

Contents

1	Background of Array Processing	1
1.1	Introduction	1
1.2	Array Signal Model	1
1.2.1	Signal Model	1
1.2.2	Noise Models	5
1.2.3	Data Model	7
1.3	Beamformer	9
1.3.1	Frequency-Wavenumber Response Function	9
1.3.2	Array Performance Measures	11
1.4	Traditional Beamformer	19
1.4.1	Delay-and-Sum (DAS) Beamformer	20
1.4.2	Optimum Beamformer	20
1.5	Summary	26
	References	28
2	Frequency-Domain Broadband Beamforming	29
2.1	Introduction	29
2.2	Frequency-Domain Snapshot Model	30
2.2.1	Frequency-Domain Snapshots	30
2.2.2	Covariance Matrix	33
2.3	DFT Beamformer	35
2.3.1	DFT Implementation	35
2.3.2	Broadband Beam Pattern	38
2.3.3	DFT Beamforming	39
2.3.4	Signal Not Along MRA	44
2.4	Summary	46
	Reference	46

3	Optimal Design of Subband Beamformers	47
3.1	Introduction	47
3.2	Robust Beamformers	48
3.2.1	Loaded Sample Matrix Inversion Beamformer	48
3.2.2	Norm Constrained Beamformer	52
3.2.3	Worst-Case Constrained Beamformer	56
3.2.4	Comparison of Robust Beamformers	61
3.3	Low-Sidelobe Beamformers	65
3.3.1	Windows for Uniform Linear Arrays	65
3.3.2	Low-Sidelobe Designs	69
3.3.3	Robust Against Manifold Uncertainty	75
3.4	Mainlobe Pattern Synthesis	86
3.4.1	Norms	86
3.4.2	Least Squares Error Pattern Synthesis	88
3.4.3	Minimum-Norm Pattern Synthesis	90
3.4.4	Mixed-Norm Pattern Synthesis	93
3.4.5	Frequency-Invariant Beam Pattern	96
3.5	Multiple-Objective Design	98
3.6	Summary	101
	References	103
4	Time-Domain Broadband Beamforming	105
4.1	Introduction	105
4.2	FIR Beamforming	106
4.3	FIR Beamformer Design via FFT	108
4.4	FIR Filter Design for FIR Beamformer	111
4.4.1	Minimum-Norm Filter Design	112
4.4.2	Mixed-Norm Filter Design	116
4.5	FIR Beamformer via Subband Beamformers and FIR Filters Designs	119
4.5.1	Design Principles	119
4.5.2	FIR Broadband Beamformer	122
4.6	Summary	128
	References	129
5	Optimal Design of Time-Domain Broadband Beamformers	131
5.1	Introduction	131
5.2	Jointly Spatial and Frequency Responses Optimization	132
5.2.1	Drawback of Two-Stage Method	132
5.2.2	FIR Beamformer Pattern	133
5.2.3	Frequency-Invariant FIR Beamformer	135

5.3	Adaptive FIR Beamformer	142
5.3.1	Data Covariance Matrix	142
5.3.2	Design of Adaptive FIR Beamformer	145
5.3.3	Adaptive FIR Beamformer with Sidelobe Control	146
5.4	Minimum Mainlobe Spatial Pattern Variation Design	152
5.4.1	Mainlobe Spatial Response Variation	152
5.4.2	Peak Sidelobes Constrained Minimax MSRV	152
5.4.3	Peak Sidelobes Constrained Least-Square MSRV	153
5.4.4	Mean-Squared MSRV Constrained Least-Square Sidelobes	155
5.4.5	Frequency-Invariant Beamformer with Interference Rejection	156
5.5	Multiple-Objective Design of FIR Beamformers	161
5.6	Summary	163
	References	164
6	Modal Beamforming for Circular Arrays	165
6.1	Introduction	165
6.2	Continuous Circular Arrays (Apertures)	166
6.2.1	Uniform Weighting	167
6.2.2	Conventional Beamformer	169
6.2.3	Phase Mode Excitation	172
6.2.4	Circular Mode	175
6.2.5	Phase-Mode Beamformer	182
6.2.6	Modal Representation of DAS Beamformer	184
6.3	Uniform Circular Arrays	186
6.3.1	Element-Space Beamformer	186
6.3.2	Circular-Harmonics-Domain (CHD) Beamformer	192
6.3.3	Performance Measures in Circular Harmonics Domain	195
6.4	Design of CHD Beamformers	201
6.4.1	Phase-Mode Beamformer	201
6.4.2	CHD DAS Beamformer	205
6.4.3	CHD MVDR Beamformer	205
6.4.4	Maximum-Directivity-Index (MDI) Beamformer	206
6.4.5	MVDR Beamformer in Planarly Isotropic Noise Field	207
6.4.6	Maximum WNG Beamformer	209
6.4.7	Multiply Constrained CHD Beamformer	211
6.5	Frequency-Domain Broadband CHD Beamforming	215
6.5.1	Implementation of CHD Beamformer	215
6.5.2	Unbaffled Circular Array	218
6.5.3	Baffled Circular Array	219
6.6	Summary	220
	References	223

7	Time-Domain Modal Beamforming for Circular Arrays	225
7.1	Introduction	225
7.2	Beamformer with Symmetric Patterns	226
7.2.1	Design of Weight Vector	226
7.2.2	Symmetric-Pattern Beamforming	231
7.3	Time-Domain CHD Beamforming Structure	232
7.4	Design of FIR Filters for Pattern Generation	234
7.5	Time-Domain Broadband CHD Beamforming	247
7.6	Summary	253
	References	254
8	Modal Beamforming for Spherical Arrays	255
8.1	Introduction	255
8.2	Continuous Spherical Arrays (Apertures)	256
8.2.1	Spherical Apertures	256
8.2.2	Spherical Mode	257
8.2.3	Phase-Mode Beamformer	262
8.2.4	Modal Representation of DAS Beamformer	268
8.3	Spherical Arrays	271
8.3.1	Nearly-Uniform Spherical Arrays	271
8.3.2	Spherical-Harmonics-Domain (SHD) Beamformer	273
8.3.3	SHD Beamformer Structure	278
8.3.4	Performance Measures in Spherical Harmonics Domain	279
8.4	Design of SHD Beamformers	284
8.4.1	Multiply Constrained SHD Beamformer	284
8.4.2	SHD MVDR Beamformer	285
8.4.3	Maximum-Directivity-Index Beamformer	286
8.4.4	Maximum WNG Beamformer	288
8.4.5	Norm Constrained SHD Beamformer	290
8.5	Frequency-Domain Broadband SHD Beamforming	294
8.6	Summary	296
	References	297
9	Time-Domain Modal Beamforming for Spherical Arrays	299
9.1	Introduction	299
9.2	Rotationally Symmetric SHD Beamformer	300
9.2.1	Beamforming Structure	300
9.2.2	Design of Weight Vector	303
9.3	Time-Domain SHD Beamforming Structure	308
9.4	Design of FIR Filters for Pattern Generation	311
9.5	Time-Domain Broadband SHD Beamforming	323
9.6	Summary	328
	References	330
	Glossary	331