image). The scene are the five point targets behind a wall from section 7.3, Figure 7.3.


Figure 7.8: Normalized waterfall image of five point targets behind a wall and extracted linear features in the image.

This feature distinguishes point targets from the wall reflections and can be used to identify and eliminate wall returns from the image. The waterfall image is searched along range and at each range position the linear features are estimated by a best fit of a rectangular function along cross-range. The extracted linear features are considered a wall if they have a significant extent in cross-range (distinguishes point target from wall) and cover a few range bins (takes into account the thickness of the wall). The extracted features are then subtracted from the waterfall image and the raw data is regenerated to form a regular 2D SAR image. Figures 7.8 and 7.9 show this process: In Fig. 7.8 (b) the estimated walls sizes are plotted. In this case the extracted linear features are accepted as walls if they span more than 1 m in azimuth (cross-range) and at least 30 cm in range (plotted in black), the rest is omitted (plotted in gray). Figure 7.9 shows the resulting wall subtracted 2D SAR
image compared to the regularly formed SAR image. It should be noted that Figure 7.9 is the same as Fig. 7.3 except that the image was generated with windowed raw data. One can see that most of the wall return is eliminated but the return of the five point targets is preserved in the image. Only a weak wall return, which coincides in range with the first target, and the diffraction at both corners of the wall remain. The MUSIC estimated image removes much of the clutter and images the five targets as well as the corner diffraction clearly (Fig. 7.10).



Figure 7.9: 2D regular SAR image of a wall with five targets behind (left) and wall subtracted image of the same scene (right), in dB, normalized to max. wall return.


Figure 7.10: MUSIC imaging result of the SAR images of Fig. 7.9

The wall estimation algorithm was also tested against the previously introduced lab measurements of a trihedral reflector serving as a point target behind a cinderbock


Figure 7.11: Wall subtracted 2D SAR image of a trihedral reflector behind a cinderblock wall, generated regularly (a) and with MUSIC (b).
wall (section 7.3, Fig. 7.4). Again, the estimated linear features were only subtracted as wall contributions if they span 1 m in azimuth and 0.3 m in range. The wall subtracted image preserves the point target at 3.5 m while removing the wall but a significant amount of clutter remains right behind the wall (between 2 m and 3 m ). This is due to the inhomogeneity of the wall. The MUSIC estimation locates the scattering centers of the wall clutter and the target well and makes the target stand out. It should be noted that this method does not account for the excess delay caused by the transmission through the dielectric material of the wall, causing a shift of the target from its actual position.

### 7.5 Summary

Spectral estimation imaging was introduced to TWR imaging for the purpose of mapping the building layout. It was demonstrated that the spectral estimation method MUSIC can locate and extract the walls and their electrical thickness precisely in SAR images that include walls. Additionally, for the purpose of imaging
stationary objects inside buildings, it was demonstrated that homogeneous walls can be eliminated from SAR images to accentuate targets inside the buildings, although a significant amount of clutter remains if the wall shows inhomogeneities. Furthermore, applying the MUSIC algorithm can significantly clear up the image and make the targets behind the wall more visible.

In conclusion, both the described wall estimation technique and MUSIC imaging can enhance TWR imaging, allowing a clearer interpretation of the scene and building. It can serve as a more reliable basis for further processing like mapping the building layout or object detection inside buildings.

## CHAPTER VIII

## Conclusions and Future Work

The main objective of this thesis is to provide an applicable solution to the problem of EM wave propagation in an indoor environment at the UHF band, with one major application, the detection and localization of human movement inside buildings. Since the simulation domain is usually too large in terms of wavelength, a full-wave analysis of the structure is not feasible and asymptotic methods are needed to solve the problem. This thesis started with an introduction of the usually used asymptotic method for indoor wave propagation called "ray-tracing" and the typical wall types of buildings and their EM behavior at the UHF band. It was shown that ray-tracing neglects the special EM propagation phenomena of inhomogeneous periodic walls. Therefor a new hybrid method was proposed combining the asymptotic method PO with full-wave analysis that can include these phenomena. The theory and implementation of the hybrid method was discussed in 2D and validated against full-wave simulations. The method was expanded to 3D and, for a realistic 3D indoor scenario, it was shown how inhomogeneous walls affect the indoor wave propagation channel and that a homogeneous wall approximation of inhomogeneous walls can distort the wave propagation channel parameters.

