

Contents

About the Series	xi
Preface	xiii
Authors	xv
List of Abbreviations	xvii
1 Introductory concepts	1
1.1 Stochastic and deterministic signals, concepts of stationarity and ergodicity	1
1.2 Discrete signals	4
1.2.1 The sampling theorem	4
1.2.1.1 Aliasing	5
1.2.2 Quantization error	5
1.3 Linear time invariant systems	7
1.4 Duality of time and frequency domain	9
1.4.1 Continuous periodic signal	10
1.4.2 Infinite continuous signal	10
1.4.3 Finite discrete signal	11
1.4.4 Basic properties of Fourier transform	11
1.4.5 Power spectrum: the Plancherel theorem and Parseval's theorem	12
1.4.6 Z-transform	13
1.4.7 Uncertainty principle	14
1.5 Hypotheses testing	15
1.5.1 The null and alternative hypothesis	15
1.5.2 Types of tests	16
1.5.3 Multiple comparison problem	17
1.5.3.1 Correcting the significance level	18
1.5.3.2 Parametric and nonparametric statistical maps	19
1.5.3.3 False discovery rate	20
1.6 Surrogate data techniques	20
2 Single channel (univariate) signal	23
2.1 Filters	23
2.1.1 Designing filters	25

2.1.2	Changing the sampling frequency	27
2.1.3	Matched filters	28
2.1.4	Wiener filter	29
2.2	Probabilistic models	30
2.2.1	Hidden Markov model	30
2.2.2	Kalman filters	31
2.3	Stationary signals	33
2.3.1	Analytic tools in the time domain	33
2.3.1.1	Mean value, amplitude distributions	33
2.3.1.2	Entropy and information measure	34
2.3.1.3	Autocorrelation function	34
2.3.2	Analytic tools in the frequency domain	35
2.3.2.1	Estimators of spectral power density based on Fourier transform	35
2.3.2.1.1	Choice of windowing function	36
2.3.2.1.2	Errors of Fourier spectral estimate	37
2.3.2.1.3	Relation of spectral density and the autocorrelation function	39
2.3.2.1.4	Bispectrum and bicoherence	39
2.3.2.2	Parametric models: AR, ARMA	40
2.3.2.2.1	AR model parameter estimation	41
2.3.2.2.2	Choice of the AR model order	42
2.3.2.2.3	AR model power spectrum	42
2.3.2.2.4	Parametric description of the rhythms by AR model, FAD method	45
2.4	Non-stationary signals	47
2.4.1	Instantaneous amplitude and instantaneous frequency	47
2.4.2	Analytic tools in the time-frequency domain	48
2.4.2.1	Time-frequency energy distributions	48
2.4.2.1.1	Wigner-Ville distribution	49
2.4.2.1.2	Cohen class	50
2.4.2.2	Time-frequency signal decompositions	52
2.4.2.2.1	Short time Fourier transform and spectrogram	52
2.4.2.2.2	Continuous wavelet transform and scalogram	54
2.4.2.2.3	Discrete wavelet transform	56
2.4.2.2.4	Dyadic wavelet transform—multiresolution signal decomposition	56
2.4.2.2.5	Wavelet packets	59
2.4.2.2.6	Wavelets in MATLAB	60
2.4.2.2.7	Matching pursuit—MP	60
2.4.2.2.8	Comparison of time-frequency methods	63
2.4.2.2.9	Empirical mode decomposition and Hilbert-Huang transform	65

2.5	Non-linear methods of signal analysis	66
2.5.1	Lyapunov exponent	67
2.5.2	Correlation dimension	68
2.5.3	Detrended fluctuation analysis	69
2.5.4	Recurrence plots	70
2.5.5	Poincaré map	72
2.5.6	Approximate and sample entropy	72
2.5.7	Limitations of non-linear methods	73
3	Multiple channels (multivariate) signals	75
3.1	Cross-estimators: cross-correlation, cross-spectra, coherence (ordinary, partial, multiple)	75
3.2	Multivariate autoregressive model (MVAR)	77
3.2.1	Formulation of MVAR model	77
3.2.2	MVAR in the frequency domain	79
3.3	Measures of directedness	80
3.3.1	Estimators based on the phase difference	80
3.3.2	Causality measures	81
3.3.2.1	Granger causality	81
3.3.2.2	Granger causality index	82
3.3.2.3	Directed transfer function	82
3.3.2.3.1	dDTF	84
3.3.2.3.2	SDTF	85
3.3.2.4	Partial directed coherence	85
3.4	Non-linear estimators of dependencies between signals	87
3.4.1	Non-linear correlation	87
3.4.2	Kullback-Leibler entropy, mutual information and transfer entropy	87
3.4.3	Generalized synchronization	89
3.4.4	Phase synchronization	89
3.4.5	Testing the reliability of the estimators of directedness	90
3.5	Comparison of the multichannel estimators of coupling between time series	91
3.6	Multivariate signal decompositions	95
3.6.1	Principal component analysis (PCA)	95
3.6.1.1	Definition	95
3.6.1.2	Computation	96
3.6.1.3	Possible applications	96
3.6.2	Independent components analysis (ICA)	97
3.6.2.1	Definition	97
3.6.2.2	Estimation	98
3.6.2.3	Computation	98
3.6.2.4	Possible applications	99
3.6.3	Multivariate matching pursuit (MMP)	99

