

Handbook of Signal Processing in Acoustics

Volume 1

Edited by

David Havelock

National Research Council, Canada

Sonoko Kuwano

Osaka University, Japan

Michael Vorländer

RWTH Aachen University, Germany

Handbook of Signal Processing in Acoustics

Volume 1

 Springer

Editors

David Havelock
National Research Council
Institute for Microstructural
Sciences
Acoustics and Signal
Processing Group
1200 Montreal Road
Ottawa ON K1A 0R6
Canada

Sonoko Kuwano
Osaka University
Graduate School of Human
Sciences
Department of Environmental
Psychology
1-2 Yamadaok Suita
Osaka
Japan

Michael Vorländer
RWTH Aachen University
Institute of Technical Acoustics
Aachen
Germany

ISBN: 978-0-387-77698-9

e-ISBN: 978-0-387-30441-0

Library of Congress Control Number: 2008923573

© 2008 Springer Science+Business Media, LLC

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Editor Biographies

David Havelock

National Research Council
Institute for Microstructural Sciences
Acoustics and Signal Processing Group
1200 Montreal Road
Ottawa ON K1A 0R6
Canada

Sonoko Kuwano

Osaka University
Graduate School of Human Sciences
Department of Environmental Psychology
1-2 Yamadaok Suita
Osaka
Japan

Michael Vorländer

RWTH Aachen University
Institute of Technical Acoustics
Aachen
Germany

Editorial Board

Last Name	Given Name(s)	Affiliation/Address
Beauchamp	James W.	University of Illinois Urbana-Champaign, School of Music, Dept. of ECE, Urbana, IL, USA
Christie	Douglas R.	Earth Physics, Research School of Earth Sciences, The Australian National University, Canberra, AUSTRALIA
Deffenbaugh	Max	ExxonMobil Research and Engineering Company, Annandale, NJ USA
Elliott	Stephen J.	Southampton University, Institute of Sound and Vibration Research, Southampton, ENGLAND
Fastl	Hugo	Technische Universitaet Muenchen AG Technische Akustik, MMK Muenchen, GERMANY
Gierlich	Hans Wilhelm	HEAD acoustics GmbH Telecom Division, Herzogenrath, GERMANY
Guyader	Jean-Louis	Labratory for Vibration Acoustics Villeurbanne, FRANCE
Jacobsen	Finn	Technical University of Denmark, Lyngby, DENMARK
Karjalainen	Matti	Helsinki University of Technology, FINLAND
Kollmeier	Birger	Universitat Oldenburg, Oldenburg, GERMANY
O'Shaughnessy	Douglas D.	INRS-EMT (Telecommunications), Montreal, QC, CANADA
Riquimaroux	Hiroshi	Doshisha University, Department of Knowledge Engineering & Computer Sciences, Sensory & Cognitive Neuroscience Research Laboratory, Kyotanabe, Kyoto, JAPAN
Sullivan	Edmund J.	EJS Consultants Portsmouth, RI, USA

Last Name	Given Name(s)	Affiliation/Address
Suzuki	Hideo	1-2-3-S2502, Utase, Mihama-ward, Chiba-city, JAPAN 261-0013
Taroudakis	Michael	University of Crete Department of Mathematics, and FORTH, Institute of Applied and Computational Mathematics, Heraklion, GREECE
Ueha	Sadayuki	Tokyo Institute of Technology, Director, Precision and Intelligence Lab, Yokohama, JAPAN
Verrillo	Ronald T.	(deceased) Institute for Sensory Research, Syracuse, NY, USA
Yamada	Ichiro	Aviation Environment Research Center, Airport Environment Improvement Foundation, Tokyo, JAPAN
Yamasaki	Yoshio	Waseda University, Graduate School of Global Information and Telecommunication Studies, Saitama, JAPAN
Tohyama	Mikio	Waseda University, JAPAN

Preface

Acoustics has a special relationship with signal processing. Many concepts in signal processing arise naturally from our general experience with sound and vibration and, more than in many other fields, acoustics is concerned with the acquisition, analysis, and synthesis of signals. Consequently, there is a rich resource of signal processing expertise within the acoustics community.

There are many excellent reference books devoted to signal processing but the objective of the *Handbook of Signal Processing in Acoustics* is to bring together the signal processing expertise specific to acoustics and to capture the interdisciplinary nature of signal processing within acoustics. It is also hoped that the handbook will promote networking and the interchange of ideas between technical areas in acoustics.

The handbook comprises 104 *Chapters* organized into 17 *Parts*. Each *Part* addresses a technical area of acoustics, reflecting the general demarcations of specialization within the acoustics community. An expert with broad knowledge of signal processing within their respective technical area was invited to act as a Section Leader for each *Part* of the handbook. These Section Leaders contributed substantially to the handbook project by helping to define the contents and scope of each chapter, finding an appropriate contributing expert author, and managing the review and revision of material. Collectively with the Editors, they form the Editorial Board for the handbook.

Planned sections on Architectural Acoustics, Nonlinear Acoustics, and Ultrasound are unfortunately omitted from the handbook; nevertheless, the handbook otherwise provides thorough coverage of the field of acoustics and we can hope that possible future editions might include these areas.

The handbook is written from the perspective of acoustics, by acousticians with signal processing expertise. Emphasis is placed

in the description of acoustic problems and the signal processing related to their solutions. The reader is assumed to have basic knowledge of signal processing. Signal processing techniques are described but the reader is referred elsewhere for derivations and details.

The authors were not required to adhere to strict standards of style or notation, and were asked to prepare short, concise, self-sufficient chapters. This results in variations in style and notation throughout the handbook that reflects the diversity of perspectives within the acoustics community.

