

Advanced Signal Processing and Digital Noise Reduction

Saeed V. Vaseghi
Queen's University of Belfast
UK

 **WILEY**  **TEUBNER**

A Partnership between John Wiley & Sons and B. G. Teubner Publishers

Chichester · New York · Brisbane · Toronto · Singapore · Stuttgart · Leipzig

Contents

Preface	xvi
1 Introduction	1
1.1 Signals and Information	2
1.2 Signal Processing Methods	3
1.2.1 Non-parametric Signal Processing	3
1.2.2 Model-based Signal Processing	3
1.2.3 Bayesian Statistical Signal Processing	4
1.2.4 Neural Networks	4
1.3 Applications of Digital Signal Processing	4
1.3.1 Adaptive Noise Cancellation and Noise Reduction	5
1.3.2 Blind Channel Equalisation	7
1.3.3 Signal Classification and Pattern Recognition	8
1.3.4 Linear Prediction Modelling of Speech	9
1.3.5 Digital Coding of Audio Signals	11
1.3.6 Detection of Signals in Noise	13
1.3.7 Directional Reception of Waves: Beamforming	14
1.4 Sampling and Analog to Digital Conversion	16
1.4.1 Time-Domain Sampling and Reconstruction of Analog Signals ...	17
1.4.2 Quantisation	20
Bibliography	21
2 Stochastic Processes	23
2.1 Random Signals and Stochastic Processes	24
2.1.1 Stochastic Processes	25
2.1.2 The Space or Ensemble of a Random Process	26
2.2 Probabilistic Models of a Random Process	27
2.3 Stationary and Nonstationary Random Processes	31
2.3.1 Strict Sense Stationary Processes	33
2.3.2 Wide Sense Stationary Processes	34
2.3.3 Nonstationary Processes	34
2.4 Expected Values of a Stochastic Process	35
2.4.1 The Mean Value	35
2.4.2 Autocorrelation	36
2.4.3 Autocovariance	37
2.4.4 Power Spectral Density	38
2.4.5 Joint Statistical Averages of Two Random Processes	40
2.4.6 Cross Correlation and Cross Covariance	40
2.4.7 Cross Power Spectral Density and Coherence	42
2.4.8 Ergodic Processes and Time-averaged Statistics	42

2.4.9 Mean-ergodic Processes	43
2.4.10 Correlation-ergodic Processes	44
2.5 Some Useful Classes of Random Processes	45
2.5.1 Gaussian (Normal) Process	45
2.5.2 Multi-variate Gaussian Process	47
2.5.3 Mixture Gaussian Process	48
2.5.4 A Binary-state Gaussian Process	49
2.5.5 Poisson Process	50
2.5.6 Shot Noise	52
2.5.7 Poisson-Gaussian Model for Clutters and Impulsive Noise	53
2.5.8 Markov Processes	54
2.6 Transformation of a Random Process	57
2.6.1 Monotonic Transformation of Random Signals	58
2.6.2 Many-to-one Mapping of Random Signals	60
Summary	62
Bibliography	63
3 Bayesian Estimation and Classification	65
3.1 Estimation Theory: Basic Definitions	66
3.1.1 Predictive and Statistical Models in Estimation	66
3.1.2 Parameter Space	67
3.1.3 Parameter Estimation and Signal Restoration	68
3.1.4 Performance Measures	69
3.1.5 Prior, and Posterior Spaces and Distributions	71
3.2 Bayesian Estimation	74
3.2.1 Maximum a Posterior Estimation	75
3.2.2 Maximum Likelihood Estimation	76
3.2.3 Minimum Mean Squared Error Estimation	79
3.2.4 Minimum Mean Absolute Value of Error Estimation	81
3.2.5 Equivalence of MAP, ML, MMSE and MAVE	82
3.2.6 Influence of the Prior on Estimation Bias and Variance	82
3.2.7 The Relative Importance of the Prior and the Observation	86
3.3 Estimate-Maximise (EM) Method	90
3.3.1 Convergence of the EM algorithm	91
3.4 Cramer-Rao Bound on the Minimum Estimator Variance	93
3.4.1 Cramer-Rao Bound for Random Parameters	95
3.4.2 Cramer-Rao Bound for a Vector Parameter	95
3.5 Bayesian Classification	96
3.5.1 Classification of Discrete-valued Parameters	96
3.5.2 Maximum a Posterior Classification	98
3.5.3 Maximum Likelihood Classification	98
3.5.4 Minimum Mean Squared Error Classification	99
3.5.5 Bayesian Classification of Finite State Processes	99
3.5.6 Bayesian Estimation of the Most Likely State Sequence	101
3.6 Modelling the Space of a Random Signal	102
3.6.1 Vector Quantisation of a Random Process	103
3.6.2 Design of a Vector Quantiser: K-Means Algorithm	103

