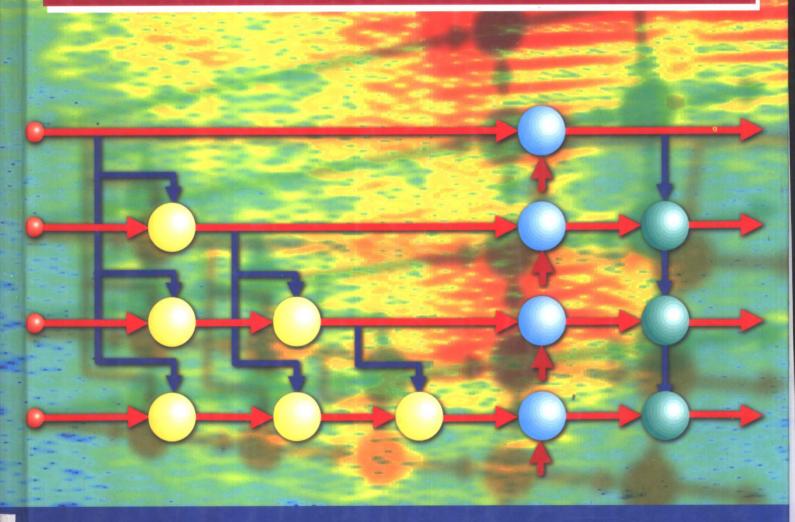
Statistical and Adaptive SIGNAL PROCESSING

Spectral Estimation, Signal Modeling, Adaptive Filtering and Array Processing



Dimitris G. Manolakis Vinay K. Ingle Stephen M. Kogon

Statistical and Adaptive Signal Processing

Spectral Estimation, Signal Modeling, Adaptive Filtering and Array Processing

Dimitris G. Manolakis

Massachusetts Institute of Technology Lincoln Laboratory

Vinay K. Ingle

Northeastern University

Stephen M. Kogon

Massachusetts Institute of Technology Lincoln Laboratory





STATISTICAL AND ADAPTIVE SIGNAL PROCESSING

Spectral Estimation, Signal Modeling, Adaptive Filtering and Array Processing

Copyright © 2000 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

This book is printed on acid-free paper.

234567890 QPKQPK 09876543210

ISBN 0-07-040051-2

Vice president/Editor-in-Chief: Kevin T. Kane

Publisher: Thomas Casson

Sponsoring editor: Catherine Fields
Editorial assistant: Michelle L. Flomenhoft
Senior marketing manager: John T. Wannemacher

Project manager: Amy Hill

Senior production supervisor: Rose Hepburn Freelance design coordinator: Pam Verros Supplement coordinator: Betty Hadala

Compositor: Techsetters, Inc. Typeface: 10/12 Times Roman

Printer: R. R. Donnelley & Sons Company

Library of Congress Cataloging-in-Publication Data

Manolakis, Dimitris G.

Statistical and adaptive signal processing: spectral estimation, signal modeling, adaptive filtering and array processing / D.

Manolakis, V. Ingle, S. Kogon.

p. cm. — (McGraw-Hill series in electrical and computer engineering. Computer engineering.)

ISBN 0-07-040051-2

1. Signal processing—Statistical methods. 2. Adaptive signal processing. 1. Ingle, Vinay K. II. Kogon, Stephen M.

III. Title. IV. Series TK5102.9.M36 2000 621.382'2—dc21

99-30380

http://www.mhhe.com

COMMUNICATIONS AND SIGNAL PROCESSING

Senior Consulting Editor

Stephen W. Director, University of Michigan, Ann Arbor

Auñón/Chandrasekar: Introduction to Probability and Random Processes

Antoniou: Digital Filters: Analysis and Design

Bose: Neural Network Fundamentals with Graphs, Algorithms, and Applications

Carlson: Communication Systems: An Introduction to Signals and Noise in Electrical

Communication

Cassandras: Discrete Event Systems Modeling and Performance Analysis

Cherin: An Introduction to Optical Fibers

Childers: Probability and Random Processes Using MATLAB

Collin: Antennas and Radiowave Propagation **Collin:** Foundations for Microwave Engineering

