

Reaffirmed by ANSI  
June 9, 2019

Arthur N. Popper · Anthony D. Hawkins · Richard R. Fay  
David A. Mann · Soraya Bartol · Thomas J. Carlson  
Sheryl Coombs · William T. Ellison · Roger L. Gentry  
Michele B. Halvorsen · Svein Løkkeborg · Peter H. Rogers  
Brandon L. Southall · David G. Zeddies · William N. Tavolga

ASA S3/SC1.4 TR-2014

# Sound Exposure Guidelines for Fishes and Sea Turtles:

A Technical Report prepared by  
ANSI-Accredited Standards Committee  
S3/SC1 and registered with ANSI



ASA Press



Springer

# **SpringerBriefs in Oceanography**

For further volumes:

<http://www.springer.com/series/11754>

## **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 N. Popper, University of Maryland  
Erica Ryherd, Georgia Tech  
Andrea Megela Simmons, Brown University  
Martin Siderius, Portland State University  
Ning Xiang, Rensselaer Polytechnic Institute  
William Yost, Arizona State University



**ASA Press**

Arthur N. Popper • Anthony D. Hawkins  
Richard R. Fay • David A. Mann  
Soraya Bartol • Thomas J. Carlson  
Sheryl Coombs • William T. Ellison  
Roger L. Gentry • Michele B. Halvorsen  
Svein Løkkeborg • Peter H. Rogers  
Brandon L. Southall • David G. Zeddies  
William N. Tavolga

ASA S3/SC1.4 TR-2014

# Sound Exposure Guidelines for Fishes and Sea Turtles:

A Technical Report prepared by  
ANSI-Accredited Standards Committee  
S3/SC1 and registered with ANSI

Registered with ANSI on 20 April 2014



Arthur N. Popper  
Department of Biology, University of Maryland  
College Park, MD 20742, USA  
apopper@umd.edu

Anthony D. Hawkins  
Loughne Ltd, Aberdeen, AB12 5YT, UK  
a.hawkins@btconnect.com

Richard R. Fay  
Marine Biological Laboratory  
Woods Hole Oceanographic Institution  
Woods Hole, MA 02540, USA  
rfay44@aol.com

David A. Mann  
Loggerhead Instruments, Sarasota, FL 34233, USA  
dmann@loggerheadinstruments.com

Soraya Bartol  
Biology Department, Virginia Wesleyan College  
Norfolk, VA 23502, USA  
sbartol@vwc.edu

Thomas J. Carlson  
ProBioSound LLC, Holmes Beach, FL 34217, USA  
tj3carlson@gmail.com

Sheryl Coombs  
Department of Biological Sciences  
Bowling Green State University  
Bowling Green, OH 43403, USA  
scoombs@bgnet.bgsu.edu

William T. Ellison  
Marine Acoustics, Inc., Middletown, RI 03801, USA  
WEMAI@aol.com

Roger L. Gentry  
ProScience Consulting, LLC  
Dickerson, MD 20842, USA  
Roger.gentry@comcast.net

Michele B. Halvorsen  
CSA Ocean Sciences, Stuart, FL 34997, USA  
mhalvy@gmail.com

Svein Løkkeborg  
Institute of Marine Research, Bergen 05005, Norway  
svein.loekkeborg@imr.no

Peter H. Rogers  
School of Mechanical Engineering  
Georgia Institute of Technology  
Atlanta, GA 30332, USA  
peter.rogers@me.gatech.edu

Brandon L. Southall  
Southall Environmental Associates Inc.  
Aptos, CA 95003, USA  
brandon.southall@sea-inc.net

David G. Zeddies  
JASCO Applied Sciences  
Silver Spring, MD 20902, USA  
david.zeddies@jasco.com

William N. Tavolga  
Sensory Biology and Behavior  
Mote Marine Laboratory, Sarasota, FL 34231, USA  
Tavolga@aol.com