3.6.3	Design of a Mixture Gaussian Model	104
3.6.4	The EM Algorithm for Estimation of Mixture Gaussian Densities	105
	Summary	108
	Bibliography	109
4	Hidden Markov Models	111
4.1	Statistical Models for Nonstationary Processes	112
4.2	Hidden Markov Models	114
4.2.1	A Physical Interpretation of Hidden Markov Models	115
4.2.2	Hidden Markov Model As a Bayesian Method	116
4.2.3	Parameters of a Hidden Markov Model	117
4.2.4	State Observation Models	118
4.2.5	State Transition Probabilities	119
4.2.6	State-Time Trellis Diagram	120
4.3	Training Hidden Markov Models	121
4.3.1	Forward-Backward Probability Computation	122
4.3.2	Baum-Welch Model Re-Estimation	124
4.3.3	Training Discrete Observation Density HMMs	125
4.3.4	HMMs with Continuous Observation PDFs	127
4.3.5	HMMs with Mixture Gaussian pdfs	128
4.4	Decoding of Signals Using Hidden Markov Models	129
4.4.1	Viterbi Decoding Algorithm	131
4.5	HMM-based Estimation of Signals in Noise	133
4.5.1	HMM-based Wiener Filters	135
4.5.2	Modelling Noise Characteristics	136
	Summary	137
	Bibliography	138
5	Wiener Filters	140
5.1	Wiener Filters: Least Squared Error Estimation	141
5.2	Block-data Formulation of the Wiener Filter	145
5.3	Vector Space Interpretation of Wiener Filters	148
5.4	Analysis of the Least Mean Squared Error Signal	150
5.5	Formulation of Wiener Filter in Frequency Domain	151
5.6	Some Applications of Wiener Filters	152
5.6.1	Wiener filter for Additive Noise Reduction	153
5.6.2	Wiener Filter and Separability of Signal and Noise	155
5.6.3	Squared Root Wiener Filter	156
5.6.4	Wiener Channel Equaliser	157
5.6.5	Time-alignment of Signals	158
5.6.6	Implementation of Wiener Filters	159
	Summary	161
	Bibliography	162
6	Kalman and Adaptive Least Squared Error Filters	164
6.1	State-space Kalman Filters	165
6.2	Sample Adaptive Filters	171
6.3	Recursive Least Squares (RLS) Adaptive Filters	172

6.4 The Steepest Descent Method	177
6.5 The LMS Adaptation Method	181
Summary	182
Bibliography	183
7 Linear Prediction Models	185
7.1 Linear Prediction Coding	186
7.1.1 Least Mean Squared Error Predictor	189
7.1.2 The Inverse Filter: Spectral Whitening	191
7.1.3 The Prediction Error Signal	193
7.2 Forward, Backward and Lattice Predictors	193
7.2.1 Augmented Equations for Forward and Backward Predictors	195
7.2.2 Levinson-Durbin Recursive Solution	196
7.2.3 Lattice Predictors	198
7.2.4 Alternative Formulations of Least Squared Error Predictors	200
7.2.5 Model Order Selection	201
7.3 Short-term and Long-term Predictors	202
7.4 MAP Estimation of Predictor Coefficients	204
7.5 Signal Restoration Using Linear Prediction Models	207
7.5.1 Frequency Domain Signal Restoration	209
Summary	212
Bibliography	212
8 Power Spectrum Estimation	214
8.1 Fourier Transform, Power Spectrum and Correlation	215
8.1.1 Fourier Transform	215
8.1.2 Discrete Fourier Transform (DFT)	217
8.1.3 Frequency Resolution and Spectral Smoothing	217
8.1.4 Energy Spectral Density and Power Spectral Density	218
8.2 Non-parametric Power Spectrum Estimation	220
8.2.1 The Mean and Variance of Periodograms	221
8.2.2 Averaging Periodograms (Bartlett Method)	221
8.2.3 Welch Method :Averaging Periodograms from Overlapped and Windowed Segments	222
8.2.4 Blackman-Tukey Method	224
8.2.5 Power Spectrum Estimation from Autocorrelation of Overlapped Segments	225
8.3 Model-based Power Spectrum Estimation	225
8.3.1 Maximum Entropy Spectral Estimation	227
8.3.2 Autoregressive Power Spectrum Estimation	229
8.3.3 Moving Average Power Spectral Estimation	230
8.3.4 Autoregressive Moving Average Power Spectral Estimation	231
8.4 High Resolution Spectral Estimation Based on Subspace Eigen Analysis ..	232
8.4.1 Pisarenko Harmonic Decomposition	232
8.4.2 Multiple Signal Classification (MUSIC) Spectral Estimation	235
8.4.3 Estimation of Signal Parameters via Rotational Invariance	

