Sounds in the Sea

From Ocean Acoustics to Acoustical Oceanography

The oceans are a vast, complex, mostly dark, optically opaque but acoustically transparent world that has been only thinly sampled by today's limited technology and science. Underwater acousticians and acoustical oceanographers use sound as the premier tool to determine the detailed characteristics of physical and biological bodies and processes at sea. Myriad components of the ocean world are being discovered, identified, characterized, and imaged by their interactions with sound.

Sounds in the Sea is a comprehensive and accessible textbook on ocean acoustics and acoustical oceanography. "Ocean acoustics" describes the traditional way in which our knowledge of ocean temperature and salinity allows us to use sound to find fish, submarines, icebergs, and the depth of the ocean. "Acoustical oceanography" interprets the distinctive details of time-varying, sound amplitudes, and phase, over acoustical paths to deduce the physical and biological parameters of the specific ocean through which the sound has traveled.

This is an invaluable textbook for any course in ocean acoustics in the physical and biological ocean sciences, engineering, and physics. It will also serve as a reference for researchers and professionals in ocean acoustics, and an excellent introduction to the topic for scientists from related fields.

Chapters 1 to 9 provide the basic tools of ocean acoustics. The following 15 chapters are written by many of the world's most successful ocean researchers, who use sound in innovative ways to learn about the sea and its contents. These chapters describe modern developments, and are divided into four parts: Studies of the near-surface ocean; Bioacoustical studies; Studies of ocean dynamics; Studies of the ocean bottom.

Herman Medwin is Emeritus Professor at the Naval Postgraduate School, Monterey, California. He is a Fellow and Past President of the Acoustical Society of America, and has won both the Silver and Gold Medals in Acoustical Oceanography from the Society. He is co-author, with C. S. Clay, of the influential textbooks *Acoustical Oceanography* (1977) and *Fundamentals of Acoustical Oceanography* (1998). He has authored over 100 professional articles in the *Journal of the Acoustical Society of America* and *Journal of Geophysical Research*, and others.

Sounds in the Sea

From Ocean Acoustics to Acoustical Oceanography

Herman Medwin
Naval Postgraduate School,
Monterey, California

With contributions from

Joseph E. Blue, Leviathan Legacy Inc., Florida
Mike Buckingham, University of California, San Diego
Douglas H. Cato, DSTO, Australia
Ching-Sang Chiu, Naval Postgraduate School, Monterey
Daniela Di Iorio, University of Georgia
Orest Diachok, Naval Research Laboratory
David R. Dowling, University of Michigan
David M. Farmer, University of Rhode Island
Ann E. Gargett, Old Dominion University, Virginia
Edmund R. Gerstein, Leviathan Legacy Inc., Florida
Gary J. Heald, DSTL, UK.
D. Vance Holliday, BAE Systems, San Diego
John K. Horne, University of Washington, Seattle
Josef M. Jech, National Oceanic and Atmospheric Administration
T. G. Leighton, University of Southampton, UK
Rob McCauley, Curtin University, Australia
Nicholas Makris, Massachusetts Institute of Technology
Christopher Miller, Naval Postgraduate School, Monterey
Michael J. Noad, University of Queensland, Australia
Jeffrey A. Nystuen, University of Washington, Seattle
David Palmer, National Oceanic and Atmospheric Administration
Peter Rona, Rutgers University, New Jersey
Heechun Song, University of California, San Diego
Robert Spindel, University of Washington, Seattle
Timothy K. Stanton, Woods Hole Oceanographic Institution

CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

4843/24, 2nd Floor, Ansari Road, Daryaganj, Delhi - 110002, India

79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108448147

First published 2005
First paperback edition 2017

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging in Publication data
Medwin, Herman, 1920–
Sounds in the Sea : From Ocean Acoustics to Acoustical Oceanography/Herman Medwin, with contributions from Joseph E. Blue... [*et al*.].
p. cm.
Includes bibliographical references and index.
ISBN 0 521 82950 X (hardback)
1. Underwater acoustics. 2. Seawater – Acoustic properties. 3. Oceanography. I. Title.
QC242.2.M44 2005
551.46′54 – dc22 2004051867