Cooper and McGillem: Modern Communications and Spread Spectrum

Davenport: Probability and Random Processes: An Introduction for Applied Scientists and

Engineers

Drake: Fundamentals of Applied Probability Theory

Gardner: Introduction to Random Processes

Jong: Method of Discrete Signal and System Analysis

Keiser: Local Area Networks

Keiser: Optical Fiber Communications

Kershenbaum: Telecommunication Network Design and Algorithms

Kraus: Antennas

Kuc: Introduction to Digital Signal Processing Lee: Mobile Communications Engineering Lindner: Introduction to Signals and Systems

Mitra: Digital Signal Processing: A Computer-Based Approach
Papoulis: Probability, Random Variables, and Stochastic Processes

Papoulis: Signal Analysis

Papoulis: The Fourier Integral and Its Applications

Parsons: Voice and Speech Processing

Peebles: Probability, Random Variables, and Random Signal Principles

Powers: An Introduction to Fiber Optic Systems

Proakis: Digital Communications **Russell:** Telecommunications Protocols

Schwartz: Information Transmission, Modulation, and Noise

Siebert: Circuits, Signals, and Systems **Smith:** Modern Communication Circuits

Taub and Schilling: Principles of Communication Systems

Taylor: Principles of Signals and Systems **Taylor:** Hands-On Digital Signal Processing

Viterbi and Omura: Principles of Digital Communications and Coding

Viniotis: Probability and Random Processes Walrand: Communications Networks

Waters: Active Filter Design

ABOUT THE AUTHORS

DIMITRIS G. MANOLAKIS, a native of Greece, received his education (B.S. in physics and Ph.D. in electrical engineering) from the University of Athens, Greece. He is currently a member of the technical staff at MIT Lincoln Laboratory, in Lexington, Massachusetts. Previously, he was a Principal Member, Research Staff, at Riverside Research Institute. Dr. Manolakis has taught at the University of Athens, Northeastern University, Boston College, and Worcester Polytechnic Institute; and he is coauthor of the textbook *Digital Signal Processing: Principles, Algorithms, and Applications* (Prentice-Hall, 1996, 3d ed.). His research experience and interests include the areas of digital signal processing, adaptive filtering, array processing, pattern recognition, and radar systems.

VINAY K. INGLE is Associate Professor of Electrical and Computer Engineering at Northeastern University. He received his Ph.D. in electrical and computer engineering from Rensselaer Polytechnic Institute in 1981. He has broad research experience and has taught courses on topics including signal and image processing, stochastic processes, and estimation theory. Professor Ingle is coauthor of the textbooks *DSP Laboratory Using the ADSP-2101 Microprocessor* (Prentice-Hall, 1991) and *DSP Using Matlab* (PWS Publishing Co., Boston, 1996).

STEPHEN M. KOGON received the Ph.D. degree in electrical engineering from Georgia Institute of Technology. He is currently a member of the technical staff at MIT Lincoln Laboratory in Lexington, Massachusetts. Previously, he has been associated with Raytheon Co., Boston College, and Georgia Tech Research Institute. His research interests are in the areas of adaptive processing, array signal processing, radar, and statistical signal modeling.

To my beloved wife, Anna, and to the loving memory of my father, Gregory. DGM

To my beloved wife, Usha, and adoring daughters, Natasha and Trupti. VKI

To my wife and best friend, Lorna, and my children, Gabrielle and Matthias. SMK

One must learn by doing the thing; for though you think you know it You have no certainty, until you try.
—Sophocles, Trachiniae

PREFACE

The principal goal of this book is to provide a unified introduction to the theory, implementation, and applications of statistical and adaptive signal processing methods. We have focused on the key topics of spectral estimation, signal modeling, adaptive filtering, and array processing, whose selection was based on the grounds of theoretical value and practical importance. The book has been primarily written with students and instructors in mind. The principal objectives are to provide an introduction to basic concepts and methodologies that can provide the foundation for further study, research, and application to new problems. To achieve these goals, we have focused on topics that we consider fundamental and have either multiple or important applications.