David Havelock

Acknowledgments

David Havelock gratefully acknowledges support from the Institute for Microstructural Sciences, of the National Research Council of Canada, for making time and resources available during the preparation of this handbook. He also thanks John C. Burgess (University of Hawaii, retired) for the encouragement to begin this project and expresses his gratitude to the co-Editors, Sonoko Kuwano and Michael Vorländer, who were a pleasure to work with throughout this project. The efforts of all of the Section Leaders are greatly appreciated and we thank each of them sincerely for their patience, perseverance, and faith that were required to see this project to completion. We thank each of the authors for their contributions.

Contents

Editor Biographies	v
Editorial Board	vii
Preface	ix
Acknowledgments	xi
Contributors	xvii
 PART I ACOUSTIC SIGNALS AND SYSTEMS	 1
1 Signals and Systems	3
2 Acoustic Data Acquisition	17
3 Spectral Analysis and Correlation	33
4 The FFT and Tone Identification	53
5 Measuring Transfer-Functions and Impulse Responses	65
6 Digital Sequences	87
7 Filters	107
8 Adaptive Processing	125
9 Beamforming and Wavenumber Processing	131

PART II	AUDITORY SYSTEM AND HEARING	145
10	Anatomy, Physiology and Function of the Auditory System	147
11	Physiological Measures of Auditory Function	159
12	Auditory Processing Models	175
13	Speech Intelligibility	197
14	Signal Processing in Hearing Aids	205
PART III	PSYCHOACOUSTICS	213
15	Methods for Psychoacoustics in Relation to Long-Term Sounds	215
16	Masking and Critical Bands	229
17	Aspects of Modeling Pitch Perception	241
18	Calculation of Loudness for Normal and Hearing-Impaired Listeners	251
19	Psychoacoustical Roughness	263
PART IV	MUSICAL ACOUSTICS	275
20	Automatic Music Transcription	277
21	Music Structure Analysis from Acoustic Signals	305
22	Computer Music Synthesis and Composition	333
23	Singing Voice Analysis, Synthesis, and Modeling	359
24	Instrument Modeling and Synthesis	375
25	Digital Waveguide Architectures for Virtual Musical Instruments	399
26	Modeling of Musical Instruments	419

PART V SPEECH	447
27 Display and Analysis of Speech	449
28 Estimation of Speech Intelligibility and Quality	483
29 Gaussian Models in Automatic Speech Recognition	521
30 Speech Synthesis	557
31 Speech Coders	587
 PART VI AUDIO ENGINEERING	 621
32 Transducer Models	623
33 Loudspeaker Design and Performance Evaluation	649
34 PA Systems for Indoor and Outdoor	669
35 Beamforming for Speech and Audio Signals	691
36 Digital Audio Recording Formats and Editing Principles	703
37 Audiovisual Interaction	731
38 Multichannel Sound Reproduction	747
39 Virtual Acoustics	761
40 Audio Restoration	773
41 Audio Effects Generation	785
42 Perceptually Based Audio Coding	797
 PART VII TELECOMMUNICATIONS	 819
43 Speech Communication and Telephone Networks	821
44 Methods of Determining the Communicational Quality of Speech Transmission Systems	831

45 Efficient Speech Coding and Transmission Over Noisy Channels	853
46 Echo Cancellation	883
47 Noise Reduction and Interference Cancellation	897
48 Terminals and Their Influence on Communication Quality	909
49 Networks and Their Influence on Communication Quality	915
50 Interaction of Terminals, Networks and Network Configurations	921
List of Important Abberviations	927

Contributors

Tomonari Akamatsu

National Research Institute of Fisheries Engineering, Fisheries Research Agency of Japan, Kamisu, Ibaraki, Japan

Benoit Alcoverro

CEA/DASE, BP 12, 91680 Bruyères Le Châtel, France

Lydia Ayers

Computer Science Department, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China, e-mail: layers@cs.ust.hk

Juha Reinhold Backman

Nokia, Espoo, Finland

Rolf Bader

Institute of Musicology, University of Hamburg, Hamburg, Germany

James W. Beauchamp

School and Music and Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 2136 Music Building, 1114 West Nevada Street, Urbana, IL 61801, USA, e-mail: jwbeauch@uiuc.edu

Kim Benjamin

Naval Undersea Warfare Center, Newport, RI, USA

A.J. Berkhout

Delft University of Technology, Delft, The Netherlands

Jeff Bilmes

Department of Electrical Engineering, University of Washington, Seattle, WA, USA

Ole-Herman Bjor

Norsonic AS, Lierskogen, Norway, e-mail: ohbjor@norsonic.com

Stanley J. Bolanowski (deceased)

Institute for Sensory Research, Syracuse University, Syracuse,
NY 13244, USA

Baris Bozkurt

Izmir Institute of Technology (IYTE), Izmir, Turkey

Nicolas Brachet

Provisional Technical Secretariat, CTBTO, Vienna International
Centre, Vienna, Austria

Thomas Brand

University of Oldenburg, Oldenburg, Germany

David J. Brown

Geoscience Australia, Canberra, Australia, (Provisional Technical
Secretariat, CTBTO, Vienna International Centre, Vienna,
Austria), e-mail: David.Brown@CTBTO.org

John C. Burgess

Department of Mechanical Engineering, University of Hawaii,
2540 Dole Street, Honolulu, HI 968221, USA, e-mail:
jcb@hawaii.edu

Paola Campus

Provisional Technical Secretariat, CTBTO, Vienna International
Centre, Vienna, Austria

Yves Cansi

CEA/DASE/LDG, BP12, 91680 Bruyères-le-Châtel, France

Josef Chalupper

Siemens Audiological Engineering Group, Gebbertstrasse 125,
Erlangen 91058, Germany, e-mail: Josef.Chalupper@siemens.com

