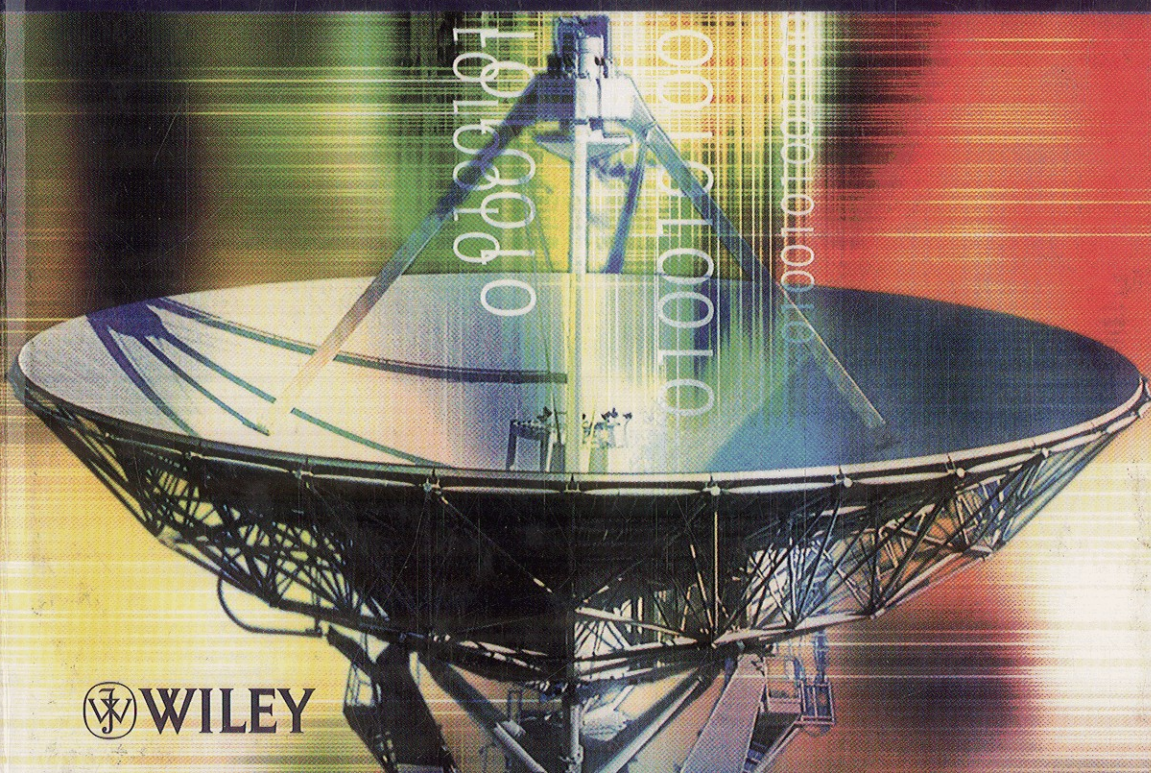


MIMO

RADAR SIGNAL

PROCESSING

Edited by **JIAN LI • PETRE STOICA**



 **WILEY**

CONTENTS

PREFACE	xiii
CONTRIBUTORS	xvii
1 MIMO Radar — Diversity Means Superiority	1
<i>Jian Li and Petre Stoica</i>	
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

1.6.4	Numerical Examples	40
1.6.5	Application to Ultrasound Hyperthermia Treatment of Breast Cancer	47
1.7	Conclusions	56
	Appendix IA Generalized Likelihood Ratio Test	57
	Appendix 1B Lemma and Proof	59
	Acknowledgments	60
	References	60
2	MIMO Radar: Concepts, Performance Enhancements, and Applications	65
	<i>Keith W. Forsythe and Daniel W. Bliss</i>	
2.1	Introduction	65
2.1.1	A Short History of Radar	65
2.1.2	Definition and Characteristics of MIMO Radar	66
2.1.3	Uses of MIMO Radar	68
2.1.4	The Current State of MIMO Radar Research	70
2.1.5	Chapter Outline	71
2.2	Notation	72
2.3	MIMO Radar Virtual Aperture	73
2.3.1	MIMO Channel	73
2.3.2	MIMO Virtual Array: Resolution and Sidelobes	74
2.4	MIMO Radar in Clutter-Free Environments	77
2.4.1	Limitations of Cramér–Rao Estimation Bounds	77
2.4.2	Signal Model	77
2.4.3	Fisher Information Matrix	79
2.4.4	Waveform Correlation Optimization	82
2.4.5	Examples	85
2.5	Optimality of MIMO Radar for Detection	87
2.5.1	Detection	88
2.5.2	High SNR	89
2.5.3	Weak-Signal Regime	90
2.5.4	Optimal Beamforming without Search	92
2.5.5	Nonfading Targets	92
2.5.6	Some Additional Benefits of MIMO Radar	93
2.6	MIMO Radar with Moving Targets in Clutter: GMTI Radars	93
2.6.1	Signal Model	93
2.6.2	Localization and Adapted SNR	96
2.6.3	Inner Products and Beamwidths	101
2.6.4	SNR Loss	103