ISSN 2196-1212

ISBN 978-3-319-06658-5

DOI 10.1007/978-3-319-06659-2

Springer Cham Heidelberg New York Dordrecht London

ISSN 2196-1220 (electronic)

ISBN 978-3-319-06659-2 (eBook)

Library of Congress Control Number: 2014940282

© Acoustical Society of America 2014

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 or the Acoustical Society of America. 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](http://www.springer.com))

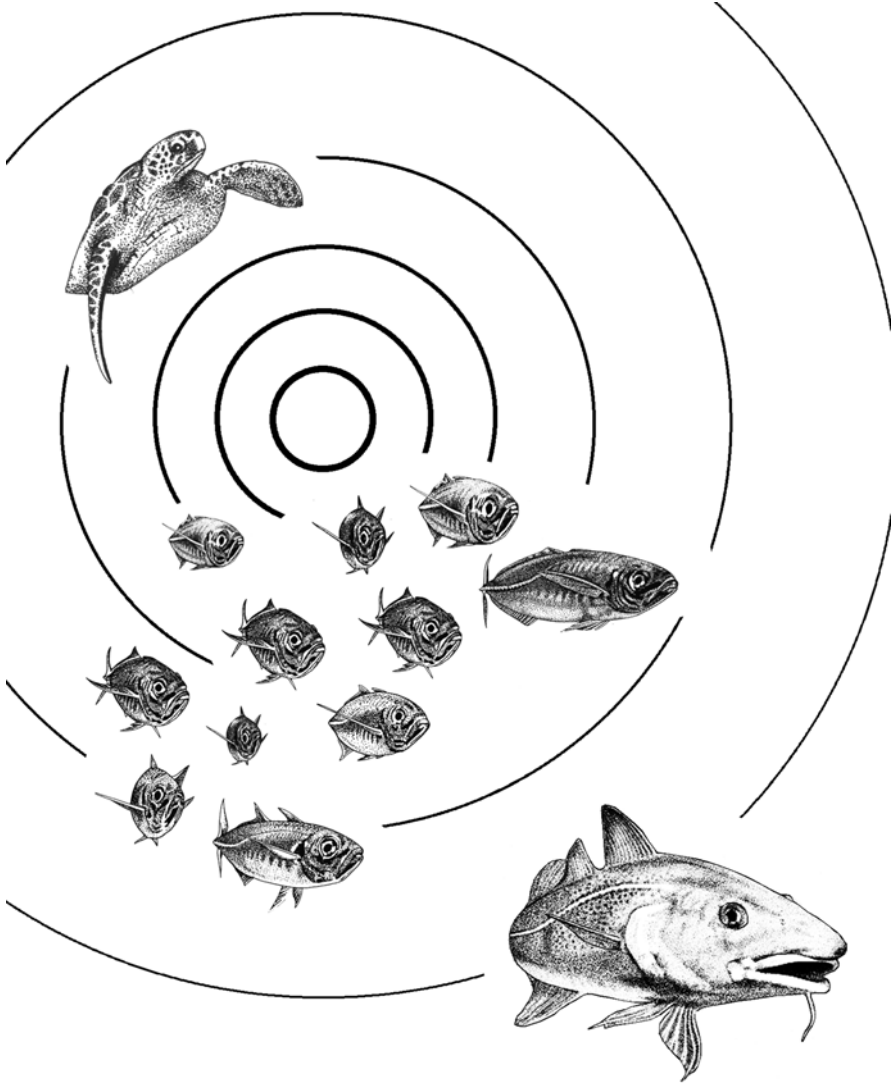
## **Acoustical Society of America**

The mission of the **Acoustical Society of America** ([www.acousticalsociety.org](http://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 7,000 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* ([www.acousticstoday.org](http://www.acousticstoday.org)), 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.