N. Ross Chapman

University of Victoria, Victoria BC, Canada

Jakob Christensen-Dalsgaard

Institute of Biology, University of Southern Denmark, Campusvej
55, DK-5230 Odense M, Denmark, e-mail: jcd@biology.sdu.dk

Peter Daniel

Brüel & Kjær, GmbH, Bremen, Germany

Roger B. Dannenberg

Carnegie Mellon University, Pittsburgh, PA, USA

Torsten Dau

Technical University of Denmark, Lyngby, Denmark, e-mail:
tda@elektro.dtu.dk

Hans-Elias de Bree

Microflown Technologies, The Netherlands, USA

Max Deffenbaugh

ExxonMobil Research and Engineering Company, Annandale, NJ, USA

Thierry Dutoit

Faculte Polytechnique de Mons, Mons, Belgium

Stephen J. Elliott

Institute of Sound and Vibration Research, Southampton, UK

Paulo A.A. Esquef

Nokia Institute of Technology, Rod. Torquato Tapajós, 7200, Tarumã 69048-660 Manaus-AM, Brazil, e-mail: paulo@esquef@indt.org.br

Richard R. Fay

Parmly Hearing Institute, Loyola University Chicago, 6525 N. Sheridan Rd., Chicago, IL 60626, USA, e-mail: rfay@luc.edu

Michael Fehler

Massachusetts Institute of Technology, Cambridge, USA

Sandy Fidell

Fidell Associates, Inc., Woodland Hills, CA, USA

Petr Firbas

Provisional Technical Secretariat, CTBTO, Vienna International Centre, Vienna, Austria (International Atomic Energy Agency, Vienna International Centre, Vienna, Austria)

Erling Frederiksen

Brüel & Kjær, Sound and Vibration Measurement A/S, Skodsborgvej 307, 2850 Nærum, Denmark

Milton A. Garcés

Infrasound Laboratory, University of Hawaii, Manoa, HI, USA, e-mail: milton@isla.hawaii.edu

H.W. Gierlich

HEAD acoustics GmbH, Herzogenrath, Germany

Norbert Goertz

Institute for Digital Communications, School of Engineering and Electronics, University of Edinburgh, King's Buildings, Mayfield Road, Edinburgh EH9 3JL, UK

Masataka Goto

National Institute of Advanced Industrial Science and Technology (AIST), Tokoyo, Japan

Philippe Gournay

Université de Sherbrooke, Sherbrooke, QC, Canada

Jørgen Hald

Brüel & Kjær, Sound & Vibration Measurements A/S, Nærum, Denmark

Joe Hammond

University of Southampton, Southampton, UK

Colin H. Hansen

School of Mechanical Engineering, University of Adelaide, Adelaide, SA 5005, Australia, e-mail: chanson@mecheng.adelaide.edu.au

Uwe Hansen

Department of Physics, Indiana State University, Terre Haute, IN, USA

Sabih I. Hayek

Department of Engineering Science and Mechanics, University Park, PA 16802, USA

Ulrich Heute

Institute for Circuit and System Theory, Faculty of Engineering, Christian-Albrecht, University, Kaiserstr. 2, D-24143 Kiel, Germany

Thomas Hoffmann

Provisional Technical Secretariat, CTBTO, Vienna International Centre, Vienna, Austria

Volker Hohmann

University of Oldenburg, Oldenburg, Germany

Masaaki Honda

Waseda University, Tokyo, Japan

Andrew B. Horner

Department of Computer Science, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China, e-mail: horner@cs.ust.hk

Adrianus J.M. Houtsma

Aircrew Protection Division, U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL 36362-0577, USA, e-mail: adrian.houtsma@amedd.army.mil

Finn Jacobsen

Technical University of Denmark, Lyngby, Denmark, e-mail: fja@elektro.dtu.dk

Finn B. Jensen

NATO Undersea Research Centre, La Spezia, Italy, e-mail: jensen@nurc.nato.int

Walter Kellermann

Multimedia Communications and Signal Processing, University Erlanger-Nuremberg, Erlanger, Germany, e-mail: wk@lnt.de

Youngmoo E. Kim

Electrical & Computer Engineering, Drexel University, Philadelphia, PA, USA, e-mail: ykim@drexel.edu

Anssi Klapuri

Institute of Signal Processing, Tampere University of Technology, Korkeakoulunkatu 1, 33720 Tampere, Finland, e-mail: Anssi.Klapuri@tut.fi

Birger Kollmeier

University of Oldenburg, Oldenburg, Germany

Jan Felix Krebber

Institute of Communication Acoustics, Ruhr-University Bochum, Bochum, Germany, e-mail: jan.krebber@rub.de

Christine E. Krohn

ExxonMobil Upstream Research Company, Houston, TX, USA

Sonoko Kuwano

Osaka University, Osaka, Japan

Gerald C. Lauchle

State College, PA, USA

Walter Lauriks

Katholieke Universiteit Leuven, Heverlee, Belgium; Laboratorium voor Akoestiek en Thermische Fysica, K.U. Leuven, Leuven, Belgium

Alexis Le Pichon

CEA/DASE/LDG, BP12, 91680 Bruyères-le-Châtel, France

Philippe Leclaire

Université de Bourgogne, Nevers, France; Laboratorium voor Akoestiek en Thermische Fysica, K.U. Leuven, Leuven, Belgium

Roch Lefebvre

Université de Sherbrooke, Sherbrooke, QC, Canada

Cuiping Li

Department of Earth and Atmospheric Science, Purdue University, West Lafayette IN 47907, USA

Tapio Lokki

Department of Media Technology, Helsinki University of Technology, Helsinki, Finland, e-mail: Tapio.Lokki@tkk.fi

