Contents

Preface xix
Glossary xxi
List of Contributors xxxi

Section A Suppression of clutter in moving radar 1

Part I Space-slow time processing for airborne MTI radar 3

1 Space–time adaptive processing for manoeuvring airborne radar 5
Peter G. Richardson
1.1 Introduction 5
1.2 STAP fundamentals 6
1.3 Clutter angle-Doppler relationships 9
1.3.1 Straight and level flight 9
1.3.2 Effect of variations in platform orientation 11
1.4 Clutter suppression in forward-looking radar 12
1.4.1 Mainlobe clutter suppression 12
1.4.2 Sidelobe clutter suppression 18
1.5 Slow moving target detection under conditions of manoeuvre 23
1.5.1 Effects of platform manoeuvre 23
1.5.2 Motion compensation 24
1.6 Jammer rejection under conditions of manoeuvre 27
1.6.1 Mainlobe clutter filtering requirements 27
1.6.2 Advantages of using STAP 27
1.7 Summary 33
Contents

2 Non-linear and adaptive two-dimensional FIR filters for STAP: theory and experimental results 37
Pierfrancesco Lombardo and Fabiola Colone

2.1 Introduction 37
2.2 Adaptive linear filters 38
2.3 AR-based FIR filters 45
2.4 Non-linear combination of non-adaptive filters 51
2.4.1 Filter bank design 52
2.4.2 Detection threshold and performance 55
2.4.3 AR-based non-linear detector 56
2.5 Non-linear combination of adaptive AR-based two-dimensional FIR filters 61
2.6 Conclusions 66
2.7 Acknowledgments 69
2.8 Appendix: ML estimation of two-dimensional AR parameters 69

3 Space–time techniques for SAR 73
Alfonso Farina and Pierfrancesco Lombardo

3.1 Summary 73
3.2 Description of the problem and state of the art 73
3.3 Model of MSAR echoes 76
3.3.1 Aberrations due to target motion 76
3.3.2 Space–time–frequency representation 77
3.4 Processing schemes 82
3.4.1 Taxonomy of processing schemes for MSAR 82
3.4.2 MTI + PD 87
3.4.3 DPCA 94
3.4.4 Along-track interferometry (ATI)-SAR 95
3.4.5 Processor in the space–time–frequency domain 98
3.4.6 Optimum processing for MSAR 107
3.5 Conclusions 119
3.6 Acknowledgments 120

4 ΣΔ-STAP: an efficient, affordable approach for clutter suppression 123
Hong Wang, Richard A. Schneible, Russell D. Brown and Yuhong Zhang

4.1 Definition of the difference (Δ) beams 123
4.2 ΣΔ-STAP algorithms 125
4.3 Analytical performance formulas of ΣΔ-STAP 129
4.3.1 SINR potential 129
4.3.2 Probabilities of detection and false alarm 130
4.4 A real-data demonstration of ΣΔ-STAP 131
## Contents

4.5 Desired $\Delta$-beam characteristics 135
  4.5.1 Mathematical equivalence of subarray and $\Sigma\Delta$-STAP 142

4.6 Summary 143
  4.6.1 Advantages of the $\Sigma\Delta$-STAP approach 143
  4.6.2 Limitations of $\Sigma\Delta$-STAP 145
  4.6.3 Potential applications of $\Sigma\Delta$-STAP 146

5 STAP with omnidirectional antenna arrays 149

  Richard Klemm

5.1 Introduction 149
  5.1.1 Preliminaries on STAP antennas 149
  5.1.2 The circular ring array concept 151

5.2 Array configurations for 360° coverage 152
  5.2.1 Four linear arrays 153
  5.2.2 Displaced circular rings 156
  5.2.3 Circular planar array with randomly distributed elements 157
  5.2.4 Octagonal planar array 160

5.3 Discussion 164
  5.3.1 Directivity patterns 164
  5.3.2 Range-ambiguous clutter 165

5.4 Effect of array tilt 167
  5.4.1 Side-looking linear and rectangular arrays 167
  5.4.2 Omnidirectional arrays 168

5.5 Conclusions 169

Part II Space-slow time processing for space-based MTI radar 175

6 SAR-GMTI concept for RADARSAT-2 177

  Christoph H. Gierull and Chuck Livingstone

6.1 Introduction 177
  6.1.1 Background 177
  6.1.2 Addition of MTI modes to spaceborne SAR 178
  6.1.3 RADARSAT-2 moving object detection experiment 179