© Anthony D. Hawkins, reproduced with permission

# Abstract

This Technical Report presents the outcome of a Working Group that was established to determine broadly applicable sound exposure guidelines for fishes and sea turtles. After consideration of the diversity of fish and sea turtles, guidelines were developed for broad groups of animals, defined by the way they detect sound. Different sound sources were considered in terms of their acoustic characteristics and appropriate metrics defined for measurement of the received levels. The resultant sound exposure guidelines are presented in a set of tables. In some cases numerical guidelines are provided, expressed in appropriate metrics. When there were insufficient data to support numerical values, the *relative* likelihood of effects occurring was evaluated, although the *actual* likelihood of effects depends on the received level. These sound exposure guidelines, which are based on the best scientific information at the time of writing, should be treated as interim. The expectation is that with more research, the guidelines can be refined and more cells in the tables completed. Recommendations are put forward defining the research requirements of highest priority for extending these interim exposure guidelines.

# Foreword

*[This Foreword is for information only, and is not a part of the Technical Report ASA S3/SC1.4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles.]*

This Technical Report comprises a part of a group of definitions, standards, and specifications for use in animal bioacoustics. It was developed and approved by Accredited Standards Committee S3/SC 1 Animal Bioacoustics, under its approved operating procedures. Those procedures have been accredited by the American National Standards Institute (ANSI). The Scope of Accredited Standards Committee S3/SC 1 is as follows:

Standards, specifications, methods of measurement and test, instrumentation, and terminology in the field of psychological and physiological acoustics, including aspects of general acoustics which pertain to biological safety, tolerance, and comfort of non-human animals, including both risk to individual animals and to the long-term viability of populations. Animals to be covered may potentially include commercially grown food animals; animals harvested for food in the wild; pets; laboratory animals; exotic species in zoos, oceanaria or aquariums; or free-ranging wild animals.

Publication of this Technical Report that has been registered with ANSI has been approved by the ANSI-Accredited Standards Committee S3/SC 1, Animal Bioacoustics. This document is registered as a Technical Report according to the Procedures for the Registration of Technical Reports with ANSI. This document is not an American National Standard and the material contained herein is not normative in nature. Comments on the content of this document should be sent to Standards Secretariat of the Acoustical Society of America, 1305 Walt Whitman Rd., Ste. 300 Melville, New York 11747-4300. Telephone: 631-390-0215; FAX: 631-923-2875; E-mail: [asastds@aip.org](mailto:asastds@aip.org).

As required by ASC S3/SC 1's operating procedures, this Technical Report will be subjected to periodic review by ASC S3/SC 1 at least every five years. However, it is possible that the committee will revise or withdraw it at any time. Users should check to confirm if a newer version is available.

The rationale for publishing this technical report is detailed in the Introduction.

At the time this Technical Report was submitted to Accredited Standards Committee S3/SC 1, Animal Bioacoustics, for approval the membership was as follows:

D.K. Delaney, *Chair*  
M.C. Hastings, *Vice Chair*  
S.B. Blaeser, *Secretary*

---

Acoustical Society of America	M.C. Hastings
American Academy of Otolaryngology, Head and Neck Surgery	R.A. Dobie
American Speech-Language-Hearing Association	B.M. Ryals
	N. DiSarno (Alt.)
G.R.A.S. Sound & Vibration	J. Soendergaard
	B. Schustrich (Alt.)
International Association of Geophysical Contractors	S. Tsoflias
National Oceanographic and Atmospheric Administration	J. Gedamke
	A. Scholik-Schlomer (Alt.)
National Park Service	K. Frstrup
	M. McKenna (Alt.)
Ocean Conservation Research	M. Stocker
SpeakDolphin.com	J. Kassewitz
	S. Kuczaj (Alt.)
U.S. Army Aeromedical Research Lab	W.A. Ahroon
U.S. Army Construction Engineering Research Laboratory	D.K. Delaney
	M.J. White (Alt.)
U.S. Navy Marine Mammal Program	J.J. Finneran
	D.S. Houser (Alt.)
University of Cincinnati Animal Audiology Clinic/Bioacoustics Lab	P.M. Scheifele
	D.K. Brown (Alt.)