APPROACH AND PREREQUISITES

The adopted approach is intended to help both students and practicing engineers understand the fundamental mathematical principles underlying the operation of a method, appreciate its inherent limitations, and provide sufficient details for its practical implementation. The academic flavor of this book has been influenced by our teaching whereas its practical character has been shaped by our research and development activities in both academia and industry. The mathematical treatment throughout this book has been kept at a level that is within the grasp of upper-level undergraduate students, graduate students, and practicing electrical engineers with a background in digital signal processing, probability theory, and linear algebra.

ORGANIZATION OF THE BOOK

Chapter 1 introduces the basic concepts and applications of statistical and adaptive signal processing and provides an overview of the book. Chapters 2 and 3 review the fundamentals of discrete-time signal processing, study random vectors and sequences in the time and frequency domains, and introduce some basic concepts of estimation theory. Chapter 4 provides a treatment of parametric linear signal models (both deterministic and stochastic) in the time and frequency domains. Chapter 5 presents the most practical methods for the estimation of correlation and spectral densities. Chapter 6 provides a detailed study of the theoretical properties of optimum filters, assuming that the relevant signals can be modeled as stochastic processes with known statistical properties; and Chapter 7 contains algorithms and structures for optimum filtering, signal modeling, and prediction. Chapter

Preface

8 introduces the principle of least-squares estimation and its application to the design of practical filters and predictors. Chapters 9, 10, and 11 use the theoretical work in Chapters 4, 6, and 7 and the practical methods in Chapter 8, to develop, evaluate, and apply practical techniques for signal modeling, adaptive filtering, and array processing. Finally, Chapter 12 introduces some advanced topics: definition and properties of higher-order moments, blind deconvolution and equalization, and stochastic fractional and fractal signal models with long memory. Appendix A contains a review of the matrix inversion lemma, Appendix B reviews optimization in complex space, Appendix C contains a list of the MATLAB functions used throughout the book, Appendix D provides a review of useful results from matrix algebra, and Appendix E includes a proof for the minimum-phase condition for polynomials.

USE OF THE BOOK

This book can be used in a number of different ways to teach either one-semester or two-semester graduate courses in a typical electrical engineering curriculum. Most topics in the book can be covered in a two-semester course on statistical and adaptive signal processing. Typical one-term courses are outlined in the following table:

Courses	Chapters
Discrete-time random signals and statistical signal processing	Review of Chapters 1, 2, and 3; Sections 4.1–4.4, 6.1–6.6
Spectrum estimation and signal modeling	Review of Chapters 1, 2, and 3; Chapters 4 and 5, Sections 6.1–6.5, 7.4–7.5, 8.1–8.9, Chapter 9, and possibly Sections 12.1, 12.5–12.6
Adaptive filtering	Review of Chapters 1, 2, and 3; Chapters 6, 7, 8, 10, and Sections 12.1–12.4
Introduction to array processing	Review of Chapter 3, Sections 6.1~6.5, review of Section 2.2, Sections 5.1, 11.1–11.4. Chapter 8, Sections 9.5, 9.6, 11.5, 11.6, 11.7

THEORY AND PRACTICE

It is our belief that sound theoretical understanding goes hand-in-hand with practical implementation and application to real-world problems. Therefore, the book includes a large number of computer experiments that illustrate important concepts and help the reader to easily implement the various methods. Every chapter includes examples, problems, and computer experiments that facilitate the comprehension of the material. To help the reader understand the theoretical basis and limitations of the various methods and apply them to real-world problems, we provide MATLAB functions for all major algorithms and examples illustrating their use. The MATLAB files and additional material about the book can be found at http://www.mhhe.com/catalogs/0070400512.mhtml. A Solutions Manual with detailed solutions to all the problems is available to the instructors adopting the book for classroom use.

