

Kensuke Sekihara · Srikatan S. Nagarajan

Adaptive Spatial Filters for Electromagnetic Brain Imaging

 Springer

Contents

1	Introduction	1
1.1	Functional brain mapping	1
1.2	Electromagnetic brain imaging	2
1.3	Spatial filters	3
1.4	Book chapter organization	5
1.5	Acknowledgements	7
2	Sensor array outputs and spatial filters	9
2.1	Neuromagnetic signals as sensor-array outputs	9
2.1.1	Definitions	9
2.1.2	Sensor lead field	10
2.1.3	Linear independence of lead-field vectors	11
2.2	Bioelectromagnetic inverse problem	13
2.3	Expressions of data covariance matrices	15
2.3.1	Data and source covariance relationship	15
2.3.2	Formulation for uncorrelated sources	17
2.4	Low-rank signal modeling	18
2.4.1	Definition of noise and signal subspaces	18
2.4.2	Property of the data covariance matrix	19
2.5	Spatial filters	22
2.5.1	Source reconstruction using a spatial filter	22
2.5.2	Scalar and vector spatial filters	23
2.5.3	Resolution kernel, point-spread function, and beam response	25
3	Tomographic reconstruction and nonadaptive spatial filters	27
3.1	Minimum-norm method	27
3.1.1	Tomographic reconstruction formulation	27
3.1.2	Nonadaptive spatial-filter formulation	31
3.2	Variants of the minimum-norm filter	32
3.2.1	Weight-normalized minimum-norm filter	32
3.2.2	sLORETA filter	32
3.3	Spatial matched filter	34
3.4	Deriving the minimum-norm-based filters using leakage minimization	35

4	Adaptive spatial filters	37
4.1	Deriving weights for adaptive spatial filters	37
4.1.1	Minimum-variance spatial filter with the unit-gain constraint	37
4.1.2	Minimum-variance spatial filter with the array-gain constraint	39
4.1.3	Minimum-variance spatial filter with the unit-noise-gain constraint	39
4.2	Prerequisites for the adaptive spatial-filter formulation	40
4.2.1	Uncorrelated source time courses	40
4.2.2	Low-rank signals	43
4.3	Scalar adaptive spatial filter: deriving the optimum source orientation	44
4.4	LCMV spatial filter	46
4.5	Vector adaptive spatial filter formulation	48
4.5.1	Unit-gain constraint spatial filter	48
4.5.2	Array-gain constraint spatial filter	49
4.5.3	Unit-noise-gain constraint spatial filter	51
4.5.4	Equivalence between the adaptive scalar and vector formu- lations	53
4.6	Frequency-domain implementation	54
4.7	Numerical examples	57
5	Location bias, spatial resolution, and beam response	65
5.1	Bias properties of various spatial filters	65
5.1.1	Definition of source location bias	65
5.1.2	Bias for the spatial matched filter	66
5.1.3	Bias for the minimum-norm filter	67
5.1.4	Bias for the weight-normalized minimum-norm filter	67
5.1.5	Bias for the sLORETA filter	68
5.1.6	Bias for the unit-gain minimum-variance spatial filter . . .	68
5.1.7	Bias for the array-gain minimum-variance spatial filter . . .	69
5.1.8	Bias for the unit-noise-gain minimum-variance spatial filter	69
5.2	Effects of noise on the location bias	70
5.3	Spatial resolution	71
5.4	Spatial-filter beam response	72
5.5	Numerical examples	74
6	Output SNR and array mismatch	83
6.1	Output SINR	83
6.2	Adaptive spatial filters that attain the maximum SINR	85
6.3	SNR transfer factor	87
6.4	Two types of SNR definitions for the vector minimum-variance spa- tial filter	89
6.5	Influence of array mismatch	92
6.6	Diagonal loading	93
6.7	Asymmetric diagonal loading	95
6.8	Eigenspace-projection spatial filter	97