2.6.5	SNR Loss and Waveform Optimization	107
2.6.6	Area Search Rates	109
2.6.7	Some Examples	109
2.7	Summary	111
Appendix 2A	A Localization Principle	111
Appendix 2B	Bounds on $R(N)$	114
Appendix 2C	An Operator Norm Inequality	115
Appendix 2D	Negligible Terms	115
Appendix 2E	Bound on Eigenvalues	115
Appendix 2F	Some Inner Products	116
Appendix 2G	An Invariant Inner Product	117
Appendix 2H	Kronecker and Tensor Products	118
2H.1	Lexicographical Ordering	118
2H.2	Tensor and Kronecker Products	118
2H.3	Properties	119
	Acknowledgments	119
	References	120
3	Generalized MIMO Radar Ambiguity Functions	123
	<i>Geoffrey San Antonio, Daniel R. Fuhrmann, and Frank C. Robey</i>	
3.1	Introduction	123
3.2	Background	124
3.3	MIMO Signal Model	127
3.4	MIMO Parametric Channel Model	131
3.4.1	Transmit Signal Model	131
3.4.2	Channel and Target Models	132
3.4.3	Received Signal Parametric Model	133
3.5	MIMO Ambiguity Function	134
3.5.1	MIMO Ambiguity Function Composition	137
3.5.2	Cross-Correlation Function under Model Simplifications	138
3.5.3	Autocorrelation Function and Transmit Beampatterns	141
3.6	Results and Examples	143
3.6.1	Orthogonal Signals	143
3.6.2	Coherent Signals	147
3.7	Conclusion	149
	References	150

4	Performance Bounds and Techniques for Target Localization Using MIMO Radars	153
	<i>Joseph Tabrikian</i>	
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	193
	<i>Benjamin Friedlander</i>	
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 Beam pattern	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
	<i>Chun-Yang Chen and P. P. Vaidyanathan</i>	
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

6.8	Conclusions	278
	Acknowledgments	279
	References	279
7	Slow-Time MIMO SpaceTime Adaptive Processing	283
	<i>Vito F. Mecca, Dinesh Ramakrishnan, Frank C. Robey, and Jeffrey L. Krolik</i>	
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
	<i>H. D. Griffiths, C. J. Baker, P. F. Sammartino, and M. Rangaswamy</i>	
8.1	Introduction	319
8.2	Systems	321
8.2.1	Signal Model	323
8.2.2	Spatial MIMO System	325

8.2.3	Netted Radar Systems	325
8.2.4	Decentralized Radar Network (DRN)	327
8.3	Performance	329
8.3.1	False-Alarm Rate (FAR)	329
8.3.2	Probability of Detection (P_d)	336
8.3.3	Jamming Tolerance	348
8.3.4	Coverage	352
8.4	Conclusions	359
	Acknowledgment	361
	References	361
9	Concepts and Applications of A MIMO Radar System with Widely Separated Antennas	365
	<i>Hana Godrich, Alexander M. Haimovich, and Rick S. Blum</i>	
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: $N \times N$ MIMO	407
9D.2	Special Case: $1 \times N$ MIMO	408
9D.3	General Case: $M \times N$ MIMO	408
	Acknowledgments	408
	References	408

10	SpaceTime Coding for MIMO Radar	411
	<i>Antonio De Maio and Marco Lops</i>	
10.1	Introduction	411
10.2	System Model	415
10.3	Detection In MIMO Radars	417
10.3.1	Full-Rank Code Matrix	419
10.3.2	Rank 1 Code Matrix	420
10.4	Spacetime Code Design	421
10.4.1	Chernoff-Bound-Based (CBB) Code Construction	423
10.4.2	SCR-Based Code Construction	426
10.4.3	Mutual-Information-Based (MIB) Code Construction	427
10.5	The Interplay Between STC and Detection Performance	429
10.6	Numerical Results	431
10.7	Adaptive Implementation	437
10.8	Conclusions	441
	Acknowledgment	442
	References	442
	INDEX	445