In the following, the method was completed with a movable human body model in order to analyze human backscattering inside building structures. The accuracy of
the used body model was proven through comparison to a human body model derived from a MRI scan and the interface of the hybrid method and the human body model through a Huygens surface was validated against full wave simulations.

Based on this simulation tool, human scattering inside a realistic building to UWB radar systems was thoroughly analyzed and the special propagation phenomena of a human body inside a building have been pointed out. Based on the findings, a viable way for the detection and localization of human movement inside buildings utilizing multistatic radar systems was proposed and tested against simulation and measurement. An example for tracking a human inside a building was given. The effects of the building on the human scattering was pointed out with the possibility of producing additional false detections of the human.

At the end an advanced imaging method for the mapping of interior and exterior building walls was introduced, which can be used to facilitate the detection of human movement. This imaging method was further extended to improve imaging of static objects inside buildings by removing the return of the buildings walls.

### 8.1 Contribution

The contributions of this thesis are listed in the following subsections.

## Development of hybrid method for indoor wave propagation

For the first time, a hybrid method was introduced and implemented that can fully include the propagation phenomena of inhomogeneous periodic walls. Being an asymptotic method based on PO, it is still computationally tractable and allows the analysis of large building structures, but does not suffer from the homogeneous wall assumption of GO. The 2D implementation showed the accuracy of the hybrid method in the presence of inhomogeneous walls and the 3D implementation of the method allowed quantizing the error made in estimating the indoor propagation channel pa-
rameters through replacing inhomogeneous walls with effective homogeneous walls for analysis with GO.

## Development of accurate simulation model of human movement in buildings

Secondly, this accurate tool for indoor wave propagation was combined with a sophisticated human body model based on a full-wave analysis to enhance the method to include moving humans in the indoor propagation simulations. Being able to predict the special scattering phenomena of a human body and the building effects on it, a thorough and close-to-reality study of human scattering in buildings to UWB radar systems was carried out.

## Detection and localization of human movement inside buildings

Having this accurate analysis at hand it was possible to suggest and validate a viable way for the detection and localization of human motion inside buildings and point out the limitations and possible sources of error for the detection and localization.

### 8.2 Future Work

There are many possibilities to build on this work for further investigations. First, the introduced hybrid method itself can be extended for more accurate simulations of indoor wave propagation. The assumption of surface currents of an infinite wall on all bricks including corner and terminal bricks in a scenario leads to erroneous corner diffractions. Also if the wall shows a non-periodic inhomogeneity like a pipe or wiring in the wall, it cannot be included in the brick-tracing simulations. Through a full-wave analysis of these special bricks for a plane wave of all incident angles,
correct corner diffraction or scattering of non-periodic inhomogeneous brick can be introduced to the hybrid method, enhancing its accuracy.

Another possibility for future work is to actually build the proposed radar system for the detection of human motion. This includes the design of dual polarized UWB antennas, building the Rx array with its signal processing down to implementing the instantaneous imaging. The theoretical findings of this thesis have only been validated with simple scenarios in the lab. With an actual working real aperture polarimetric UWB radar system at the UHF band, the detection and localization schemes can be tested against measurements of buildings comparable to simulation. The imaging and detection method can be validated, further refined and its limitations can be evaluated based on these measurements.

Furthermore, the actual human detection and localization can be further developed. The localization and detection of this thesis stops after a 2D time-difference reflectivity image of the scene has been generated, leaving the identification of the human target and its ghosts and shadows to the user of the radar system. Further image processing can be applied, the reflectivity of the scene and its history has to be processed into an image which only shows the real human and its position and identifies the human ghosts and their positions. While the real humans and its ghosts just correspond to the local maxima of the reflectivity, distinguishing humans from ghost is challenging and requires underlying assumptions about the building layout and statistical analysis of the time-difference image history. Another approach to refine the human localization is to use more advanced inversion schemes of the raw radar data than the generation of a radar image based on point targets in free space. The inversion scheme can include building information that was previously determined (like mapping of the walls with SAR), reducing ghosts and shadows. The main challenge is keep the inversion real-time to be able to use it for human tracking.

