MIMO RADAR
SIGNAL PROCESSING
MIMO RADAR
SIGNAL PROCESSING

Edited by

JIAN LI
PETRE STOICA

WILEY
A JOHN WILEY & SONS, INC., PUBLICATION
CONTENTS

PREFACE xiii

CONTRIBUTORS xvii

1 MIMO Radar — Diversity Means Superiority 1

Jian Li and Petre Stoica

1.1 Introduction 1
1.2 Problem Formulation 4
1.3 Parameter Identifiability 5
  1.3.1 Preliminary Analysis 5
  1.3.2 Sufficient and Necessary Conditions 7
  1.3.3 Numerical Examples 8
1.4 Nonparametric Adaptive Techniques for Parameter Estimation 11
  1.4.1 Absence of Array Calibration Errors 12
  1.4.2 Presence of Array Calibration Errors 15
  1.4.3 Numerical Examples 18
1.5 Parametric Techniques for Parameter Estimation 28
  1.5.1 ML and BIC 28
  1.5.2 Numerical Examples 34
1.6 Transmit Beampattern Designs 35
  1.6.1 Beampattern Matching Design 35
  1.6.2 Minimum Sidelobe Beampattern Design 38
  1.6.3 Phased-Array Beampattern Design 39
2 MIMO Radar: Concepts, Performance Enhancements, and Applications

Keith W. Forsythe and Daniel W. Bliss

2.1 Introduction
2.1.1 A Short History of Radar
2.1.2 Definition and Characteristics of MIMO Radar
2.1.3 Uses of MIMO Radar
2.1.4 The Current State of MIMO Radar Research
2.1.5 Chapter Outline

2.2 Notation

2.3 MIMO Radar Virtual Aperture
2.3.1 MIMO Channel
2.3.2 MIMO Virtual Array: Resolution and Sidelobes

2.4 MIMO Radar in Clutter-Free Environments
2.4.1 Limitations of Cramér–Rao Estimation Bounds
2.4.2 Signal Model
2.4.3 Fisher Information Matrix
2.4.4 Waveform Correlation Optimization
2.4.5 Examples

2.5 Optimality of MIMO Radar for Detection
2.5.1 Detection
2.5.2 High SNR
2.5.3 Weak-Signal Regime
2.5.4 Optimal Beamforming without Search
2.5.5 Nonfading Targets
2.5.6 Some Additional Benefits of MIMO Radar

2.6 MIMO Radar with Moving Targets in Clutter: GMTI Radars
2.6.1 Signal Model
2.6.2 Localization and Adapted SNR
2.6.3 Inner Products and Beamwidths
2.6.4 SNR Loss
3 Generalized MIMO Radar Ambiguity Functions

Geoffrey San Antonio, Daniel R. Fuhrmann, and Frank C. Robey

3.1 Introduction
3.2 Background
3.3 MIMO Signal Model
3.4 MIMO Parametric Channel Model
3.5 MIMO Ambiguity Function
3.6 Results and Examples
3.7 Conclusion
References
4 Performance Bounds and Techniques for Target Localization Using MIMO Radars

Joseph Tabrikian

4.1 Introduction 153
4.2 Problem Formulation 155
4.3 Properties 158
   4.3.1 Virtual Aperture Extension 159
   4.3.2 Spatial Coverage and Probability of Exposure 162
   4.3.3 Beampattern Improvement 163
4.4 Target Localization 165
   4.4.1 Maximum-Likelihood Estimation 165
   4.4.2 Transmission Diversity Smoothing 167
4.5 Performance Lower Bound for Target Localization 170
   4.5.1 Cramér–Rao Bound 170
   4.5.2 The Barankin Bound 173
4.6 Simulation Results 175
4.7 Discussion and Conclusions 180

Appendix 4A Log-Likelihood Derivation 181
   4A.1 General Model 182
   4A.2 Single Range–Doppler with No Interference 184
Appendix 4B Transmit–Receive Pattern Derivation 185
Appendix 4C Fisher Information Matrix Derivation 186

References 189

5 Adaptive Signal Design For MIMO Radars

Benjamin Friedlander

5.1 Introduction 193
5.2 Problem Formulation 195
   5.2.1 Signal Model with Reduced Number of Range Cells 199
   5.2.2 Multipulse and Doppler Effects 200
   5.2.3 The Complete Model 203
   5.2.4 The Statistical Model 203
5.3 Estimation 203
   5.3.1 Beamforming Solution 204
   5.3.2 Least-Squares Solutions 210
   5.3.3 Waveform Design for Estimation 210
5.4 Detection 214
   5.4.1 The Optimal Detector 214
   5.4.2 The SINR 215
5.4.3 Optimal Waveform Design 217
5.4.4 Suboptimal Waveform Design 218
5.4.5 Constrained Design 219
5.4.6 The Target and Clutter Models 220
5.4.7 Numerical Examples 221