Aki Vihtori Mäkitvirta

Genelec Oy, Iisalmi, Finland

Brian H. Maranda

Defence Research and Development Canada – Atlantic, Dartmouth, NS, Canada

James Mathews

PCB Piezoelectronics Inc., San Clemente, CA, USA

Manfred Mauermann

University of Oldenburg, Oldenburg, Germany

Walter Metzner

Department of Physiological Science, University of California, California, USA

Yasushi Miki

Computer Science, Faculty of Engineering, Takushoku University, Tokyo, Japan

Ben Milner

School of Computing Sciences, University of East Anglia, Norwich, Norfolk, UK

Riikka Möttönen

Department of Biomedical Engineering and Computational Science, Helsinki University of Technology, Helsinki, Finland

Swen Müller

National Institute of Metrology, Xerém, Brazil

Seiichiro Namba

Osaka University, Osaka, Japan

Ramesh Neelamani

ExxonMobil Upstream Research Company, Houston, TX, USA

David E. Norris

BBN Technologies, 1300 N. 17th St., Arlington, VA 22209, USA

Robert L. Nowack

Department of Earth and Atmospheric Science, Purdue University, West Lafayette, IN 47907, USA

Yasuhiro Oikawa

Waseda University, Tokyo, Japan

Kazuo Okanoya

Laboratory for Biolinguistics, Brain Science Institute,
Riken, 2-1 Hirosawa, Saitama 351-0198, Japan, e-mail:
okanoya@brain.riken.jp

John V. Olson

Geophysical Institute, University of Alaska, Fairbanks, USA

Thorkild Find Pedersen

Brüel & Kjær, Sound & Vibration Measurements A/S, Nærum,
Denmark

Ville Pulkki

Department of Signal Processing and Acoustics, Helsinki
University of Technology, Helsinki, Finland, e-mail:
ville.pulkki@tkk.fi

Robert B. Randall

University of New South Wales, Sydney, Australia

Helmut Riedel

University of Oldenburg, Oldenburg, Germany

Francis Rumsey

Institute of Sound Recording, University of Surrey, Guildford,
UK

Masahiko Sakai

Ono Sokki Co., Ltd., 1-16-1 Hakusan, Midori-ku, Yokohama, 226-
8507 Japan, e-mail: msakai@onosokki.co.jp

Rebecca Saltzer

ExxonMobil Upstream Research Company, Houston, TX, USA

Mikko Sams

Department of Biomedical Engineering and Computational
Science, Helsinki University of Technology, Helsinki, Finland

Lauri Savioja

Department of Media Technology, Helsinki University of
Technology, Helsinki, Finland, e-mail: Lauri.Savioja@tkk.fi

Julius O. Smith

Center for Computer Research in Music and Acoustics
(CCRMA), Stanford University, Stanford, CA 94305, USA,
website: <http://ccrma.stanford.edu/~jos/>

Stefka Stefanova

Provisional Technical Secretariat, CTBTO, Vienna International
Centre, Vienna, Austria

Edmund J. Sullivan

EJS Consultants, Portsmouth, RI, USA

David C. Swanson

The Applied Research Laboratory, The Pennsylvania State University, Philadelphia, PA, USA

Curt A.L. Szuberla

Geophysical Institute, University of Alaska, Fairbanks, USA

Hideki Tachibana

Institute of Industrial Science, University of Tokyo, Tokyo, Japan

Yasushi Takano

Department of Mechanical Engineering Research Laboratory, Hitachi, Ltd., Ibaraki, Japan

Ernst Terhardt

Technical University of Munich, Munich, Germany, e-mail: teirhardt@ei.tum.de

Christine Thomas

Department of Earth and Ocean Sciences, University of Liverpool, Liverpool, UK

Ippei Torigoe

Department of Mechanical Engineering and Materials, Science Faculty of Engineering Kumamoto University, Kumamoto, Japan

Stefan Uppenkamp

University of Oldenburg, Oldenburg, Germany

Ronald T. Verrillo (deceased)

Institute for Sensory Research, Syracuse University, Syracuse, NY 13244, USA

Tuomas Virtanen

Institute of Signal Processing, Tampere University of Technology, Korkeakoulunkatu 1, 33720 Tampere, Finland, e-mail: Tuomas.Virtanen@tut.fi

Stephen Voran

Institute for Telecommunication Sciences, Boulder, CO, USA

Erhard Werner

Tannenweg 16, D 29693 Hademstorf, Germany

Rodney W. Whitaker

Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87544, USA

Paul White

University of Southampton, Southampton, UK

Ru-Shan Wu

University of California, Santa Cruz, CA, USA

Xianyn Wu

ExxonMobil Upstream Research Company, Houston, TX, USA

Ning Xiang

School of Architecture and Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA, e-mail: xiangn@rpi.edu

Ichiro Yamada

Aviation Environment Research Center, Airport Environment Improvement Foundation, Tokyo, Japan

Kohei Yamamoto

Kobayasi Institute of Physical Research, Tokyo, Japan

Yoshio Yamasaki

Waseda University, Tokyo, Japan

Nobutoshi Yoshida

Ono Sokki Co. Ltd., 1-16-1 Hakusan, Midori-ku, 226-8507 Yokohama, Japan, e-mail: yoshi@onosokki.co.jp

Udo Zölzer

Helmut Schmidt University, Hamburg, Germany

Handbook of Signal Processing in Acoustics

Volume 2

Edited by

David Havelock

National Research Council, Canada

Sonoko Kuwano

Osaka University, Japan

Michael Vorländer

RWTH Aachen University, Germany

Handbook of Signal Processing in Acoustics

Volume 2

 Springer

Editors

David Havelock
National Research Council
Institute for Microstructural
Sciences
Acoustics and Signal
Processing Group
1200 Montreal Road
Ottawa ON K1A 0R6
Canada

Sonoko Kuwano
Osaka University
Graduate School of Human
Sciences
Department of Environmental
Psychology
1-2 Yamadaok Suita
Osaka
Japan

Michael Vorländer
RWTH Aachen University
Institute of Technical Acoustics
Aachen
Germany

ISBN: 978-0-387-77698-9

e-ISBN: 978-0-387-30441-0

Library of Congress Control Number: 2008923573

© 2008 Springer Science+Business Media, LLC

All rights reserved. This work may not be translated or copied in whole or in part without the written permission of the publisher (Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), except for brief excerpts in connection with reviews or scholarly analysis. Use in connection with any form of information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed is forbidden.

