

Modern Acoustics and Signal Processing

Editor-in-Chief

William M. Hartmann, East Lansing, USA

Editorial Board

Yoichi Ando, Kobe, Japan

Whitlow W. L. Au, Kane'ohe, USA

Arthur B. Baggeroer, Cambridge, USA

Neville H. Fletcher, Canberra, Australia

Christopher R. Fuller, Blacksburg, USA

William A. Kuperman, La Jolla, USA

Joanne L. Miller, Boston, USA

Manfred R. Schroeder, Göttingen, Germany

Alexandra I. Tolstoy, McLean, USA

For further volumes:

<http://www.springer.com/series/3754>

Series Preface for Modern Acoustics and Signal Processing

In the popular mind, the term “acoustics” refers to the properties of a room or other environment—the acoustics of a room are good or the acoustics are bad. But as understood in the professional acoustical societies of the world, such as the highly influential Acoustical Society of America, the concept of acoustics is much broader. Of course, it is concerned with the acoustical properties of concert halls, classrooms, offices, and factories—a topic generally known as architectural acoustics, but it is also concerned with vibrations and waves too high or too low to be audible. Acousticians employ ultrasound in probing the properties of materials, or in medicine for imaging, diagnosis, therapy, and surgery. Acoustics includes infrasound—the wind-driven motions of skyscrapers, the vibrations of the earth, and the macroscopic dynamics of the sun.

Acoustics studies the interaction of waves with structures, from the detection of submarines in the sea to the buffeting of spacecraft. The scope of acoustics ranges from the electronic recording of rock and roll and the control of noise in our environments to the inhomogeneous distribution of matter in the cosmos.

Acoustics extends to the production and reception of speech and to the songs of humans and animals. It is in music, from the generation of sounds by musical instruments to the emotional response of listeners. Along this path, acoustics encounters the complex processing in the auditory nervous system, its anatomy, genetics, and physiology—perception and behavior of living things.

Acoustics is a practical science, and modern acoustics is so tightly coupled to digital signal processing that the two fields have become inseparable. Signal processing is not only an indispensable tool for synthesis and analysis, it informs many of our most fundamental models about how acoustical communication systems work.

Given the importance of acoustics to modern science, industry, and human welfare Springer presents this series of scientific literature, entitled *Modern Acoustics and Signal Processing*. This series of monographs and reference books is intended to cover all areas of today’s acoustics as an interdisciplinary field. We expect that scientists, engineers, and graduate students will find the books in this series useful in their research, teaching, and studies.

July 2012

William M. Hartmann
Series Editor-in-Chief

The ASA Press

The ASA Press imprint represents a collaboration between the Acoustical Society of America and Springer dedicated to encouraging the publication of important new books in acoustics. Published titles are intended to reflect the full range of research in acoustics. ASA Press books can include all types of books published by Springer and may appear in any appropriate Springer book series.

Editorial Board

James Cottingham (Chair), Coe College
Diana Deutsch, University of California, San Diego
Mark Hamilton, University of Texas at Austin
William Hartmann, Michigan State University
Philip Marston, Washington State University
Allan Pierce, Boston University
Arthur Popper, University of Maryland
Erica Ryherd, Georgia Tech
Andrea Simmons, Brown University
Martin Siderius, Portland State University
Ning Xiang, Rensselaer Polytechnic Institute
William Yost, Arizona State University



ASA Press

Acoustical Society of America

The mission of the **Acoustical Society of America** (www.acousticalsociety.org) is to increase and diffuse the knowledge of acoustics and promote its practical applications. The ASA is recognized as the world's premier international scientific society in acoustics, and counts among its more than 7,000 members professionals in the fields of bioacoustics, engineering, architecture, speech, music, oceanography, signal processing, sound and vibration, and noise control.

Since its first meeting in 1929, The Acoustical Society of America has enjoyed a healthy growth in membership and in stature. The present membership of approximately 7500 includes leaders in acoustics in the United States of America and other countries. The Society has attracted members from various fields related to sound including engineering, physics, oceanography, life sciences, noise and noise control, architectural acoustics; psychological and physiological acoustics; applied acoustics; music and musical instruments; speech communication; ultrasonics, radiation, and scattering; mechanical vibrations and shock; underwater sound; aeroacoustics; macrosonics; acoustical signal processing; bioacoustics; and many more topics.

