
Contents

1	Introduction	1
2	Acoustic Wavefields	5
2.1	Mathematical Foundations	6
2.1.1	Euler's Equation	7
2.1.2	The Acoustic Wave Equation	8
2.2	Point Sources and Plane-Waves	9
2.2.1	Point Sources in Three Dimensions	9
2.2.2	Plane-Waves in Three Dimensions	12
2.2.3	Point Sources and Plane-Waves in Two Dimensions	13
2.3	Acoustic Wave Equation in Cylindrical Coordinates	15
2.3.1	General Solution of the Acoustic Wave Equation in Cylindrical Coordinates	15
2.3.2	The Cylindrical Radiator	19
2.3.3	The Cylindrical Scatterer	23
2.4	Acoustic Wave Equation in Spherical Coordinates	33
2.4.1	General Solution of the Acoustic Wave Equation in Spherical Coordinates	33
2.4.2	The Spherical Radiator	35
2.4.3	The Spherical Scatterer	38
3	Wavefield Decomposition	41
3.1	Wavefield Decomposition Using Circular Apertures and Arrays	42
3.1.1	Continuous Circular Apertures	42
3.1.2	Directional Circular Apertures	53
3.1.3	Circularly Symmetric Microphone Arrays	57

3.1.4	Representation of a 2D Wavefield Using a Finite Number of Harmonics.....	63
3.1.5	Circular Apertures and Nearfield Sources	64
3.2	Wavefield Decomposition Using Spherical Apertures and Arrays	68
3.2.1	Continuous Spherical Apertures	68
3.2.2	Directional Spherical Apertures	74
3.2.3	Spherical Microphone Arrays	78
3.2.4	Representation of a 3D Wavefield Using a Finite Number of Harmonics.....	84
3.2.5	Spherical Apertures and Nearfield Sources	86
3.3	Wavefield Decomposition Using Other Types of Apertures	87
3.3.1	Linear Apertures	87
3.3.2	Cylindrical Apertures	90
4	Acoustic Scene Analysis Using Classical Array Signal Processing	95
4.1	Overview	96
4.2	Signal Models and Assumptions	97
4.2.1	Sensor-Related Assumptions	98
4.2.2	Time-Domain Signal Model	99
4.2.3	Frequency-Domain Signal Model	100
4.3	Waveform Estimation	102
4.3.1	Space-Time Filtering and Beamforming	102
4.3.2	Performance Measures	105
4.3.3	Data-Independent Waveform Estimation.....	112
4.3.4	Data-Dependent Waveform Estimation	119
4.4	Parameter Estimation	121
4.4.1	Performance Measure – The Cramér-Rao Lower Bound.	122
4.4.2	TDOA-Based Algorithms	124
4.4.3	Subspace-Based DOA Estimation Algorithms	130
4.4.4	Detection of the Number of Active Sources	146
5	Acoustic Scene Analysis Using Modal Array Signal Processing	149
5.1	Waveform Estimation Using Eigenbeam Processing	149
5.1.1	The Modal Beamformer – Pattern Synthesis	150
5.1.2	Optimum Beampattern Design Using Eigenbeams	152
5.1.3	The Adaptive Modal Beamformer	156
5.2	Parameter Estimation Using Eigenbeam Processing	157
5.2.1	Eigenbeam Array Manifold Vectors	157
5.2.2	Eigenbeam Signal Model and Modal Signal Subspaces ..	158
5.2.3	Eigenbeam Processing and the CRLB	159
5.2.4	Eigenbeam-Based DOA Estimation Using Circular Apertures	160
5.2.5	Eigenbeam Processing Using Spherical Apertures	170

5.2.6 Resolution Capacity and DOA Estimation of More than Two Wideband Sources	177
5.2.7 Detection of the Number of Active Sources	178
6 A Practical Acoustic Scene Analysis System	189
6.1 System Details	189
6.1.1 Hardware	189
6.1.2 Algorithm Implementation	191
6.1.3 Software	192
6.2 Evaluations	192
6.2.1 Evaluation Setup	192
6.2.2 Waveform Estimation	195
6.2.3 Parameter Estimation	198
7 Summary and Conclusions	205
A Signal Transforms	209
A.1 One- and Multi-dimensional Fourier Transforms	209
A.2 Fourier Series	209
A.3 Spherical Harmonics Transform	210
B Special Functions	211
B.1 Bessel Functions	211
B.2 Spherical Bessel Functions	214
B.3 Legendre Polynomials, Associated Legendre Functions, and Spherical Harmonics	216
C Microphone Arrays and Nearfield/Farfield Sources	221
D Eigenbeam-CRLB for a Single Source	225
E Frequency-Independence of EB-ESPRIT for a Single Source	227
F A Practical Acoustic Scene Analysis System – Further Results	231
References	243
Index	251