6.2 Analysis of SAR-GMTI modes for RADARSAT-2 180
  6.2.1 Background 181
  6.2.2 Statistical models of measured signals 184
  6.2.3 SCNR optimum processing 188
  6.2.4 SAR displaced phase centre antenna 193
  6.2.5 SAR along-track interferometry 194

6.3 SAR-STAP scheme for RADARSAT-2 196
  6.3.1 Detection 196
  6.3.2 Parameter estimation 201
7 STAP simulation and processing for spaceborne radar 207
Tim J. Nohara and Peter Weber

7.1 Introduction 207

7.2 Spaceborne radar applications and design 208
    7.2.1 Spaceborne MTI radar applications 208
    7.2.2 Spaceborne MTI radar design 209

7.3 STAP processing for SBR 212
    7.3.1 Typical GMTI signal processing 212
    7.3.2 Extension to other modes 215
    7.3.3 Other issues 216

7.4 Simulation and processing for SBR 217
    7.4.1 User interface 218
    7.4.2 Model the radar 224
    7.4.3 Model the environment 225
    7.4.4 Generate the signals 227
    7.4.5 Model the processing 228
    7.4.6 Evaluate the results 229

7.5 Discussion and conclusions 231

8 Techniques for range-ambiguous clutter mitigation in space-based radar systems 235
Stephen M. Kogon and Michael Zatman

8.1 Introduction 235

8.2 Moving target detection with SBR 236
    8.2.1 STAP for SBR systems 238

8.3 Clutter characteristics of pulse-Doppler waveforms in SBR 240
    8.3.1 Clutter Doppler ambiguities 241
    8.3.2 Clutter range ambiguities 242

8.4 Impact of range-ambiguous clutter on STAP performance 244

8.5 Range-ambiguous clutter mitigation techniques with pulse-Doppler waveforms 247
    8.5.1 PRF diversity 247
    8.5.2 Aperture trade offs 249

8.6 Long single pulse phase-encoded waveforms 250
    8.6.1 Properties of long single pulse phase-encoded waveform (LSPW) 252
    8.6.2 Integrated sidelobe clutter levels 254
    8.6.3 STAP simulations 257

8.7 Summary 260
Part III Processing architectures

9 Parallel processing architectures for STAP 265
Alfonso Farina and Luca Timmoneri
9.1 Summary and introduction 265
9.2 Baseline systolic algorithm 265
9.3 Lattice and vectorial lattice algorithms 269
9.4 Inverse QRD-based algorithms 271
9.5 Experiments with general purpose parallel processors 272
9.6 Experiments with VLSI-based CORDIC board 273
9.7 Modern signal processing technology overview and its impact on real-time STAP 275
9.8 Processing of recorded live data 277
9.8.1 Systolic algorithm for live data processing 277
9.8.2 Data files used in the data reduction experiments 278
9.8.3 Performance evaluation 280
9.8.4 Detection of vehicular traffic 284
9.9 Concluding remarks 285
9.10 Appendix A: Givens rotations and systolic implementation of sidelobe canceller 286
9.11 Appendix B: lattice working principle 288
9.12 Appendix C: the CORDIC algorithm 289
9.13 Appendix D: the SLC implementation via CORDIC algorithm 292
9.14 Appendix E: an example of existing processors for STAP 293

Part IV Clutter inhomogeneities 303

10 STAP in heterogeneous clutter environments 305
William L. Melvin
10.1 Introduction 305
10.1.1 Adaptivity with finite sample support 307
10.1.2 STAP performance metrics 308
10.1.3 Covariance matrix errors 311
10.2 Classes of space–time clutter heterogeneity 312
10.2.1 General simulation characteristics 315
10.3 Amplitude heterogeneity 315
10.3.1 Clutter discreties 315
10.3.2 Range-angle varying clutter RCS 320
10.3.3 Clutter edges 322
10.4 Spectral heterogeneity 325
10.5 CNR-induced spectral mismatch 327
10.6 Targets in the secondary data 330
10.7 Joint angle-Doppler mismatch and clutter heterogeneity 337
Contents

10.8 Site-specific examples of clutter heterogeneity 339
  10.8.1 Measured multichannel airborne radar data 339
  10.8.2 Site-specific simulation 342
10.9 STAP techniques in heterogeneous environments 344
  10.9.1 Data-dependent training techniques 344
  10.9.2 Minimal sample support STAP 348
  10.9.3 Clutter discretes 350
  10.9.4 Targets in training data 350
  10.9.5 Covariance matrix tapers 351
  10.9.6 Knowledge-aided space–time processing 352
10.10 Summary 353
10.11 Acknowledgments 353