---

Working Group S3/SC 1/WG 2, Effects of Sound on Fish and Turtles, which assisted Accredited Standards Committee S3/SC 1, Animal Bioacoustics, in the development of this Technical Report, had the following membership.

R.R. Fay, Co-Chair  
A.N. Popper, Co-Chair

S. Bartol	R.L. Gentry	P.H. Rogers
T.J. Carlson	M.B. Halvorsen	B.L. Southall
S. Coombs	A.D. Hawkins	W.N. Tavolga
W.T. Ellison	S. Løkkeborg	D.G. Zeddies
	D.A. Mann	

# Keywords

Acoustics, Active Sonar, Anthropogenic, Airgun, Air-gun, Audiogram, Auditory Scene Analysis, Barotrauma, Behavior, Criteria, Ear, Eggs, Damage, Directional Hearing, Explosions, Explosives, Fitness, Frequency Weighting, Hearing, Injury, Intensity, Larvae, Lateral Line, Masking, Noise, Particle Motion, Peak, Pile Driving, Pressure, PTS, RMS, Scene Analysis, Seismic Airgun, Ship, Sonar, Sound Exposure Level, Swim Bladder, Threshold, Threshold Shift, TTS

# Acknowledgements

The need for this panel was identified by Roger Gentry, then at NOAA in the U.S. Department of Commerce. He and Brandon L. Southall, also then at NOAA, identified the original panel members and allocated NOAA funds for its first three meetings. Subsequently, support for the meetings was provided by the National Science Foundation, the Office of Naval Research, and the Joint Industry Program (JIP) of the Oil and Gas Producers Association. Additional funds and support were provided by the Acoustical Society of America (ASA). We are grateful to all of these agencies for their support. Most of our meetings took place at the Mote Marine Laboratory in Sarasota, Florida. We want to thank the staff at Mote for their hospitality and their efforts to make the meetings comfortable and productive. We are grateful to members of the ANSI-Accredited Standards Committee S3/SC 1, Animal Bioacoustics, which is sponsored by the Acoustical Society of America, for their thorough and very useful review of this MS. Finally, we thank Dr. Peggy Edds-Walton for editing the final MS and Susan Blaeser of ASA for additional thoughtful suggestions.

# Contents

<b>1</b>	<b>Introduction</b> .....	1
1.1	Background.....	1
1.2	Background Literature.....	2
1.3	Terminology.....	3
<b>2</b>	<b>Aquatic Organisms of Concern</b> .....	5
2.1	Fishes.....	5
2.2	Sea Turtles.....	6
2.3	Eggs and larvae.....	6
<b>3</b>	<b>Hearing – A General Overview</b> .....	7
3.1	Fish Hearing: Sensitivity to Sound.....	7
3.2	Lateral Line System.....	10
3.3	Turtle Hearing.....	11
3.4	Masking.....	12
3.5	Auditory Scene Analysis.....	13
3.6	Directional Hearing.....	13
<b>4</b>	<b>Classification of Fishes and Sea Turtles with Respect to Sound Exposure Risk</b> .....	15
4.1	Fishes.....	15
4.2	Sea Turtles.....	16
4.3	Larval Fish.....	16
4.4	Categories.....	16
<b>5</b>	<b>Effects of Sound Exposure</b> .....	17
5.1	Death and Injury.....	17
5.2	Effects on Hearing.....	18
5.3	Effects on Behavior.....	19
5.4	Population-Level Effects on Fitness and Survival.....	20