To assure adequate attention to these separate fields and to new ones that may develop, the Society establishes technical committees and technical groups charged with keeping abreast of developments and needs of the membership in their specialized fields. This diversity and the opportunity it provides for interchange of knowledge and points of view has become one of the strengths of the Society.

The Society's publishing program has historically included the *Journal of the Acoustical Society of America*, the magazine *Acoustics Today*, a newsletter, and various books authored by its members across the many topical areas of acoustics. In addition, ASA members are involved in the development of acoustical standards concerned with terminology, measurement procedures, and criteria for determining the effects of noise and vibration.

Jens Blauert
Editor

The Technology of Binaural Listening



Editor

Jens Blauert
Fak. Elektrotechnik
LS Allgm.Elektrotechn.+Akustik
Univ. Bochum
Bochum
Germany

ISBN 978-3-642-37761-7 ISBN 978-3-642-37762-4 (eBook)

DOI 10.1007/978-3-642-37762-4

Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013938218

© Springer-Verlag Berlin Heidelberg 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law. The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

For more than six decades, scientists have developed binaural models of the human auditory system. Some of them, for instance, the so-called coincidence model and the so-called equalization-and-cancellation model, have indeed been quite successful in explaining basic functions of binaural localization and signal detection.

Recently, advances in digital signal processing and the availability of suitable hardware have prepared the ground for applying binaural models in the context of modern technology in many stimulating ways. Recognizing this situation, in 2009 15 laboratories in Europe and the US have founded the research group AABBA, with the aim of setting up “*Aural Assessment by Means of Binaural Algorithms.*” Now, after its first 4-year term of activity, the group presents their most relevant results in the form of this book.

All chapters underwent the same rigorous review process as known from international archival journals. In other words, each chapter was reviewed by three members of the AABBA group plus by at least two anonymous external reviewers.

Yet, unlike usual journal papers, the chapters have been written with the intention to provide, besides their scientifically new content, illustrative introductions to their respective areas. In addition, there is an introductory chapter on binaural modeling at large and a chapter that gives an outlook to the future of these models. The volume further provides a MATLAB toolbox that enables readers to construct binaural models of their own, tailored to their specific demands. These features make the book suitable for teaching and a versatile source of references.

Current members of AABBA are research labs at Universities/Technical Universities in Helsinki, Boston, Cardiff, Oldenburg, Lyon, Troy NY (Rensselaer), Bochum, Berlin, Copenhagen (Lyngby), Dresden, Eindhoven, Munich, Paris (Pierre et Marie Curie), Patras, Rostock, Toulouse, and at the Austrian Academy’s Acoustics Research Institute in Vienna. Altogether, 50 coauthors participated in writing this volume.

It is hoped that the book, which is indeed the first and only of its kind so far, will pave the way to many further advanced applications of binaural models in technology in the near future. AABBA intends to stay part of this exciting development and has just started on a second 4-years term of joint R&D activity.

Bochum, March 2013

Jens Blauert

Contents

An Introduction to Binaural Processing	1
A. Kohlrausch, J. Braasch, D. Kolossa and J. Blauert	
The Auditory Modeling Toolbox	33
P. L. Søndergaard and P. Majdak	
Trends in Acquisition of Individual Head-Related Transfer Functions	57
G. Enzner, Chr. Antweiler and S. Spors	
Assessment of Sagittal-Plane Sound-Localization Performance in Spatial-Audio Applications	93
R. Baumgartner, P. Majdak and B. Laback	
Modeling Horizontal Localization of Complex Sounds in the Impaired and Aided Impaired Auditory System	121
N. Le Goff, J. M. Buchholz and T. Dau	
Binaural Scene Analysis with Multidimensional Statistical Filters	145
C. Spille, B. T. Meyer, M. Dietz and V. Hohmann	
Extracting Sound-Source-Distance Information from Binaural Signals	171
E. Georganti, T. May, S. van de Par and J. Mourjopoulos	
A Binaural Model that Analyses Acoustic Spaces and Stereophonic Reproduction Systems by Utilizing Head Rotations	201
J. Braasch, S. Clapp, A. Parks, T. Pastore and N. Xiang	
Binaural Systems in Robotics.	225
S. Argentieri, A. Portello, M. Bernard, P. Danès and B. Gas	