ISBN 978-0-521-82950-2 Hardback
ISBN 978-1-108-44814-7 Paperback

Cambridge University Press
978-1-108-44674-7 — Floods in a Changing Climate
Ramesh S. V. Teegavarapu
Frontmatter
More Information

This book is dedicated to my dear wife, Eileen

Contents

Notes on contributors

Herman Medwin (Chapters 1–9) is Emeritus Professor, Naval Postgraduate School, Monterey, California; Fellow, Silver Medalist in Acoustical Oceanography, Gold Medalist, and Past President of the Acoustical Society of America. He is co-author, with C. S. Clay, of graduate textbooks published in 1977 (Russian translation 1980) and 1998, which defined the field of acoustical oceanography. He plays classical string quartets weekly with a geophysicist-musician, a violin-making organic chemist, and a well-known marine biologist. E-mail <oceanac@mbay.net>

David M. Farmer (Chapter 10) is Dean of the Graduate School of Oceanography, University of Rhode Island, Narragansett, Fellow of the Royal Society of Canada, Fellow of the American Geophysical Union, Fellow of the Acoustical Society of America and recipient of the Rosenstiel Award in Marine Sciences, The US Navy and Oceanography Society's Walter Munk Award, and the Canadian Meteorological and Oceanography Society President's Prize. E-mail <TheDean@gso.uri.edu>

Jeffrey A. Nystuen (Chapter 11) is Principal Oceanographer, Applied Physics Laboratory, College of Ocean and Fisheries Sciences, University of Washington, Seattle, where he was recognized in 2000 for the Development and Disclosure of Innovative Technology. In 2003 he received the Medwin Prize in Acoustical Oceanography from the Acoustical Society of America and became a Fellow of ASA. He has authored or co-authored 27 refereed scientific publications. He travels widely, enjoying birdwatching, dancing and exploring foreign cultures. E-mail <nystuen@apl.washington.edu>

D. Vance Holliday (Chapter 12) is Director of Analysis and Applied Research, Applied Technologies, Electronic Systems Division, BAE Systems. He is a Fellow and Silver Medalist in Acoustical Oceanography of the Acoustical Society of America and a senior member of the US delegation to the International Council for the Exploration of the Sea (ICES). He is a member of American Society of Limnology and Oceanography (ASLO) and serves on the Editorial Board of the new ASLO Journal

on Methods. A charter member of The Oceanography Society (TOS), he is currently the representative for technology on the TOS Executive Council. With David Farmer, Dr. Holliday co-chairs SCOR Working Group 118 on the introduction of new technology for the detection and study of marine life. In the summer of 2002, for his work in bioacoustics and its impact on naval systems, the Chief of Naval Research presented him the US Navy's Meritorious Public Service Award. He continues to search for more time to play with his two granddaughters and one grandson. E-mail <van.holliday@baesystems.com>

Tim K. Stanton is Senior Scientist and former Chair of the Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution (WHOI). He is also on the teaching staff in the Massachusetts Institute of Technology/WHOI Joint Graduate Education Program. Trained in physics, Dr. Stanton has conducted research on a wide range of topics in underwater acoustics. He is a Fellow of the Acoustical Society of America (ASA) and member of The Oceanography Society (TOS) where he has chaired or co-chaired several international meetings. He has served as Associate Editor of JASA, and Guest Associate Editor of IEEE Journal of Oceanic Engineering and Deep Sea Research. He has been awarded the A. B. Wood Medal for his contributions to research in underwater acoustics. Outside of his professional activities, Stanton performs trombone in various groups, including the Metropolitan Wind Symphony in Boston, and plays piano accompaniment for his church choir. E-mail <tstanton@whoi.edu>

John K. Horne (Chapter 13) splits his time between Research Assistant Professor at the University of Washington, School of Aquatic and Fishery Sciences, and member of the Fisheries Acoustics Group, Alaska Fisheries Science Center in Seattle, Washington. He is a member of the Acoustical Society of America, the American Society of Limnology and Oceanography, and the Fisheries Society of the British Isles. When not working, traveling for work, or out on a research cruise, he enjoys exploring the northwest by following the dog up a mountain. E-mail <john.horne@noaa.gov>