The use in this publication of trade names, trademarks, service marks, and similar terms, even if they are not identified as such, is not to be taken as an expression of opinion as to whether or not they are subject to proprietary rights.

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Editor Biographies

David Havelock

National Research Council
Institute for Microstructural Sciences
Acoustics and Signal Processing Group
1200 Montreal Road
Ottawa ON K1A 0R6
Canada

Sonoko Kuwano

Osaka University
Graduate School of Human Sciences
Department of Environmental Psychology
1-2 Yamadaok Suita
Osaka
Japan

Michael Vorländer

RWTH Aachen University
Institute of Technical Acoustics
Aachen
Germany

Editorial Board

Last Name	Given Name(s)	Affiliation/Address
Beauchamp	James W.	University of Illinois Urbana-Champaign, School of Music, Dept. of ECE, Urbana, IL, USA
Christie	Douglas R.	Earth Physics, Research School of Earth Sciences, The Australian National University, Canberra, AUSTRALIA
Deffenbaugh	Max	ExxonMobil Research and Engineering Company, Annandale, NJ USA
Elliott	Stephen J.	Southampton University, Institute of Sound and Vibration Research, Southampton, ENGLAND
Fastl	Hugo	Technische Universitaet Muenchen AG Technische Akustik, MMK Muenchen, GERMANY
Gierlich	Hans Wilhelm	HEAD acoustics GmbH Telecom Division, Herzogenrath, GERMANY
Guyader	Jean-Louis	Labratory for Vibration Acoustics Villeurbanne, FRANCE
Jacobsen	Finn	Technical University of Denmark, Lyngby, DENMARK
Karjalainen	Matti	Helsinki University of Technology, FINLAND
Kollmeier	Birger	Universitat Oldenburg, Oldenburg, GERMANY
O'Shaughnessy	Douglas D.	INRS-EMT (Telecommunications), Montreal, QC, CANADA
Riquimaroux	Hiroshi	Doshisha University, Department of Knowledge Engineering & Computer Sciences, Sensory & Cognitive Neuroscience Research Laboratory, Kyotanabe, Kyoto, JAPAN
Sullivan	Edmund J.	EJS Consultants Portsmouth, RI, USA

Last Name	Given Name(s)	Affiliation/Address
Suzuki	Hideo	1-2-3-S2502, Utase, Mihama-ward, Chiba-city, JAPAN 261-0013
Taroudakis	Michael	University of Crete Department of Mathematics, and FORTH, Institute of Applied and Computational Mathematics, Heraklion, GREECE
Ueha	Sadayuki	Tokyo Institute of Technology, Director, Precision and Intelligence Lab, Yokohama, JAPAN
Verrillo	Ronald T.	(deceased) Institute for Sensory Research, Syracuse, NY, USA
Yamada	Ichiro	Aviation Environment Research Center, Airport Environment Improvement Foundation, Tokyo, JAPAN
Yamasaki	Yoshio	Waseda University, Graduate School of Global Information and Telecommunication Studies, Saitama, JAPAN
Tohyama	Mikio	Waseda University, JAPAN

Preface

Acoustics has a special relationship with signal processing. Many concepts in signal processing arise naturally from our general experience with sound and vibration and, more than in many other fields, acoustics is concerned with the acquisition, analysis, and synthesis of signals. Consequently, there is a rich resource of signal processing expertise within the acoustics community.

There are many excellent reference books devoted to signal processing but the objective of the *Handbook of Signal Processing in Acoustics* is to bring together the signal processing expertise specific to acoustics and to capture the interdisciplinary nature of signal processing within acoustics. It is also hoped that the handbook will promote networking and the interchange of ideas between technical areas in acoustics.

The handbook comprises 104 *Chapters* organized into 17 *Parts*. Each *Part* addresses a technical area of acoustics, reflecting the general demarcations of specialization within the acoustics community. An expert with broad knowledge of signal processing within their respective technical area was invited to act as a Section Leader for each *Part* of the handbook. These Section Leaders contributed substantially to the handbook project by helping to define the contents and scope of each chapter, finding an appropriate contributing expert author, and managing the review and revision of material. Collectively with the Editors, they form the Editorial Board for the handbook.

Planned sections on Architectural Acoustics, Nonlinear Acoustics, and Ultrasound are unfortunately omitted from the handbook; nevertheless, the handbook otherwise provides thorough coverage of the field of acoustics and we can hope that possible future editions might include these areas.

The handbook is written from the perspective of acoustics, by acousticians with signal processing expertise. Emphasis is placed

in the description of acoustic problems and the signal processing related to their solutions. The reader is assumed to have basic knowledge of signal processing. Signal processing techniques are described but the reader is referred elsewhere for derivations and details.

The authors were not required to adhere to strict standards of style or notation, and were asked to prepare short, concise, self-sufficient chapters. This results in variations in style and notation throughout the handbook that reflects the diversity of perspectives within the acoustics community.

David Havelock

Acknowledgments

David Havelock gratefully acknowledges support from the Institute for Microstructural Sciences, of the National Research Council of Canada, for making time and resources available during the preparation of this handbook. He also thanks John C. Burgess (University of Hawaii, retired) for the encouragement to begin this project and expresses his gratitude to the co-Editors, Sonoko Kuwano and Michael Vorländer, who were a pleasure to work with throughout this project. The efforts of all of the Section Leaders are greatly appreciated and we thank each of them sincerely for their patience, perseverance, and faith that were required to see this project to completion. We thank each of the authors for their contributions.