5.5 MIMO Radar and Phased Arrays 226
5.5.1 Scan Transmit Beam after Receive 228
5.5.2 Adaptation of Transmit Beampattern 229
5.5.3 Combined Transmit–Receive Beamforming 229

Appendix 5A Theoretical SINR Calculation 231

References 232

6 MIMO Radar Spacetime Adaptive Processing and Signal Design 235
Chun-Yang Chen and P. P. Vaidyanathan

6.1 Introduction 236
6.1.1 Notations 238

6.2 The Virtual Array Concept 238

6.3 Spacetime Adaptive Processing in MIMO Radar 242
6.3.1 Signal Model 243
6.3.2 Fully Adaptive MIMO-STAP 246
6.3.3 Comparison with SIMO System 247
6.3.4 The Virtual Array in STAP 248

6.4 Clutter Subspace in MIMO Radar 249
6.4.1 Clutter Rank in MIMO Radar: MIMO Extension of Brennan’s Rule 250
6.4.2 Data-Independent Estimation of the Clutter Subspace with PSWF 253

6.5 New STAP Method for MIMO Radar 257
6.5.1 The Proposed Method 258
6.5.2 Complexity of the New Method 259
6.5.3 Estimation of the Covariance Matrices 259
6.5.4 Zero-Forcing Method 260
6.5.5 Comparison with Other Methods 260

6.6 Numerical Examples 261

6.7 Signal Design of the STAP Radar System 265
6.7.1 MIMO Radar Ambiguity Function 265
6.7.2 Some Properties of the MIMO Ambiguity Function 267
6.7.3 The MIMO Ambiguity Function of Periodic Pulse Radar Signals 272
6.7.4 Frequency-Multiplexed LFM Signals 274
6.7.5 Frequency-Hopping Signals 276
7 Slow-Time MIMO SpaceTime Adaptive Processing 283
Vito F. Mecca, Dinesh Ramakrishnan, Frank C. Robey, and Jeffrey L. Krolik

7.1 Introduction 283
  7.1.1 MIMO Radar and Spatial Diversity 284
  7.1.2 MIMO and Target Fading 286
  7.1.3 MIMO and Processing Gain 286
7.2 SIMO Radar Modeling and Processing 289
  7.2.1 Generalized Transmitted Radar Waveform 289
  7.2.2 SIMO Target Model 290
  7.2.3 SIMO Covariance Models 291
  7.2.4 SIMO Radar Processing 292
7.3 Slow-Time MIMO Radar Modeling 293
  7.3.1 Slow-Time MIMO Target Model 293
  7.3.2 Slow-Time MIMO Covariance Model 295
7.4 Slow-Time MIMO Radar Processing 297
  7.4.1 Slow-Time MIMO Beampattern and VSWR 299
  7.4.2 Subarray Slow-Time MIMO 301
  7.4.3 SIMO versus Slow-Time MIMO Design Comparisons 301
  7.4.4 MIMO Radar Estimation of Transmit–Receive Directionality Spectrum 302
7.5 OTHr Propagation and Clutter Model 303
7.6 Simulations Examples 307
  7.6.1 Postreceive/Transmit Beamforming 307
  7.6.2 SINR Performance 311
  7.6.3 Transmit–Receive Spectrum 315
7.7 Conclusion 316
Acknowledgment 316
References 316

8 MIMO as a Distributed Radar System 319
H. D. Griffiths, C. J. Baker, P. F. Sammartino, and M. Rangaswamy

8.1 Introduction 319
8.2 Systems 321
  8.2.1 Signal Model 323
  8.2.2 Spatial MIMO System 325
9 Concepts and Applications of A MIMO Radar System with Widely Separated Antennas

Hana Godrich, Alexander M. Haimovich, and Rick S. Blum

9.1 Background 365

9.2 MIMO Radar Concept 369
  9.2.1 Signal Model 369
  9.2.2 Spatial Decorrelation 373
  9.2.3 Other Multiple Antenna Radars 375

9.3 NonCoherent MIMO Radar Applications 377
  9.3.1 Diversity Gain 377
  9.3.2 Moving-Target Detection 380

9.4 Coherent MIMO Radar Applications 383
  9.4.1 Ambiguity Function 385
  9.4.2 CRLB 388
  9.4.3 MLE Target Localization 390
  9.4.4 BLUE Target Localization 393
  9.4.5 GDOP 395
  9.4.6 Discussion 399