11 Adaptive weight training for post-Doppler STAP algorithms in non-homogeneous clutter 359
  Stephen M. Kogon

  11.1 Introduction 359
  11.2 Training of STAP algorithms 361
  11.3 Post-Doppler STAP algorithms 364
  11.4 Phase and power-selected training for STAP 365
  11.5 Experimental results 367
    11.5.1 Example of phase/power selection 368
    11.5.2 STAP results 369
    11.5.3 Experimental versus theoretical STAP performance 372
  11.6 Summary 372

12 Application of deterministic techniques to STAP 375
  Jeffrey T. Carlo, Tapan K. Sarkar, Michael C. Wicks and Magdalena Salazar-Palma

  12.1 Introduction 375
  12.2 Direct data domain least-squares (D3LS) approach, one dimension 379
  12.3 D3LS approach with main beam constraints 385
  12.4 A D3LS approach with main beam constraints for space–time adaptive processing 387
    12.4.1 Space–time D3LS eigenvalue processor 389
    12.4.2 Space–time D3LS forward processor 390
    12.4.3 Space–time D3LS backward processor 392
    12.4.4 Space–time D3LS forward–backward processor 393
  12.5 Determining the degrees of freedom 394
  12.6 An airborne radar example 396
    12.6.1 Simulation setup 396
    12.6.2 Case I: single constraint space–time example 398
    12.6.3 Case II: multiple constraint space–time example 403
13 Robust techniques in space–time adaptive processing 413
Keith F. McDonald and Rick S. Blum
13.1 Introduction 413
13.1.1 Initial development of space–time adaptive
processing (STAP) algorithms 414
13.1.2 Hypothesis testing problem 417
13.2 Real-world detection environments 418
13.3 Non-homogeneity – causes and impact on performance 420
13.3.1 Signal contamination 423
13.3.2 Non-homogeneity detection 425
13.3.3 Knowledge-based signal processing 428
13.3.4 Analysis of degraded performance due to
non-homogeneity 428
13.4 Antenna array errors 430
13.5 Deviation from Gaussian assumption 431
13.6 Jamming and terrain scattered interference 433
13.6.1 Constraining detection schemes 434
13.6.2 Two-stage processors 434
13.6.3 Three-dimensional STAP 436
13.7 Reduction in computational complexity 437
13.7.1 Reduced-rank methods and covariance matrix tapers 437
13.7.2 Techniques implementing limited reference cells 439
13.7.3 Low complexity approaches to STAP 441
13.8 Conclusions 443

Section B Miscellaneous space–time processing applications 463

Part V Ground target tracking with STAP radar 465

14 Ground target tracking with STAP radar: the sensor 467
Richard Klemm
14.1 Introduction 467
14.2 Properties of the STAP radar sensor 467
14.2.1 Processing techniques 468
14.2.2 Array properties 472
14.2.3 Summary of the data output provided by the STAP
radar 473
14.3 The scenario 474
14.3.1 SNIR and $P_d$ of a moving target 474
14.3.2 System aspects 480
xii Contents

14.4 Degrading effects 486
  14.4.1 Bandwidth effects 486
  14.4.2 Doppler ambiguities 488
  14.4.3 Range ambiguities 489
  14.4.4 STAP radar under jamming conditions 492
14.5 Issues in convoy tracking 494
  14.5.1 Convoy detection by range-only information 495
  14.5.2 Convoy detection by azimuth variance analysis 496
14.6 Summary 499

15 Ground target tracking with STAP radar: selected tracking aspects 501
  Wolfgang Koch
  15.1 Introduction 501
    15.1.1 Discussion of an idealised scenario 502
    15.1.2 Summary of observations 505
  15.2 Tracking preliminaries 507
    15.2.1 Coordinate systems 507
    15.2.2 Target dynamics model 509
  15.3 GMTI sensor model 510
    15.3.1 GMTI characteristics 510
    15.3.2 Convoy resolution 512
    15.3.3 Doppler ambiguities 513
    15.3.4 Measurements 513
  15.4 GMTI data processing 514
    15.4.1 Prediction 514
    15.4.2 Data processing 515
    15.4.3 Filtering process 517
    15.4.4 Realisation aspects 518
    15.4.5 Discussion 519
    15.4.6 Retrodiction 522
    15.4.7 Effect of Doppler ambiguities 524
  15.5 Road map information 528
    15.5.1 Modelling of roads 529
    15.5.2 Densities on roads 530
  15.6 Quantitative discussion 533
    15.6.1 Simulation parameters 533
    15.6.2 Numerical results 534
  15.7 List of variables 537
Part VI  Space-fast time techniques  