FEEDBACK

Although we are fully aware that there always exists room for improvement, we believe that this book is a big step forward for an introductory textbook in statistical and adaptive signal processing. However, as engineers, we know that every search for the optimum

xix

Preface

ACKNOWLEDGMENTS

We are indebted to a number of individuals who have contributed in different, but important, ways to the shaping of our knowledge in general and the preparation of this book in particular. In this respect we wish to extend our appreciation to C. Caroubalos, G. Carayannis, J. Makhoul (DGM), M. Schetzen (VKI), and J. Holder, S. Krich, and D. Williams (SMK). We are grateful to E. Baranoski, G. Borsari, J. Schodorf, S. Smith, A. Steinhardt, and J. Ward for helping us to improve the presentation in various parts of the book.

We express our sincere gratitude to Kevin Donohue, University of Kentucky; Amro El-Jaroudi, University of Pittsburgh; Edward A. Lee, University of California-Berkeley; Ray Liu, University of Maryland; Randy Moses, The Ohio State University; and Kristina Ropella, Marquette University, for their constructive and helpful reviews.

Lynn Cox persuaded us to choose McGraw-Hill, Inc., as our publisher, and we have not regretted that decision. We are grateful to Lynn for her enthusiasm and her influence in shaping the scope and the objectives of our book. The fine team at McGraw-Hill, including Michelle Flomenhoft, Catherine Fields, Betsy Jones, and Nina Kreiden, has made the publication of this book an exciting and pleasant experience. We also thank N. Bulock and Mathworks, Inc., for promptly providing various versions of Matlab and A. Turcotte for helping with some of the drawings in the book.

Last, but not least, we would like to express our sincere appreciation to our families for their full-fledged support and understanding over the past several years. We fully realize that the completion of such a project would not be possible without their continual sustenance and encouragement.

Dimitris G. Manolakis Vinay K. Ingle Stephen M. Kogon

BRIEF CONTENTS

Contents	х
Preface	xvii
1 Introduction	1
2 Fundamentals of Discrete-Time Signal Processing	33
3 Random Variables, Vectors, and Sequences	75
4 Linear Signal Models	149
5 Nonparametric Power Spectrum Estimation	195
6 Optimum Linear Filters	26 1
7 Algorithms and Structures for Optimum Linear Filters	333
8 Least-Squares Filtering and Prediction	395
9 Signal Modeling and Parametric Spectral Estimation	445
10 Adaptive Filters	499
11 Array Processing	621
12 Further Topics	691
Appendix A Matrix Inversion Lemma	745
Appendix B Gradients and Optimization in Complex Space	e 747
Appendix C MATLAB Functions	753
Appendix D Useful Results from Matrix Algebra	755
Appendix E Minimum Phase Test for Polynomials	767
Bibliography	769
Index	78 7

CONTENTS

Preface		Xvii	2.3	Discrete-Time Systems	47
1 Int	roduction	1		2.3.1 Analysis of Linear, Time-Invariant Systems / 2.3.2 Response to Periodic Inputs / 2	3 .3
1.1	Random Signals	1		Correlation Analysis and Spectra	
1.2	Spectral Estimation	8	2.4	Density	
1.3	Signal Modeling	11	2.4	Minimum-Phase and System Invertibility	54
	1.3.1 Rational or Pole-Zero Models / 1.3.2 Fractional Pole-Zero Models and Fractal Models			2.4.1 System Invertibility and Minimum-Phase Systems / 2.4.2 All-Pass Systems / 2.4.3 Minimum-Phase and All-Pass	31
1.4	Adaptive Filtering	16		Decomposition / 2.4.4 Spectral	
	1.4.1 Applications of Adaptive			Factorization	
	Filters / 1.4.2 Features of		2.5	Lattice Filter Realizations	64
1.5	Adaptive Filters Array Processing	25		2.5.1 All-Zero Lattice Structures 2.5.2 All-Pole Lattice Structures	/
	1.5.1 Spatial Filtering or		2.6	Summary	70
	Beamforming / 1.5.2 Adaptive Interference Mitigation in Radar Systems / 1.5.3 Adaptive		1 D	Problems	70
	Sidelobe Canceler			ndom Variables, Vectors, Sequences	75
1.6	Organization of the Book	29	ų rio	bequences	
	ndamentals of Discrete- ne Signal Processing	33	3.1	Random Variables 3.1.1 Distribution and Density Functions / 3.1.2 Statistical	75
2.1	Discrete-Time Signals	33		Averages / 3.1.3 Some Useful Random Variables	
	2.1.1 Continuous-Time, Discrete- Time, and Digital Signals /	-	3.2	Random Vectors	83
2.2	2.1.2 Mathematical Description of Signals / 2.1.3 Real-World Signal Transform-Domain			3.2.1 Definitions and Second-Orde Moments / 3.2.2 Linear Transformations of Random	e r
	Representation of Deterministic Signals	37		Vectors / 3.2.3 Normal Random Vectors / 3.2.4 Sums of Independent Random Variables	ent
	2.2.1 Fourier Transforms and Fourier Series / 2.2.2 Sampling of Continuous-Time Signals /		3.3	Discrete-Time Stochastic Processes	97
	2.2.3 The Discrete Fourier Transform / 2.2.4 The z-Transform / 2.2.5 Representation of Narrowband Signals	on		3.3.1 Description Using Probability Functions / 3.3.2 Second-Order Statistical Description / 3.3.3 Stationarity /	,

