



PRINCIPLES OF UNDERWATER SOUND

third edition

Robert J. Urick

Robert J. Urick

***Formerly, Professor, The Catholic University
of America, Washington D.C., and
Senior Research Physicist
U.S. Naval Surface Weapons Center Headquarters
White Oak, Silver Spring, Maryland***

***principles of
underwater
sound*** 3rd edition

***First edition published in 1967
under the title "Principles of
Underwater Sound for Engineers"***



Peninsula Publishing
Westport, Connecticut

Library of Congress Cataloging in Printing Data

Urlick, Robert J.

Principles of underwater sound (third edition)

Includes bibliographies and index.

1. Underwater acoustics. 2. Sonar. I. Title.

QC242.2.U74 1983 534'.23 96-068876

ISBN 0-932146-62-7

Copyright © 1983 by McGraw-Hill, Inc.

The copyright and all rights to *Principles of Underwater Sound (Third Edition)* were purchased from McGraw-Hill, Inc. by Peninsula Publishing in 2010 and all rights are owned by Peninsula Publishing.

Except as permitted under the Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in any data base or retrieval system, without the prior written permission of Peninsula Publishing.

Reprint of *Principles of Underwater Sound (Third Edition)*

Published by

**Peninsula Publishing
1630 Post Road East
Westport, CT 06880 USA**

Telephone: 203-292-5621

Email: sales@PeninsulaPublishing.com

Website: <http://www.PeninsulaPublishing.com>

ISBN-13: 9780932146625 - Hardcover edition

ISBN-10: 0932146627

ISBN-13: 9780932146274 - Softcover edition

This book was set in Baskerville by Bi-Comp, Inc.

Published in the United States of America

contents

Preface to the Third Edition ix
Preface the First Edition xi
Abbreviations Used in the Book xiii

one The Nature of Sonar 1

1.1 Historical Survey 2
1.2 Postwar Developments 6
1.3 Nonmilitary Uses of Underwater Sound 7
1.4 Military Uses of Underwater Sound 7
1.5 Some Basic Concepts 11
1.6 The Micropascal Reference Unit and the Decibel 14
References 16

two The Sonar Equations 17

2.1 Basic Considerations 18
2.2 The Active and Passive Equations 19
2.3 Names for Various Combinations of Parameters 22
2.4 The Parameters in Metric Units 23
2.5 Echo, Noise, and Reverberation Level as Functions of Range 23
2.6 Transient Form of the Sonar Equations 25
2.7 Statement of the Equations 28
2.8 Limitations of the Sonar Equations 29
References 30

three Properties of Transducer Arrays: Directivity Index 31

3.1 Array Gain 33
3.2 Measuring the Coherence of Sound Fields 41
3.3 Receiving Directivity Index 42
3.4 Limitations of Directivity Index 42
3.5 Transducer Responses 44
3.6 Calibration Methods 44