16  Superresolution and jammer suppression with broadband arrays for multifunction radar  

Ulrich Nickel  
16.1  Introduction  
16.2  Broadband array signal model and beamforming  
16.2.1  Received signal and notation  
16.2.2  Digital beamforming with subarray outputs  
16.2.3  Influence of channel imperfections  
16.3  Superresolution with broadband arrays  
16.3.1  Spatial-only processing of broadband data  
16.3.2  Space and time processing methods  
16.3.3  Conclusions on broadband superresolution  
16.4  Jammer suppression with broadband arrays  
16.4.1  General principles of adaptive interference suppression  
16.4.2  Spatial-only adaptation  
16.4.3  Space and time adaptation  
16.5  Final remarks  

Part VII  Over-the-horizon radar applications  

17  Stochastically constrained spatial and spatio–temporal adaptive processing for non-stationary hot clutter cancellation  

Yuri I. Abramovich, Stuart J. Anderson, Alexei Y. Gorokhov and Nicholas K. Spencer  
17.1  Overview  
17.2  SC STAP fundamentals and supervised training applications  
17.2.1  SC STAP algorithm: analytic solution  
17.2.2  SC STAP algorithm: operational routines  
17.2.3  SC STAP algorithm: efficiency analysis by simulation results  
17.2.4  SC STAP algorithm: efficiency analysis by real data processing  
17.2.5  Summary  
17.3  SC STAP unsupervised training applications  
17.3.1  Operational routine for unsupervised training  
17.3.2  Operational SC STAP algorithm: simulation and real data processing results  
17.3.3  Summary
## Contents

17.4 SC STAP convergence analysis 665
   17.4.1 Introduction 665
   17.4.2 Conditional loss factor $\eta_1$ analysis: LSMI versus SMI for SC SAP 667
   17.4.3 Conditional loss factor $\eta_1$ analysis: LSMI for SC STAP 678
   17.4.4 Conditional loss factor $\eta_2$ analysis: exact PDF for a single stochastic constraint 681
   17.4.5 Conditional loss factor $\eta_2$ analysis: approximate PDF for multiple stochastic constraints 685

17.5 List of variables 690

### Part VIII Applications in acoustics and seismics 699

18 Space–time adaptive matched field processing (STAMP) 701
   Yung P. Lee
   18.1 Introduction 701
   18.2 Adaptive matched field processing (MFP) 703
   18.3 Wideband–narrowband feedback loop white-noise-constrained method (FLWNC) 705
   18.4 MFP examples 707
   18.5 Space–time adaptive matched field processing (STAMP) 709
   18.6 Forward sector processing simulation geometry 711
   18.7 Summary 713

19 Space–time signal processing for surface ship towed active sonar 715
   Dirk Maiwald, Stephan Benen and Helmut Schmidt-Schierhorn
   19.1 Introduction 715
   19.2 Narrowband multiple ping processing 720
      19.2.1 Data model 720
      19.2.2 Fully adaptive CW processing 721
      19.2.3 Partially adaptive processing techniques 723
   19.3 FM processing 724
      19.3.1 Image processing background 726
      19.3.2 Echogram image enhancement 726
      19.3.3 Automatic echogram detection 726
   19.4 Experimental results 727
      19.4.1 Sonar system description 727
      19.4.2 CW pulse sea data analysis 728
      19.4.3 Echogram sea data analysis (ACTAS) 729
      19.4.4 Echogram enhancement 730
      19.4.5 Automatic echogram detection 730
20 EM and SAGE algorithms for towed array data  
Pei–Jung Chung and Johann F. Böhme
20.1 Introduction 733
20.2 Signal model 734
20.3 EM and SAGE algorithms 736
  20.3.1 EM algorithm 736
  20.3.2 SAGE algorithm 739
20.4 Fast EM and SAGE algorithms 741
20.5 Recursive EM and SAGE algorithms 742
  20.5.1 Recursive EM algorithm 743
  20.5.2 Recursive SAGE algorithm 745
20.6 Experimental results 746
  20.6.1 EM and SAGE algorithms 747
  20.6.2 Recursive EM and SAGE algorithms 749
20.7 Conclusions 751

