Contents

Preface **xi**

1 Micro-Doppler Signatures – Review, Challenges, and Perspectives **1**
1.1 Introduction 1
1.2 Review of Micro-Doppler Effect in Radar 2
1.2.1 Micro-Doppler Signatures of Rigid Body Motion 2
1.2.2 Micro-Doppler Signatures of Nonrigid Body Motion 7
1.2.3 Review of Current Micro-Doppler Signature Research 9
1.3 Challenges in Radar Micro-Doppler Signature Research 14
1.3.1 Decomposition of Micro-Doppler Features 15
1.3.2 Detection of Anomalous Human Behavior 15
1.3.3 Feature Extraction and Target Identification Based on Micro-Doppler Signatures 15
1.4 Perspectives of Micro-Doppler Signature's Research 15
1.4.1 Multistatic Micro-Doppler Signatures 16
1.4.2 Micro-Doppler Signature-Based Target Classification 16
1.4.3 Aural Micro-Doppler Signals for Target Classification 16
1.4.4 Through-the-Wall Micro-Doppler Signatures 16
1.4.5 Polarimetric Micro-Doppler Analysis 17
References 17

2 Phenomenology of Radar Micro-Doppler Signatures **27**
2.1 Introduction 27
2.2 Micro-Doppler Effect Induced by Micro Motion 28
2.2.1 Euler Angles and Rotation Matrices 29
2.2.2 Mathematics of Micro-Doppler Effect 31
2.3 How to Analyze Time-Varying Micro-Doppler Shifts 42
2.3.1 Joint Time-Frequency Analysis of Micro-Doppler Signature 43
2.3.2 Doppler Aliasing in Micro-Doppler Signatures 44
2.3.3 PRF Selection Determined by Unambiguous Velocity and Range 46
2.3.4 Illustration of Extracted Micro-Doppler Signature 47
References 49

3 Analysis of Human Signatures using High-Range Resolution Micro-Doppler Radar **51**
3.1 Introduction 51
3.2 Micro-Range Micro-Doppler Human Radar Signature Analysis 52
3.3 Decomposition Algorithm 58
3.3.1 Range-Doppler Feature Extraction 59
3.3.2 Feature Association 60
3.3.3 Expectation–Maximization 60
3.3.4 Macro-/Micro-Doppler Separation 62
3.3.5 Decomposition Example 63
3.4 Conclusion 65
References 65

4 Range and Micro-Doppler Analysis of Human Motion Using High Resolution Experimental HYCAM Radar **69**
4.1 Introduction 69
4.1.1 Micro-Doppler Effect in Radar Imaging 69
4.1.2 Application to Human Motion Analysis 70
4.2 Some Insights on Human Motion 71
4.2.1 Walking and Running Principle 71
4.2.2 Human Motion Model and Kinematic Analysis 72
4.3 Signal Processing Tools for Radar Observation of Human Motion 75
4.3.1 Radar Asset for Human Observation 75
4.3.2 Time-Doppler Analysis 76
4.3.3 Range-Doppler Imaging 77
4.3.4 Range-Doppler "Movies" 78
4.4 Simulation of Human Motion Radar Observation 79
4.4.1 Simulation Configuration 79
4.4.2 Radar Signal Model 80
4.4.3 Model-Based Time-Doppler Imaging 80
4.4.4 Model-Based Range-Doppler Movies 82
4.5 High Resolution Range-Doppler Radar HYCAM 85
4.5.1 General Concepts and Architecture 85
4.5.2 Waveform and Processing 87
4.6 Experimental Setup and Results 89
4.6.1 Experimental Setup 89
4.6.2 Results on Pedestrian Motions 90
4.7 Conclusions and Perspectives 92
References 93

5 Through-the-Wall Micro-Doppler Signatures **97**
5.1 Introduction 97
5.2 Design Considerations for Through-the-Wall Radars 98
5.2.1 Wall Attenuation 98
5.2.2 Wall Reflection 99
5.2.3 Dispersion 101
5.3 Time-Frequency Transforms 101

5.3.1 Short-Time Fourier Transform 102
5.3.2 Continuous Wavelet Transform 103
5.3.3 The Hilbert–Huang Transform and Empirical Mode Decomposition 103
5.3.4 Other Time-Frequency Transforms 106
5.4 Wall Effects on Micro-Doppler Signatures 107
5.4.1 Constant Phase Offset 107
5.4.2 Signal-to-Noise Ratio and Maximum Detectable Range 109
5.5 Micro-Doppler Signals of Targets with a Translational Velocity 111
5.5.1 Walking Humans 112
5.5.2 Animals 114
5.6 Micro-Doppler Signals of Stationary Targets 116
5.6.1 Experimental Micro-Doppler of Human Motions 116
5.6.2 Models of Simple Human Motions Micro-Doppler Signal of a Pendulum 120
5.6.3 Comparison of Through-the-Wall Micro-Doppler Signatures versus Non-Through-the-Wall Micro-Doppler Signatures 128
5.6.4 Classification of Micro-Doppler Signatures 129
References 134