Contents

Editor Biographies	v
Editorial Board	vii
Preface	ix
Acknowledgments	xi
Contributors	xvii
 PART VIII NOISE	 931
51 Sound Levels of Noise Sources	933
52 Outdoor Measurements	949
53 Measurements of Physical Characteristics Using Sound at Audible or Lower Frequencies	983
54 Community Response to Noise	1005
 PART IX ACTIVE NOISE CONTROL	 1021
Introduction	1023
55 Forward Control in Single-Channel Systems	1029
56 Forward Control in Multichannel Systems	1057
57 Feedback Control Systems	1081

PART X STRUCTURAL ACOUSTICS AND VIBRATION	1107
58 Intensity Techniques	1109
59 Nearfield Acoustical Holography	1129
60 Actuator Design and Deployment	1141
61 Materials Testing	1167
 PART XI BIORESPONSE TO VIBRATION	 1183
62 Tactile Responses to Vibration	1185
63 Uses and Applications of Somatosensation	1215
64 Sensory Substitution	1231
 PART XII TRANSDUCERS FOR ACOUSTIC MEASUREMENT	 1245
65 Condenser Microphones	1247
66 Dynamic Pressure Microphones	1267
67 Dynamic Pressure Difference Microphones	1275
68 The Microflown Particle Velocity Sensor	1283
69 Microphone Calibration	1293
70 Piezoceramic Accelerometer	1313
71 Laser Doppler Velocimeter	1329
72 Capacitive Sensors	1339

PART XIII ENGINEERING ACOUSTICS	1347
73 Energy Saving Transducers and Thermoacoustics	1349
74 Sinusoidal Representation of Acoustic Signals	1365
75 Room Transfer Function	1381
76 Spatial Information of Sound Fields	1403
PART XIV INFRASONICS	1423
77 Infrasound Event Detection Using the Progressive Multi-Channel Correlation Algorithm	1425
78 Ray Tracing in an Inhomogeneous Atmosphere with Winds	1437
79 Infrasonic Data Processing at the Provisional Technical Secretariat of the Comprehensive Nuclear-Test-Ban Organization	1461
80 The Design and Performance of Infrasound Noise-Reducing Pipe Arrays	1473
81 Processing Infrasonic Array Data	1487
82 Infrasound Propagation	1497
PART XV SEISMOLOGY	1521
83 Structure and Elastic Properties of the Earth	1523
84 Seismic Wave Propagation	1535
85 Seismic Data Acquisition	1545
86 Signal Models in Seismic Processing	1559
87 Deconvolution and Optimal Filtering in Seismology	1571

88	Seismic Migration Imaging	1585
89	Geophysical Parameter Estimation	1593
90	Earthquake Localization	1627
91	Seismic Tomography	1635
92	Array Signal Processing	1655

PART XVI	UNDERWATER AND OCEANOGRAPHIC ACOUSTICS	1667
-----------------	---	-------------

93	Propagation and Signal Modeling	1669
94	Statistical Signal Processing	1695
95	Inverse Problems in Underwater Acoustics	1723
96	Active Sonar	1737
97	Passive Sonar	1757
98	Transducers for Sonar Systems	1783
99	Flow Noise	1821

PART XVII	ANIMAL BIOACOUSTICS	1833
------------------	----------------------------	-------------

100	Bat Bioacoustics	1835
101	Fish Bioacoustics	1851
102	Amphibian Bioacoustics	1861
103	Avian Bioacoustics	1887
104	Cetacean Bioacoustics with Emphasis on Recording and Monitoring	1897
	Index	1909
	Cumulative Contents	1931

Contributors

Tomonari Akamatsu

National Research Institute of Fisheries Engineering, Fisheries Research Agency of Japan, Kamisu, Ibaraki, Japan

Benoit Alcoverro

CEA/DASE, BP 12, 91680 Bruyères Le Châtel, France

Lydia Ayers

Computer Science Department, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China, e-mail: layers@cs.ust.hk

Juha Reinhold Backman

Nokia, Espoo, Finland

Rolf Bader

Institute of Musicology, University of Hamburg, Hamburg, Germany

James W. Beauchamp

School and Music and Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 2136 Music Building, 1114 West Nevada Street, Urbana, IL 61801, USA, e-mail: jwbeauch@uiuc.edu

Kim Benjamin

Naval Undersea Warfare Center, Newport, RI, USA

A.J. Berkhout

Delft University of Technology, Delft, The Netherlands

Jeff Bilmes

Department of Electrical Engineering, University of Washington, Seattle, WA, USA

Ole-Herman Bjor

Norsonic AS, Lierskogen, Norway, e-mail: ohbjor@norsonic.com

Stanley J. Bolanowski (deceased)

Institute for Sensory Research, Syracuse University, Syracuse,
NY 13244, USA

Baris Bozkurt

Izmir Institute of Technology (IYTE), Izmir, Turkey

Nicolas Brachet

Provisional Technical Secretariat, CTBTO, Vienna International
Centre, Vienna, Austria

Thomas Brand

University of Oldenburg, Oldenburg, Germany

David J. Brown

Geoscience Australia, Canberra, Australia, (Provisional Technical
Secretariat, CTBTO, Vienna International Centre, Vienna,
Austria), e-mail: David.Brown@CTBTO.org

John C. Burgess

Department of Mechanical Engineering, University of Hawaii,
2540 Dole Street, Honolulu, HI 968221, USA, e-mail:
jcb@hawaii.edu

Paola Campus

Provisional Technical Secretariat, CTBTO, Vienna International
Centre, Vienna, Austria