Binaural Assessment of Multichannel Reproduction	255
H. Wierstorf, A. Raake and S. Spors	
Optimization of Binaural Algorithms for Maximum Predicted Speech Intelligibility	279
A. Schlesinger and Ch. Luther	
Modeling Sound Localization with Cochlear Implants	309
M. Nicoletti, Chr. Wirtz and W. Hemmert	
Binaural Assessment of Parametrically Coded Spatial Audio Signals	333
M. Takanen, O. Santala and V. Pulkki	
Binaural Dereverberation	359
A. Tsilfidis, A. Westermann, J. M. Buchholz, E. Georganti and J. Mourjopoulos	
Binaural Localization and Detection of Speakers in Complex Acoustic Scenes	397
T. May, S. van de Par and A. Kohlrausch	
Predicting Binaural Speech Intelligibility in Architectural Acoustics	427
J. F. Culling, M. Lavandier and S. Jelfs	
Assessment of Binaural–Proprioceptive Interaction in Human-Machine Interfaces	449
M. Stamm and M. E. Altinsoy	
Further Challenges and the Road Ahead	477
J. Blauert, D. Kolossa, K. Obermayer and K. Adiloğlu	
Index	503

Contributors

Kamil Adilođlu Neural Information Processing Group, Institut für Software-technik und Theoretische Informatik, Technische Universität Berlin, Berlin, Germany; now with HörTech gGmbH, Oldenburg, Oldenburg, Germany

M. Ercan Altinsoy Chair of Communication Acoustics, Technische Universität Dresden, Dresden, Germany

Christiane Antweiler Institute of Communication Systems and Data Processing, RWTH Aachen University, Aachen, Germany

Sylvain Argentieri Institute for Intelligent Systems and Robotics, Pierre and Marie Curie University (Univ Paris 06), National Centre for Scientific Research (CNRS), Paris, France

Robert Baumgartner Acoustics Research Institute, Austrian Academy of Sciences, Vienna, Austria

Mathieu Bernard Institute for Intelligent Systems and Robotics, Pierre and Marie Curie University (Univ Paris 06), National Centre for Scientific Research (CNRS), Paris, France

Jens Blauert Institute of Communication Acoustics, Ruhr-Universität Bochum, Bochum, Germany

Jonas Braasch Graduate Program in Architectural Acoustics, Center of Cognition, Communication and Culture, Rensselaer Polytechnic Institute, Troy, NY, USA

Jörg M. Buchholz National Acoustic Laboratories, Australian Hearing, Department of Linguistics, Macquarie University, Sydney, Australia

Samuel Clapp Graduate Program in Architectural Acoustics, Center of Cognition, Communication and Culture, Rensselaer Polytechnic Institute, Troy, NY, USA

John Culling School of Psychology, Cardiff University, Cardiff, UK

Patrick Danès Laboratory for Analysis and Architecture of Systems, Université Paul Sabatier (Univ. Toulouse), National Centre for Scientific Research (CNRS), Toulouse, France

Torsten Dau Department of Electrical Engineering, Centre for Applied Hearing Research, Technical University of Denmark, Kgs. Lyngby, Denmark

Mathias Dietz Department of Medical Physics and Acoustics, Carl-von-Ossietzky Universität, Oldenburg, Germany

Gerald Enzner Institute of Communication Acoustics, Ruhr-Universität Bochum, Bochum, Germany

Bruno Gas Institute for Intelligent Systems and Robotics, Pierre and Marie Curie University (Univ Paris 06), National Centre for Scientific Research (CNRS), Paris, France

Eleftheria Georganti Audio and Acoustic Technology Group, Electrical and Computer Engineering Department, University of Patras, Rio, Patras, Greece

Werner Hemmert Bio-Inspired Information Processing, Institute of Medical Engineering, Technische Universität München, Garching, Germany

Volker Hohmann Department of Medical Physics and Acoustics, Carl-von-Ossietzky Universität, Oldenburg, Germany