	3.3.4 Ergodicity / 3.3.5 Rando	m	4.4	Pole-Zero Models	177
	Signal Variability / 3.3.6 Frequency-Domain Description of Stationary Processes	ı		4.4.1 Model Properties / 4.4.2 Autoregressive Moving-Average Models / 4.4.3 The First-Order	
3.	4 Linear Systems with Stationary Random Inputs	115		Pole-Zero Model 1: PZ (1,1) / 4.4.4 Summary and Dualities	
	3.4.1 Time-Domain Analysis / 3.4.2 Frequency-Domain Analy		4.5	Models with Poles on the Unit Circle	182
	3.4.3 Random Signal Memory 3.4.4 General Correlation Matrices / 3.4.5 Correlation	/	4.6	Cepstrum of Pole-Zero Models	184
3.5	Matrices from Random Process Innovations Representation	es		4.6.1 Pole-Zero Models / 4.6.2 All-Pole Models / 4.6.3 All-Zero Mod 189	9
	of Random Vectors	125	4.7	Summary	100
	3.5.1 Transformations Using Eigen-decomposition / 3.5.2		4. /	Problems	189 189
	Transformations Using Triangular Decomposition / 3.5.3 The Discrete Karhunen- Loève Transform		5 No	nparametric Power	
3.6	Principles of Estimation		Spe	ectrum Estimation	195
3.0	Theory	133			
	3.6.1 Properties of Estimators /		5.1	Spectral Analysis of Deterministic Signals	196
	3.6.2 Estimation of Mean /			5.1.1 Effect of Signal Sampling /	
	3.6.3 Estimation of Variance			5.1.2 Windowing, Periodic	
3. 7	Summary	142		Extension, and Extrapolation /	
	Problems	143		5.1.3 Effect of Spectrum Sampling / 5.1.4 Effects of	
4 Lir	near Signal Models	149		Windowing: Leakage and Loss of Resolution / 5.1.5 Summary	
4.1	Introduction	149	5.2	Estimation of the Autocorrelation of	
	4.1.1 Linear Nonparametric Signal Models / 4.1.2 Parametr	ic		Stationary Random Signals	209
	Pole-Zero Signal Models / 4.1.3		5.3	Estimation of the Power	
	Mixed Processes and the Wold Decomposition			Spectrum of Stationary Random Signals	212
4.2		156		5.3.1 Power Spectrum Estimation	
	4.2.1 Model Properties /			Using the Periodogram / 5.3.2	
	4.2.2 All-Pole Modeling and			Power Spectrum Estimation by	
	Linear Prediction / 4.2.3			Smoothing a Single Periodogram- The Blackman-Tukey Method /	_
	Autoregressive Models / 4.2.4 Lower-Order Models			5.3.3 Power Spectrum Estimation	
43	All-Zero Models	172		by Averaging Multiple	
7.0	4.3.1 Model Properties / 4.3.2	172		Periodograms—The Welch- Bartlett Method / 5.3.4 Some	
	Moving-Average Models / 4.3.3			Practical Considerations and	
	Lower-Order Models			Examples	