J. Michael Jech is a Research Fisheries Biologist, Northeast Fisheries Science Center, Woods Hole, Massachusetts. He has had the opportunity to work on a variety of aquatic environments and sail on an assortment of vessels in the Laurentian Great Lakes, Chesapeake Bay, Southern and Northern Atlantic Ocean, and in estuaries along the US east coast. He is a member of the Acoustical Society of America, American Fisheries Society, and Sigma Xi. When not out on a research cruise or in front of a computer, he enjoys fishing, mountain biking, and going to the beach. E-mail <michael.jech@noaa.gov>

Orest Diachok (Chapter 14) is a research physicist with the Naval Research Laboratory, Washington, DC. He is a Fellow of the Acoustical Society of America and a member of the American Fisheries Society. He is the author of numerous papers on acoustical sensing of the biological and physical properties of the ocean. The Naval Research Laboratory recently recognized his work on applications of matched field processing to acoustic remote sensing as one of NRL's top 75 achievements. Between 1980 and 1992 he served as Head of the Applied Ocean Acoustics Branch at NRL, and between 1992 and 1996 held the post of Chief Scientist of the NATO Undersea Research Centre in Italy. He enjoys billiards, archeology, art history, Puccini arias, B. B. King laments, Ukrainian folk songs, pale ale and Italian wines. He and his wife Olha, are proud parents of three sons, one of whom, Mateo (10), wants to become an acoustical oceanographer. E-mail <OrestDia@aol.com>

Douglas Cato (Chapter 15) is Head of the Shallow Water Environment Group of the Defence Science and Technology Organisation in Sydney, Australia. He is a Fellow of the Acoustical Society of America and has honorary positions at the Universities of Sydney and Queensland, and Curtin University in Perth. His main research contributions have been in ambient noise in the ocean and marine bioacoustics. When he has time, he enjoys playing classical guitar or returning to his earlier interest as a visual artist. E-mail <Doug.Cato@bigpond.net.au>

Michael Noad is Postdoctoral Research Fellow at the University of Queensland, Australia, who recently completed his Ph.D. in Marine Biology at the University of Sydney. His postdoctoral work is a continuation of his doctoral work, concerning the use of sound by humpback whales as well as the way their songs change as a cultural phenomenon. He continues to work in close collaboration with Doug Cato who supervised his Ph.D. During his spare time he surfs, sails, skis, and travels. E-mail <mnoad@uq.edu.au>

Robert McCauley is Senior Research Fellow with the Centre for Marine Science and Technology at Curtin University in Western Australia. As a biologist, his main research focus is on the use of passive acoustics to study marine animals and on the impacts of noise on marine animals. He enjoys coaching hockey and surfing with his son. E-mail <r.mccauley@cmst.curtin.edu.au>

Joseph E. Blue (Chapter 16) retired from US Navy's Senior Executive Service in 1996, prior to which he served as Superintendent of the Underwater Sound Reference Division (USRD) for the Naval Research Laboratory in Orlando, FL. He was a Fellow of the Acoustical Society of America, is listed in *Who's Who in Science in America*, and in *1000 Great Americans*, International Biographical Centre, Cambridge,

England. When his grandson was the manatee spokesman for his elementary school class and asked him to help save the manatees, Dr. Blue volunteered his services and began to work with Edmund Gerstein. From that beginning, his avocation was centered on acoustical causes of collision between watercraft and marine mammals. Dr. Blue spent much time assisting students in solving marine mammal acoustical measurement problems. Joe Blue passed away on January 7, shortly after writing his contribution to Chapter 16.