4 Application to biomedical signals	101
4.1 Brain signals: local field potentials (LFP), electrocorticogram (ECoG), electroencephalogram (EEG), and magnetoencephalogram (MEG), event-related responses (ERP), and evoked fields (EF)	101
4.1.1 Generation of brain signals	103
4.1.2 EEG/MEG rhythms	105
4.1.3 EEG measurement, electrode systems	107
4.1.4 MEG measurement, sensor systems	109
4.1.5 Elimination of artifacts	109
4.1.6 Analysis of continuous EEG signals	115
4.1.6.1 Single channel analysis	116
4.1.6.2 Multiple channel analysis	117
4.1.6.2.1 Mapping	117
4.1.6.2.2 Measuring of dependence between EEG signals	118
4.1.6.3 Sleep EEG analysis	122
4.1.6.4 Analysis of EEG in epilepsy	129
4.1.6.4.1 Quantification of seizures	130
4.1.6.4.2 Seizure detection and prediction	133
4.1.6.4.3 Localization of an epileptic focus	137
4.1.6.5 EEG in monitoring and anesthesia	138
4.1.6.5.1 Monitoring brain injury by quantitative EEG	138
4.1.6.5.2 Monitoring of EEG during anesthesia	138
4.1.7 Analysis of epoched EEG signals	139
4.1.7.1 Analysis of phase locked responses	141
4.1.7.1.1 Time averaging	141
4.1.7.1.2 Influence of noise correlation	143
4.1.7.1.3 Variations in latency	143
4.1.7.1.4 Habituation	144
4.1.7.2 In pursuit of single trial evoked responses	145
4.1.7.2.1 Wiener filters	145
4.1.7.2.2 Model based approach	145
4.1.7.2.3 Time-frequency parametric methods	146
4.1.7.2.4 ERP topography	147
4.1.7.3 Analysis of non-phase locked responses	150
4.1.7.3.1 Event-related synchronization and desynchronization	150
4.1.7.3.2 Classical frequency band methods	151
4.1.7.3.3 Time-frequency methods	153
4.1.7.3.4 ERD/ERS in the study of iEEG	156
4.1.7.3.5 Event-related time-varying functional connectivity	158
4.1.7.3.6 Functional connectivity estimation from intracranial electrical activity	163

4.1.7.3.7 Statistical assessment of time-varying connectivity	166
4.1.8 Multimodal integration of EEG and fMRI signals	167
4.2 Heart signals	169
4.2.1 Electrocardiogram	169
4.2.1.1 Measurement standards	169
4.2.1.2 Physiological background and clinical applications	170
4.2.1.3 Processing of ECG	173
4.2.1.3.1 Artifact removal	173
4.2.1.3.2 Morphological ECG features	175
4.2.1.3.3 Spatial representation of ECG activity: body surface potential mapping and vectorcardiography	176
4.2.1.3.4 Statistical methods and models for ECG analysis	178
4.2.1.3.5 ECG patterns classification	179
4.2.2 Heart rate variability	180
4.2.2.1 Time-domain methods of HRV analysis	180
4.2.2.2 Frequency-domain methods of HRV analysis	181
4.2.2.3 Relation of HRV to other signals	183
4.2.2.4 Non-linear methods of HRV analysis	184
4.2.2.4.1 Empirical mode decomposition	185
4.2.2.4.2 Entropy measures	186
4.2.2.4.3 Detrended fluctuation analysis	187
4.2.2.4.4 Poincaré and recurrence plots	188
4.2.2.4.5 Effectiveness of non-linear methods	189
4.2.3 Fetal ECG	190
4.2.4 Magnetocardiogram and fetal magnetocardiogram	195
4.2.4.1 Magnetocardiogram	195
4.2.4.2 Fetal MCG	199
4.3 Electromyogram	200
4.3.1 Measurement techniques and physiological background	201
4.3.2 Quantification of EMG features	205
4.3.3 Decomposition of needle EMG	206
4.3.4 Surface EMG	210
4.3.4.1 Surface EMG decomposition	211
4.4 Gastro-intestinal signals	218
4.5 Acoustic signals	221
4.5.1 Phonocardiogram	221
4.5.2 Otoacoustic emissions	224
References	231
Index	291