At last, the detection and localization of humans in this thesis is based on its
movement. A stationary (i.e. sleeping, unconscious or sitting still) human target will remain undetected. Focusing on a non-moving human body one has evaluate other unique features of the human body or the gear a human carries that allows detection and localization in building structures. This may lead into a completely different direction than using UWB radar systems from outside, it could be accomplished by small autonomous devices that can enter and search a building, the detection could be based on human infrared radiation, or based on active devices carried by humans like cell phones, MP3 players, etc.

BIBLIOGRAPHY

## BIBLIOGRAPHY

[1] G. W. Stimson, Introduction to Airborne Radar. SciTech Publishing, 2000.
[2] M. Skolnik, Radar Handbook. McGraw-Hill Professional, 2008.
[3] A. R. V. Hipple, Dielectric Materials and Applications, A. R. V. Hipple, Ed. MIT Press, 1954.
[4] W. Honcharenko and H. L. Bertoni, "Transmission and reflection characteristicsat concrete block walls in the UHFbands proposed for future PCS," IEEE Transactions on Antennas and Propagation, vol. 42, no. 2, pp. 232-239, 1994.
[5] M. Yang and S. Savrou, "Rigorous coupled-wave analysis of radio wave propagation through periodic building structures," IEEE Antennas and Wireless Propagation Letters, vol. 3, pp. 204-207, 2004.
[6] E. Richalot, M. Bonilla, M.-F. Wong, V. Fouad-Hanna, H. Baudrand, and J. Wiart, "Electromagnetic propagation into reinforced-concrete walls," IEEE Transactions on Microwave Theory and Techniques, vol. 48, no. 3, pp. 357-366, 2000.
[7] C. L. Holloway, P. L. Perini, R. R. DeLyser, and K. C. Allen, "Analysis of composite walls and their effectson short-path propagation modeling," IEEE Transactions on Vehicular Technology, vol. 46, no. 3, pp. 730-738, 1997.
[8] M. Dehmollaian and K. Sarabandi, "An approximate solution of scattering from reinforced concrete walls," IEEE Transactions on Antennas and Propagation, vol. 56, no. 8, pp. 2681-2690, August 2008.
[9] R. B. R. Marhefka and J. Volakis, "Radar imaging through cinder block walls and other periodic structures," in IEEE Antennas and Propagation Society International Symposium 2008, 2008.
[10] M. Dehmollaian, "Hybrid electromagnetic models for the purpose of detection and identification of visually obscured targets," Ph.D. dissertation, University of Michigan, 2007.
[11] M. Dehmollaian and K. Sarabandi, "Refocusing through building walls using synthetic aperture radar," IEEE Transactions on Geoscience and Remote Sensing, vol. 46, no. 6, pp. 1589-1599, 2008.
[12] L. M. Frazier, "Radar surveillance through solid materials," in Proceedings SPIE, vol. 2938, 1997, pp. 139-146.
[13] J. David D. Ferris and N. C. Currie, "Survey of current technologies for through-the-wall surveillance (tws)," in Proceedings of the SPIE, vol. 3577, 1999, pp. 62-72.
[14] A. Alighanbari and C. D. Sarris, "Rigorous and efficient time-domain modelingof electromagnetic wave propagation and fadingstatistics in indoor wireless channels," IEEE Transactions on Antennas and Propagation, vol. 55, no. 8, pp. 23732381, 2007.
[15] A. Yun, M. F. Iskander, and Z. Zhang, "Complex-wall effect on propagation characteristics and MIMO capacities for an indoor wireless communication enviroment," IEEE Transactions on Antennas and Propagation, vol. 52, no. 4, pp. 914-922, 2004.
[16] S. Y. Seidel and T. S. Rappaport, "Site-specific propagation prediction for wirelessin-building personal communication system design," IEEE Transactions on Vehicular Technology, vol. 43, no. 4, pp. 879-892, 1994.