Contents

Contents

5.4	Joint Signal Analysis	237		Linear Prediction Using the Infinite Past—Whitening	
	5.4.1 Estimation of Cross-Power Spectrum / 5.4.2 Estimation of Frequency Response Functions		6.7	Inverse Filtering and Deconvolution	306
5.5	Multitaper Power Spectrum Estimation	246	6.8	Channel Equalization in Data Transmission Systems	a 310
	5.5.1 Estimation of Auto Power Spectrum / 5.5.2 Estimation of Cross Power Spectrum			6.8.1 Nyquist's Criterion for Zen 1SI / 6.8.2 Equivalent Discrete- Channel Model / 6.8.3 Linear	
5.6	Summary	254		Equalizers / 6.8.4 Zero-Forcing	
	Problems	255		Equalizers / 6.8.5 Minimum MS Equalizers	E
6 Op	timum Linear Filters	261	6.9	Matched Filters and Eigenfilters	319
6.1	Optimum Signal Estimation	261		6.9.1 Deterministic Signal in Noi 6.9.2 Random Signal in Noise	se /
62	Linear Mean Square	201	6.10	Summary	325
0.2	Error Estimation	264		Problems	325
	6.2.2 Derivation of the Linear MMSE Estimator / 6.2.3 Princip Component Analysis of the Optin Linear Estimator / 6.2.4 Geome Interpretations and the Principle Orthogonality / 6.2.5 Summary and Further Properties	num tric	for	7.1.1 Matrix Partitioning and	334
6.3	Solution of the Normal Equations	274		Optimum Nesting / 7.1.2 Inversi of Partitioned Hermitian Matrice 7.1.3 Levinson Recursion for the	
6.4	Optimum Finite Impulse Response Filters 6.4.1 Design and Properties / 6.4.2 Optimum FIR Filters for Stationary Processes / 6.4.3	278		Optimum Estimator / 7.1.4 Order Recursive Computation of the LD Decomposition / 7.1.5 Order- Recursive Computation of the Optimum Estimate	
	Frequency-Domain Interpretation	ıs	7.2	Interpretations of	
6.5	Linear Prediction	286			343
6,6	6.5.1 Linear Signal Estimation / 6.5.2 Forward Linear Prediction 6.5.3 Backward Linear Prediction 6.5.4 Stationary Processes / 6.5.5 Properties Optimum Infinite Impulse	/		7.2.1 Innovations and Backward Prediction / 7.2.2 Partial Correlation / 7.2.3 Order Decomposition of the Optimum Estimate / 7.2.4 Gram-Schmidt Orthogonalization	
3.0	Response Filters 6.6.1 Noncausal IIR Filters / 6.6.2 Causal IIR Filters / 6.6.3 Filtering of Additive Noise / 6.6.	295 4		Order-Recursive Algorithms for Optimum FIR Filters 7.3.1 Order-Recursive Computation of the Optimum Filter / 7.3.2	347 on