3.7	<i>Reciprocity Calibration</i>	51
3.8	<i>Calibration of Large Arrays</i>	53
3.9	<i>Beam Patterns</i>	54
3.10	<i>The Product Theorem and the Mills Cross</i>	60
3.11	<i>Shading and Superdirectivity</i>	62
3.12	<i>Adaptive Beam Forming</i>	64
3.13	<i>Multiplicative Arrays</i>	65
	<i>References</i>	68
four	<i>Generation of Underwater Sound: Projector Source Level</i>	71
4.1	<i>Relation between Source Level and Radiated Acoustic Power</i>	73
4.2	<i>Limitations on Sonar Power</i>	76
4.3	<i>Nonlinear Effects in Sonar</i>	81
4.4	<i>Explosions as Sources of Underwater Sound</i>	86
	<i>References</i>	97
five	<i>Propagation of Sound in the Sea: Transmission Loss, I</i>	99
5.1	<i>Introduction</i>	99
5.2	<i>Spreading Laws</i>	100
5.3	<i>Absorption of Sound in the Sea</i>	102
5.4	<i>Velocity of Sound of the Sea</i>	111
5.5	<i>Velocity Structure of the Sea</i>	116
5.6	<i>Propagation Theory and Ray Tracing</i>	120
5.7	<i>The Sea Surface</i>	128
5.8	<i>The Sea Bottom</i>	136
	<i>References</i>	143
six	<i>Propagation of Sound in the Sea: Transmission Loss, II</i>	147
6.1	<i>The Mixed-Layer Sound Channel</i>	147
6.2	<i>The Deep Sound Channel</i>	159
6.3	<i>Caustics and Convergence Zones</i>	164
6.4	<i>Internal Sound Channels</i>	169
6.5	<i>Arctic Propagation</i>	169
6.6	<i>The Shallow-Water Channel</i>	172
6.7	<i>Fluctuation of Transmitted Sound</i>	182
6.8	<i>Horizontal Variability</i>	190
6.9	<i>Coherence of Transmitted Sound</i>	193
6.10	<i>Multipaths in the Sea</i>	193
6.11	<i>Deep-Sea Paths and Losses: A Summary</i>	194
	<i>References</i>	197
seven	<i>The Noise Background of the Sea: Ambient-Noise Level</i>	202
7.1	<i>Sources of Ambient Noise in Deep Water</i>	203
7.2	<i>Deep-Water Spectra</i>	209
7.3	<i>Shallow-Water Ambient Noise</i>	211

7.4 *Variability of Ambient Noise* 215
 7.5 *Intermittent Sources of Ambient Noise* 216
 7.6 *Effect of Depth* 221
 7.7 *Amplitude Distribution* 223
 7.8 *Noise in Ice-Covered Waters* 224
 7.9 *Directional Characteristics of Deep-Water Ambient Noise* 227
 7.10 *Spatial Coherence of Ambient Noise* 231
 7.11 *Summary* 233
 References 233

eight *Scattering in the Sea: Reverberation Level* 237

8.1 *Types of Reverberation* 237
 8.2 *The Scattering-Strength Parameter* 238
 8.3 *Equivalent Plane-Wave Reverberation Level* 240
 8.4 *Volume-Reverberation Theory* 240
 8.5 *Surface-Reverberation Theory* 244
 8.6 *Target Strength and Scattering Strength* 246
 8.7 *Surface Scattering by a Layer of Volume Scatterers* 247
 8.8 *Reverberation Level for Short Transients* 248
 8.9 *Air Bubbles in Water* 249
 8.10 *Volume Reverberation: The Deep Scattering Layer* 255
 8.11 *Sea-Surface Reverberation* 262
 8.12 *Theories and Causes of Sea-Surface Scattering* 267
 8.13 *Sea-Bottom Reverberation* 271
 8.14 *Under-Ice Reverberation* 280
 8.15 *Reverberation in Shallow Water* 281
 8.16 *Characteristics of Reverberation* 281
 8.17 *Reverberation Prediction* 285
 References 287

nine *Reflection and Scattering by Sonar Targets: Target Strength* 291

9.1 *The Echo as the Sum of Backscattered Contributions* 294
 9.2 *Geometry of Specular Reflection* 295
 9.3 *Target Strength of a Small Sphere* 298
 9.4 *Complications for a Large Smooth Solid Sphere* 301
 9.5 *Target Strength of Simple Forms* 302
 9.6 *Bistatic Target Strength* 302
 9.7 *Target-Strength Measurement Methods* 306
 9.8 *Target Strength of Submarines* 308
 9.9 *Target Strength of Surface Ships* 314
 9.10 *Target Strength of Mines* 314
 9.11 *Target Strength of Torpedoes* 315
 9.12 *Target Strength of Fish* 315
 9.13 *Target Strength of Small Organisms* 317
 9.14 *Echo Formation Processes* 317
 9.15 *Reduction of Target Strength* 320
 9.16 *Echo Characteristics* 322
 9.17 *Summary of Numerical Values* 325
 References 325