[17] T. M. Schaefer and W. Wiesbeck, "Simulation of radiowave propagation in hospitals based on FDTD and ray-optical methods," IEEE Transactions on Antennas and Propagation, vol. 53, no. 8, pp. 2381-2388, 2005.
[18] M. F. Iskander and Z. Yun, "Propagation prediction models for wirelesscommunication systems," IEEE Transactions on Microwave Theory and Techniques, vol. 50, no. 3, pp. 662-674, 2002.
[19] Y. Wang, S. Safavi-Naeini, and S. K. Chaudhuri, "A hybrid technique based on combining ray tracing and FDTD methods for site-specific modeling of indoor radio wave propagation," IEEE Transactions on Antennas and Propagation, vol. 48, no. 5, pp. 743-754, 2000.
[20] Y. Wang, S. K. Chaudhuri, and S. Safavi-Naeini, "An FDTD/ray-tracing analysis method for wavepenetration through inhomogeneous walls," IEEE Transactions on Antennas and Propagation, vol. 50, no. 11, pp. 1598-1605, 2002.
[21] M. Thiel and K. Sarabandi, "An hybrid method for indoor wave propagation modeling," IEEE Transactions on Antennas and Propagation, vol. 56, no. 8, pp. 2703-2709, 2008.
[22] M. Porebska, T. Kayser, and W. Wiesbeck, "Verification of a hybrid raytracing/FDTD model for indoor ultra-wideband channels," in Proceeding of the 10th European Conference on Wireless Technology, 2007, pp. 169-172.
[23] C.-F. Yang and B.-C. Wu, "A ray-tracing/PMM hybrid approach fordetermining wave propagationthrough periodic structures," IEEE Transactions on Vehicular Technology, vol. 50, no. 3, pp. 791-795, 2001.
[24] M. Thiel and K. Sarabandi, "3D-wave propagation analysis of indoor wireless channels utilizing hybrid methods," May 2009, scheduled for publication in IEEE Transaction on Antennas and Propagation.
[25] S. Z. Gilrbilzl, W. L. Melvin, and D. B. Williams, "Comparison of radar-based human detection techniques," in Conference Record of the Forty-First Asilomar Conference on Signals, Systems and Computers (ACSSC 2007), 2007, pp. 2199 - 2203.
[26] A. G. Yarovoy, L. Ligthart, J. Matuzas, and B. Levitas, "Uwb radar for human being detection," IEEE Aerospace and Electronic Systems Magazine, vol. 21, pp. 22-26, 2006.
[27] L. M. Frazier, "Surveillance through walls and other opaque materials," in Proceedings SPIE, vol. 2497, 1995, pp. 115-119.
[28] M. Nishi, T. Kawaguchi, S. Takahashi, and T. Yoshida, "Human detection system using uhf band terrestrial tv receiving waves," in IEEE Antennas and Propagation Society International Symposium, 2006, pp. 3097 - 3100.
[29] C. Consultants, "prism 200 through-wall radar," http://www.cambridgeconsultants.com/, Tech. Rep., 2006.
[30] C. Debes, A. M. Zoubir, and M. G. Amiin, "Target detection in multiple-viewing through-the-wall radar imaging," in IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2008), vol. 1, 2008, pp. 173-176.
[31] P. C. Chang, R. J. Burkholder, and J. L. Volakis, "Through-wall building image improvement via signature-based clean," in IEEE Antennas and Propagation Society International Symposium (AP-S 2008), 2008.
[32] M. M. Nikolic, M. Ortner, A. Nehorai, and A. R. Djordjevic, "An approach to estimating building layouts using radar and jump-diffusion algorithm," IEEE Transactions on Antennas and Propagation, vol. 57, pp. 768-776, 2009.
[33] T. Fuegen, J. Maurer, T. Kayser, and W. Wiesbeck, "Capability of 3-D ray tracing for defining parameter sets for the specification of future mobile communications systems," IEEE Transactions on Antennas and Propagation, vol. 54, no. 11, pp. 3125-3138, 2006.
[34] C. A. Balanis, Advanced Engineering Electromagnetics. John Wiley\&Sons, 1989.