		Lattice-Ladder Structure / 7.3 Simplifications for Stationary	.3	8.	4 Linear Least-Squares Signal Estimation	411
		Stochastic Processes / 7.3.4 Algorithms Based on the UDU Decomposition	Н		8.4.1 Signal Estimation and Lin Prediction / 8.4.2 Combined Forward and Backward Linear	iear
	7.4	Algorithms of Levinson and Levinson-Durbin	355		Prediction (FBLP) / 8.4.3 Narrowband Interference	
	7.5	Lattice Structures for Optimum FIR Filters and Predictors	361	8.2	Cancelation LS Computations Using the Normal Equations	416
		7.5.1 Lattice-Ladder Structures 7.5.2 Some Properties and Interpretations / 7.5.3 Parame			8.5.1 Linear LSE Estimation / 8.5.2 LSE FIR Filtering and Prediction	
	7.6	Conversions Algorithm of Schür	368	8.0	LS Computations Using Orthogonalization Techniques	422
		7.6.1 Direct Schür Algorithm / 7.6.2 Implementation Considerations / 7.6.3 Inverse Schür Algorithm			8.6.1 Householder Reflections / 8.6.2 The Givens Rotations / 8. Gram-Schmidt Orthogonalization	6.3
	7. 7	Triangularization and Invers of Toeplitz Matrices	sion 374	8.7	LS Computations Using the Singular Value Decomposition	431
		7.7.1 LDL ^H Decomposition of Inverse of a Toeplitz Matrix / 7.7.2 LDL ^H Decomposition of a Toeplitz Matrix / 7.7.3 Inversion of Real Toeplitz Matrice			8.7.1 Singular Value Decomposition / 8.7.2 Solution of the LS Problem / 8.7.3 Rank-Deficient LS Problems	
	7.8	Kalman Filter Algorithm	378	8.8	Summary	438
		7.8.1 Preliminary Development 7.8.2 Development of Kalman F			Problems	439
	7.9	Summary	387			
		Problems	389	and	mal Modeling d Parametric ectral Estimation	445
8		st-Squares Filtering Prediction	395	9.1	The Modeling Process: Theory and Practice	445
	8.1	The Principle of Least		9.2	Estimation of All-Pole Models	449
	8.2	Squares Linear Least-Squares Error Estimation 8.2.1 Derivation of the Normal	395 396		9.2.1 Direct Structures / 9.2.2 Lattice Structures / 9.2.3 Maximum Entropy Method / 9.2 Excitations with Line Spectra	.4
		Equations / 8.2.2 Statistical Properties of Least-Squares Estimators		9.3	Estimation of Pole-Zero Models	462
	8.3	Least-Squares FIR Filters	406		9.3.1 Known Excitation / 9.3.2 Unknown Excitation / 9.3.3	

xiii Contents

\sim		
Co	nte	nts

	Nonunear Least-squares Optimization		10.5	Adaptive Filters	548
9.	4 Applications 9.4.1 Spectral Estimation / 9.4.2 Speech Modeling	467		10.5.1 LS Adaptive Filters / 10.5.2 Conventional Recurs Least-Squares Algorithm /	ive 10.5.3
	5 Minimum-Variance Spectrum Estimation	471		Some Practical Consideration 10.5.4 Convergence and Performance Analysis	ons /
9.0	6 Harmonic Models and Frequency Estimation Techniques	478	10.6	RLS Algorithms for Array Processing	560
	9.6.1 Harmonic Model / 9.6.2 Pisarenko Harmonic Decomposition / 9.6.3 MUS. Algorithm / 9.6.4 Minimum- Method / 9.6.5 ESPRIT Algo	Norm		10.6.1 LS Computations Usi the Cholesky and QR Decompositions / 10.6.2 To Useful Lemmas / 10.6.3 Th QR-RLS Algorithm / 10.6.4 Extended QR-RLS	vo
9.7	7 Summary	493		Algorithm / 10.6.5 The Inve	
	Problems	494		QR-RLS Algorithm / 10.6.6 Implementation of QR-RLS Algorithm Using the Givens	
	laptive Filters	499		Rotations / 10.6.7 Implement of Inverse QR-RLS Algorithm	n
10	Adaptive Filters	500		Using the Givens Rotations 10.6.8 Classification of RLS Algorithms for Array Proces	
	10.1.1 Echo Cancelation in Communications / 10.1.2 Equalization of Data Communications Channels 10.1.3 Linear Predictive Co 10.1.4 Noise Cancelation		10.7	Fast RLS Algorithms for FIR Filtering 10.7.1 Fast Fixed-Order RLS Filters / 10.7.2 RLS Lattice- Ladder Filters / 10.7.3 RLS	573 S FIR
10.	2 Principles of Adaptive Filters	506		Lattice-Ladder Filters Using Feedback Updatings / 10.7.	Error 4
	10.2.1 Features of Adaptive Filters / 10.2.2 Optimum v Adaptive Filters / 10.2.3 St and Steady-State Performan	ability		Givens Rotation–Based LS L Ladder Algorithms / 10.7.5 Classification of RLS Algorit for FIR Filtering	
	Adaptive Filters / 10.2.4 So Practical Considerations	ome		Tracking Performance of Adaptive Algorithms	590
10.	3 Method of Steepest Descent	516		10.8.1 Approaches for Nonstationary SOE / 10.8.2	
10.	4 Least-Mean-Square Adaptive Filters	524		Preliminaries in Performance Analysis / 10.8.3 The LMS Algorithm / 10.8.4 The RLS	
	10.4.1 Derivation / 10.4.2 Adaptation in a Stationary S 10.4.3 Summary and Design			Algorithm with Exponential Forgetting / 10.8.5 Compari of Tracking Performance	
	Guidelines / 10.4.4 Applica of the LMS Algorithm / 10.4		10.9	Summary	607
	Some Practical Consideration			Problems	608