Edmund R. Gerstein (Chapter 16) has a Ph.D. in Psychobiology and Neuroscience. He holds faculty appointments in both the Departments of Psychology and Biology at Florida Atlantic University, where he is Director of Marine Mammal Research and Behavior. His research is focused on marine mammal hearing and underwater bioacoustics. Working with Joseph E. Blue in their research corporation, Leviathan Legacy Inc., he has studied marine mammal behavioral ecology and has revealed the underlying sensory and acoustical causes for vessel collisions on manatees and whales. When not studying marine mammals, he relaxes by watching and raising birds in his backyard aviary in Boca Raton, where his neighbors affectionately refer to him as the Birdman of Boca. E-mail <gerstein2@aol.com>

Ching-Sang Chiu (Chapter 17) is Professor of Oceanography, Naval Postgraduate School, Monterey, California, Fellow of the Acoustical Society of America, and Editor-in-Chief, Journal of Computational Acoustics. He has authored or co-authored over 40 refereed publications in the areas of ocean acoustics and acoustical oceanography. E-mail <chiu@nps.edu>

Christopher W. Miller is an electrical engineer, working as Research Associate at the NPS Ocean Acoustics Laboratory, and is Manager of the NPS Ocean Acoustic Observatory at Point Sur, CA. He has also been a Docent at the Monterey Bay Aquarium for the past 16 years. His 10 years' experience working with sea otter rescue and rehabilitation has provided his background and stimulated his interest in applying acoustics to marine biology. E-mail <cwmiller@nps.edu>

Robert C. Spindel (Chapter 18) is Director Emeritus of the Applied Physics Laboratory, University of Washington, Seattle, and Professor of Electrical Engineering. He is the recipient of the A. B. Wood Medal, British Institute of Acoustics, and the Walter Munk Award, US Navy and The Oceanography Society. He is a Fellow of the Acoustical Society of America and the Institute of Electrical and Electronics Engineers, and Fellow and Past President of the Marine Technology Society. In his

spare time he enjoys rebuilding cars; old Porsches are a specialty. E-mail <spindel@apl.washington.edu>

David R. Dowling (Chapter 19) is Associate Professor of Mechanical Engineering and Applied Mechanics at the University of Michigan, Ann Arbor where he received an Outstanding Accomplishment Award in 2001 for contributions to research and education. He is a Fellow of the Acoustical Society of America and has authored or co-authored 36 refereed publications, about half of which cover topics in acoustics. He lives with his wife and their six children, and enjoys recreational swimming and other water sports. E-mail <drd@engin.umich.edu>

Heechun Song is Research Scientist, Marine Physical Laboratory, Scripps Institution of Oceanography, La Jolla, California. He has authored or co-authored 20 refereed scientific publications. He is a Fellow of the Acoustical Society of America. E-mail <hcsong@mpl.ucsd.edu>

Daniela Di Iorio (Chapter 20) is Assistant Professor, Department of Marine Sciences, University of Georgia, Athens, Georgia. She enjoys teaching acoustical and physical oceanography at all student levels and is committed to be a soccer-, bike- and music-mom for her two little energetic boys. E-mail <daniela@arches.uga.edu>

Ann Gargett is Professor of Physical Oceanography at the Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, Virginia, She is a Fellow of the Royal Society of Canada and Emeritus Senior Scientist at the Institute of Ocean Sciences, Canada. Mother of a grown daughter, she now has more time for rowing.

Tim Leighton (Chapter 21) is Professor of Ultrasonics and Underwater Acoustics at the Institute of Sound and Vibration Research, University of Southampton, England. His interest in acoustical oceanography began when, as an undergraduate at Cambridge University, he began to research the sources of sound in babbling brooks. At age 28 he completed his monograph *The Acoustic Bubble* and moved to Southampton University, where he has researched physical, oceanographic and biomedical acoustics, publishing over 200 articles. He received the Inaugural Medwin Prize in Acoustical Oceanography of the Acoustical Society of America (ASA), and is the only person to have been awarded both the A. B. Wood and Tyndall Medals of the UK Institute of Acoustics. He is a Fellow of the ASA, UK Institute of Acoustics, and the UK Institute of Physics. In 2000 he was awarded a Leverhulme Trust Senior Research Fellowship from the Royal Society. E-mail <T.G.Leighton@soton.ac.uk>