[35] W. D. Burnside and K. W. Burgener, "High frequency scattering by a thin lossless dielectric slab," IEEE Transactions on Antennas and Propagation, vol. 31, no. 1, pp. 104-111, 1983.
[36] J. A. Kong, Electromagnetic Wave Theory. EMW Publishing, Cambridge, Massachusetts, 2000.
[37] M. Yang and S. Savrou, "Rigorous coupled-wave analysis of radio wave propagation through periodic building structures," IEEE Antennas and Wireless Propagation Letters, vol. 3, pp. 204-207, 2004.
[38] P. Bernardi, R. Cicchetti, and O. Testa, "A three-dimensional UTD heuristic diffraction coefficient for complex penetrable wedges," IEEE Transactions on Antennas and Propagation, vol. 50, no. 2, pp. 217-224, 2002.
[39] R. F. Harrington, Ed., Time-Harmonic Electromagnetic Fields. IEEE Press, 2001.
[40] HFSS 10. Ansoft Corporation, 2006.
[41] K. Sarabandi and E. S. Li, "Microstrip ring resonator for soil moisture measurements," IEEE Transactions on Geoscience and Remote Sensing, vol. 35, no. 5, pp. 1223-1231, 1997.
[42] T. S. Rappaport, Ed., Wireless Communications: Principles and Practice. Prentice Hall PRT, 2001.
[43] H. Yacoub and T. K. Sarkar, "A homomorphic approach for through-wall sensing," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 5, pp. 1318-1327, 2009.
[44] K. M. Yemelyanov, N. Engheta, A. Hoorfar, and J. A. McVay, "Adaptive polarization contrast techniques for through-wall microwave imaging applications," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 5, pp. 13621374, 2009.
[45] T. Dogaru and C. Le, "Sar images of rooms and buildings based on FDTD computer models," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 5, pp. 1388-1401, 2009.
[46] An Internet resource for the calculation of the dielectric properties of human body tissues. http://niremf.ifac.cnr.it/tissprop/, 2007.
[47] Virtual family models. IT'IS Foundation, 2008.
[48] SEMCAD X. Schmid \& Partner Engineering AG, 2008.
[49] MakeHuman project. http://www.makehuman.org/, 2008.
[50] Y.-S. Yoon and M. G. Amin, "High-resolution through-the-wall radar imaging using beamspace MUSIC," IEEE Transactions on Antennas and Propagation, vol. 56, no. 6, pp. 1763-1774, 2008.
[51] N. Maaref, P. Millot, P. Pichot, and O. Picon, "A study of UWB FM-CW radar for the detection of human beings in motion inside a building," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 5, pp. 1297-1300, 2009.
[52] C. Debes, M. G. Amin, and A. M. Zoubir, "Target detection in single- and multiple-view through-the-wall radar imaging," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 5, pp. 1349-1361, 2009.
[53] B. Michael, W. Menzel, and A. Gronau, "A real-time close-range imaging system with fixed antennas," IEEE Microwave Theory and Transactions, vol. 48, no. 12, pp. 2736-2741, 2000.
[54] [Online]. Available: http://www.lessemf.com/paint.html
[55] S. R. DeGraaf, "SAR imaging via modern 2-D spectral estimation methods," IEEE Transactions on Image Processing, vol. 7, no. 5, pp. 729-761, 1998.
[56] J. W. Odendaal, E. Barnard, and C. W. I. Pistorius, "Two-dimensional superresolution radar imaging using the music algorithm," IEEE Transactions on Antennas and Propagation, vol. 42, no. 10, pp. 1386-1391, 1994.
[57] M. Dehmollaian, M. Thiel, and K. Sarabandi, "Through-the-wall imaging using differentail SAR," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 5, pp. 1289-1300, 2009.
[58] Y.-S. Yoon and M. G. Amin, "Spatial filtering for wall-clutter mitigation in through-the-wall radar imaging," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 9, pp. 3192-3208, 2009.