Arra	ny Processing	621	11.8	Space-Time AdaptiveProcessing	683
11.1	Array Fundamentals	622	11.9	Summary	685
	11.1.1 Spatial Signals / 11.1. Modulation-Demodulation / 11.1.3 Array Signal Model /			Problems	686
	11.1,4 The Sensor Array: Spat Sampling	rial	12 Fur	ther Topics	691
11.2	Conventional Spatial Filtering: Beamforming	631	12.1	Higher-Order Statistics in Signal Processing	691
	11.2.1 Spatial Matched Filter 11.2.2 Tapered Beamforming	/		12.1.1 Moments, Cumulants, Polyspectra / 12.1.2 Higher-	
11.3	Optimum Array Processing	641		Order Moments and LTI Syste 12.1.3 Higher-Order Moment Linear Signal Models	
	11.3.1 Optimum Beamforming 11.3.2 Eigenanalysis of the	/	12.2		697
	Optimum Beamformer / 11.3. Interference Cancelation Performance / 11.3.4 Tapered Optimum Beamforming / 11.3	ı	12.3	Unsupervised Adaptive Filters—Blind Equalizers 12.3.1 Blind Equalization /	702
11.4	The Generalized Sidelobe Cand Performance			12.3.2 Symbol Rate Blind Equalizers / 12.3.3 Constant	-
11.7	Considerations for Optimum Beamformers	652	12.4	Modulus Algorithm Fractionally Spaced Equalizers	709
	11.4.1 Effect of Signal Mismate 11.4.2 Effect of Bandwidth			12.4.1 Zero-Forcing Fractional Spaced Equalizers / 12.4.2	ılly
11.5	Adaptive Beamforming 11.5.1 Sample Matrix Inversion 11.5.2 Diagonal Loading with			MMSE Fractionally Spaced Equalizers / 12.4.3 Blind Fractionally Spaced Equalizer	rc
	SMI Beamformer / 11.5.3 Implementation of the SMI		12.5	Fractional Pole-Zero Signal Models	716
	Beamformer / 11.5.4 Sample-l Sample Adaptive Methods	by-		12.5.1 Fractional Unit-Pole Model / 12.5.2 Fractional Po	le-
11.6	Other Adaptive Array Processing Methods	671		Zero Models: FPZ (p, d, q) / 12.5.3 Symmetric α-Stable Fractional Pole-Zero Processe	· c
	11.6.1 Linearly Constrained Minimum-Variance Beamforme 11.6.2 Partially Adaptive Array 11.6.3 Sidelobe Cancelers		12.6	Self-Similar Random Signal Models 12.6.1 Self-Similar Stochastic	725
	Angle Estimation 11.7.1 Maximum-Likelihood Angle Estimation / 11.7.2 Cramér-Rao Lower Bound on Angle Accuracy / 11.7.3 Beamsplitting Algorithms / 11.7.4 Model-Based Methods	678		Processes / 12.6.2 Fractional Brownian Motion / 12.6.3 Fractional Gaussian Noise / 12.6.4 Simulation of Fractional Brownian Motions and Fractional Gaussian Noises / 12.6.5 Estimation of Long Memory /	ıl onal

χv

Contents

11

Definitions

xvi

Contents