Yves Cansi

CEA/DASE/LDG, BP12, 91680 Bruyères-le-Châtel, France

Josef Chalupper

Siemens Audiological Engineering Group, Gebbertstrasse 125,
Erlangen 91058, Germany, e-mail: Josef.Chalupper@siemens.com

N. Ross Chapman

University of Victoria, Victoria BC, Canada

Jakob Christensen-Dalsgaard

Institute of Biology, University of Southern Denmark, Campusvej
55, DK-5230 Odense M, Denmark, e-mail: jcd@biology.sdu.dk

Peter Daniel

Brüel & Kjær, GmbH, Bremen, Germany

Roger B. Dannenberg

Carnegie Mellon University, Pittsburgh, PA, USA

Torsten Dau

Technical University of Denmark, Lyngby, Denmark, e-mail:
tda@elektro.dtu.dk

Hans-Elias de Bree

Microflown Technologies, The Netherlands, USA

Max Deffenbaugh

ExxonMobil Research and Engineering Company, Annandale, NJ, USA

Thierry Dutoit

Faculte Polytechnique de Mons, Mons, Belgium

Stephen J. Elliott

Institute of Sound and Vibration Research, Southampton, UK

Paulo A.A. Esquef

Nokia Institute of Technology, Rod. Torquato Tapajós, 7200, Tarumã 69048-660 Manaus-AM, Brazil, e-mail: paulo@esquef@indt.org.br

Richard R. Fay

Parmly Hearing Institute, Loyola University Chicago, 6525 N. Sheridan Rd., Chicago, IL 60626, USA, e-mail: rfay@luc.edu

Michael Fehler

Massachusetts Institute of Technology, Cambridge, USA

Sandy Fidell

Fidell Associates, Inc., Woodland Hills, CA, USA

Petr Firbas

Provisional Technical Secretariat, CTBTO, Vienna International Centre, Vienna, Austria (International Atomic Energy Agency, Vienna International Centre, Vienna, Austria)

Erling Frederiksen

Brüel & Kjær, Sound and Vibration Measurement A/S, Skodsborgvej 307, 2850 Nærum, Denmark

Milton A. Garcés

Infrasound Laboratory, University of Hawaii, Manoa, HI, USA, e-mail: milton@isla.hawaii.edu

H.W. Gierlich

HEAD acoustics GmbH, Herzogenrath, Germany

Norbert Goertz

Institute for Digital Communications, School of Engineering and Electronics, University of Edinburgh, King's Buildings, Mayfield Road, Edinburgh EH9 3JL, UK

Masataka Goto

National Institute of Advanced Industrial Science and Technology (AIST), Tokoyo, Japan

Philippe Gournay

Université de Sherbrooke, Sherbrooke, QC, Canada

Jørgen Hald

Brüel & Kjær, Sound & Vibration Measurements A/S, Nærum, Denmark

Joe Hammond

University of Southampton, Southampton, UK

Colin H. Hansen

School of Mechanical Engineering, University of Adelaide, Adelaide, SA 5005, Australia, e-mail: chanson@mecheng.adelaide.edu.au

Uwe Hansen

Department of Physics, Indiana State University, Terre Haute, IN, USA

Sabih I. Hayek

Department of Engineering Science and Mechanics, University Park, PA 16802, USA

Ulrich Heute

Institute for Circuit and System Theory, Faculty of Engineering, Christian-Albrecht, University, Kaiserstr. 2, D-24143 Kiel, Germany

Thomas Hoffmann

Provisional Technical Secretariat, CTBTO, Vienna International Centre, Vienna, Austria

Volker Hohmann

University of Oldenburg, Oldenburg, Germany

Masaaki Honda

Waseda University, Tokyo, Japan

Andrew B. Horner

Department of Computer Science, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China, e-mail: horner@cs.ust.hk

Adrianus J.M. Houtsma

Aircrew Protection Division, U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL 36362-0577, USA, e-mail: adrian.houtsma@amedd.army.mil

Finn Jacobsen

Technical University of Denmark, Lyngby, Denmark, e-mail: fja@elektro.dtu.dk

Finn B. Jensen

NATO Undersea Research Centre, La Spezia, Italy, e-mail: jensen@nurc.nato.int

Walter Kellermann

Multimedia Communications and Signal Processing, University Erlanger-Nuremberg, Erlanger, Germany, e-mail: wk@lnt.de

Youngmoo E. Kim

Electrical & Computer Engineering, Drexel University, Philadelphia, PA, USA, e-mail: ykim@drexel.edu

Anssi Klapuri

Institute of Signal Processing, Tampere University of Technology, Korkeakoulunkatu 1, 33720 Tampere, Finland, e-mail: Anssi.Klapuri@tut.fi

Birger Kollmeier

University of Oldenburg, Oldenburg, Germany

Jan Felix Krebber

Institute of Communication Acoustics, Ruhr-University Bochum, Bochum, Germany, e-mail: jan.krebber@rub.de

Christine E. Krohn

ExxonMobil Upstream Research Company, Houston, TX, USA

Sonoko Kuwano

Osaka University, Osaka, Japan

Gerald C. Lauchle

State College, PA, USA

Walter Lauriks

Katholieke Universiteit Leuven, Heverlee, Belgium; Laboratorium voor Akoestiek en Thermische Fysica, K.U. Leuven, Leuven, Belgium

Alexis Le Pichon

CEA/DASE/LDG, BP12, 91680 Bruyères-le-Châtel, France

Philippe Leclaire

Université de Bourgogne, Nevers, France; Laboratorium voor Akoestiek en Thermische Fysica, K.U. Leuven, Leuven, Belgium

Roch Lefebvre

Université de Sherbrooke, Sherbrooke, QC, Canada

Cuiping Li

Department of Earth and Atmospheric Science, Purdue University, West Lafayette IN 47907, USA