21 The common reflection surface (CRS) stack – a data-driven space–time adaptive seismic reflection imaging procedure  
Jürgen Mann, Eric Duveneck, Steffen Bergler and Peter Hubral
21.1 Introduction 755
21.2 Seismic reflection imaging 756
  21.2.1 The seismic wavefield 756
  21.2.2 Acquisition of reflection seismic data 758
  21.2.3 Seismic reflection processing 762
21.3 Common reflection surface stack 766
  21.3.1 Classic data-driven approaches 767
  21.3.2 Second-order traveltime approximations 768
  21.3.3 Physical interpretation of the coefficients 769
  21.3.4 Implementation 771
  21.3.5 Practical aspects 772
  21.3.6 A synthetic data example 773
21.4 CRS attributes and velocity model estimation 775
21.5 Conclusions 777
21.6 Glossary 778
  21.6.1 List of variables 778
  21.6.2 Specific terminology 779

Part IX Space–time techniques in communications  

22 STAP for space/code/time division multiple access systems  
Christoph M. Walke
22.1 Introduction 785
22.2 System model 789
Contents

22.3 Time domain linear joint detection 791
   22.3.1 Zero forcing block linear equalisation 792
   22.3.2 Minimum mean square error block linear equalisation 793
22.4 Frequency-domain linear joint detection 793
   22.4.1 Block-diagonal FD system model 793
   22.4.2 FD ZF-BLE and MMSE-BLE 796
22.5 Performance of FD joint detection 797
   22.5.1 Exploitation of spatial and frequency diversity 798
   22.5.2 Intracell interference cancellation 804
   22.5.3 Intra- and intercell interference cancellation 813
22.6 Conclusions 821
22.7 List of variables 822
   22.7.1 Variables with roman/calligraphic letters 822
   22.7.2 Variables with calligraphic letters 823
   22.7.3 Variables with greek letters 823

23 Underwater communication with vertical receiver arrays 827
   Johann F. Böhme and Rolf Weber
   23.1 Introduction 827
   23.2 The underwater acoustic channel 828
      23.2.1 Transmission loss and ambient noise 828
      23.2.2 Sound speed variability 829
      23.2.3 Multipath propagation 830
      23.2.4 Doppler effect 831
      23.2.5 Summary 832
   23.3 Underwater acoustic communications – a brief overview 832
      23.3.1 Incoherent digital receivers 832
      23.3.2 Coherent digital receivers 833
   23.4 Spatial–temporal receiver architecture 834
      23.4.1 Communication over channels with ISI 834
      23.4.2 Multichannel digital receiver 835
      23.4.3 Signal model 837
      23.4.4 Multichannel equalisation 839
   23.5 Multichannel constant modulus algorithm 841
      23.5.1 Blind stochastic gradient descent algorithms 841
      23.5.2 The constant modulus algorithm 842
      23.5.3 Experimental results 844
   23.6 Super-exponential blind equalisation 847
      23.6.1 Iterative Shalvi–Weinstein algorithm 847
      23.6.2 Recursive Shalvi–Weinstein algorithm 849
      23.6.3 Adaptive implementation 850
      23.6.4 Experimental results 853
   23.7 Concluding remarks 853
24 Reduced-rank interference suppression and equalisation for GPS and downlink CDMA

Wilbur L. Myrick and Michael D. Zoltowski

24.1 Reduced-rank interference suppression and equalisation
24.1.1 Motivation for reduced-rank MMSE processing
24.1.2 Understanding the multistage Wiener filter
24.1.3 Lattice structure of the MSWF
24.1.4 MSWF related to Wiener–Hopf filter weights

24.2 Application of MSWF to CDMA downlink
24.2.1 Introduction
24.2.2 Data and channel model
24.2.3 Edge of cell/soft hand-off
24.2.4 Chip-level MMSE estimator
24.2.5 Performance examples

24.3 Application of MSWF to GPS jammer suppression
24.3.1 Introduction
24.3.2 Power minimisation and joint space–time preprocessing
24.3.3 Space–time filter characteristics
24.3.4 Data and channel model
24.3.5 Dimensionality reduction techniques
24.3.6 Performance examples

24.4 Summary of concepts involving reduced-rank filtering

25 Introduction to space–time coding

Sumeet Sandhu, Dhananjay Gore, Rohit Nabar and Arogyaswami Paulraj

25.1 Introduction
25.2 Multiple antenna channel model
25.3 Benefits of smart antenna technology
25.3.1 Array gain
25.3.2 Diversity gain
25.3.3 Multiplexing gain
25.3.4 Interference reduction

25.4 Background on space–time codes
25.4.1 Space–time trellis codes
25.4.2 Linear space–time block codes

25.5 New design criteria
25.5.1 Error performance
25.5.2 Capacity performance
25.5.3 Unified design

25.6 Receiver design
25.6.1 Modulation and coding for MIMO

25.7 Concluding remarks

Index