6 Identifying Human Movements Using Micro-Doppler Features 139
6.1 Introduction 139
6.1.1 Radar Recognition 139
6.1.2 Human Motion Estimation 140
6.1.3 Chapter Overview 142
6.2 The Human Model 142
6.2.1 The Shape and Size of Human Body Parts 144
6.2.2 The Kinematics According to Boulic 145
6.2.3 The Boulic Model Trajectories 148
6.2.4 The Radar Equipment Model 150
6.2.5 The Human Model Spectrogram Trajectories 152
6.3 Model-Based Human Motion Estimation 155
6.3.1 Introduction 155
6.3.2 Overview of the Method 156
6.3.3 The Fit Function 156
6.3.4 Results 162
6.3.5 Discussion 166
6.3.6 Conclusions 167
6.4 Feature-Based Human Motion Estimation 168
6.4.1 Introduction 168
6.4.2 Overview of the Method 168
6.4.3 Feature Extraction 170
6.4.4 Results 174
6.4.5 Discussion 181
6.4.6 Conclusions 182
References 183

7 Micro-Doppler Signatures of Helicopter Rotor Blades 187
7.1 Introduction 187
7.2 Background 188
7.2.1 Background Theory 188
7.2.2 Rotor Blade RCS 191
7.2.3 Measurements on Scale Model 195
7.3 Monostatic and Bistatic Helicopter Micro-Doppler 201
7.3.1 DiMuRa System Description 201
7.3.2 Signal Processing Fundamentals 202
7.3.3 Quasi-monostatic Signatures 214
7.3.4 Bistatic Signatures 217
7.4 Conclusions 224
References 225

8 Micro-Doppler Signatures of Small Boats 229
8.1 Introduction 229
8.2 Characterization and Modeling of Sea Clutter 229
8.2.1 Doppler Spectra Characteristics of Sea Clutter 230
8.2.2 Characterizing Small Boats in Sea Clutter 232
8.3 Small Boats in Sea Clutter 232
8.3.1 A Rigid Inflatable Boat in Sea Clutter 234
8.3.2 A Paddled Kayak in Sea Clutter 234
8.4 Small Vessels Conclusions 236
References 238

9 Multistatic Micro-Doppler Signature Processing 241
9.1 Introduction 241
9.2 Background 244
9.3 Bistatic and Multistatic Radar Properties 246
9.3.1 Range 247
9.3.2 Location 247
9.3.3 Range Resolution 249
9.3.4 Detection Performance 250
9.3.5 Doppler 251
9.4 The Multistatic Micro-Doppler Signature 253
9.4.1 Multistatic Micro-Doppler Mathematics 253
9.4.2 Multistatic Micro-Doppler Simulation Example 257
9.5 Multistatic Micro-Doppler Signatures of Human Motion 260
9.5.1 Gathering Experimental Data 260
9.5.2 Experimental Results and Their Implications 262
9.6 Summary and Conclusions 265
Appendix A: Generalized Micro-Doppler Derivation 266
References 269

10 Signal Decomposition of Micro-Doppler Signatures **273**
10.1 Introduction 273
10.2 Micro-Doppler Signal Model 274
10.2.1 ISAR Setup 275
10.2.2 Spectral Analysis 278
10.2.3 SAR Setup 280
10.3 Inverse Radon Transform Based Micro-Doppler Parameters Estimation 283
10.3.1 The Inverse-Radon Transform Review 283
10.3.2 Parameters Estimation 284
10.3.3 The Micro-Doppler Period Estimation 293
10.3.4 Sparsity Domain of the Micro-Doppler Signal 296
10.3.5 The Micro-Doppler Analysis from a Reduced Data Set 297
10.4 Micro-Doppler Effects Separation Based on the L-Statistics 299
10.4.1 Time-Frequency Analysis and the L-Statistics 299
10.4.2 Restoring the High FT Concentration from the STFT 300
10.4.3 Basic Idea for Rigid Body and Micro-Doppler Separation 302
10.4.4 Adaptive Percentage of Missing Values 313
10.4.5 Algorithm for the Micro-Doppler Effects Removal 314
10.5 The Micro-Doppler Signature Tracking by Using the Viterbi Algorithm 316
10.6 Conclusion 324
References 324

11 Sonar Micro-Doppler Signatures: Principles and Applications **329**
11.1 Introduction 329
11.2 Micro-Doppler Theory 331
11.3 Applications 332
11.3.1 Micro-Doppler Signature Collection at 40 kHz 332
11.3.2 Micro-Doppler Signature Collection at 80 kHz 338
11.4 Conclusions 342
References 343

12 Radar Micro-Doppler Signature of Wind Turbines **345**
12.1 Introduction 345
12.2 Interactions between Radar and Wind Farms 346
12.3 Impacts of Wind Turbines on Existing Weather Radar Operation 350
12.4 Radar Cross Section (RCS) of Wind Turbines 355
12.5 Micro-Doppler Signatures of Scaled Wind Turbine Model 357
12.5.1 Frequency Domain Measurement 357
12.5.2 Time Domain Measurement 361

12.6 Time-Frequency Analysis of Wind Turbine Micro-Doppler Signatures from Operational Radars 372
12.6.1 Micro-Doppler Signatures from WSR-88D Weather Radar 372
12.6.2 Micro-Doppler Signatures of Wind Turbines from a Mobile X-band Radar 373
12.7 Mitigation of Wind Turbine Clutter 377
12.8 Summary 378
References 378

Index **383**