ten	<i>Radiated Noise of Ships, Submarines, and Torpedoes:</i>	
	<i>Radiated-Noise Levels</i>	328
	10.1 <i>Source Level and Noise Spectra</i>	328
	10.2 <i>Methods of Measurement</i>	329
	10.3 <i>Sources of Radiated Noise</i>	332
	10.4 <i>Summary of the Sources of Radiated Noise</i>	341
	10.5 <i>Total Radiated Acoustic Power</i>	343
	10.6 <i>Radiated-Noise Levels</i>	345
	10.7 <i>Cautionary Remark</i>	351
	<i>References</i>	352
eleven	<i>Self-Noise of Ships, Submarines, and Torpedoes:</i>	
	<i>Self-Noise Levels</i>	354
	11.1 <i>Self-Noise Measurements and Reduction</i>	356
	11.2 <i>Sources and Paths of Self-Noise</i>	357
	11.3 <i>Flow Noise</i>	360
	11.4 <i>Flow-Noise Reduction</i>	365
	11.5 <i>Domes</i>	367
	11.6 <i>Self-Noise of Cable-Suspended and Bottomed Hydrophones</i>	370
	11.7 <i>Self-Noise of Towed Sonars</i>	371
	11.8 <i>Self-Noise Levels</i>	372
	<i>References</i>	376
twelve	<i>Detection of Signals in Noise and Reverberation:</i>	
	<i>Detection Threshold</i>	377
	12.1 <i>Definition of Detection Threshold</i>	378
	12.2 <i>The Threshold Concept</i>	380
	12.3 <i>Input Signal-to-Noise Ratio for Detection</i>	383
	12.4 <i>Modifications to the ROC Curves</i>	386
	12.5 <i>Estimating Detection Threshold</i>	390
	12.6 <i>Effect of Duration and Bandwidth</i>	392
	12.7 <i>Example of a Computation</i>	393
	12.8 <i>Detection Threshold for Reverberation</i>	395
	12.9 <i>Tabular Summary</i>	396
	12.10 <i>Auditory Detection</i>	396
	<i>References</i>	403
thirteen	<i>Design and Prediction in Sonar Systems</i>	406
	13.1 <i>Sonar Design</i>	406
	13.2 <i>Sonar Prediction</i>	407
	13.3 <i>The Optimum Sonar Frequency</i>	408
	13.4 <i>Applications of the Sonar Equations</i>	411
	13.5 <i>Concluding Remarks</i>	416
	<i>References</i>	416
	<i>Index</i>	417



***preface
to the
third edition***

The purpose of the third edition, like that of the second, is to present new ideas, facts, and concepts that have emerged in recent years. At the same time some older and useful material has been added as deemed appropriate by the use of the book in course teaching.

The question of metric units has been given much consideration. Although scientists and engineers today use metric units universally, operations analysts and the users of sonar equipments do not, preferring to cling to the yard instead of the meter as the unit of distance—not because of the natural human reluctance to change, but because the range scales and manuals of existing equipments are calibrated in yards and nautical miles. A curious benefit of the yard in practical work is that the nautical mile can be taken with little error to be an even 2 kiloyards (actually, it is 2.025), but it is an unhandy, uneven number of kilometers (1.853). While the yard has been retained as the unit of distance, a section on the metric conversion of the sonar parameters has been included.

The basic plan of the book has remained the same: to introduce the sonar equations after an introductory chapter and then, at the end, to illustrate their use in practical sonar problem solving after the many diverse and perplexing phenomena hidden within them have been explained in the intervening chapters.

Robert J. Urick



***preface
to
the
first
edition***

Underwater sound, as a specialized branch of science and technology, has seen service in two world wars. Although it has roots deep in the past, underwater sound, as a quantitative subject, may be said to be only a quarter of a century old. Its modern era began with the precise quantitative studies undertaken with great vigor during the days of World War II. In subsequent years, its literature has grown to sizable proportions, and its practical uses have expanded in keeping with man's continuing exploration and exploitation of the seas.

This book attempts to summarize the principles of underwater sound from the viewpoint of the engineer and the practical scientist. It lies squarely in the middle of the spectrum—between theory at one end and sonar technology at the other. Its intent is to provide a summary of the principles, effects, and phenomena of underwater sound and to give numerical quantitative data, wherever possible, for the solution of practical problems.