Gary Heald is an Acoustics Technical Expert with the Defence Science and Technology Laboratory (DSTL), Winfrith, England. His Ph.D. was from the Physics Department, University of Bath, for research on sediment classification using acoustic scattering. He has worked on

underwater acoustics and sonar for over 20 years, with a special interest in high frequency underwater acoustics and scattering. He is a Fellow of the Institute of Acoustics (UK) and in 2000 was the recipient of the A. B. Wood medal. He is a Fellow of the Acoustical Society of America and has served on the ASA Technical Committee on Acoustical Oceanography since 1998. In April 2003 he was elected Chair of the Underwater Acoustics Group of the Institute of Acoustics. In 2001 he was given an achievement award from the Non-Atomic Research and Development Technical Cooperation Panel for his international collaboration on environmental reconnaissance. Gary is a visiting senior lecturer at the Institute of Sound and Vibration Research, University of Southampton. In his spare time Gary is interested in cabinet making, woodturning, photography, and ham radio. E-mail <gjheald@mail.dstl.gov.uk>

David R. Palmer (Chapter 22) is Research Physicist, Atlantic Oceanographic and Meteorological Laboratory in Miami. He has over 25 years experience conducting experimental and theoretical research in acoustical oceanography and related fields and has published over 150 scientific papers. He is a member of several honor and professional societies including Phi Beta Kappa and the Acoustical Society of America. When time permits he teaches physics at Florida International University. He grew up in Colorado and spent much of his summers hiking the mountains searching for ghost towns from the mining era. E-mail <David.R.Palmer@noaa.gov>

Peter Rona is Professor of Marine Geology and Geophysics at Rutgers University. His interest in ocean acoustics began in the 1960s when he worked under his mentor C. S. Clay at the former Hudson Laboratories of Columbia University. He was Senior Research Geophysicist with NOAA before coming to Rutgers in 1994 to build marine programs. He is presently working with others in applying innovative methods to acoustically image and measure plumes that buoyantly rise from black smoker vents and diffuse hydrothermal flow on the sea floor. He is Fellow of Acoustical Society of America, Geological Society of America, Society of Economic Geologists, and the American Association for the Advancement of Science, and recipient of Francis Shepard Medal for Excellence in Marine Geology, Gold Medal of the US Department of Commerce for exceptional scientific contributions to the nation, and the Hans Pettersson Bronze Medal of the Royal Swedish Academy of Sciences. He enjoys exploration of the Earth wherever it leads. E-mail <rona@imcs.rutgers.edu>

Nicholas Makris (Chapter 23) is a Professor at the Massachusetts Institute of Technology. He is a Secretary of the Navy/Chief of Naval Operations Scholar of Oceanographic Sciences, a recipient of the A. B. Wood Medal, the Doherty Professorship of Ocean Utilization, the MIT

Edgerly Fellowship, the ONR Young Investigator Award, NRL's Alan Berman Award and is a Fellow of the Acoustical Society of America. He teaches acoustical sensing to both undergraduates and graduate students at MIT and is currently helping to prove that there are oceans of liquid water on some of Jupiter's moon, as part of NASA's Jupiter Icy Moons Orbiter (JIMO) Science Definition Team. He likes to play an old-fashioned Fender Stratocaster and brings one on oceanographic cruises to jam with his piano-obsessed friend from WHOI. He used to sail and windsurf a lot in his spare time but now finds traveling around the planet more fun. E-mail <makris@keel.mit.edu>

Michael J. Buckingham (Chapter 24) is Professor of Ocean Acoustics, Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego and Visiting Professor, University of Southampton, UK. Previously an Individual Merit Senior Principal Scientific Officer, Royal Aerospace Establishment, UK, he has used a jet aircraft for acoustics research in ice-covered seas. Recipient of the A. B. Wood Medal (UK Institute of Acoustics), Clerk Maxwell Premium (UK Institution of Electronic & Radio Engineers). Fellow, Acoustical Society of America, UK Institute of Acoustics, UK Institution of Electrical Engineers, Explorers Club; member, New York Academy of Sciences. Has published some 200 scientific papers and a book on solid-state physics. Weekend photographer and flier, he holds a private pilot's license with instrument and glider ratings. E-mail <mjb@ucsd.edu>

Preface
The world of ocean sounds

This book is the reader's gateway to a science that spans physics, oceanography and marine biology. Wherever possible we perform the trick of Janus, the mythological Roman God, who simultaneously faces in opposite directions. One view, called "ocean acoustics," is the traditional direction in which the knowledge of (or assumptions about) the ocean temperature and salinity allows one to use sound to find fish, submarines, icebergs, and the depth of the ocean. The opposite view, "acoustical oceanography," interprets the distinctive details of time-varying, sound amplitudes and phases over acoustical paths to deduce the physical and biological parameters of the specific ocean through which the sound has traveled . . . It is best to look in both directions.