9.5 Chapter Summary 399

Appendix 9A Deriving the FIM 400
Appendix 9B Deriving the CRLB on the Location Estimate Error 403
Appendix 9C MLE of Time Delays — Error Statistics 405
Appendix 9D Deriving the Lowest GDOP for Special Cases 407
  9D.1 Special Case: N × N MIMO 407
  9D.2 Special Case: 1 × N MIMO 408
  9D.3 General Case: M × N MIMO 408

Acknowledgments 408
References 408
10 **SpaceTime Coding for MIMO Radar**

*Antonio De Maio and Marco Lops*

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>411</td>
</tr>
<tr>
<td>10.2</td>
<td>415</td>
</tr>
<tr>
<td>10.3</td>
<td>417</td>
</tr>
<tr>
<td>10.3.1</td>
<td>419</td>
</tr>
<tr>
<td>10.3.2</td>
<td>420</td>
</tr>
<tr>
<td>10.4</td>
<td>421</td>
</tr>
<tr>
<td>10.4.1</td>
<td>423</td>
</tr>
<tr>
<td>10.4.2</td>
<td>426</td>
</tr>
<tr>
<td>10.4.3</td>
<td>427</td>
</tr>
<tr>
<td>10.5</td>
<td>429</td>
</tr>
<tr>
<td>10.6</td>
<td>431</td>
</tr>
<tr>
<td>10.7</td>
<td>437</td>
</tr>
<tr>
<td>10.8</td>
<td>441</td>
</tr>
<tr>
<td>Acknowledgment</td>
<td>442</td>
</tr>
<tr>
<td>References</td>
<td>442</td>
</tr>
</tbody>
</table>

**INDEX**
PREFACE

Multiple-input multiple-output (MIMO) radar has been receiving increasing attention in recent years from researchers, practitioners, and funding agencies. MIMO radar is characterized by using multiple antennas to simultaneously transmit diverse (possibly linearly independent) waveforms and by utilizing multiple antennas to receive the reflected signals. Like MIMO communications, MIMO radar offers a new paradigm for signal processing research. MIMO radar possesses significant potentials for fading mitigation, resolution enhancement, and interference and jamming suppression. Fully exploiting these potentials can result in significantly improved target detection, parameter estimation, as well as target tracking and recognition performance.

The objective of this contributed book is to introduce more recent developments on MIMO radar, to stimulate new concepts, theories, and applications of the topic, and to foster further cross-fertilization of ideas with MIMO communications. This book, which is the first to present a coherent picture of the MIMO radar topic, includes an excellent list of contributions by distinguished authors from both academia and research laboratories.

The book is organized as follows. The first seven chapters focus on the merits of the waveform diversity, allowed by transmit and receive antenna arrays containing elements that are collocated, to improve the radar performance, while the last three chapters exploit the diversity, offered by widely separated transmit/receive antenna elements, to achieve performance gains.

Chapter 1, by J. Li (University of Florida) and P. Stoica (Uppsala University), shows that waveform diversity enables MIMO radar superiority in several fundamental aspects, including improved parameter identifiability, direct applicability of many adaptive as well as parametric techniques to the received data to improve target
detection and parameter estimation performance, and better flexibility of transmit beampattern designs. Chapter 2, by K. W. Forsythe and D. W. Bliss (MIT Lincoln Laboratory), provides an interesting historical review of radar as well as the current state of the MIMO radar research. This chapter also covers a wide range of fundamental topics from MIMO virtual aperture, performance bounds, and waveform optimization, to minimum detectable velocity of MIMO ground moving-target indicator (GMTI) radars. Chapter 3, by G. San Antonio, D. R. Fuhrmann (Washington University), and F. C. Robey (MIT Lincoln Laboratory), addresses a basic radar issue: how to extend the conventional Woodward’s ambiguity function to MIMO radars. The MIMO ambiguity functions provided in the chapter can simultaneously characterize the effects of array geometry, transmitted waveforms, and target scattering on resolution performance. Chapter 4, by J. Tabrikian (Ben-Gurion University of the Negev) presents performance bounds and techniques for target localization using MIMO radar. Insights into and properties of the target localization techniques are also given. Chapter 5, by B. Friedlander (University of California at Santa Cruz), considers waveform design, based on target and clutter statistics, to improve the radar target detection and parameter estimation performance. Chapter 6, by C.-Y. Chen and P. P. Vaidyanathan (California Institute of Technology), focuses on fast-time MIMO spacetime adaptive processing (STAP) and provides new algorithms to fully utilize the geometry and structure of the covariance matrix of the jammer and clutter to achieve reduced computational complexity while maintaining a good signal-to-interference-and-noise ratio (SINR). Chapter 7, by V. F. Mecca (Duke University) and D. Ramakrishnan (Qualcomm Inc.), F. C. Robey (MIT Lincoln Laboratory), and J. L. Kroll (Duke University), is concerned with slow-time MIMO spacetime adaptive processing and its application to over-the-horizon radar clutter mitigation. The waveform orthogonality is achieved by phase coding from pulse-to-pulse (and hence the term “slowtime”), which has the important advantage of hardware implementation simplicity.