- 6 The Nature of Man-Made Sound**..... 23
  - 6.1 Metrics ..... 24
    - 6.1.1 Sound Pressure..... 24
    - 6.1.2 Particle Motion..... 24
    - 6.1.3 Peak Levels ..... 25
    - 6.1.4 Sound Intensity ..... 25
    - 6.1.5 Impulse..... 26
    - 6.1.6 Sound Exposure Level ..... 26
    - 6.1.7 Cumulative Energy (Cumulative Sound Exposure Level) ..... 26
    - 6.1.8 Frequency Weighting ..... 27
  - 6.2 Sources..... 28
    - 6.2.1 Explosions..... 28
    - 6.2.2 Seismic Airguns ..... 29
    - 6.2.3 Pile Driving ..... 30
    - 6.2.4 Active Sonar..... 31
    - 6.2.5 Continuous Sound Sources ..... 31
- 7 Sound Exposure Guidelines** ..... 33
  - 7.1 Current Guidelines for Injury..... 33
  - 7.2 Current Guidelines for Behavior..... 35
  - 7.3 Practical Approach to Recommending Sound Exposure Guidelines ..... 36
  - 7.4 Explanation of the Analyses ..... 37
  - 7.5 Guidelines ..... 37
    - 7.5.1 Source: Explosions..... 37
    - 7.5.2 Source: Pile Driving..... 41
    - 7.5.3 Source: Seismic Airguns..... 44
    - 7.5.4 Source: Low- and Mid-Frequency Naval Sonar ..... 47
    - 7.5.5 Source: Shipping and Other Continuous Noises..... 49
- 8 Research Recommendations** ..... 53
  - 8.1 General Comments..... 53
    - 8.1.1 The Importance of Providing an Appropriate Acoustic Environment for Experiments..... 53
    - 8.1.2 The Difficulties in Examining Behavior ..... 54
    - 8.1.3 The Diversity of Fishes and Sea Turtles ..... 55
  - 8.2 Research Requirements of Highest Priority..... 55
    - 8.2.1 Fishes ..... 55
    - 8.2.2 Eggs and Larvae..... 57
    - 8.2.3 Sea Turtles..... 57
- 9 Summary and Conclusions**..... 59
- References**..... 61

# Chapter 1

## Introduction

### 1.1 Background

In many countries, legislation requires the assessment of sound-producing activities that may have an impact on animals in the aquatic environment (TNO 2011; Johnson 2012; Lewandowski et al. 2012; Tasker 2012, 2015; Dekeling et al. 2015; Gedamke et al. 2015). There is also often a requirement to prepare environmental assessments or statements that can lead to mitigation measures and/or restrictions for proposed activities. Because few scientific data are available regarding the effects of sound, particularly for fishes and sea turtles, assessment procedures and subsequent regulatory and mitigation measures are often severely limited in their relevance and efficacy. This creates uncertainty among all stakeholders as to how sound-producing exploration and operations should proceed.

In 1998 the U.S. National Oceanic and Atmospheric Administration (NOAA) convened an international panel of experts to prepare noise exposure guidelines for marine mammals. NOAA's intent was to provide its regulatory staff with the means of issuing permits on underwater noise production based on a set of organized principles and facts instead of on a case-by-case basis. The aim was to reduce regulatory uncertainty for all stakeholders by replacing precaution with scientific facts. The panel's initial guidelines appeared in a seminal paper (Southall et al. 2007).

In 2004, NOAA convened a similar panel to develop noise exposure criteria for fishes and turtles with the same goals in mind. It included three members of the marine mammal panel (WTE, RLG, and BLS) for continuity. When NOAA's support for this effort ended in 2006, the panel was organized as a Working Group (WG) under the ANSI-Accredited Standards Committee S3/SC 1, Animal Bioacoustics, which is sponsored by the Acoustical Society of America.

In addition, this Working Group, through its own efforts, obtained external funding for the project (see Acknowledgements). The Working Group met eight times between 2004 and 2010. It gathered and reviewed papers from both the peer-review and grey literature that presented data on the exposure of fish and sea turtles to