We will be considering the diverse potentialities of passive listening, as well as benign probing by unobtrusive sound: in rough seas and smooth seas; deep seas and shallow seas; clean seas and seas made locally dirty by dumping of man's garbage; seas of uniform temperature and those that are thermally layered; dead seas and seas noisily filled with abundant life ranging from the grand whales to microscopic zooplankton and phytoplankton. It is a vast, complex, mostly dark, optically opaque, but acoustically transparent world that has been only thinly sampled by today's limited technology and science.

Tragic beginnings

In retrospect, the impetus for the effective use of sound in the sea occurred in 1912 when the steamship TITANIC struck an iceberg. The subsequent loss of hundreds of lives triggered man's use of sound to sense scatterers in the oceans of the world. Within a month of the disaster, a patent application was filed by L. R. Richardson in the United Kingdom (10 May 1912) for "detecting the presence of large objects under water by means of the echo of compressional waves – directed in a beam – by a projector." The basic idea was that a precise knowledge of the speed of sound in water, and the travel time of the sound from source to scatterer and back to the source/receiver, permits the calculation of the distance to the scattering body. This was to be the beginning of the use of underwater

sound projectors and receivers. They were to be called "SONARs" i.e. devices for **SO**und **NA**vigation and **R**anging.

In fact, the speed of sound in fresh water had already been measured very accurately almost a century before. Corrections for depth dependence and salinity dependence of the speed were soon determined. A grand variety of new commercial and military activities were immediately practical, including acoustical fish finding (patented in 1935), acoustical measurements of ocean depth, and acoustical detection of submarines.

Present status, future promise

Since those early days, underwater acousticians and acoustical oceanographers have used sound as the premier tool to determine the detailed characteristics of physical and biological bodies and processes at sea. Myriad components of the ocean world are being discovered, identified, characterized, and imaged by their interactions with sound. Chapters 1 through 9 of this textbook, "Fundamentals," provide the basic tools of ocean acoustics. The following 15 chapters, written by some of the world's most successful ocean researchers, who are using sound in innovative ways to learn about the sea and its contents, describe several modern developments. Their contributions are divided into the four sections, titled: "Studies of the near-surface ocean"; "Bioacoustical studies"; "Studies of ocean dynamics"; "Studies of the ocean bottom."

Acknowledgements

Inspiration for this book has come from my professors at the University of California at Los Angeles, my students and associates at the Naval Postgraduate School and colleagues in the Acoustical Society of America. I had the great fortune of being a student at UCLA during those vital, early post-WWII years when the Physics Department at UCLA was the world's finest academic environment for teaching and research in physical acoustics. The names of my professors read like a "who's who" of acoustics in the latter half of the twentieth century: Leo Delsasso, Carl Eckart, Vern O. Knudsen, Robert W. Leonard, and my outstanding thesis advisor, Isadore Rudnick.

Let me pay tribute to my Naval Officer students at the Naval Postgraduate School, who were some of the brightest, most energetic people I have ever had the pleasure of working with. They wrote theses, part of the requirement for their M.S. degrees in Acoustical Engineering, that would have satisfied the academic quality and significance of Ph.D. research at many of the world's colleges and universities. Most of these energetic students went on to become Admirals and Captains in the navies of the USA and Turkey and West Germany; their fine student research is appropriately identified and referenced throughout this book.

My years of book co-authorship with C. S. Clay (1977, 1998) remain a high point of my work in the field of acoustics. The first nine chapters of this book have been extracted from the graduate level textbook, Medwin and Clay, *Fundamentals of Acoustical Oceanography*, Academic Press (1998), (abbreviated *M&C*). Much of that material has been updated and rewritten here for undergraduates or beginning graduate students in physical and biological sciences. Many of the unidentified figures were drawn by C. S. Clay, for *M&C*, and I am grateful that he allowed them to be re-used here.