Chapter 8, by H. D. Griffiths (Cranfield University), C. J. Baker and P. F. Sammartino (University College London), and M. Rangaswamy (Air Force Research Laboratory), studies the performance and utilities of distributed MIMO radar networks that exploit the target scintillation as an advantage, and provides insights into the MIMO framework as applied to radar. Chapter 9, by H. Godrich, and A. M. Haimovich (New Jersey Institute of Technology) and R. S. Blum (Lehigh University), contains a comprehensive overview of the concepts and applications of a MIMO radar system with widely separated antennas. This chapter also discusses ambiguity functions and performance bounds, as well as techniques for high-resolution target localization. Finally, Chapter 10, by A. De Maio (Università degli Studi di Napoli “Federico II”) and M. Lops (Università degli Studi di Cassino), concentrates on developing statistical MIMO techniques via optimizing spacetime code matrices and on providing useful insights into the interplay between detection performance and code matrix choice.

We are grateful to the authors who have contributed the chapters of this book for their excellent work. We would also like to acknowledge the contributions of several other people and organizations to the completion of this book. Most of our work in
the area of waveform diversity exploitation and its applications to MIMO radar and biomedical engineering has been an outgrowth of our research programs in array signal processing. We would like to thank those who have supported our research in this area: the National Science Foundation (NSF), the Office of Naval Research (ONR), the Army Research Office (ARO), the Defense Advanced Research Projects Agency (DARPA), and the Swedish Science Council (VR). We also wish to thank George Telecki (Associate Publisher) and Melissa Valentine as well as Rachel Witmer (Editorial Assistants) at Wiley for their efforts on the publication of this book. Finally, we gratefully acknowledge Mr. Xing Tan, who helped us put this book together.

JIAN LI AND PETRE STOICA
CONTRIBUTORS

C. J. Baker, Department of Electronic and Electrical Engineering, University College, London, WC1E TJE, UK

Daniel W. Bliss, MIT Lincoln Laboratory, Lexington, MA 02420

Rick S. Blum, Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, PA 18015

Chun-Yang Chen, Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125

Antonio De Maio, Università degli Studi di Napoli “Federico II,” DIET Via Claudio 21, I-80125 Napoli, Italy

Keith W. Forsythe, MIT Lincoln Laboratory, Lexington, MA 02420

Benjamin Friedlander, Department of Electrical Engineering, University of California, Santa Cruz, CA 95064

Daniel R. Fuhrmann, Department of Electrical and System Engineering, Washington University, St. Louis, MO 63130

Hana Godrich, Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102

H. D. Griffiths, DCMT, Shrivenham, Cranfield University, Shrivenham, Swindon, SN6 8LA, UK

Alexander M. Haimovich, Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102
Jeffrey L. Krolik, Department of Electrical and Computer Engineering, Duke University, PO Box 90291, Durham, NC 27708

Jian Li, Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611

Marco Lops, Università degli Studi di Cassino, DAEIMI Via Di Biasio 43, I-03043 Cassino, Italy

Vito F. Mecca, Department of Electrical and Computer Engineering, Duke University, PO Box 90291, Durham, NC 27708

Dinesh Ramakrishnan, Audio Systems, Qualcomm Inc., 5775 Morehouse Dr, San Diego, CA, 92121

M. Rangaswamy, Air Force Research Laboratory (AFRL) Sensors Directorate, Hanscom Air Force Base, MA 01731

Frank C. Robey, MIT Lincoln Laboratory, Lexington, MA 02420

P. F. Sammartino, Department of Electronic and Electrical Engineering, University College, London, WC1E 7JE, UK

Geoffrey San Antonio, Department of Electrical and System Engineering, Washington University, St. Louis, MO 63130

Petre Stoica, Information Technology Department, Uppsala University, PO Box 337, SE-751 05 Uppsala, Sweden

Joseph Tabrikian, Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva, 84105, Israel

P. P. Vaidyanathan, Department of Electrical Engineering, California Institute of Technology, Pasadena, CA 91125