The framework of the book is the sonar equations—the handy set of relationships that tie together all the essential elements of underwater sound. The approach is, after an introductory chapter, to state the equations in a convenient form and then to discuss in subsequent chapters each one of the quantities occurring in the equations. The final chapter is largely devoted to problem solving, in which the use of the equations is illustrated by hypothetical problems taken from some of many practical applications of the subject.

In the desire to keep the book within sizable bounds, some aspects of underwater sound have had to be slighted. One is the subject of transducers—the conversion of electricity into sound and vice versa. Although transducer arrays are discussed, only one sound source—the underwater explosion—is dealt with at any length. It is felt that the design of electroacoustic transducers for generating and receiving sound is truly an art in itself, with a technology and theoretical background that deserves a book of its own. In addition, much of the basic theory of underwater sound is confined to references to the literature, and engineering matters of sonar hardware are omitted entirely. Although the book will therefore appeal neither to the theoretician nor to the hardware builder, it hopes to cover the vast middle ground between them and be of interest to both the design engineer and the practical physicist. It is based on a course given for several years at the Catholic University, Washington, D.C., and at Westinghouse Electric Co., and the Martin Co. in Baltimore.

The book owes a great deal to my colleagues at the Naval Ordnance Laboratory for many discussions and helpful criticism. In particular, Mr. T. F. Johnston, chief of the acoustics division, has been a constant encouragement and stimulant in the long and arduous task of writing the book. My students have been helpful too in providing me with a receptive and critical audience for whatever is original in the presentation.

Robert J. Urick

About the Author

ROBERT J. URICK, a consultant, author and teacher in underwater sound, was Adjunct Professor of Mechanical Engineering at the Catholic University of America, Washington, D.C. Professor Urick graduated from Brooklyn College and then conducted study at Columbia University and the California Institute of Technology, where he received a master's degree in geological science. His career included work for the Shell Oil and Texas Company, the Naval Sound Lab at San Diego, and The Pennsylvania State University. He headed the research division of the Naval Mine Defense Laboratory at Panama City, Florida before joining the U.S. Navy Surface Weapons Center at Silver Spring, Maryland as a senior research physicist. Over the years Dr. Urick contributed to nearly all phases of underwater sound research and published more than 200 reports and papers, receiving the Distinguished Civilian Service Award from the Navy for his outstanding work.

In 1986 Dr. Urick was awarded the Engineering Society Distinguished Technical Achievement Award. In 1988 the Acoustical Society of America awarded Dr. Urick the Pioneers of Underwater Acoustics Medal for his book, *Principles of Underwater Noise*, and for his many experiments on sound propagation, scattering, reverberation, and ambient noise. Professor Urick authored two other books: *Sound Propagation of Sound in the Sea* and *Ambient Noise in the Sea*. In 1997 Professor Urick died at age 81, ending a life of grand scholarship and leadership in the field of underwater acoustics.

principles of underwater sound

third edition

Robert J. Urick

Principles of Underwater Sound by Robert J. Urick is the most widely used book on underwater acoustics and sonar published today. For more than three decades this book has been the standby of practicing engineers, scientists, technicians, underwater systems managers, teachers, and students. Its contents lie squarely in the middle between theory at one end and practical technology at the other. *Principles* encapsulates the fundamental principles and the various phenomena of underwater sound as they apply to sonar equation, the heart of prediction of sonar performance and the quantitative assessment of effectiveness of a sonar's target detection capability. Explanations are clear and well written for teaching and self-study and the book has a problem section with solutions.

Dr. Robert Urick, the author, was an eminent underwater acoustics scientist and engineer, contributing to nearly all phases of underwater sound research. Among his many awards, Robert Urick received the Distinguished Civilian Service Award from the Navy and The Pioneers Medal from the Acoustical Society of America for his authorship of this book, his many experiments on sound propagation scattering, reverberation and ambient noise, and his grand scholarship and leadership in the field of underwater acoustics.



Peninsula Publishing
Westport, Connecticut