Sam Jelfs Smart Sensing and Analysis, Philips Research Europe, Eindhoven, The Netherlands

Armin Kohlrausch Human Technology Interaction, Technische Universität Eindhoven, Smart Sensing and Analysis Philips Research Europe, Eindhoven, The Netherlands

Dorothea Kolossa Institute of Communication Acoustics, Ruhr-Universität Bochum, Bochum, Germany

Bernardt Laback Acoustics Research Institute, Austrian Academy of Sciences, Vienna, Austria

Mathieu Lavandier Laboratoire Génie Civil et Bâtiment, Ecole Nationale des Travaux Publics de l'Etat, Université de Lyon, Vaulx-en-Velin, France

Nicolas Le Goff Department of Electrical Engineering, Centre for Applied Hearing Research, Technical University of Denmark, Kgs. Lyngby, Denmark

Christian Luther Institute of Communication Acoustics, Ruhr-Universität Bochum, Bochum, Germany

Piotr Majdak Acoustics Research Institute, Austrian Academy of Sciences, Vienna, Austria

Tobias May Department of Electrical Engineering, Centre for Applied Hearing Research, Technical University of Denmark, Kgs. Lyngby, Denmark

Bernd Meyer Department of Medical Physics and Acoustics, Carl-von-Ossietzky Universität, Oldenburg, Germany

John Mourjopoulos Audio and Acoustic Technology Group, Electrical and Computer Engineering Department, University of Patras, Rio, Patras, Greece

Michele Nicoletti Bio-Inspired Information Processing, Institute of Medical Engineering, Technische Universität München, Garching, Germany

Klaus Obermayer Neural Information Processing Group, Institut für Software-technik und Theoretische Informatik, Technische Universität Berlin, Berlin, Germany

Anthony Parks Graduate Program in Architectural Acoustics, Center of Cognition, Communication and Culture, Rensselaer Polytechnic Institute, Troy, NY, USA

Torben Pastore Graduate Program in Architectural Acoustics, Center of Cognition, Communication and Culture, Rensselaer Polytechnic Institute, Troy, NY, USA

Alban Portello Laboratory for Analysis and Architecture of Systems, Université Paul Sabatier (Univ. Toulouse), National Centre for Scientific Research (CNRS), Toulouse, France

Ville Pulkki Department of Signal Processing and Acoustics, Aalto University, Espoo, Finland

Alexander Raake Assessment of IP-based Applications, Telekom Innovation Laboratories (T-Labs), Technische Universität Berlin, Berlin, Germany

Olli Santala Department of Signal Processing and Acoustics, Aalto University, Espoo, Finland

Anton Schlesinger Institute of Communication Acoustics, Ruhr-Universität Bochum, Bochum, Germany

Peter Søndergaard Department of Electrical Engineering, Centre for Applied Hearing Research, Technical University of Denmark, Kgs. Lyngby, Denmark; Acoustics Research Institute, Austrian Academy of Sciences, Vienna, Austria

Constantin Spille Department of Medical Physics and Acoustics, Carl-von-Ossietzky Universität, Oldenburg, Germany

Sascha Spors Institute of Communications Engineering, Universität Rostock, Rostock, Germany

Maik Stamm Chair of Communication Acoustics, Technische Universität Dresden, Dresden, Germany

Marko Takanen Department of Signal Processing and Acoustics, Aalto University, Espoo, Finland

Alexandros Tsilfidis Audio and Acoustic Technology Group, Electrical and Computer Engineering Department, University of Patras, Rio, Patras, Greece

Steven van de Par Acoustics Group, Institute of Physics, Carl-von-Ossietzky Universität, Oldenburg, Germany

Adam Westermann National Acoustic Laboratories, Australian Hearing, Department of Linguistics, Macquarie University, Sydney, Australia

Hagen Wierstorf Assessment of IP-based Applications, Telekom Innovation Laboratories (T-Labs), Technische Universität Berlin, Berlin, Germany

Christian Wirtz MED-EL Deutschland GmbH, Starnberg, Germany

Ning Xiang Graduate Program in Architectural Acoustics, Center of Cognition, Communication and Culture, Rensselaer Polytechnic Institute, Troy, NY, USA