Some topics, based on the research of others, are identified simply by the author names and the date of publication. More complete references will be found in the References or Bibliography sections, or on the Internet. Descriptions of a special few publications are in "Further reading" at the ends of each of the first nine chapters.

Valuable extensive discussions have been held with Aubrey Anderson, Steven Baker, Mohsen Badiey, Jonathan Berkson, William Carey, Jacques Chamuel, N. Ross Chapman, Dezang Chu, Lawrence Crum, William Cummings, Peter Dahl, Grant Deane, Chris Feuillade, Fred Fisher, Charles Greenlaw, Mark Hamilton, Richard Keiffer, Saimu Li, Michael Longuet-Higgins, James Lynch, Kendall Melville, James H. Miller, Jorge Novarini, Wesley Nyborg, John Potter, Andrea Prosperetti, Jeffrey Simmens, Kevin Smith, Eric Thorsos, Alex Tolstoy, Ivan Tolstoy, and O. Bryan Wilson.

My co-authors acknowledge the significant contributions by their many students and their research colleagues: Karen G. Bemis, Kevin Conley Michael Czarneçki, Henry S. Fleming, Eric Giddens, Charles Greenlaw, Thomas Hahn, Darrell R. Jackson, Christopher D. Jones, Grace Kamitakahara-King, Duncan McGehee, Kyohiko Mitsuzawa, Michael Richardson, Deborah Silver, Fernando Simonet, Ron Teichrob, Svein Vagle, Timothy Wen, Peter Wiebe, Norman Zabusky.

Several ocean scientists have looked at early versions of the marine biology sections of the book and have made useful suggestions. I am greatly indebted to Susanna Blackwell, Steven Haddock, and Redwood W. Nero who have helped me to bridge the gap between physical scientists and biological scientists.

I am most grateful to my oceanographer colleague at the Naval Postgraduate School, Professor Ching-Sang Chiu, who has been generously critical of my attempt to open our subject to undergraduates in the ocean sciences. Also special thanks to Dr. Steve Haddock, marine biologist of the Monterey Bay Aquarium Research Institute, who has gently led me into twenty-first-century word processing techniques.

I am particularly indebted to the 25 prominent acoustical oceanographers from Australia, Canada, England, and the United States of America who wrote Chapters 10 to 24 to describe their recent important research. My co-authors are: David M. Farmer; Jeffrey A. Nystuen; D. Vance Holliday and Timothy K. Stanton; John K. Horne and J. Michael Jech; Orest Diachok; Douglas Cato, Michael Noad, and Robert McCauley; Edmund Gerstein and Joseph Blue; Ching-Sang Chiu and Christopher W. Miller; Robert C. Spindel; David R. Dowling and Heechun Song; Daniela Di Iorio and Ann Gargett; T. G. Leighton and Gary Heald; David Palmer and Peter Rona; Nicholas Makris; Michael J. Buckingham.

A bow to the many anonymous professionals of the Acoustical Society of America, whose collegial conversations and e-mails I so thoroughly enjoy at, and between, the semi-annual meetings of the ASA.

Research support for the works reported here has come from several sources; most importantly from US Office of Naval Research (ONR), but also from US National Science Foundation (NSF), US Strategic

Environmental Research Development Program (SERDP), US National Oceanographic and Atmospheric Administration (NOAA)'s National Undersea Research Program, West Coast and Polar National Undersea Research Center, NASA, USA, Navy Submarine Development Group ONE, Deep Submergence Group of the Woods Hole Oceanographic Institution, Department of Fisheries and Oceans, Canada.

The encouragement and early offer of support from the US Office of Naval Research, was particularly appreciated; that branch of the US Navy was among the first to see a need for an undergraduate textbook on ocean acoustics.

Finally, my appreciation to my contacts at Cambridge University Press: Matt Lloyd, Publisher for Earth and Space Sciences, and Jo Bottrill, Production Editor, for their wise comments and challenging questions.

Herman Medwin