Tapio Lokki

Department of Media Technology, Helsinki University of Technology, Helsinki, Finland, e-mail: Tapio.Lokki@tkk.fi

Aki Vihtori Mäkitvirta

Genelec Oy, Iisalmi, Finland

Brian H. Maranda

Defence Research and Development Canada – Atlantic, Dartmouth, NS, Canada

James Mathews

PCB Piezoelectronics Inc., San Clemente, CA, USA

Manfred Mauermann

University of Oldenburg, Oldenburg, Germany

Walter Metzner

Department of Physiological Science, University of California, California, USA

Yasushi Miki

Computer Science, Faculty of Engineering, Takushoku University, Tokyo, Japan

Ben Milner

School of Computing Sciences, University of East Anglia, Norwich, Norfolk, UK

Riikka Möttönen

Department of Biomedical Engineering and Computational Science, Helsinki University of Technology, Helsinki, Finland

Swen Müller

National Institute of Metrology, Xerém, Brazil

Seiichiro Namba

Osaka University, Osaka, Japan

Ramesh Neelamani

ExxonMobil Upstream Research Company, Houston, TX, USA

David E. Norris

BBN Technologies, 1300 N. 17th St., Arlington, VA 22209, USA

Robert L. Nowack

Department of Earth and Atmospheric Science, Purdue University, West Lafayette, IN 47907, USA

Yasuhiro Oikawa

Waseda University, Tokyo, Japan

Kazuo Okanoya

Laboratory for Biolinguistics, Brain Science Institute,
Riken, 2-1 Hirosawa, Saitama 351-0198, Japan, e-mail:
okanoya@brain.riken.jp

John V. Olson

Geophysical Institute, University of Alaska, Fairbanks, USA

Thorkild Find Pedersen

Brüel & Kjær, Sound & Vibration Measurements A/S, Nærum,
Denmark

Ville Pulkki

Department of Signal Processing and Acoustics, Helsinki
University of Technology, Helsinki, Finland, e-mail:
ville.pulkki@tkk.fi

Robert B. Randall

University of New South Wales, Sydney, Australia

Helmut Riedel

University of Oldenburg, Oldenburg, Germany

Francis Rumsey

Institute of Sound Recording, University of Surrey, Guildford,
UK

Masahiko Sakai

Ono Sokki Co., Ltd., 1-16-1 Hakusan, Midori-ku, Yokohama, 226-
8507 Japan, e-mail: msakai@onosokki.co.jp

Rebecca Saltzer

ExxonMobil Upstream Research Company, Houston, TX, USA

Mikko Sams

Department of Biomedical Engineering and Computational
Science, Helsinki University of Technology, Helsinki, Finland

Lauri Savioja

Department of Media Technology, Helsinki University of
Technology, Helsinki, Finland, e-mail: Lauri.Savioja@tkk.fi

Julius O. Smith

Center for Computer Research in Music and Acoustics
(CCRMA), Stanford University, Stanford, CA 94305, USA,
website: <http://ccrma.stanford.edu/~jos/>

Stefka Stefanova

Provisional Technical Secretariat, CTBTO, Vienna International
Centre, Vienna, Austria

Edmund J. Sullivan

EJS Consultants, Portsmouth, RI, USA

David C. Swanson

The Applied Research Laboratory, The Pennsylvania State University, Philadelphia, PA, USA

Curt A.L. Szuberla

Geophysical Institute, University of Alaska, Fairbanks, USA

Hideki Tachibana

Institute of Industrial Science, University of Tokyo, Tokyo, Japan

Yasushi Takano

Department of Mechanical Engineering Research Laboratory, Hitachi, Ltd., Ibaraki, Japan

Ernst Terhardt

Technical University of Munich, Munich, Germany, e-mail: teirhardt@ei.tum.de

Christine Thomas

Department of Earth and Ocean Sciences, University of Liverpool, Liverpool, UK

Ippei Torigoe

Department of Mechanical Engineering and Materials, Science Faculty of Engineering Kumamoto University, Kumamoto, Japan

Stefan Uppenkamp

University of Oldenburg, Oldenburg, Germany

Ronald T. Verrillo (deceased)

Institute for Sensory Research, Syracuse University, Syracuse, NY 13244, USA

Tuomas Virtanen

Institute of Signal Processing, Tampere University of Technology, Korkeakoulunkatu 1, 33720 Tampere, Finland, e-mail: Tuomas.Virtanen@tut.fi

Stephen Voran

Institute for Telecommunication Sciences, Boulder, CO, USA

Erhard Werner

Tannenweg 16, D 29693 Hademstorf, Germany

Rodney W. Whitaker

Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87544, USA

Paul White

University of Southampton, Southampton, UK

Ru-Shan Wu

University of California, Santa Cruz, CA, USA

Xianyn Wu

ExxonMobil Upstream Research Company, Houston, TX, USA

Ning Xiang

School of Architecture and Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA, e-mail: xiangn@rpi.edu

Ichiro Yamada

Aviation Environment Research Center, Airport Environment Improvement Foundation, Tokyo, Japan

Kohei Yamamoto

Kobayasi Institute of Physical Research, Tokyo, Japan

Yoshio Yamasaki

Waseda University, Tokyo, Japan

Nobutoshi Yoshida

Ono Sokki Co. Ltd., 1-16-1 Hakusan, Midori-ku, 226-8507 Yokohama, Japan, e-mail: yoshi@onosokki.co.jp

Udo Zölzer

Helmut Schmidt University, Hamburg, Germany

<http://www.springer.com/978-0-387-77698-9>

Handbook of Signal Processing in Acoustics

Havelock, D.; Kuwano, S.; Vorländer, M. (Eds.)

2008, L, 1950 p. In 2 volumes, not available separately.,

Hardcover

ISBN: 978-0-387-77698-9