Techniques (ESPRIT)	238
Summary	240
Bibliography	240
9 Spectral Subtraction	242
9.1 Spectral Subtraction	243
9.1.1 Power Spectrum Subtraction	246
9.1.2 Magnitude Spectrum Subtraction	247
9.1.3 Spectral Subtraction Filter: Relation to Wiener Filters	247
9.2 Processing Distortions	248
9.2.1 Effect of Spectral Subtraction on Signal Distribution	250
9.2.2 Reducing the Noise Variance	251
9.2.3 Filtering Out the Processing Distortions	251
9.3 Non-linear Spectral Subtraction	252
9.4 Implementation of Spectral Subtraction	255
9.4.1 Application to Speech Restoration and Recognition	257
Summary	259
Bibliography	259
10 Interpolation	261
10.1 Introduction	262
10.1.1 Interpolation of a Sampled Signal	262
10.1.2 Digital Interpolation by a Factor of I	263
10.1.3 Interpolation of a Sequence of Lost Samples	265
10.1.4 Factors that Affect Interpolation	267
10.2 Polynomial Interpolation	268
10.2.1 Lagrange Polynomial Interpolation	269
10.2.2 Newton Interpolation Polynomial	270
10.2.3 Hermite Interpolation Polynomials	273
10.2.4 Cubic Spline Interpolation	273
10.3 Statistical Interpolation	276
10.3.1 Maximum a Posterior Interpolation	277
10.3.2 Least Squared Error Autoregressive Interpolation	279
10.3.3 Interpolation Based on a Short-term Prediction Model	279
10.3.4 Interpolation Based on Long-term and Short-term Correlations	282
10.3.5 LSAR Interpolation Error	285
10.3.6 Interpolation in Frequency-Time Domain	287
10.3.7 Interpolation using Adaptive Code Books	289
10.3.8 Interpolation Through Signal Substitution	289
Summary	291
Bibliography	292
11 Impulsive Noise	294
11.1 Impulsive Noise	295
11.1.1 Autocorrelation and Power Spectrum of Impulsive Noise	297
11.2 Stochastic Models for Impulsive Noise	298
11.2.1 Bernoulli-Gaussian Model of Impulsive Noise	299
11.2.2 Poisson-Gaussian Model of Impulsive Noise	299

11.2.3	A Binary State Model of Impulsive Noise	300
11.2.4	Signal to Impulsive Noise Ratio	302
11.3	Median Filters	302
11.4	Impulsive Noise Removal Using Linear Prediction Models	304
11.4.1	Impulsive Noise Detection	304
11.4.2	Analysis of Improvement in Noise Detectability	306
11.4.3	Two-sided Predictor	308
11.4.4	Interpolation of Discarded Samples	308
11.5	Robust Parameter Estimation	309
11.6	Restoration of Archived Gramophone Records	311
	Summary	312
	Bibliography	312
12	Transient Noise	314
12.1	Transient Noise Waveforms	315
12.2	Transient Noise Pulse Models	316
12.2.1	Noise Pulse Templates	317
12.2.2	Autoregressive Model of Transient Noise	317
12.2.3	Hidden Markov Model of a Noise Pulse Process	318
12.3	Detection of Noise Pulses	319
12.3.1	Matched Filter	320
12.3.2	Noise Detection Based on Inverse Filtering	321
12.3.3	Noise Detection Based on HMM	322
12.4	Removal of Noise Pulse Distortions	323
12.4.1	Adaptive Subtraction of Noise pulses	323
12.4.2	AR-based Restoration of Signals Distorted by Noise Pulses	324
	Summary	327
	Bibliography	327
13	Echo Cancellation	328
13.1	Telephone Line Echoes	329
13.1.1	Telephone Line Echo Suppression	330
13.2	Adaptive Echo Cancellation	331
13.2.1	Convergence of Line Echo Canceller	333
13.2.2	Echo Cancellation for Digital Data Transmission over Subscriber's Loop	334
13.3	Acoustic Feedback Coupling	335
13.4	Sub-band Acoustic Echo Cancellation	339
	Summary	341
	Bibliography	341
14	Blind Deconvolution and Channel Equalisation	343
14.1	Introduction	344
14.1.1	The Ideal Inverse Channel Filter	345
14.1.2	Equalisation Error, Convolutional Noise	346
14.1.3	Blind Equalisation	347
14.1.4	Minimum and Maximum Phase Channels	349

14.1.5 Wiener Equaliser	350
14.2 Blind Equalisation Using Channel Input Power Spectrum	352
14.2.1 Homomorphic Equalisation	354
14.2.2 Homomorphic Equalisation using a Bank of High Pass Filters..	356
14.3 Equalisation Based on Linear Prediction Models	356
14.3.1 Blind Equalisation Through Model Factorisation	358
14.4 Bayesian Blind Deconvolution and Equalisation	360
14.4.1 Conditional Mean Channel Estimation	360
14.4.2 Maximum Likelihood Channel Estimation	361
14.4.3 Maximum a Posterior Channel Estimation	361
14.4.4 Channel Equalisation Based on Hidden Markov Models	362
14.4.5 MAP Channel Estimate Based on HMMs	365
14.4.6 Implementations of HMM-Based Deconvolution	366
14.5 Blind Equalisation for Digital Communication Channels	369
14.6 Equalisation Based on Higher-Order Statistics	375
14.6.1 Higher-Order Moments	376
14.6.2 Higher Order Spectra of Linear Time-Invariant Systems	379
14.6.3 Blind Equalisation Based on Higher Order Cepstrum	379
Summary	385
Bibliography	385
Frequently used Symbols and Abbreviations	388
Index	391