6.8.1	Eigenspace projection	97
6.8.2	Extension to vector spatial-filter formulation	101
6.9	Numerical examples	103
7	Effects of low-rank interference	109
7.1	Influence of low-rank interference	109
7.1.1	Low-rank interference	109
7.1.2	Analysis when \mathbf{R}_d is a rank-one matrix	111
7.1.3	Analysis when \mathbf{R}_d is a rank-two matrix	113
7.2	Influence on output of the unit-noise-gain minimum-variance filter	114
7.3	Effects on the output of the eigenspace-projected spatial filter . . .	115
7.4	Numerical examples	116
8	Effects of high-rank interference	125
8.1	Influence of background brain activity	125
8.1.1	Point-spread function under background interference	125
8.1.2	Numerical examples	127
8.2	Prewhitening eigenspace-projection spatial filter	129
8.2.1	Prewhitening signal covariance estimation	129
8.2.2	Prewhitening eigenspace-projection spatial filter	132
8.3	Overestimation of signal-subspace dimensionality	133
8.4	Reconstruction of induced activity	135
8.4.1	General background	135
8.4.2	Prewhitening method	136
8.5	Numerical examples	138
9	Effects of source correlation	145
9.1	Performance of adaptive spatial filters in the presence of correlated sources	145
9.2	Signal cancellation and estimation of source correlation	147
9.3	Suppression of coherent interferences using the LCMV spatial filter	149
9.3.1	Weight-vector derivation	149
9.3.2	Extension to eigenspace-projected spatial filter	151
9.4	Imaging magnitude source coherence	152
9.5	Numerical examples	155
10	Effects of using the sample covariance matrix	163
10.1	Sample covariance matrix: the maximum-likelihood estimate of the true covariance matrix	163
10.2	Effects of using sample covariance matrices on the minimum- variance filters	164
10.3	Recovering from the sample covariance effects: Beamspace processing	166
10.4	Numerical examples	168
10.4.1	Effects of using sample covariance matrices	168
10.4.2	Recovering from the sample covariance effects	168

10.4.3	Effects of using sample covariance matrices on unit-noise-gain minimum-variance filter	169
11	Statistical evaluation of the spatial filter output	179
11.1	Problem with Gaussian-distribution-based methods	179
11.2	Evaluation of statistical significance using nonparametric statistics	180
11.2.1	Voxel-by-voxel statistical significance test	180
11.2.2	Multiple comparisons using maximum statistics	181
11.2.3	Modification for power image	182
11.2.4	Multiple comparisons using the false discovery rate	183
11.3	Deriving a voxel-wise empirical null distribution	185
11.3.1	Method when the signal is time-locked and the interference is non-time-locked to the stimulus	185
11.3.2	Method when both the signal and the interference are non-time-locked to the stimulus	186
11.4	Non-parametric method using reconstructed voxel time courses . .	187
11.5	Numerical examples	188
12	Methods related to adaptive spatial filters	193
12.1	Wiener filter	193
12.1.1	Minimum-mean-squared-error criterion	193
12.1.2	Derivation of the minimum-variance spatial filter	195
12.2	MUSIC algorithm	196
12.2.1	Single- and multi-dipole search	196
12.2.2	Making use of the noise subspace—the MUSIC algorithm . .	197
12.3	Scanning with the generalized-likelihood-ratio test function	198
12.3.1	Data model	199
12.3.2	Deriving the scanning function	200
12.3.3	Numerical examples	203
13	Appendices	205
13.1	Maximum-likelihood estimation of noise and signal subspaces . . .	205
13.2	Additional topics related to non-adaptive spatial filters	207
13.2.1	Determination of the optimum orientation for scalar non-adaptive spatial filters	207
13.2.2	Equivalence between the vector and scalar minimum-norm filters	208
13.3	Rayleigh-Ritz formula	209
13.4	Supplementary formulae when only one or two sources exist	211
13.5	Robustness of the prewhitening signal covariance estimation to the control-only-sources scenario	214
13.6	Derivation of GLRT scanning function in Eq. (12.45)	217
13.7	Bioelectromagnetic forward modeling	220
13.7.1	Quasi-static Maxwell's equations	221
13.7.2	Magnetic field in an infinite homogeneous conductor	221

13.7.3	Electric potential in an infinite homogeneous conductor . .	223
13.7.4	Formulae in a bounded conductor with piecewise-constant conductivity	223
13.7.5	Magnetic field from a homogeneous spherical conductor . .	224
13.7.6	Magnetic field from a realistically-shaped conductor	226
13.7.7	Electric potential for a multiple-shell conductor	231

Bibliography	233
---------------------	------------

Index	243
--------------	------------